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JOURNAL CLUB: CT Dose Optimization for Whole-Body PET/CT Examinations

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OBJECTIVE. The objective of this study was to optimize CT protocols for whole-body PET/CT by reducing radiation dose while minimizing effects on image quality.

MATERIALS AND METHODS. Before protocol optimization, a survey of 140 consecutive patients was conducted to establish the baseline dose from a whole-body PET/CT examination. Another sample of 100 patients was surveyed to evaluate the reduction of radiation dose after implementation of the new protocol. Effective dose from the CT component of the examination was estimated using dose-length product (DLP) values from reports generated by the scanner and anatomy-specific conversion factors. Twenty-six patients who underwent studies before and after the optimization were included in an analysis of image quality. All 26 patients had maintained the same weight between the examinations and were scanned in the same position using a similar technique except for the changes made for CT dose optimization. The studies were randomized and blinded for an experienced PET and CT reader who graded the imaging quality of anatomic structures.

RESULTS. CT protocol optimization resulted in a 32% reduction of the mean CT radiation dose: The mean effective dose was reduced from 8.1 to 5.5 mSv. The blinded analysis of image quality showed no clinically significant degradation of the lower-dose studies. The only structures visualized statistically better on the higher-dose CT scans were the carotid arteries and the region of the posterior triangle.

CONCLUSION. The results of this study showed that optimization of CT acquisition can effectively reduce radiation dose in a whole-body PET/CT examination without significantly sacrificing image quality.

PET/CT has shown improved diagnostic accuracy, sensitivity, and specificity over PET or CT alone [1, 2]. The CT component of PET/CT is described as "nondiagnostic"; it is used for attenuation correction of the PET data, allows anatomic localization of regions shown on PET images, and does provide some limited anatomic diagnostic information. In recent years the clinical applications of this hybrid modality have rapidly expanded, especially in oncologic diagnosis, staging, and treatment planning and in assessing response to therapy [3, 4]. However, PET/CT examinations result in increased radiation exposure from the combined PET and CT components of the scan [5–7]. The PET effective dose is determined by the injected activity and typically does not exceed 22 mSv [8]. The radiation dose from the CT component depends on the technique used to acquire the images. A typical average effective dose to the head or neck, chest, abdomen, and pelvis is 3, 7, 8, and 6 mSv, respectively [9], making the effective dose for whole-body CT equal to 24 mSv and the total PET/CT dose equal to 46 mSv [8]. Patients often undergo multiple follow-up studies that further contribute to cumulative radiation dose, increase lifetime attributable risk of cancer incidence [10], and add more radiation dose to the already high dose burden of radiotherapy patients.

There are different approaches to reduce patient dose in PET/CT. For the PET component, the method to minimize dose is reducing the amount of the injected radiopharmaceutical (most often ^{18}F-labeled FDG); however, if activity is too low, it may compromise image quality. Increasing the duration of scanning per bed position can help mitigate the dose, but this change may increase patient motion artifacts and decrease scanner throughput [8]. Reducing dose from the CT component of PET/CT is another method of dose optimization. Various meth-

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ods and strategies based on CT technology have been explored for dose reduction [11–13]. When CT is used only for attenuation correction of the PET data, the range of exposure settings that can be used is extremely wide; however there are limitations if the CT data are also used for anatomic localization [14–16]. Careful consideration of the acquisition parameters is required to achieve low patient dose with acceptable image quality.

The goals of this investigation were optimization of clinical CT acquisition protocols for whole-body PET/CT, reducing radiation dose without a significant degradation of image quality, evaluating mean patient dose from the examination, and assessing the effect on image quality.

Materials and Methods

All data were acquired on a PET/CT scanner (Discovery STE 16, GE Healthcare). Patients were injected with 407–444 MBq (11–12 mCi) of ^{18}F-FDG and scanned from the head to the mid thighs. The whole-body PET component was performed with a 3-minute acquisition per bed position with the scanner operating in the 3D mode. Normally, scans of 5–7 bed positions were obtained. Estimation of PET radiation dose was based on Publication 80 of the International Commission on Radiological Protection [17], which suggests 0.019 mSv/MBq of administered activity for an adult patient. A nondiagnostic low-dose unenhanced CT protocol developed by the vendor was used only for attenuation correction and anatomic localization of the PET data. The CT data were acquired with a tube voltage of 120 kVp and reconstructed slice thickness of 3.75 mm; automated tube current modulation was used with the tube current varied from 10 to 210 mA.

