Original Investigation

Body Weight-Based Protocols During Whole Body FDG PET/CT Significantly Reduces Radiation Dose without Compromising Image Quality: Findings in a Large Cohort Study

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Rationale and Objectives: To investigate radiation dose reduction during whole body fluorodeoxyglucose (^{18}F-FDG) positron emission tomographic (PET)/computed tomography (CT) by employing weight-based protocols.

Materials and Methods: One thousand and twenty-eight patients were referred for ^{18}F-FDG PET/CT study with one of two protocols: conventional protocol I; 120 kVp, 120 mAs, 0.5 second rotation time, pitch 0.8 mm/rot across all body weights; four-tier body weight protocol II all used 140 kVp, 0.75 seconds rotation time and pitch 0.8 mm/rot: Protocol A ($\leq$60 kg): 35 mAs, Protocol B (61–80 kg): 50 mAs, Protocol C (81–100 kg): 65 mAs, and Protocol D: (>101 kg): 100 mAs. All protocols employed tube current modulation. Quantitative and qualitative image visual grading characteristics assessed image quality.

Results: Patient demographics demonstrated no significant difference between each protocol except for patient weight in weight protocol IIB ($p < 0.009$). Mean effective dose in all protocols were significantly lower in Protocol B compared to A ($p < 0.009$). Contrast-to-noise ratio demonstrated no differences between each protocol ($p < 0.21$) except for weight protocol in protocol IIA (<60 kg, $p = 0.035$) with the visual grading characteristics demonstrating preference over protocol II compared to I.

Conclusion: Significant reduction in radiation dose can be achieved using patient-specific body weight-based protocols during whole-body ^{18}F-FDG PET/CT without compromising image quality when employing weight-based protocols.

INTRODUCTION

Positron emission tomography computed tomography (PET/CT) has emerged clinically as an anatomical and functional imaging modality in oncology patients. This hybrid approach has resolved the limitations of spatial resolution of PET in the absence of clearly visible anatomic landmarks (1,2). However, with limited spatial resolution of PET, radiation exposure can be of concern due to the combined effects of ionizing radiation of both the PET and CT radiation (3).

International recommendations for the dose of ^{18}F-fluorodeoxyglucose (^{18}F-FDG) activity in PET/CT provides two options for administered FDG doses; first, dose range between 370 and 470 MBq (4,5) and second, weight-based ^{18}F-FDG dosing (6). There have been a series of studies aimed at reducing FDG dose to patients (7); however, with the ever expanding use of PET/CT, the CT component is now under another focus of investigation to further reduce the overall radiation dose administered to patients during PET/CT (8).

Radiation dose characterization, optimization, and reference levels based on the CT dose index concept have been well-studied and understood for diagnostic CT (9,10). Dose reference levels have been established in the United States and Europe for diagnostic CT based on the 75th percentile of CT dose index values recorded from national surveys of different body regions (11).

Acad Radiol 2018; ■:1–6

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https://doi.org/10.1016/j.acra.2018.07.014

Epidemiologic studies have shown a correlation between exposure to low-dose, ionizing radiation with the development of solid cancers and leukemia (12). Radiation exposure in patients who undergo PET/CT procedures are typically monitored; however, patient data on longitudinal radiation exposure from these procedures is inadequate, even though in clinical practice these types of procedures are frequently performed multiple times in the same patient in short periods of time. Typical PET/CT radiation dose ranges from 2.5 to 33 mSv (13−15). The aim of our study is to investigate radiation dose reduction during head-to-toe ^{18}F-FDG PET/CT by employing CT weight-based protocols.

MATERIALS AND METHODS

Patient Selection

The institutional review board approved this retrospective study and waived written informed consent. Patients were referred by oncologists for PET/CT studies between February 2014 and December 2015. One thousand and twenty-eight consecutive patients underwent ^{18}F-FDG PET/CT study using a 16-detector PET/CT (Gemini TF PET/CT, Philips Healthcare, The Netherlands). The 18F-FDG dose calculation and administration occurred employing an automatic dose injector that determined the volume of 18F-FDG by employing body mass index calculation approach and a ± 2% dose accuracy (6).

