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PET/CT and SPECT/CT Dosimetry in Children: The Challenge to the Pediatric Imager

Michael J. Gelfand, MD,* and Lisa C. Lemen, PhD†

Both positron emission tomography (PET) and computed tomography (CT) contribute significantly to the effective dose from PET/CT imaging. For PET imaging, the effective dose is related to the administered activity and age of patient. For CT, there are many factors that determine effective dose. Effective dose is dependent on tube current (mA), tube potential (kVp), rotation speed, pitch, slice thickness, patient mass, and the exact volume of the patient that is being imaged. The CT scan may be acquired at exposure parameters similar to those used for diagnostic CT, but more commonly, the tube current is reduced and a localization CT scan of somewhat less than optimal diagnostic quality is obtained. A very low dose CT scan for attenuation correction may also be considered.
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When the children who survived the 1945 atomic bomb explosions were followed into the 1990s, it became apparent that they had an excess risk of acquiring malignant solid tumors that extended well into middle age, unlike the excess risk of leukemia, which largely disappeared by 15 years after exposure.[1,2] It also was observed in a population of children and adults that excess risk could be detected down to a whole body absorbed radiation dose of 6 rem (60 mSv; Fig. 1).[1,2] Data indicated that the risk per unit of radiation was increased in all pediatric age groups, particularly in infants and small children, when compared with adults. For example, it was estimated that lifetime risk for those exposed to radiation at age 10 was 1.0 to 1.8 times greater than the risk for those exposed at age 30 (Fig. 2).[1,2]

These data became available at the same time that the use of computed tomography (CT) in children was increasing rapidly, particularly for indications other than cancer and major trauma.[3] When calculations of risk were made from CT dose estimates and the updated data from atomic bomb survivors, a re-examination of the risks in children from CT imaging took place.[3,4] Serious efforts were then made to reduce radiation exposure from CT imaging.[5-7]

The calculated risk per unit of absorbed radiation dose from CT imaging of children that was stated by some observers was worrisome. Assuming a linear no-threshold hypothesis, an effective dose of 1 rem (10 mSv) was estimated to carry a risk of 1 in 1,000 of eventual death from radiation induced malignancy.[4] CT scans often were being performed using adult exposure settings that did not take into account the age and size of the patient, which resulted in unnecessarily high radiation exposures at these CT parameter settings.[6]

It is beyond the scope of this article to examine all the assumptions behind these risk estimates. When discussing small increases in risk at doses of 0 to 10 rem (0-0.1 Sv), the authors of the recent analyses of Japanese atomic bomb data, Pierce and Preston, stated that "assessing risks at this level greatly strains any epidemiological investigation, since, within the scope of the study, cancer rates may vary to at least that degree due to other risk factors."[2] Although it is argued by some that the aforementioned calculated risks are too high and that the linear no threshold hypothesis may significantly overestimate the risk from very low radiation exposures, the linear no threshold is still a reasonable conservative working assumption at this time. Therefore, for the purpose of the ensuing discussion, it is assumed that (1) there is no threshold for radiation risk and (2) that the amount of radiation that the pediatric patient receives should be the lowest amount that is consistent with the diagnostic requirements and accuracy of the imaging study.

Absorbed Radiation Dose From CT Over Three Decades

As CT technology advanced from the original translate-rotate scanners to fan beam axial scanners, fan beam helical scan-

*Nuclear Medicine Section, Department of Radiology, Cincinnati Children's Hospital Medical Center, Cincinnati, OH.
†Department of Radiology, University of Cincinnati, Cincinnati, OH.
Address reprint requests to Michael J. Gelfand, MD, Nuclear Medicine Section, Department of Radiology, Cincinnati Children's Hospital Medical Center, 3333 Burnet Ave, Cincinnati, OH 45229-3039. E-mail: michael.gelfand@cchmc.org

