Radiation Exposure of Patients Undergoing Whole-Body Dual-Modality ^{18}F-FDG PET/CT Examinations

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We investigated radiation exposure of patients undergoing whole-body ^{18}F-FDG PET/CT examinations at 4 hospitals equipped with different tomographs. **Methods:** Patient doses were estimated by using established dose coefficients for ^{18}F-FDG and from thermoluminescent measurements performed on an anthropomorphic whole-body phantom. **Results:** The most relevant difference between the protocols examined was the incorporation of CT as part of the combined PET/CT examination: Separate low-dose CT scans were acquired at 2 hospitals for attenuation correction of emission data in addition to a contrast-enhanced CT scan for diagnostic evaluation, whereas, at the other sites, contrast-enhanced CT scans were used for both purposes. Nevertheless, the effective dose per PET/CT examination was similar, about 25 mSv. **Conclusion:** The dosimetric concepts presented in this study provide a valuable tool for the optimization of whole-body ^{18}F-FDG PET/CT protocols. Further reduction of patient exposure can be achieved by modifications to the existing hardware and software of PET/CT systems.

Key Words: PET/CT; patient exposure; dosimetry; dose reduction

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In recent years, PET has gained increasing clinical acceptance as an important functional imaging modality. However, accurate localization and interpretation of tissue structures with increased radiotracer uptake—particularly, in the abdomen or pelvis—are frequently challenged by the limited spatial resolution of PET and the absence of clearly visible anatomic landmarks in the PET images (*1*).

The development of dual-modality PET/CT systems has addressed these problems (*2*). These systems allow the quasisimultaneous acquisition of anatomic (CT) and functional (PET) information of a patient within a single examination and, thus, provide intrinsically coregistered images of the 2 modalities (*3–5*). In addition, the "hardware" fusion concept offers the possibility of CT-based attenuation correction of the emission scans instead of using noisy transmission data measured separately by means of an external positron-emitting source (*6*). The use of CT-based attenuation correction results not only in a marked reduction of the total examination time but also in an improved quality of the corrected PET scans (*5,7,8*).

On the other hand, whole-body PET/CT examinations incur an increased patient exposure compared with an individual CT or PET examination (*8*). Thus, patient referral for PET/CT studies must be justified in each case to avoid repeated exposure or overexposure of patients (*9*). Besides justification, optimization is the second general principle in radiologic protection (*10*). It was, therefore, the aim of the present study (a) to evaluate radiation exposure of patients undergoing whole-body PET/CT examinations after administration of ^{18}F-FDG, (b) to derive a practical dosimetric concept for dose estimation in whole-body CT, and (c) to discuss strategies for dose reduction to decrease radiation risks to patients.

MATERIALS AND METHODS

We reviewed whole-body PET/CT acquisition protocols used between September 2003 and May 2004 in 4 German university hospitals. Table 1 summarizes the main technical details of the 4 different PET/CT models installed in these hospitals. ^{18}F-FDG PET scans were characterized by the administered activity and the scan time; CT scans were characterized by the tube potential U, electrical current-time product Q_{el}, volume CT dose index $CTDI_{vol}$, scan length L, slice collimation h_{col}, and pitch factor p.

Internal Exposure

Absorbed doses D_T to a tissue or organ T resulting from intravenous administration of an activity A of ^{18}F-FDG were computed by means of dose coefficients Γ_T^{FDG} provided by the Inter-

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TABLE 1
Characterization of 4 PET/CT Tomographs Considered in This Study

Hospital	PET/CT tomograph		CT system		PET system			
	Manufacturer	Model	Model	*n**	Model	Detector material	Acquisition mode	Axial field of view (cm)
H1	General Electric	Discovery LS	Lightspeed Plus	4	Advance Nxi	BGO	2D and 3D	15.2
H2	Philips	Gemini	Mx8000	2	Allegro	GSO	3D	18.0
H3	CPS Innovations	Biograph Emotion Duo	Emotion Duo	2	ECAT EXACT HR+	BGO	3D	15.5
H4	CPS Innovations	Biograph Sensation 16	Sensation 16	16	ECAT ACCEL	LSO	3D	16.2

*n = number of simultaneously acquired slices.
BGO = bismuth germanate; 2D = 2-dimensional; 3D = 3-dimensional; GSO = germanium oxyorthosilicate; LSO = lutetium oxyorthosilicate.

national Commission on Radiological Protection (ICRP) in its Publication 80 (*11*) for a variety of organs and tissues of the adult hermaphrodite MIRD phantom—that is, $D_T = A \cdot \Gamma_T^{FDG}$. Effective doses were estimated by:

$$E = \sum_T w_T \cdot D_T = A \cdot \sum_T w_T \cdot \Gamma_T^{FDG} = A \cdot \Gamma_E^{FDG}, \qquad \text{Eq. 1}$$

where $\Gamma_E^{FDG} = 19$ μSv/MBq is the dose coefficient for the effective dose and w_T are the tissue weighting factors ($\Sigma_T w_T = 1$) given in ICRP Publication 60 (*12*).