CT dose increases linearly with scanning time, which is determined by the rotation time and beam coverage (collimation). A lower pitch will generally increase the dose when all other scanning parameters are kept the same, but only certain combinations of detector-array configurations and pitches are allowed on this scanner model. Thus, to increase beam width from 10 to 20 mm, we used a lower pitch. The goal of x-ray tube current modulation is to make all images contain similar quantum noise independent of patient size and anatomy. To achieve that, we adjusted the tube current to maintain a user-selected noise level in the image data, which is determined by noise index on GE scanners. The maximum tube current value may occur in only an extreme case of a very large patient. The peak kilovoltage value is typically adapted to a specific diagnostic task and average patient diameter. For MDCT, the reconstructed slice thickness is determined by detector configuration and has no primary influence on dose. Indirectly, there may be an effect when the tube current–exposure time product (mAs) value increases to compensate for higher noise when thinner slices are selected. However, a higher slice thickness degrades spatial resolution. Based on this, the tube voltage value, tube current range, and reconstructed slice thickness were not changed during optimization. To avoid a sudden degradation in image quality, we modified the scanning parameters in three steps: First, the x-ray tube rotation time was decreased from 0.8 to 0.5 second; second, the x-ray beam collimation was changed from 16 × 0.625 mm to 16 × 1.25 mm and pitch was changed from 1.75 to 1.35; and, third, the noise index was gradually increased in small increments from 25 to 27.1. The details of the protocol modification are summarized in Table 1.

TABLE 1: CT Protocol Parameters Before and After Optimization

Parameter	Initial Protocol	Optimized Protocol
Noise index	25	27.1
Pitch	1.75	1.35
Rotation time (s)	0.8	0.5
Beam collimation (mm)	16 × 0.625	16 × 1.25

Note—Tube voltage of 120 kVp, automated tube current modulation range of 10–210 mA, and reconstructed slice thickness of 3.75 mm were used for both protocols.

To assess radiation dose from the CT component of the examination, we used dose-length product (DLP) values from the scanner-generated dose reports and a conversion factor—that is, the region-specific normalized effective dose per DLP (mSv × mGy^{-1} × cm^{-1}) [18]. Effective dose (*ED*) was estimated as the product of the *DLP* and the corresponding conversion factor (*k*):

$$ED\ (\text{mSv}) \approx k \times DLP.$$

For the whole-body scan, we used a k value of 0.015 mSv × mGy^{-1} × cm^{-1}, which is the conversion factor suggested for trunk [19]. An initial survey of 140 consecutive patients was conducted before the protocol changes and the mean effective dose was calculated. The patients were not categorized by age, sex, or weight because the same scanning protocol was used with automated tube current modulation, which accounted for differences in patient size. For estimation of the achieved dose savings, we surveyed another 100 consecutive patients scanned after protocol optimization and calculated the mean effective dose using the same method.

To evaluate the impact on image quality, we identified patients who underwent follow-up examinations before and after the optimization. Paired studies of 26 patients who maintained the same weight and were scanned in the same position (arms up) were selected. The studies were blinded and randomized for assessment by an experienced PET and CT reader who is certified by the Royal College of Radiologists in nuclear medicine and diagnostic radiology.