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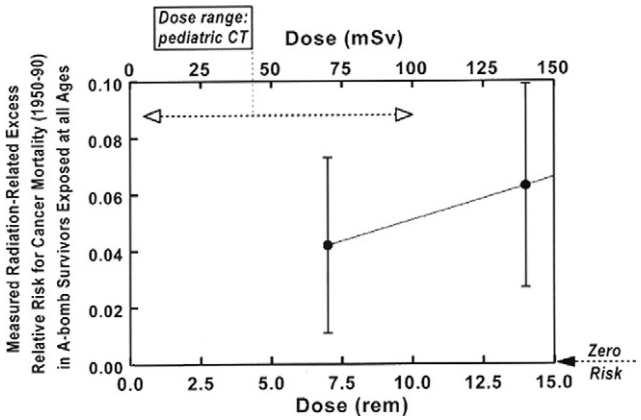

Figure 1 Excess radiation related risk for cancer mortality in atomic bomb survivors using data from 1950 through 1990. The approximate dose range from pediatric CT prior to dose reduction efforts is superimposed across the top of the graph. (Reprinted from Brenner,[4] with kind permission from Springer Science and Business Media.)

ners, and multidetector helical scanners, there was some upward creep in CT exposure parameters in a quest for increasingly better image quality.[8-11] During the 1980s and 1990s, a few observers noted that the quest for perfection in image quality had led to radiation exposures higher than were required for diagnostic quality images.[12-17] Robinson and coworkers found that "pediatric abdominal CT scans could maintain diagnostic quality with at least a 50% reduction in dose from the manufacturers' suggested protocol."[15] It was also demonstrated that infants and children studied at adult CT exposure parameters received considerably greater radiation doses than adults, with the highest radiation doses occurring in the smallest children.[8,10] Putting the risk estimates derived from the 1996 and 2000 studies of atomic bomb survivors together with pediatric CT exposure data, pediatric radiologists tried to find the lowest CT scanner settings that can be used in children without sacrificing the diagnostic accuracy of the CT scan.[5] Donnelly, Frush, and others called for a re-examination of CT exposure parameters and called for a reduction in CT exposure to the lowest levels that consistently generated diagnostic quality images, a goal that, for the most part, appears to have been achieved, at least in teaching hospitals.[5,6,18]

Absorbed Radiation Dose From Nuclear Medicine Procedures

The principles of dose reduction also apply to nuclear medicine imaging studies. The calculated absorbed radiation dose from a nuclear medicine procedure depends on the radiopharmaceutical used, the administered activity and the age and body mass of the patient. The MIRD model combines pharmacokinetic data (as cumulated activity) with S factors that take into account the radiation that each organ (or tissue) receives from the activity in that organ (or tissue) and from activity in surrounding organs (or tissues). In the absence of pediatric pharmacokinetic data, pediatric absorbed radiation and effective doses usually are calculated from adult cumulated activity data.[19] Pediatric cumulated activity data have been determined for only a limited number of radiopharmaceuticals and for a limited number of organs (or tissues).[20]

The amount of radiopharmaceutical that is administered must be reduced in infants and children. In our institution, we reduce the administered activity for most radiopharmaceuticals from adult doses in proportion to patient weight, using the following formula:

$$\text{Pediatric administered activity} = [(\text{adult administered activity}) \times (\text{patient weight in kg})] / 70\ \text{kg}$$

An alternative approach is to use body surface area (BSA) to calculate administered activity, using the formula:

$$\text{Pediatric administered activity} = [(\text{adult administered activity}) \times (\text{patient BSA in } m^2)] / 1.73\ m^2$$

However, when the calculation is based on BSA, administered and thus organ and effective doses are greater than when patient weight is used. When administered activity is based on weight, small children receive somewhat-lower effective doses than adolescents or adults. We have been able to use body weight for calculation of administered activity, without compromising our ability to obtain high-quality images in small children. There are extensive published tables of effective dose and absorbed radiation dose to specific organs and tissues for commonly available radiopharmaceuticals.[19,21]

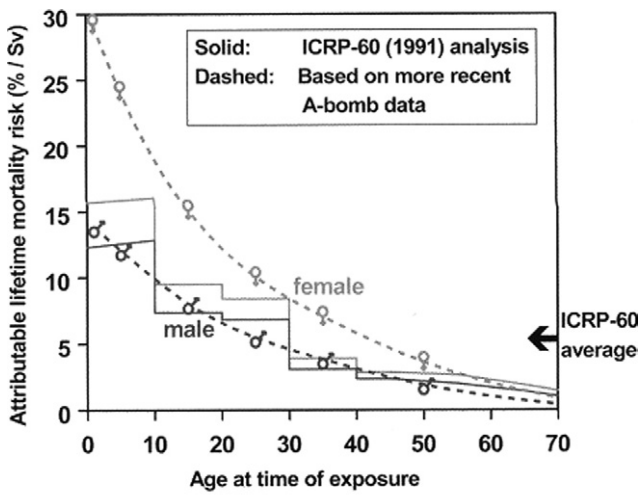

Figure 2 Lifetime risk estimates (%/Sv) based on atomic bomb data through 1990. (Reprinted from Brenner,[4] with kind permission from Springer Science and Business Media.)