External Exposure

To estimate radiation exposure of patients resulting from the acquisition of topograms and scans in CT, dose measurements were performed on an anthropomorphic whole-body Alderson RANDO phantom (Alderson Research Laboratories Inc.) using thermoluminescent dosimeters (TLDs). The method has been described in detail in a previous article (*13*). In brief, at least 180 dosimeters (TLD-100; Bicron-Harshaw) were suitably distributed inside and at the surface of the phantom. For smaller organs, absorbed doses were obtained by averaging the TLD values measured within the specified organs, whereas, for extended organs (e.g., skin and bone), they were estimated using specific weighting factors for the various cross sections of the Alderson phantom. The effective dose E was calculated from the absorbed doses D_T according to Equation 1.

In analogy to the formalism presented for the case of internal dosimetry, organ doses were described by:

$$D_T = \Gamma_T^{CT} \cdot CTDI_{vol}, \qquad \text{Eq. 2}$$

where Γ_T^{CT} is an organ-specific dose coefficient that relates the volume CT dose index $CTDI_{vol}$—that is, the average dose for a standardized CT dosimetry phantom—with the organ dose D_T. Variations in the organ doses with tube potential are considered by using the $CTDI_{vol}$ value indicated for the specific CT scan on the operators's console of the scanner. Organ-specific dose coefficients were estimated according to Equation 2, using the organ doses derived from the TLD measurements on the Alderson phantom and the corresponding $CTDI_{vol}$ values.

RESULTS

Table 2 gives an overview of the routine acquisition protocols used for whole-body ^{18}F-FDG PET/CT examinations at the 4 university hospitals (designated H1–H4). For each protocol, the type and sequence of the various scans performed as well as the effective doses per scan and examination are listed. In hospital H3, a high-quality protocol is used in the majority of cases. However, in cases in which a recent diagnostic CT scan exists, the high-quality diagnostic CT scan (D-CT) is replaced by a low-dose scan acquired without intravenous contrast medium (LD-CT). At sites H2 and H4, no high-quality diagnostic CT scan is performed as part of the combined PET/CT examination in such cases. The effective dose values for the 4 high-quality PET/CT protocols (Table 2) were nearly identical. The uterine dose, which is often used to estimate exposure to an embryo in the early stage of pregnancy, was between 20.9 and 23.2 mGy.

Average ^{18}F-FDG activities of 300 MBq (H2) and of 370 MBq (H1, H3, and H4) were administered, which resulted in estimated effective doses of 5.7 and 7.0 mSv, respectively. The acquisition time for the whole-body ^{18}F-FDG PET scans was <45 min at all sites. The scan parameters used for the different CT scans are specified in Table 3. Because the symphysis was defined as the lower limit of the CT scan range, the testes were not in the imaged body region. Nevertheless, they were exposed by scattered radiation and due to the overranging effect to a varying amount (0.7–7.2 mGy). At the upper side, the thyroid was within the scan region in all cases. For a more detailed assessment of the dose distribution within the human body, dose coefficients for the relevant organs are listed in Table 4 for both ^{18}F-FDG PET and CT examinations. Estimated CT dose coefficients for some representative organs are plotted in Figure 1 along with the corresponding mean values.

For the 7 CT protocols used (Table 3), the effective dose was calculated on the basis of Equation 2 using the mean dose coefficient of $\Gamma_E^{CT} = 1.47 \pm 0.02$ mSv/mGy given in Table 4. The resulting dose values are plotted versus the corresponding values determined from the TLD measurements on the Alderson phantom in Figure 2. Linear regression analysis (SigmaPlot, version 7.101; SPSS Inc.) yielded a slope of 1.03.