The reader compared studies for 11 anatomic structures and four comprehensive categories including overall quality, noise, contrast resolution, and edge definition. The images were graded using a 4-point scale on the basis of diagnostic acceptability as follows: score of 1, nondiagnostic study; 2, suboptimal study; 3, good study; and 4, excellent study. Mean values and SDs were determined in

TABLE 2: Patient Dosimetry Surveys

Value	Initial Protocol			Optimized Protocol		
	$CTDI_{vol}$ (mGy)	DLP (mGy × cm)	Effective Dose (mSv)	$CTDI_{vol}$ (mGy)	DLP (mGy × cm)	Effective Dose (mSv)
Mean	6.4	536.6	8.1	4.3	368.2	5.5
SD	2.4	222.4	3.3	1.6	145.3	2.1
Minimum	1.7	116.7	1.8	1.5	91.9	1.4
Maximum	10.7	1027.1	15.4	7.1	694.5	10.4

Note—The effective dose was calculated from the dose-length product (DLP) values and the conversion factor (k = 0.015 mSv × mGy−1 × cm−1). $CTDI_{vol}$ = volume CT dose index.

each category. A paired two-tailed Student t test was used to determine the significance of differences between the means of the two distributions (i.e., before vs after optimization). A value of $p < 0.05$ was considered significant.

Results

Optimization of the whole-body CT component used for attenuation correction and anatomic localization of the PET data resulted in a 32% reduction of the mean CT radiation dose: The volume CT dose index ($CTDI_{vol}$) decreased from (6.4 ± 2.4) mGy to (4.3 ± 1.6) mGy, and the effective dose was reduced from (8.1 ± 3.3) mSv to (5.5 ± 2.1) mSv. Table 2 shows the mean, SD, and minimum and maximum values for $CTDI_{vol}$, DLP, and effective dose obtained from the patient analyses. The effective dose from ^{18}F-FDG was 8.1 mSv; therefore, the mean total dose from the examination was reduced by 16%, changing from 16.2 to 13.6 mSv.

The results of the image quality assessment are summarized in Table 3, which shows the means, SDs, and p values for all scoring categories and $CTDI_{vol}$ values. The total group average was 55.81 of 60 for the initial examinations, and it was 54.31 in the follow-up group; however, nine of 26 patients had a higher total score after the optimization. The difference between the means was not statistically significant, with a p value > 0.05 ($p = 0.118$). The difference in $CTDI_{vol}$ values was significant ($p < 0.05$), with a 44.1% dose reduction after the optimization. Only two of 15 graded anatomic structures were found to have statistically significant differences between the initial and the follow-up scans. Those structures were the carotid arteries (mean score before vs after optimization, 3.46 vs 3.00, respectively; $p = 0.020$) and the posterior triangle region (3.81 vs 3.54; $p = 0.016$), but the scans obtained after optimization still maintained diagnostic accuracy for the purpose. The mean scores in most categories were up to 13.3% higher before the optimization; however, the mean scores of two categories—contrast resolution (3.85) and bowel (3.69)—were unchanged. Three anatomic structures had higher mean scores after the optimization: lung parenchyma (mean score before vs after optimization, 3.86 vs 3.92, respectively), airways (3.62 vs 3.73), and bone (3.65 vs 3.77).

Examples of two patient studies are shown in Figures 1 and 2, which show images obtained at the same locations in the upper thorax, lungs, and abdomen obtained before (Figs. 1A–1C and 2A–2C) and after (Figs. 1D–1F and 2D–2F) the optimization. Figure 1 shows a 69-year-old woman patient with a body mass index (BMI) of 24. After the protocol change, the CT study scored 52 points, which was 8.8% lower than the score of the initial scan (57 points). However, there was a substantial dose reduction of 47%: The $CTDI_{vol}$ was decreased from 4.89 to 2.59 mGy. Figure 2 shows images of a 65-year-old woman with a BMI of 29. In this study, the score was de-