Effective Dose for Comparison of Risk From Very Different Dose Distribution Patterns

CT, plain radiographic procedures, and nuclear medicine procedures do not irradiate the body uniformly. For CT, each organ's dose is related to multiple factors including the entrance dose, the mass of the patient and the fraction of the organ within the irradiated field. CT irradiates the portion of the body that is imaged, and the dose to tissues and organs within a cross section is relatively uniform. If CT parameters are kept constant, body regions with a smaller cross section or body regions that contain air will get a higher absorbed radiation dose than the abdomen or pelvis.

In nuclear medicine, each organ dose is determined by the administered activity and the amount of the radiopharmaceutical in the organ and nearby organs and tissues integrated over time. Radiopharmaceuticals that are administered IV or absorbed from the gastrointestinal tract are distributed throughout the body. The chemical structure of the radiopharmaceutical determines the organs in which the radiopharmaceutical is concentrated and through which it is excreted.

The very different patterns of absorbed radiation dose from CT and radiopharmaceuticals can be compared through calculations of effective dose. Effective dose calculations assign weighting factors to each organ (tissue) that reflect the excess risk of fatal malignancy arising in that organ (or tissue) per unit of absorbed radiation dose. The effective dose (ED) is then calculated according to the equation:

$$ED = \sum_T W_T H_T$$

where W_T is weighting factor for tissue T and H_T is the calculated dose for tissue T. An effective dose of 1 rem (10 mSv) represents an excess risk of fatal malignancy equal to the risk from 1 rem (10 mSv) of uniform whole body radiation.

Effective Dose From Diagnostic CT Imaging

Absorbed radiation doses from CT in children at children's hospitals and university hospitals have decreased significantly during the last 5 years.[18] At our hospital, the calculated effective dose, using the ImPACT program[22] received from a CT scan of the neck, chest, abdomen, and pelvis, as performed for many oncologic indications, ranges from 1.0 rem to 1.6 rem (10 to 16 mSv), with the lower exposures occurring in young (ie, smaller) patients. Adjustment for patient body mass (and, therefore, for age) is accomplished by keeping the tube potential constant at 120 kVp and varying the tube current (mA) according to patient weight. For daily use by technologists, weight-based tables have been created that list tube current, tube potential, pitch, and exposure time; in these tables, tube current increases as patient weight increases. Only for very large patients (larger than an average adult) is the tube potential increased to 140 kVp. Other hospitals report similar effective dose levels using tube potentials of 110 to 120 kVp, again varying the tube current according to weight.[5] It should be noted, however, that not all hospitals use the same weight-based tables for CT exposure parameters, and effective dose received by different age groups will differ between institutions.[23] The Appendix[24,25] at the end of the article provides a quick guide to the effects of changes in CT imaging parameters on effective dose.

Table 1 Organ Doses and Effective Doses From ^{18}F-FDG and ^{18}F-Fluoride Imaging

	1 Year	5 Years	10 Years	15 Years
Estimated weight (kg)	10.2	18.5	32.4	55.5
^{18}F-FDG[19]				
Administered activity				
mCi (0.140 mCi/kg)	1.4	2.6	4.5	7.8
MBq (5.2 MBq/kg)	53	99	168	287
Bladder wall (rad)	1.7	3.0	3.6	3.86
Red marrow (rad)	0.50	0.56	0.64	0.86
Effective dose (rem)	0.50	0.56	0.64	0.86
^{18}F-fluoride[26]				
Administered activity				
mCi (0.055 mCi/kg)	0.57	1.13	1.89	2.34
MBq (2.0 MBq/kg)	21	42	70	120
Bladder wall (rad)	2.8	3.0	3.3	3.8
Bone surfaces (rad)	0.57	0.79	0.75	0.72
Red marrow (rad)	0.49	0.47	0.40	0.41
Effective dose (rem)	0.31	0.32	0.32	0.35