CT Scanning Parameters

Patients were allocated to one of two scanning protocols equally: protocol I, the conventional protocol; 120 kVp, 120 mAs, 0.5 seconds rotation time, pitch 0.8 mm/rot across all body weights; protocol II, employed a four-tier body weight protocol II all used 140 kVp, 0.75 sec rotation time and pitch 0.8 mm/rot: Protocol A (≤60 kg): 35 mAs, Protocol B (61−80 kg): 50 mAs, Protocol C (81−100 kg): 65 mAs, and Protocol D: (>101 kg): 100 mAs with all protocols employing tube current modulation. Protocol B employed body weight-based protocols based on three factors; first, employing a 140 kVp allows the reduction of hard beam artifacts from the shoulders and pelvis (16); and second, with a higher kVp, the ability to employ lower mA energies when automatic exposure control is not used which results in radiation dose variability (17). Finally, changing the rotation time in larger weight-based groups allows a slower rotation time, which results in greater time for the photons leaving the X-ray tube and being detected by the detector. Therefore, with weight-based protocols, the variability of patient dose is further reduced (17).

Image Assessment

CT transaxial images were reconstructed with 5 mm slice thickness (5 mm increment) using a smoothing convolution kernel (field of view, 380 × 380 mm; image matrix, 512 × 512). Image quality was assessed using a reporting workstation (IMPAX 6.3.1, AGFA) with greyscale standard display function (GSDF)-calibrated 3 megapixel monitor included attenuation measurements, visual grading characteristic (VGC) techniques to evaluate image artifacts.

Contrast-to-Noise Ratio Measurement

Contrast-to-noise ratio (CNR) analysis was calculated employing a 5 mm transaxial image. The Region of Interest (ROI) was drawn as large as the vessel lumen diameter carefully avoiding calcified and/or soft plaques of the vessel wall. When calculating the CNR, the attenuation of the right psoas muscle (ROI_{PSM}) was measured at the level of the 1st lumbar vertebra followed by the second measurement of noise in the radiograph (average of all four corners of the image; Fig 1). Mean attenuation for each patient was measured at the level of the renal bifurcation in the abdominal aorta (ROI_{AA}). Finally, the CNR was calculated based on the measured parameters described previously with an empirically derived formula; $CNR = (ROI_{AA} - ROI_{PSM})/Noise$.

Radiation Dose Estimation

For each of the CT-scans, individual effective dose (E_{ff} [mSv]) was calculated from the dose-length products value (DLP [mGy × cm]), which was recorded from the patient's protocol. A modified conversion factor (k [mSv/mGy × cm]) of 0.013 mSv/mGy/cm and sex-specific conversion factors of 0.012 and 0.014 mSv/mGy/cm for men and women (18) respectively was used to calculate the E_{ff} (19): $E_{ff} = DLP \times k$.

VGC Analysis

Two nuclear medicine radiologists who had been certified by the French Society of Nuclear Medicine and the American Board of Radiology/American Board of Nuclear Medicine respectively for a mean of 9 years (minimum, 2 years; maximum, 16 years) assessed the images. Each observer was allowed to manipulate the window width and level of the images. Same images were anonymously presented during both sittings and a score of 1−5 assigned where 5 indicates that there were no artifacts and excellent image quality and 1 represented poor image quality with definite artifacts. The VGC method of Bath and Mansson (20) was used to illustrate viewer preference of one technique over another based on the visibility of normal anatomy.

Statistical Analysis

Descriptive statistics and nonparametric Mann−Whitney U independent t tests were employed to compare gender, age, height, weight, body mass index, body surface area, AP and transverse lengths, abdominal circumference, and Eff. Results were considered statistically significant if $p \leq 0.05$.