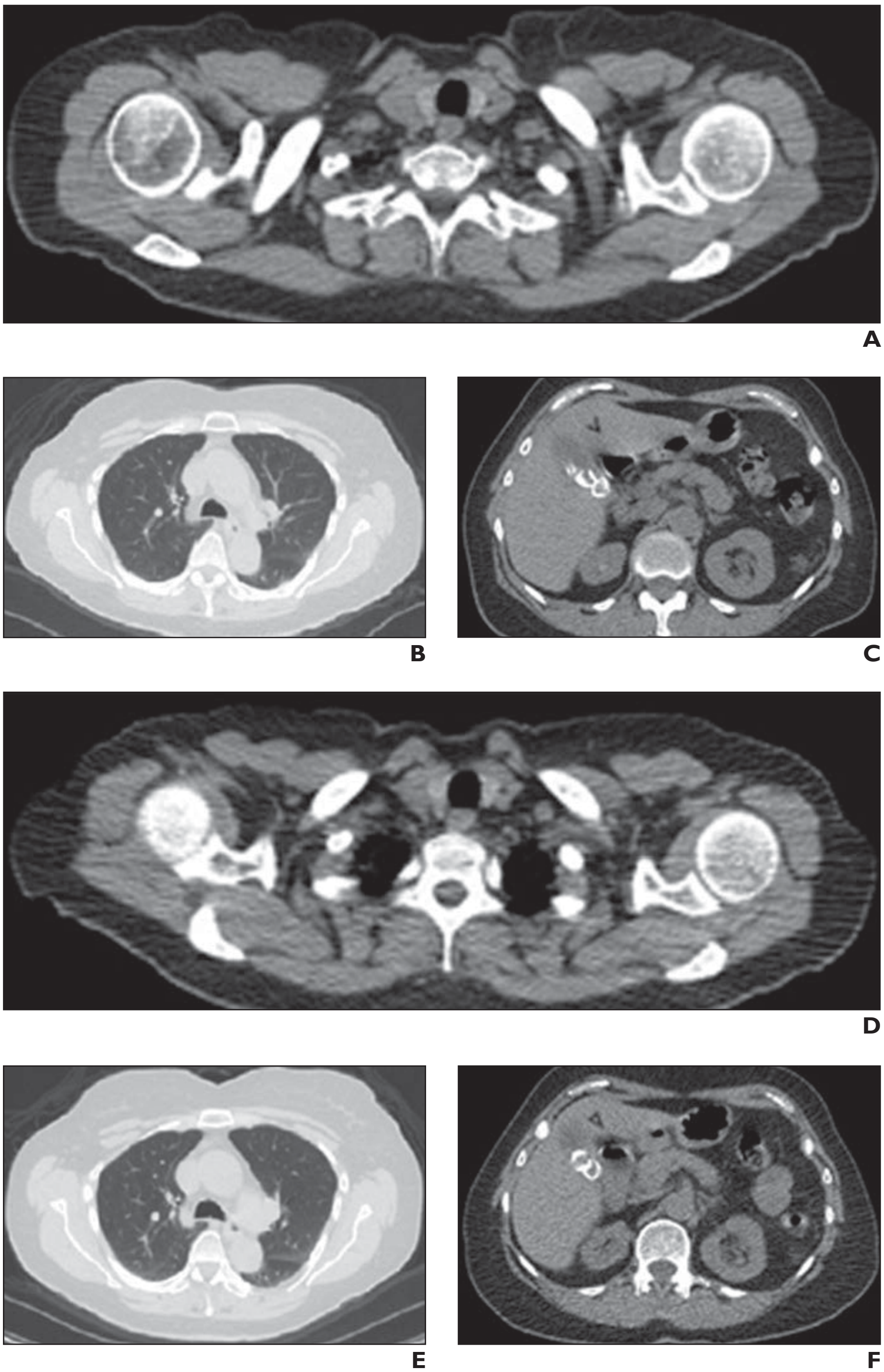

Fig. 1—69-year-old woman with body mass index of 24 who underwent scanning before and after CT protocol optimization. Same slice locations in upper thorax, lungs, and abdomen are shown for comparison.
A–C, Images obtained before optimization. Image quality score was 57 points. Volume CT dose index is ($CTDI_{vol}$) 4.89 mGy.
D–F, Images obtained after optimization. Image quality score was 52 points. $CTDI_{vol}$ = 2.59 mGy.