TABLE 2
Summary of Representative Protocols Used Routinely for Whole-Body ^{18}F-FDG-PET/CT Examinations at 4 German Hospitals Equipped with the Dual-Modality Tomographs Characterized in Table 1

Hospital	Scan		Effective dose (mSv)	
	Type	Abbreviation	Per scan	Per examination
H1	2 Topograms*		0.8	
	Diagnostic CT with CA	H1-D-CT	18.6	
	PET, 370 MBq ^{18}F-FDG	H1-PET	7.0	26.4
H2	Topogram		0.1	
	Low-dose CT	H2-LD-CT	4.5	
	PET, 300 MBq ^{18}F-FDG	H2-PET	5.7	
	Diagnostic CT with CA	H2-D-CT	14.1	24.4
H3	Low-dose protocol			
	Topogram		0.2	
	Low-dose CT	H3-LD-CT	1.3	
	PET, 370 MBq ^{18}F-FDG	H3-PET	7.0	8.5
	High-quality protocol			
	Topogram		0.2	
	Diagnostic CT with CA	H3-D-CT	17.6	
	PET, 370 MBq ^{18}F-FDG	H3-PET	7.0	24.8
H4	Topogram		0.2	
	Low-dose CT	H4-LD-CT	2.4	
	PET, 370 MBq ^{18}F-FDG	H4-PET	7.0	
	Diagnostic CT with CA	H4-D-CT	14.1	23.7

*In anteroposterior and lateral direction; dose indicated represents the dose sum from both topograms.
CA = intravenous CT contrast agent administered for most examinations.

DISCUSSION

The effective dose for patients undergoing high-quality whole-body ^{18}F-FDG PET/CT examinations at the 4 university hospitals participating in this study was about 25 mSv. Despite the similarity of the effective dose values (23.7–26.4 mSv), there were some noticeable differences between the 4 PET/CT acquisition protocols, which are representative of the imaging scenarios reported in the literature. Mainly, the 4 clinical sites (H1–H4) had a different approach to the clinical implications from the CT scan of the combined PET/CT examination.

At 2 hospitals (H2 and H4), separate low-dose CT scans were acquired for attenuation correction of emission data in addition to a contrast-enhanced CT scan. At the other 2 sites (H1 and H3), a single, contrast-enhanced CT scan was used both for a fully diagnostic evaluation and for CT-based attenuation correction. This may imply the question of whether the administration of an intravenous CT contrast

TABLE 3
Measurement Parameters Used for Low-Dose (LD-CT) and Diagnostic (D-CT) Whole-Body CT Scans Summarized in Table 2

Abbreviation of CT scan	U (kVp)	Q_{el} (mAs)	h_{col} (mm)	p	L (mm)	$CTDI_{vol}$ (mGy)
H2-LD-CT	120	60	6.5	1.5	910	2.9
H3-LD-CT	110	30	4.0	2	851	1.0
H4-LD-CT	120	32.5	0.75	1.25	887	2.0
H1-D-CT	140	150	2.5	1.5	867	14.1
H2-D-CT	120	195	5.0	1.5	890	9.5
H3-D-CT	130	111	4.0	1.0	851	11.9
H4-D-CT	120	200	1.5	1.25	887	11.2

U = tube potential; Q_{el} = electrical mAs-product; h_{col} = slice collimation; p = pitch factor; L = scan length; $CTDI_{vol}$ = volume CT dose index.

TABLE 4
Tissue Weighting Factors and Dose Coefficients for ^{18}F-FDG PET (Γ_T^{FDG}) and Whole-Body CT (Γ_T^{CT}) Scans

Organ T	w_T*	Γ_T^{FDG}† (μGy/MBq)	$w_T \cdot \Gamma_T^{FDG}$ (μSv/MBq)	Γ_T^{CT}‡	$w_T \cdot \Gamma_T^{CT}$‡ (mSv/mGy)
Gonads§	0.20	13.5	2.70	1.41 ± 0.06	0.28 ± 0.01
Red bone marrow	0.12	11	1.32	1.28 ± 0.04	0.153 ± 0.005
Colon	0.12	13	1.56	1.53 ± 0.05	0.184 ± 0.007
Lungs	0.12	10	1.20	1.45 ± 0.07	0.174 ± 0.009
Stomach	0.12	11	1.32	1.45 ± 0.06	0.174 ± 0.007
Bladder	0.05	160	8.00	1.38 ± 0.07	0.069 ± 0.003
Breast	0.05	6.8	0.34	1.44 ± 0.08	0.072 ± 0.004
Liver	0.05	11	0.55	1.58 ± 0.07	0.079 ± 0.003
Esophagus	0.05	11	0.55	1.43 ± 0.07	0.072 ± 0.003
Thyroid	0.05	10	0.50	2.4 ± 0.1	0.123 ± 0.006
Skin	0.01	8	0.08	0.66 ± 0.03	0.007 ± 0.001
Bone surfaces	0.01	11	0.11	0.86 ± 0.03	0.009 ± 0.001
Remaining organs	0.05	11	0.55	1.37 ± 0.05	0.069 ± 0.002
Uterus¶	—	21	—	1.11 ± 0.04	—
Total	—	—	19	—	1.47 ± 0.02