To convert rad to mGy, multiply by 10
To convert rem to mSv, multiply by 10

Reprinted with permission from Lim et al.[26]

Effective Dose From FDG-PET and PET/CT Imaging Protocols

In children and adolescents, a typical administered activity for ^{18}F-fluorodeoxyglucose (^{18}F-FDG) is 0.14 mCi/kg (approximately 5 MBq/kg). The effective dose from this administered activity ranges from 500 mrem (50 mSv) in a 1-year-old patient to 860 mrem (8.6 mSv) in a 15-year-old patient. The target organ is the bladder.[19] Selected organ doses are presented in Table 1.[19,26] Somewhat-smaller administered activities can be used for positron emission tomography (PET) of the brain.

Dose can be reduced without sacrificing the diagnostic quality of the PET imaging study by a decrease in administered activity although, in some cases, an increase in imaging time may be required to maintain image quality. Imaging times of 5 minutes per bed position are well tolerated by school-aged and adolescent children without sedation. 3D acquisition mode should be used when a satisfactory 3D mode is available, because of the enhanced sensitivity of the PET scanner compared with 2D mode. With optimization of administered activity and imaging time per bed position, it

should be possible, at many institutions, to reduce administered activity and effective dose by 30% or even 40% from the effective doses listed above. Very large patients may need larger administered activities per kg or relatively longer imaging times to maintain good image quality.

Radiologists traditionally have been reluctant to place themselves in the position of reading a "suboptimal" quality CT scan that fails to demonstrate all the pathology within the anatomic region covered by the imaging examination that is potentially detectable by CT imaging. For standard diagnostic oncologic CT imaging of the neck, chest, abdomen, and pelvis, intravenous and oral contrast are administered.[27] However, as new CT techniques have been developed, there are increasing numbers of imaging techniques available, and not all are used in a single examination. Patients do not automatically receive a multiple-phase CT study of the abdomen or a CT angiogram, both of which increase absorbed radiation dose significantly. Multiplanar reformatting of CT data and 3D reconstruction is not routinely performed for every case at every hospital, even though there is no impact on effective dose.

Recently pediatric radiologists have also started to look at limited examinations, in selected diagnostic situations, that limit radiation exposure and are satisfactory for a limited diagnostic indication. Lucaya looked at low-dose chest CT in children for the imaging evaluation of lung parenchyma.[28] Examples of limited, reduced-dose chest CT studies that have been proposed are a reduction in the number of images when chest CT performed for pectus excavatum (when the only diagnostic requirement is measurement of the Haller index before surgery), low-dose CT of the head in patients with possible shunt malfunction (where the diagnostic question is ventricular size) and low-dose noncontrast CT for renal colic for detection of renal or ureteral calculi.[29-31] The reduced-dose localization CT scan performed as part of a PET/CT scan might be taken as an additional example.

When PET/CT arrived, a series of questions arose about how to perform the CT portion of the examination. The answers to these questions have a significant impact on the dosimetry from the CT portion of the PET/CT study. If it were always possible to use the CT portion of the PET/CT scan as the diagnostic scan that is required in pediatric oncology protocols, the effective dose attributable to the PET scan would be limited to the effective dose from the administered activity of ^{18}F-FDG. However, there are several considerations that the pediatric imager must take into account before attempting to use the CT portion of the PET/CT scan as the diagnostic CT scan. If both a diagnostic CT scan and a reduced dose localization CT are required, the additional effective dose from the PET/CT scan now includes the dose from both injected ^{18}F-FDG and the dose from the reduced dose localization CT scan.