TABLE 3: Results of the Image Quality Evaluation

Category	Image Quality Score				% Change	p
	Before Optimization		After Optimization			
	Mean	SD	Mean	SD		
Comprehensive						
Contrast resolution	3.85	0.46	3.85	0.37	0	1.000
Edge definition	3.88	0.33	3.69	0.55	5.0	0.057
Noise	3.77	0.43	3.62	0.50	4.1	0.161
Overall quality	3.77	0.51	3.69	0.47	2.0	0.538
Anatomic structures						
Carotid arteries	3.46	0.81	3.00	0.89	13.3	0.020[a]
Thyroid	3.62	0.57	3.35	0.63	7.4	0.090
Posterior triangle	3.81	0.57	3.54	0.58	7.1	0.016[a]
Lung parenchyma	3.85	0.37	3.92	0.27	−2.0	0.327
Airways	3.62	0.50	3.73	0.45	−3.2	0.376
Mediastinal vasculature	3.73	0.45	3.62	0.57	3.1	0.265
Bone	3.65	0.49	3.77	0.43	−3.2	0.376
Adrenals	3.62	0.64	3.50	0.65	3.2	0.265
Kidneys	3.81	0.40	3.69	0.55	3.0	0.185
Liver	3.69	0.47	3.65	0.49	1.0	0.802
Bowel	3.69	0.55	3.69	0.47	0	1.000
Total score	55.81	5.00	54.31	4.48	2.7	0.118
$CTDI_{vol}$ (mGy)	7.21	2.65	4.03	1.71	44.1	4.16E-11[a]

Note—The images were graded using a 4-point scale on the basis of diagnostic acceptability as follows: score of 1, nondiagnostic study; 2, suboptimal study; 3, good study; and 4, excellent study.
[a]Difference was statistically significant ($p < 0.05$).

creased by 6.7% from 60 to 56 points and the $CTDI_{vol}$ was decreased by 42% ($CTDI_{vol}$ before vs after optimization, 8.26 vs 4.79 mGy).

Discussion

We propose a practical approach for radiation dose reduction in the CT component of PET/CT examinations based on shorter scanning time and lower tube current. This dose reduction was achieved with a faster x-ray tube rotation time, increased x-ray beam coverage, and higher noise index value. With the chosen beam collimation, the pitch value had to be decreased because only certain combinations of detector configurations and pitches are allowed on the scanner model we use. However, the overall effect of optimization resulted in decreased radiation dose. Implementation of this new protocol is justified by the results of our image quality evaluation. Comparisons of the same patients' studies performed before and after the optimization revealed statistically insignificant differences in the total score, with only a 2.7% decrease in the mean value. Although the overall average score for the reduced-dose scans was lower, the images of nine of 26 patients had a higher total score after the optimization. Three anatomic structures had a higher score after the optimization, taking advantage of the lower pitch of 1.35. None of the studies performed after the optimization was graded nondiagnostic in any category.

Our CT protocols were designed for the Healthcare Discovery STE system only, which is one of the limitations of this study. Implementation of the same CT techniques on other systems may result in a higher radiation dose. Different vendors suggest different dose reduction methods; therefore every institution needs to develop scanner-specific protocols for implementing those methods.

Another limitation of our study is the a simplified approach that we used to estimate CT effective dose. In recent years, CT dosimetry has become a highly debated topic [20, 21]. The $CTDI_{vol}$ displayed on the scanner console represents a standardized measure of the radiation output of the CT system, which is measured in a cylindric acrylic phantom of 16 cm in diameter for head examinations or 32 cm in diameter for body examinations. The DLP is the product of $CTDI_{vol}$ and scan length. The published conversion factors refer to a normal-sized patient model, which does not consider variations in body size and shape or differences in age and sex. Therefore, it is not recommended to estimate effective dose for an individual patient using the scanner dose metrics [22]. Some authors have determined sex- and age-specific conversion factors [23]; others suggest direct physical measurements of absorbed dose using an anthropomorphic phantom with multiple thermoluminescent or MOSFET (metal oxide semiconductor field effect transistor) detectors [24] or sophisticated Monte Carlo simulations based on voxelized patient models [25]. However, in spite of all the controversy, the $CTDI_{vol}$ and DLP are the only dose parameters that can be universally interpreted and compared with national and international reference values for various clinical applications [26]. Effective dose to an average-size patient, which may be estimated using a DLP value, allows comparison with other diagnostic procedures and with natural sources of radiation [27]. This approach is justified for the purpose of our study. We did not intend to estimate doses for individual patients; our goal was to evaluate dose reduction resulting from the protocol change. For this purpose we compared mean doses from two patient samples surveyed before and after the optimization. When x-ray tube current modulation is used, the $CTDI_{vol}$ and DLP values reflect differences in patient size. The mean values obtained from the patient surveys represent an average patient; therefore, conversion factors may be used for effective dose estimation.