*Tissue weighting factors from ICRP Publication 60 (*12*).
†Dose coefficients from ICRP Publication 80 (*11*).
‡Mean ± SEM.
§Since testes were not in the body region scanned in CT, absorbed doses to gonads were defined as that to ovaries.
¶Although the uterus belongs to the remaining organs, dose coefficients are also given for this organ because uterine dose is often used as surrogate for embryonic dose in the early stage of pregnancy.
Dose coefficients for CT were estimated according to Equation 2 from TLD measurements performed on Alderson phantom.

agent leads to serious artifacts in the attenuation-corrected PET images, since structures with a strong enhancement in the CT scans may be considered as bone by the attenuation correction algorithm, thus resulting in an overestimation of regional attenuation coefficients (*14*). However, recent evidence indicates that these artifacts rarely cause a diagnostic challenge in the clinical setting (*15*) and that these artifacts can be avoided prospectively when using adapted contrast administration protocols (*16*).

Nevertheless, if a contrast-enhanced diagnostic CT scan has already been performed on a conventional CT system as part of the regular clinical work-up, it is in general acceptable to acquire only a low-dose CT scan as part of the combined PET/CT study (*17*). The image quality of this scan is certainly

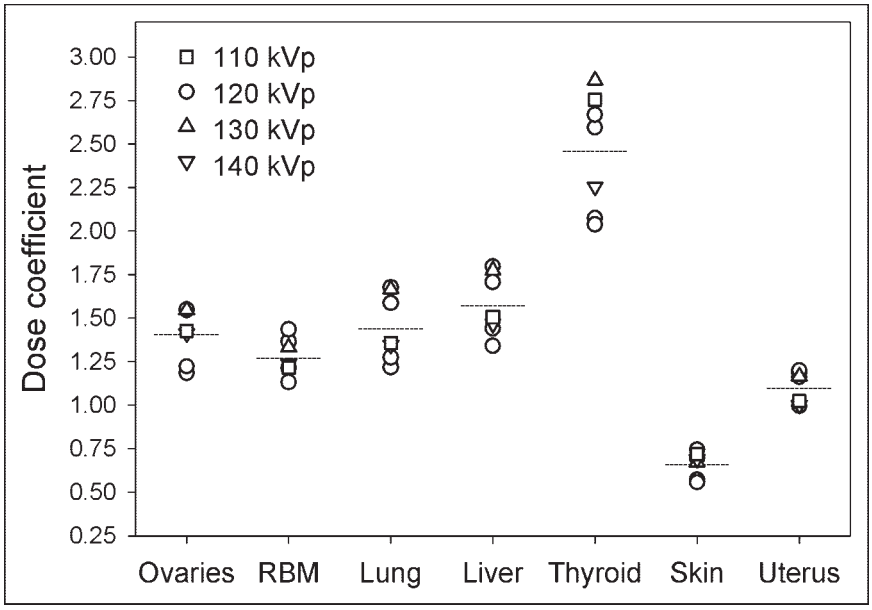

FIGURE 1. CT dose coefficients Γ_T^{CT} for some representative organs. Symbols give dose coefficients determined according to Equation 2 for each of the 7 CT scans listed in Table 3, whereas horizontal lines indicate corresponding mean values. RBM = red bone marrow.