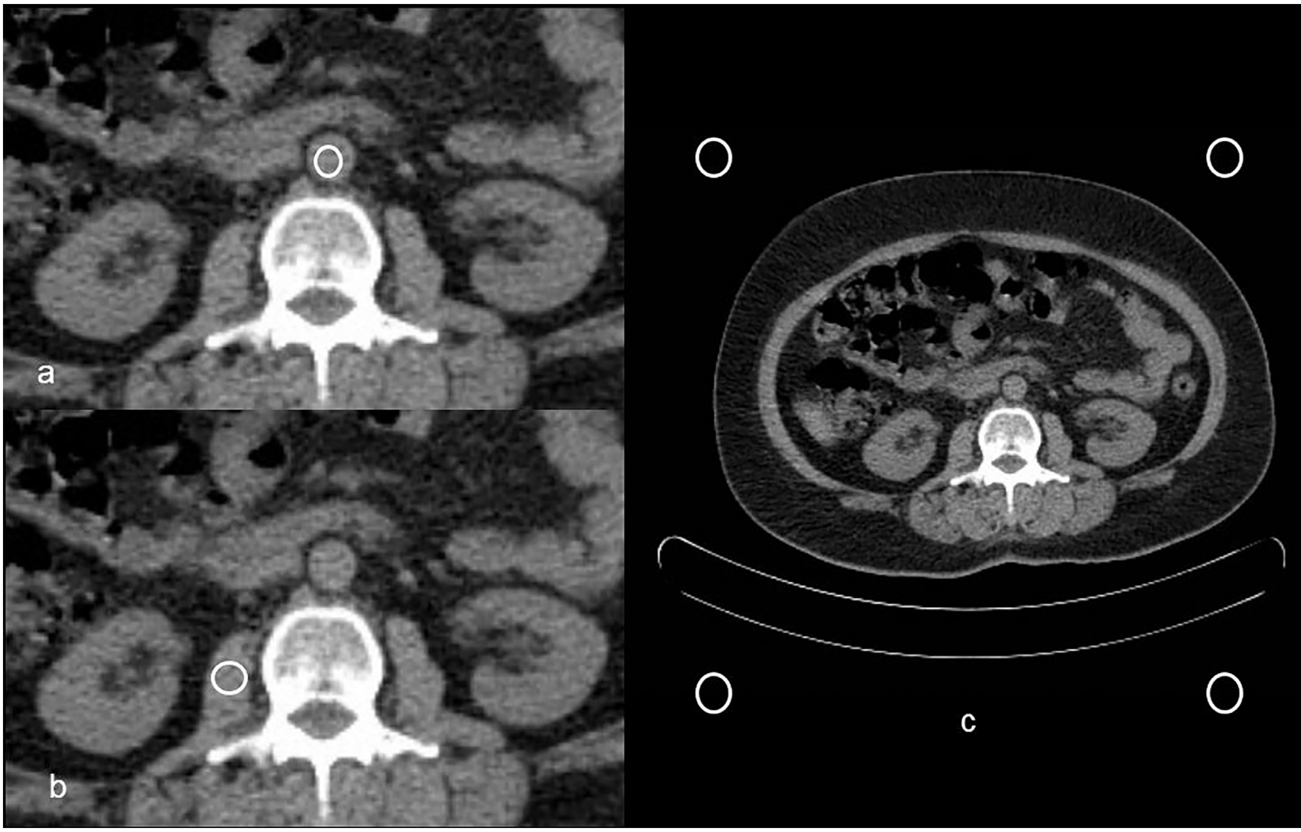

Figure 1. A. 45-year-old male with primary lung carcinoma demonstrates an axial abdominal CT scan at the level of the first lumbar vertebra. Images a and b demonstrate the region of interest placed on the abdominal aorta and right psoas major muscle respectively. Image c demonstrates the four regions of interest placed at each corner of the image where the average of these four was taken as the mean noise value.

The inter- and intraobserver agreements were calculated using Cohen's kappa analysis. A k range value of 0.60−1, 0.41−0.60, 0.21−0.40, and less than 0.20 was considered excellent, moderate, fair, and poor agreement, respectively.

RESULTS

Patient Demographics, Body Habitus, and Effective CT Radiation Dose

There were no significant differences in patient sex, age, height, weight, body mass index, and body surface area (Table 1). Effective CT radiation dose demonstrated significant reductions in protocol II compared to I by up to 43% ($p < 0.001$), with no significant difference in injected ^{18}F-FDG dose (Table 1).