Consideration 1: Respiratory Phase

Several problems arise if the respiratory phase during CT acquisition is not matched to the respiratory phase during PET acquisition. CT acquisition is rapid and can be com-

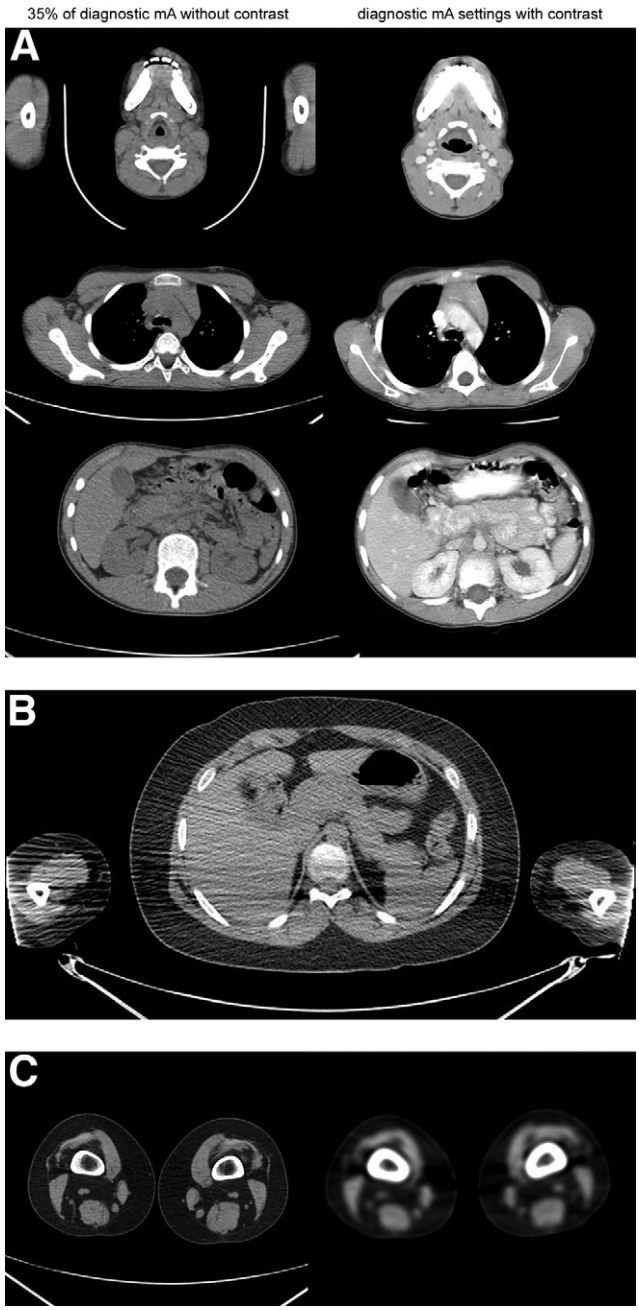

Figure 3 (A) Axial CT scans at 3 different levels in the same patient. Scans in the left column were acquired as reduced dose noncontrast localization CT scans at 35% of the tube current (mA) use for the diagnostic CT scans in the right column, all other exposure parameters kept constant. Scans in the right column were acquired after intravenous contrast at diagnostic CT exposure settings currently used for pediatric oncologic CT. (B) A noncontrast axial localization CT scan in a patient who is considerably heavier than the patient in (A), studied with the arms at the sides. Tube current was again reduced to 35% of the setting used for diagnostic pediatric oncologic CT. Note the lower quality of the images and the streak artifact caused by the arms. (C) Left, Noncontrast axial localization CT scan through the femurs acquired at exposure settings reduced as in (A) and (B). Right, Exposure parameters have been reduced to deliver 7% of the radiation dose that would be received at diagnostic pediatric oncologic CT settings. Note the extreme degradation of image quality.

pleted during a single breath hold in most children and adolescents when a multidetector CT scanner is used. PET acquisition is much slower and must be done during quiet tidal respiration. The mismatch in the position of the diaphragm causes significant misregistration between the CT and PET images for lesions in the lower chest and upper abdomen.[32-35] The mismatch between the position of the diaphragm at full inspiration and the average position of the diaphragm during quiet tidal respiration may be as much as 3 cm.

A mismatch at the diaphragm may cause errors in the localization of lesions. Attenuation correction will be incorrect near the diaphragm and will cause artifacts in many cases; "cold" artifacts along the diaphragm or a ladder like series of artifacts referred to as "banana" artifacts.[32-35] If artifacts and misregistration are to be avoided, both scans should be acquired under conditions that place the diaphragm in the same place for both scans, preferably using a end tidal respiration breath hold for the CT scan and quiet tidal breathing for the PET scan.

