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Radiation Safety With Positron Emission Tomography and Computed Tomography

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Combined positron emission tomography and computed tomography (PET/CT) has proven clinical utility, particularly in the diagnosis, staging, and management of cancer. The use of PET/CT has grown substantially in the past few years, with an increasing number of hospitals and imaging centers installing PET/CT systems each year. The combination of 2 procedures, which each imparting a radiation dose and hence the potential for deleterious health effects, creates unique radiation safety issues. This article addresses the radiation safety issues posed by PET/CT with regard to the protection and safety of PET/CT personnel, the public, and adult and pediatric patients.
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A combined positron emission tomography and computed tomography (PET/CT) system was first introduced at the University of Pittsburgh more than a decade ago.[1] Since that time, PET/CT has become a widely accepted and frequently used imaging modality.[2] Combined PET/CT improves diagnostic accuracy in comparison with PET alone[3,4] and the production of combined PET/CT systems now vastly surpasses that of stand-alone PET components.[5] State of the art PET/CT systems combine advanced, high-resolution PET devices with multidetector CT scanners, even including 128 detector row CT units.

By far, the most common clinical application of PET/CT is for known or suspected cancers. PET/CT is approved for the diagnosis and staging of certain cancers, treatment planning, and assessing response to therapy (Table 1). Other applications in the areas of cardiology, neurology, or infectious diseases are less frequent indications. The clinical usefulness of PET/CT combined with recently expanded Centers for Medicare and Medicaid Services coverage and reimbursement has led to an increasing number of hospitals and outpatient imaging centers installing PET/CT systems, thereby increasing the number of PET/CT examinations performed each year.[7]

The radiopharmaceutical most commonly used for PET imaging is fluorine-18-labeled fluorodeoxyglucose (^{18}F-FDG), an analog for glucose metabolism.[8] Fluorine-18 decays by emitting a positron that subsequently annihilates with a nearby electron to produce two 511 keV photons which travel in opposite directions and are detected by the PET scanner to create an image. These high energy 511 keV photons have a much greater penetrating ability compared with the photons produced by other radiopharmaceuticals used in general nuclear medicine.[9] Because PET/CT is performed with high-energy emitters, radiologists and nuclear medicine physicians should be familiar with the unique radiation concerns associated with operating a PET/CT facility to ensure the safety of both patients and staff.

PET/CT facilities must be designed and built with appropriate shielding and floor plans to uphold radiation safety standards. Safety measures and workflow patterns should be implemented to protect ancillary personnel and the public. The well-documented benefits of whole-body PET/CT come at the cost of a substantial radiation dose to the patient.[10] A whole-body PET/CT examination confers a higher radiation dose than a typical individual PET or CT examination.[11] Radiologists and nuclear medicine physicians should be familiar with the accepted indications for PET/CT and the appropriate selection of patients to guide referring physicians and avoid unnecessary radiation exposures. Risk-benefit ratios should be considered before every PET/CT study, particularly in pediatric patients.[10] As with any study that uses ionizing radiation, the principle of "as low as reasonably achievable" should be followed, and scanning protocols should be optimized to achieve this goal. PET/CT scanning protocols can be tailored to the clinical setting and optimized to minimize radiation dose to the individual patient. Special consid-

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Table 1 Coverage of Oncological Uses of FDG PET by Centers for Medicare and Medicaid Services (CMS)[6]

Initial and Subsequent Treatment Strategy Covered (Some With Limitations)
Colorectal
Esophagus
Head and neck (not thyroid)
Lymphoma
Nonsmall cell lung
Ovary
Brain
Myeloma
Cervix (covered for staging in newly diagnosed cervical cancer after conventional imaging that is negative for extrapelvic metastasis. All other uses are CED)
Breast (noncovered for diagnosis and/or initial staging of axillary lymph nodes. Covered for initial staging of metastatic disease)
Melanoma (noncovered for initial staging of regional lymph nodes. All other uses for initial staging are covered)
Thyroid (covered for subsequent treatment strategy of recurrent or residual thyroid cancer of follicular cell origin previously treated by thyroidectomy and radioiodine ablation and have a serum thyroglobulin, >10 ng mL^{-1} and have a negative I-131 whole body scan. All other uses for subsequent treatment strategy are CED).
Initial treatment strategy covered; subsequent treatment strategy coverage requires participation in an approved coverage with evidence development program (NOPR)
Small cell lung
Soft-tissue sarcoma
Pancreas
Testes
All other solid tumors
Coverage requires participation in an approved coverage with evidence development program (NOPR)
Prostate (noncovered for initial staging. All other uses are CED)
All other cancers not listed elsewhere in table

erations are made for pediatric patients and pregnant and lactating females.

Increased radiation dose is associated with an increased cancer risk, and therefore PET/CT facilities must uphold currently accepted radiation safety standards. The purpose of this article is to briefly review the common clinical applications for PET/CT and to focus on the issue of radiation safety for patients and PET/CT personnel.