The main contribution to patient dose from a PET/CT examination is from the PET component. The average examination dose was reduced from 16.2 to 13.6 mSv, where 8.1 mSv results from ^{18}F-FDG. The 32% reduction achieved in CT dose contributed to only a 16% reduction in total dose. However, we need to consider the fact that many patients undergo multiple follow-up examinations, increasing their cumulative radiation dose. Most organizations have adopted the linear no-threshold model [28] for radiation-induced cancer risk estimation; therefore each radiation exposure contributes to lifetime attributable risk. Huang et al. [10] have shown that for a 20-year-old woman, the lifetime attributable risk of cancer incidence is 0.016% per mSv. Therefore, the lifetime attributable risk of cancer incidence associated with radiation dose from one PET/CT study in our institution was 0.259% before CT dose reduction and 0.217% after the optimization. In our patient population, a 20-year-old woman with non-Hodgkin's lymphoma underwent nine whole-body PET/CT examinations over 3 years; the first PET/CT study was performed when she was 17 years old. Considering that this patient received an average radiation dose from the examination, her lifetime attributable risk of cancer incidence associated with PET/CT would be 1.958%, which was reduced by 0.374% due to CT protocol optimization.

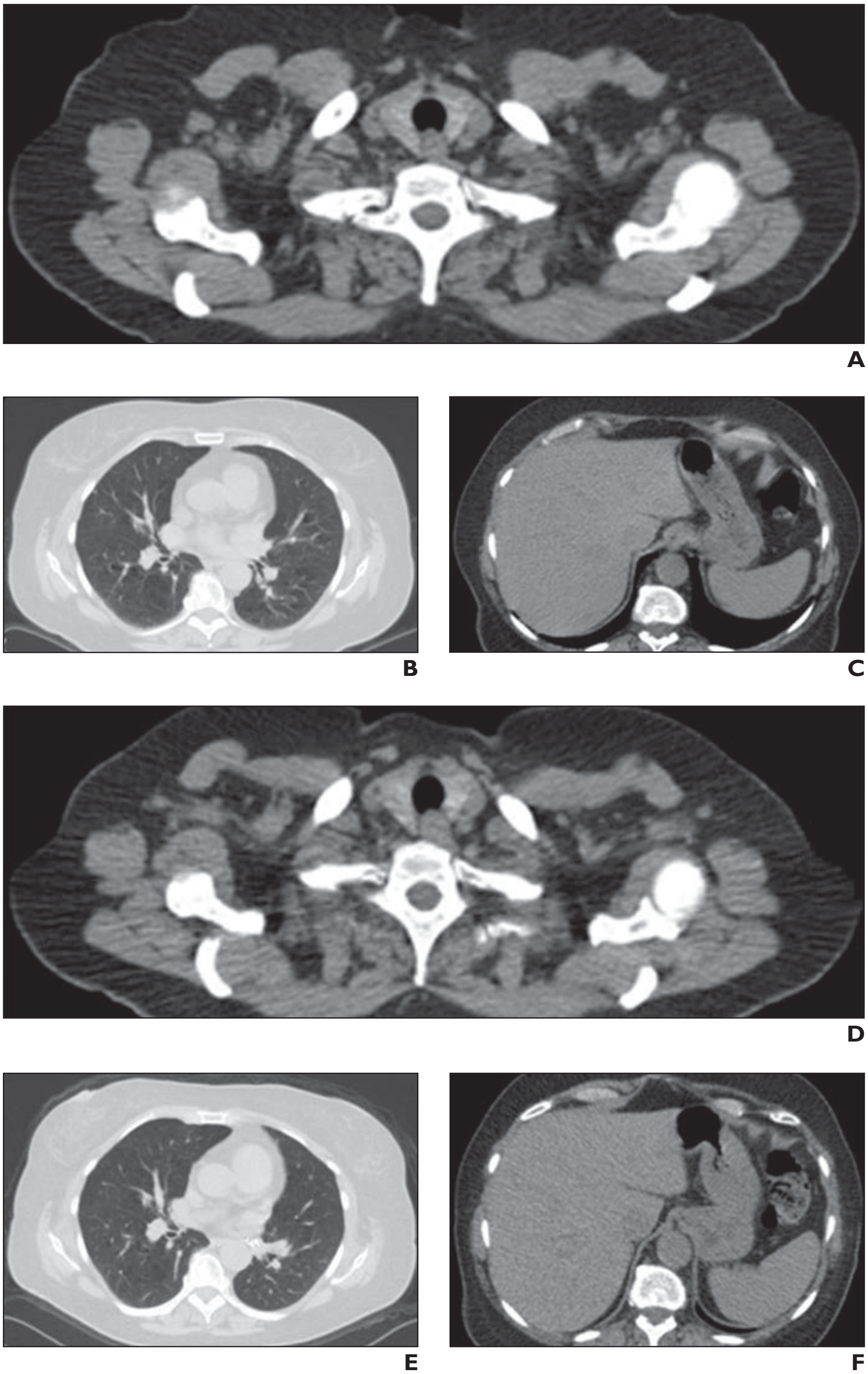

Fig. 2—A 65-year-old woman with body mass index of 29 who underwent scanning before and after CT protocol optimization. Same slice locations in upper thorax, lungs, and abdomen are shown for comparison.
A–C, Images obtained before optimization. Image quality score was 60 points. Volume CT dose index is ($CTDI_{vol}$) 8.26 mGy.
D–F, Images obtained after optimization. Image quality score was 56 points. $CTDI_{vol}$ = 4.79 mGy.

Conclusion

We developed a low-dose CT protocol for attenuation correction and anatomic localization of PET data in whole-body PET/CT examinations and found that optimization of CT acquisition can effectively reduce PET/CT radiation dose without sacrificing image quality. An out-of-box configuration may not be optimized for patient dose and needs to be considered in implementation and clinical procedures.

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FOR YOUR INFORMATION