The question remains as to when an end-tidal respiration breath hold CT scan is adequate for diagnostic purposes. For the detection of pulmonary nodules, the end-tidal respiration breath hold CT scan has been shown to be diagnostically inferior to the full inspiration breath hold CT scan, both in adult and pediatric patients. In the work of Sharp and coworkers, end tidal expiration breath hold CT scans in children and adolescents detected about 30% fewer nodules than full inspiration breath hold CT scans.[36] In some patients, lung nodules were only detected on the full inspiration scan. Their data also suggested that failure to detect malignant lung nodules would be a particular problem in bone sarcoma patients. Adult data suggest that the problem with the sensitivity of end tidal expiration low dose localization CT scans in the diagnosis of pulmonary nodules is not the reduced dose, but rather the lack of a full inspiration.[37-43]

At the time of initial diagnosis of a solid tumor malignancy, a diagnostic CT scan at full inspiration usually has been already performed before the patient is referred for PET/CT. Most often the question is how to perform the CT portion of the PET/CT for follow-up examinations. A full inspiration diagnostic CT is required at any time that pulmonary nodules are more than a trivial diagnostic consideration. This is certainly the case in bone sarcomas. In lymphoma, at least in adults, lung relapses appear most often as pulmonary nodules, but data on the frequency of lung relapse in children with lymphoma and many other pediatric malignancies are not widely available at this time.[44,45]

Consideration 2: Use of Intravenous Contrast and Oral Contrast

Intravenous contrast and soluble oral contrast generally cause only insignificant changes in standardized uptake value (SUV) on PET images. Visible artifacts occur on attenuation corrected PET images when the concentration of contrast is very high at the time of CT scan and much lower during the PET scan, for example, when the CT scan is performed immediately after bolus contrast injection.[46] Administration of intravenous contrast and soluble oral contrast do not require any changes in CT exposure settings.

Consideration 3: CT Imaging Parameters for a Localization Study

For purposes of coregistration and localization, CT imaging parameters can be reduced considerably from diagnostic levels, often by 50-65%. The resulting CT scan will have greater noise content than the diagnostic CT scan. There may also be streak artifacts from dense structures that would not be seen on a diagnostic quality study (Fig. 3). Reportedly dose modulation, where the CT scanner instantaneously measures the fraction of x-ray beam that is absorbed at each scan angle and redistributes dose to scan angles where more of the beam is absorbed, can be used to limit streak artifacts at low doses.

Consideration 4: Omission of the Localization Study, CT for Attenuation Correction Only

If a PET only study is needed, the CT scanner can be used at very low exposure settings for attenuation correction only. Absorbed radiation doses from the CT scan in this setting are still slightly larger than when PET scanners used isotopic line sources for attenuation correction, but the doses are only a small fraction of the dose received from a diagnostic or localization CT scan. Fahey and coworkers studied very low dose CT for nonimaging attenuation correction to determine the

Table 2 Effective Doses From SPECT Imaging

	Administered Activity, mCi/kg (MBq/kg)	Effective Dose, rem (mSv)
Tumor imaging		
^{67}Ga	0.100 mCi/kg (3.7 MBq/kg)	1.8-2.5 (18-25)
^{123}I-MIBG	0.140 mCi/kg (5.2 MBq/kg)	0.26-0.29 (2.6-2.9)
Infection imaging		
^{67}Ga	0.040 mCi/kg (1.5 MBq/kg)	0.72-1.00 (7.2-10.0)
^{99m}Tc-WBC	0.215 mCi/kg (8.0 MBq/kg)	0.60-0.73 (6.8-7.3)
^{111}In-WBC	0.007 mCi/kg (0.26 MBq/kg)	0.57-0.75 (5.7-7.5)
Bone imaging		
^{99m}Tc-MDP	0.200 mCi/kg (7.4 MBq/kg)	0.20-0.28 (2.0-2.8)

The lowest effective doses are for a 1-year-old patient and the highest effective doses are for a 15-year-old patient.
Adapted from Stabin et al.[19]

lowest doses that could be used.[24] Attenuation correction only CT doses could be reduced to about 3% of typical diagnostic CT doses.

Attenuation correction only CT scans can be used in conjunction with PET for brain imaging. Magnetic resonance imaging (MRI) is the key diagnostic imaging technique for the brain, and PET/CT coregistration is usually less valuable than PET/MRI coregistration performed with software.