Quantitative and Qualitative Image Assessment

The quantitative scores demonstrated no statistical difference in the CNR between each protocol (Table 1) with the inter- and intrareader agreement being equal across both protocols. The qualitative scores were individually graded by the two readers (R1 and R2) and were expressed as a graph shown in Figure 2. Diagnostic performance was then compared by calculating the area under the curve differences from each of the VGC curve analysis. Calculating the difference between each reader, the graphs show an area under the curve = 0.62 and 0.67, with a 95% confidence interval of 0.52−0.747 ($p <$ 0.018−0.035; Fig 2).

Discussion

The use of PET/CT scanning in a clinical setting is rapidly evolving with advances in medicine. It carries potential risk from radiation exposure that should be quantified and understood so that risk-benefit ratios can be assessed. There have been significant advances in reducing the dose of ^{18}F-FDG delivered with automatic body-weight-based protocols (21) and advances in detector technology (22). However, the CT component has been overlooked with numerous strategies to reduce radiation dose by weight-based protocols for pediatrics (23) and adults (21) with or without the use of automatic tube modulation; however, proposed protocols for CT can be difficult to translate into clinical practice due to its complexity. Our study investigated a simple and effective weight-based CT scanning protocol that significantly reduced both radiation dose male and female populations. The results are important from both an individual and a public health perspective, especially oncology patients who will have reoccurring tests for disease status and staging.

TABLE 1. Patient Demographics, Radiation Dose, and Contrast-to-Noise Ratio

	Protocol A	Protocol B	p Value
<60 kg			
Height (m)	1.52 ± 0.26	1.55 ± 0.13	0.931
Weight (kg)	49.74 ± 11.08	49.85 ± 11.71	0.602
BMI (kg/m^2)	70.46 ± 312.63	20.53 ± 3.77	0.967
BSA (m^2)	14.31 ± 2.81	14.54 ± 2.47	0.526
Radiation dose			
DLP (mGy-cm)	1135.94 ± 317.03	547.14 ± 83.24	0.001
CTDI$_{vol}$ (mGy)	6.68 ± 1.97	3.21 ± 0.72	0.001
CNR	−1.17 ± 3.28	0.27 ± 2.54	0.035
^{18}F-FDG (mCi)	5.45 ± 1.32	5.26 ± 1.18	0.312
61−80 kg			
Height (m)	1.63 ± 0.145	1.62 ± 0.09	0.230
Weight (kg)	69.26 ± 5.43	69.39 ± 5.69	0.884
BMI (kg/m^2)	28.26 ± 23.36	26.54 ± 3.30	0.189
BSA (m^2)	17.67 ± 1.27	17.67 ± 0.94	0.682
Radiation dose			
DLP (mGy-cm)	1243.85 ± 277.88	786.39 ± 78.01	0.001
CTDI$_{vol}$ (mGy)	7.29 ± 1.69	4.40 ± 0.48	0.001
CNR	0.51 ± 2.83	0.85 ± 3.48	0.778
^{18}F-FDG (mCi)	6.60 ± 1.39	6.68 ± 1.08	0.313
81−100 kg			
Height (m)	1.67 ± 0.11	1.68 ± 0.96	0.583
Weight (kg)	87.76 ± 5.22	85.61 ± 5.36	0.009
BMI (kg/m^2)	31.77 ± 4.46	30.57 ± 3.85	0.152
BSA (m^2)	20.17 ± 0.94	19.98 ± 0.89	0.200
Radiation dose			
DLP (mGy-cm)	1278.46 ± 274.25	994.06 ± 103.69	0.001
CTDI$_{vol}$ (mGy)	7.45 ± 1.59	5.42 ± 044	0.001
CNR	0.92 ± 2.37	0.43 ± 1.90	0.118
^{18}F-FDG (mCi)	7.26 ± 1.33	7.65 ± 1.09	0.319
>101 kg			
Height (m)	1.65 ± 0.22	1.31 ± 52.36	0.115
Weight (kg)	112.96 ± 12.95	134.65 ± 28.41	0.39
BMI (kg/m^2)	47.87 ± 37.97	46.89 ± 42.18	0.36
BSA (m^2)	22.62 ± 1.11	21.21 ± 3.70	0.186
Radiation dose			
DLP (mGy-cm)	1648.86 ± 302.54	1272.62 ± 569.69	0.009
CTDI$_{vol}$ (mGy)	9.36 ± 1.62	7.02 ± 2.99	0.009
CNR	0.385 ± 1.40	2.85 ± 8.89	0.394
^{18}F-FDG (mCi)	7.59 ± 1.96	7.83 ± 1.94	0.158

BMI, body mass index; BSA, body surface area; CNR, contrast-to-noise ratio; CTDI, CT dose index; DLP, dose-length products; fluorodeoxyglucose, FDG.