This article has been selected for *AJR* Journal Club activity. The accompanying Journal Club study guide can be found on the following page.

Study Guide

CT Dose Optimization for Whole-Body PET/CT Examinations

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Introduction

1. What is the question being asked? Is this question relevant and timely? Will answering the question impact the practice of medicine?
2. Using evidence-based medicine (PICO [patient or problem, intervention, comparison, outcome]), what are the questions being asked in this study?

Methods

3. What type of study was this? What was the study design?
4. What were the inclusion and exclusion criteria for the image quality analysis portion of the study? What were the exclusion criteria for the cases excluded from the image quality analysis portion of the study?
5. Is it relevant that only one radiologist certified in both nuclear medicine and diagnostic radiology determined image quality? How many years of interpreting PET and CT studies did the reader have?
6. What were the limitations of this study? Were these limitations adequately discussed?
7. What statistical methods were used in the analysis?

Results

8. Were the research questions answered?
9. Were the study design and sample size large enough to draw conclusions on the benefit of the CT dose reduction while maintaining diagnostic image quality?

Physics

10. How are volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP) calculated? What are the limitations of these dose estimates? What effect do slice thickness, milliampere-second (mAs), and peak kilovoltage (kVp) have on image quality? What are common methods of assessing image quality?

Discussion

11. How do the study results compare with other studies examining CT dose and image quality?
12. A 20-year-old woman with non-Hodgkin lymphoma is scheduled for routine CT of the chest, abdomen, and pelvis. She had a similar CT 3 months ago. When the patient arrives, she asks the CT technologist if she can talk to a doctor because she has heard that radiation from CT may be harmful. What would you tell her and why?
13. What are the challenges to clinical research examining image quality with dose reduction?

Background Reading

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*Please note that the authors of the Study Guide are distinct from those of the companion article.