As nononcologic PET imaging applications become more common, CT for attenuation correction only, to achieve dose reduction, may also have a role in body imaging. If the physician is willing to review the PET images at the conclusion of the study while the patient remains on the imaging table, the PET scan can be repeated with a localization CT study, only in limited regions where PET abnormalities requires precise anatomic localization and diagnostic clarification. The practicality of this approach, however, particularly in busy PET imaging centers, is open to question.

Effective Dose From ^{18}F-Fluoride PET and PET/CT Imaging Protocols

In adults, a number of studies have compared ^{18}F-sodium fluoride PET bone scans with ^{99m}Tc-MDP bone scans for the detection of metastases. These studies have shown that ^{18}F-fluoride PET bone scans have improved spatial resolution and diagnostic sensitivity over MDP bone scans.[47-49] Recently, Lim and others have demonstrated that PET bone scans in children also demonstrate improved spatial resolution and are useful in some pediatric bone diseases.[26,50] In the study of Lim and coworkers, an administered activity of 0.055 mCi/kg (2.1 MBq/kg) was chosen to keep the radiation dose from the ^{18}F-fluoride PET bone scan in the same range as the MDP bone scan; at this administered activity, effective dose from the radiopharmaceutical ranged from 0.31 rem (3.1 mSv) in a one year old to 0.35 rem (3.5 mSv) in a 15-year-old patient. Again, as with ^{18}F-FDG, the target organ was the bladder.[26]

SPECT/CT

The same dosimetry considerations and diagnostic strategies apply to single-photon emission computed tomography (SPECT)/CT. It is important to note that some SPECT/CT scanners have standard CT scanners, whereas others have CT units that are suitable for only attenuation correction and localization but unable to produce diagnostic quality images. However, it should be noted that absorbed radiation doses from some less-than-diagnostic-quality CT scanners installed in SPECT/CT units may be just as high as in the radiation dose from a reduced dose localization CT scan performed with a diagnostic quality multi-detector CT scanner.

Often a planar whole-body scan is acquired before the SPECT/CT. To achieve dose reduction, the whole-body scan can be used for planning of the volume included in the localization CT scan. However, with this approach, there is a risk that an abnormal finding will subsequently be observed only on SPECT after completion of image acquisition and reconstruction, and that the unanticipated finding will be outside the volume included in localization CT scan. Repetition of the SPECT study with coregistered localization CT will often be impractical. Effective dose ranges for tumor, infection and bone SPECT imaging studies are presented in Table 2.

Conclusion

Dose reduction in PET/CT and SPECT/CT in children can be achieved by careful attention to the CT imaging parameters and the administered activity of the radiopharmaceutical, without compromising the diagnostic information needed for high quality patient care. The coregistered CT scan can be tailored to meet the patient's diagnostic needs, and may be performed as a diagnostic quality CT scan, a localization CT scan or an attenuation correction only nonimaging examination, depending on the diagnostic requirements of the individual patient.

Appendix

How Changes in CT Imaging Parameters Affect Absorbed Radiation Dose

mA	**mA is linearly related to absorbed radiation dose. If you double mA, you double absorbed radiation dose.**
Time per rotation	**Usually 0.5 or 0.8 sec and linearly related to absorbed radiation dose. If you double-time per rotation, you double absorbed radiation dose.**
mAs	**The product of mA and time per rotation. If you double mAs, you double the absorbed radiation dose.**
kVp	**There is an exponential relationship between absorbed radiation dose and kVp. If 120 kVp is assigned a relative dose level of 1.0 and other exposure parameters are kept constant, relative absorbed radiation doses at other kVp settings will be:**

kVp	Relative absorbed radiation dose
80	0.32
100	0.63
120	1.00
140	1.43

Pitch and slice thickness	**Pitch refers to the tightness of the spiral; a lower pitch implies a tighter spiral. The tighter the spiral, the higher the absorbed radiation dose, if all other parameters are kept constant, but slice thickness and the characteristics of the individual CT scanner are also factors in absorbed radiation dose. As an isolated parameter, slice thickness is linearly related to absorbed radiation dose.**

Adapted from Fahey et al[24] and Setty et al.[25]

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