Note: Data are mean ± standard deviation.

Obesity affects both CT and PET image quality because of high photon attenuation and scatter. Therefore, we attempted to make adjustments to the CT acquisition protocols based on patient weight to optimize CT image quality. In this study, we demonstrated no changes in quantitative (CNR) image quality. In qualitative image quality (VGC), there was preference in image quality in protocol II (weight-based protocols) compared to that of I across all age and weight protocols respectively.

This study had several limitations. First, the CNR was analyzed retrospectively at a single level and not throughout each compartment such as the head, neck, chest, abdomen, and pelvis. Second, we did not measure quantitatively and qualitatively PET image quality. Finally, we did not perform the sensitivity and specificity in lesion detection as we only employed nonenhanced CT scans from head to toe.

In summary, we propose whole-body ^{18}F-FDG PET/CT protocols for four adult patient weight categories. The use of multiple categories allows for the refinement of acquisition settings to minimize dose while achieving optimal image quality at the lowest possible radiation dose.

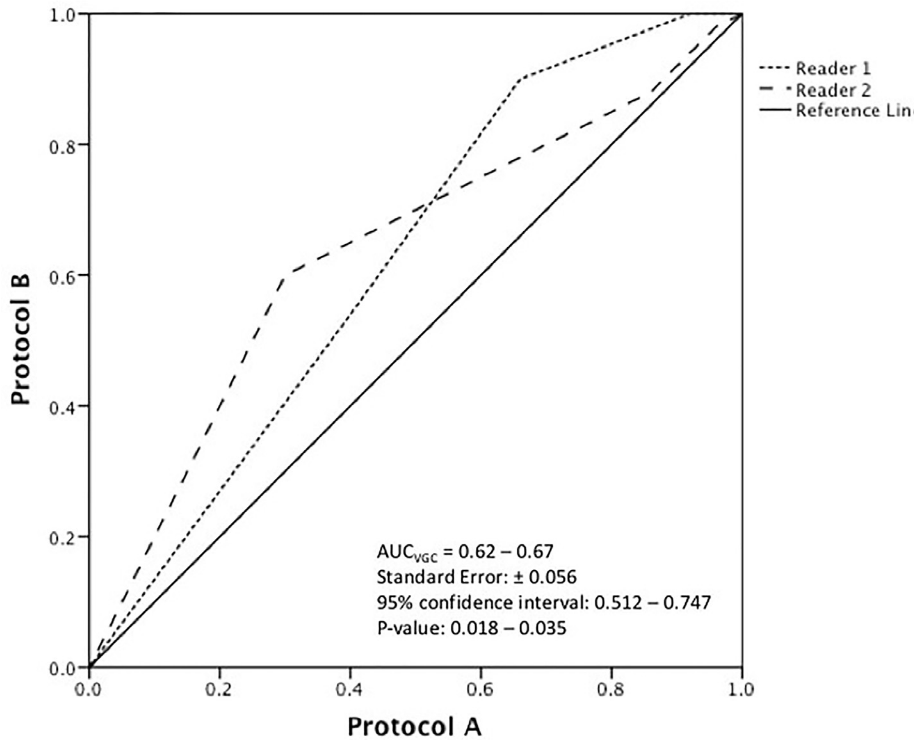

Figure 2. Visual grading characteristic curve. The graph represents positive agreement in image quality with weight-based radiation dose protocols.

CONFLICT OF INTEREST

None by all authors.

IRB APPROVAL

This study is approved by the Institution review board (RAD. MH.01) at the American University of Beirut.

ACKNOWLEDGMENTS

We would like to thank Dr. Mukbil Hourani for his administrative support and Dr. Mohammad Haidar for image interpretation and writing assistance for this study.

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