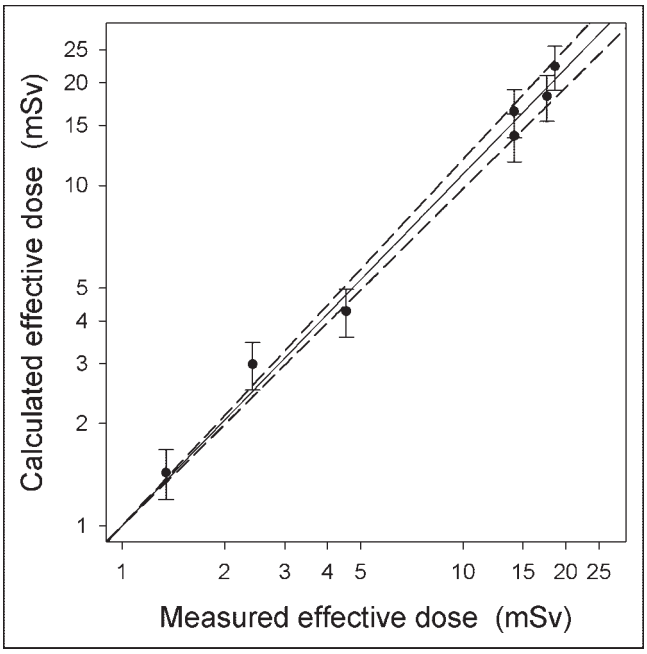

FIGURE 2. Statistical relation between calculated and measured effective doses for 7 CT scans listed in Table 3. Solid line gives result of linear regression analysis through origin with a slope of 1.03 and dashed curves indicate 95% confidence interval. Error bars indicate the uncertainty of dose estimates.

adequate for anatomic correlation and attenuation correction (*18*). In the present study, the effective dose determined for 3 low-dose scans was <5 mSv (Table 2).

The effective doses determined for the 4 high-quality CT scans listed in Table 3 varied between 14.1 and 18.6 mSv. These values are somewhat higher than the dose estimates (mean ± SD) of 14.5 ± 4.9 mSv from a recent survey on whole-body, multislice CT examinations (*19*), which is mainly due to the inclusion of the thyroid in the whole-body scan range covered in this study.

The dose coefficients listed in Table 4 make it possible to estimate organ doses and—using the corresponding tissue weighting factors—effective doses related to whole-body ^{18}F-FDG PET and CT scans. All data presented are for a standard person with a body weight of about 70 kg and are generic rather than patient specific since the age, sex, and constitution of individual patients are not considered. Nevertheless, they provide a reasonably good indicator of the relative radiation risks to patients (*12*) resulting from nonuniform exposures related to whole-body PET and CT procedures and, thus, for protocol optimization.

PET/CT users should note that the $CTDI_{vol}$ value displayed on the operator's console is the principal descriptor to characterize patient exposure in CT on a local dose level. It represents an estimate of the average dose within an irradiated slice of a standardized CT dosimetry phantom and, thus, reflects not only the combined effect of the selected scan parameters but also of scanner-specific factors such as beam filtration, beam-shaping filter, geometry, and overbeaming. A detailed discussion of the various scan parameters and system features determining patient exposure in CT as well as strategies for dose reduction can be found elsewhere (*19,20*). Besides the $CTDI_{vol}$, the length of the scan region is the second parameter that determines the effective dose and, thus, the integrated detriment to patients related to a CT examination. Whenever clinically justifiable, the range of whole-body scans should be limited by the symphysis at the lower limit and should exclude the eye lenses from the cranial imaging range.

However, adaptation of the scan length to the individual body size may not be possible at current PET/CT systems because the axial CT range can be set up only in integer multiples of the fixed axial field of view of the PET system. This technical limitation can be overcome in the future, for example, by the implementation of continuous bed motion for PET measurements. In general, noncongruent imaging ranges of PET and CT scans, as well as multiple contiguous spirals with different CT scan parameters, should become available with the clinical PET/CT acquisition software. This flexibility would open the possibility of acquiring a high-quality CT scan for only part of the body and imaging the remaining axial ranges with a low-dose CT, or even without attenuation correction. Moreover, prospective measures that offer the potential for dose reduction in CT without a considerable loss in image quality—such as automatic tube current modulation or adaptive filtering—should be adopted for routine PET/CT.

CONCLUSION

The PET/CT acquisition protocols examined in this study reflect the range of whole-body PET/CT imaging scenarios reported in the literature today. We estimated an average effective patient dose from whole-body ^{18}F-FDG PET/CT examinations of about 25 mSv independent of the acquisition protocol preferred. Considering the increased patient exposure compared with individual CT or PET examinations, a judicious medical justification has to be made with every PET/CT referral. The derived dose coefficients provide a valuable tool for estimating organ and effective doses for a diversity of whole-body CT scans and, in turn, for protocol optimization. Independently, prospective dose reduction measures from state-of-the-art CT practice should be adopted in PET/CT imaging, and modifications to the existing acquisition software should be considered.

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