PET/CT Shielding Requirements

PET/CT is most commonly performed with ^{18}F-FDG, which has a half-life of 109.8 minutes. Fluorine-18 is a positron-emitting radionuclide that leads to an annihilation reaction of a positron and electron, producing two 511 keV photons. The 511 keV annihilation photons are much more highly penetrating than other diagnostic radiations.[9] Therefore, a greater amount of lead is required for shielding in PET/CT suites compared with traditional diagnostic radiology or nuclear medicine examination rooms. For example, the half value layer for lead, which is the thickness of lead that will decrease the amount of exposure by one-half, is approximately 20 times higher for 511 keV photons than for the 140 keV photons produced by ^{99m}Tc used in general diagnostic nuclear medicine procedures.[12] A PET/CT scanner room may require half inch lead shielding and an uptake room may require a maximum of three-fourth inch lead shielding in comparison with only inch or less of lead shielding for a typical CT scanner room.[13] A PET/CT facility may require thick lead barrier shielding in floors, ceilings, and walls, resulting in high building costs and increased weight which can place additional constraints on supporting structures.[12,14]

In 2006, the American Association of Physicists in Medicine (AAPM) Task Group 108 released a report entitled "PET and PET/CT Shielding Requirements" which provides detailed information for estimating shielding requirements for PET/CT facilities. Constructing a PET/CT facility de novo or remodeling an existing facility for the addition of a PET/CT scanner require input from a medical physicist, the equipment vendor, and an architect to ensure that radiation safety standards are upheld and that the design is cost-effective.[14]

Radiation Exposure to PET/CT Technologists and Personnel

The radiation doses received by PET/CT technologists may be higher than those received by diagnostic radiology technologists or by general nuclear medicine technologists who do not perform PET/CT.[15] There are several factors that lead to an increased risk of occupational exposure for PET/CT technologists, and these are predominantly related to the PET portion of the examination. The 511 keV photons from ^{18}F-FDG have uniquely high energy and penetration. For comparison, the γ ray constant (which is the dose equivalent because of γ rays emitted from a specific amount of a source at a specific distance) for ^{18}F is 5.66 times higher than that of ^{99m}Tc. Also, the relatively high administered doses (10-20 mCi of FDG) and the high volume of patients in a typical busy facility contribute to the risk to PET/CT staff.[13] The radiation dose can be minimized and maintained below regulatory guidelines when proper radiation safety standards are followed.[13] The "as low as reasonably achievable" concepts of shielding, time, and distance can be applied to minimize occupational exposure.[9]

There are multiple steps in the PET/CT workflow process which can result in radiation exposure, but most of these steps can be performed with shielding. The radiopharmaceutical is provided in a sealed vial enclosed in a lead container. The dose is then manually transferred to a syringe behind a lead shield, the activity is assayed, and then the dose is ready for injection. Pre-prepared unit doses can minimize handling of the radiopharmaceutical. A large proportion of radiation exposure occurs at the time of patient injection, but this

exposure can be decreased significantly using syringe shields that fit over a disposable syringe.[15] Syringe shields constructed of varying thicknesses of tungsten provide hand and finger protection by attenuating ^{18}F-FDG by as much as 88%-99%, according to various manufacturers' specifications. There are additional commercially available devices designed to minimize technologist exposure, such as manual dose injectors and mobile radiation shields (Fig. 1).

PET/CT personnel should understand the concept of time as a protective mechanism. Ideally, the technologist should explain the procedure to the patient, position the patient comfortably, and complete all other similar tasks before injecting the patient. After the dose has been injected, the technologist should leave the patient's room as quickly as possible. The technologist should also minimize the amount of time spent with the patient after the examination.[15]

Another approach to minimize radiation exposure to support personnel or the public from a PET/CT scan is by using the concept of distance. In radiation measurement, the exposure rate from a point source of radiation is inversely proportional to the distance from the source squared. This relationship is known as the inverse square law and is a very inexpensive and effective method for reducing personnel exposure. For example, when handling a patient dose, the exposure rate to the fingers of the technologist/nurse holding the dose decreases by a factor of 25 between holding the syringe from the needle cap (about 1 cm between fingers and dose) vs the tip of the plunger (about 5 cm between fingers and dose). A further decrease of 9 times is gained by holding the syringe using tongs (about 15 cm between fingers and dose), resulting in huge exposure rate reduction of 225 times. In this regard, it is important for technologists and nurses to constantly maximize the distance between themselves and sources of radiation. During the design of the imaging suite, effort should be exercised to maximize the distance between the scanner and the console from where the technologist acquires and processes the data to ensure minimal amount of radiation exposure. The inverse square law is only valid for point sources (sources whose dimensions are smaller than the distance between source and object). For patients injected with radioactive material, the exposure rate would decrease less rapidly than the inverse of the distance squared.

Figure 1

Radiation Exposure to Non-PET/CT Staff and the Public

After injection of a radiopharmaceutical, the patient becomes a radiation source and should be placed in a designated uptake room with a nearby patient-only toilet. Typically, a PET/CT is performed 1 hour after injection. The patient should rest quietly and comfortably in a darkened room for this hour to minimize muscle activity during the uptake period. The main consideration for not returning the patient to the waiting room is the promotion of peaceful inactivity on the part of the patient during the uptake period, and any potential risk of radiation exposure to the public in the waiting room is a much lesser factor. On the basis of an injection range of 5-15 mCi, a 1-hour uptake time, voiding of the bladder, and a 30-minute scan time, the patient will leave the imaging suite with approximately 2.5-7.5 mCi remaining in his/her body. On the basis of standard radiation limits to the public, there is no need to restrict patients' behavior after they leave the department, regardless of the age of family

members and other contacts, because the radiation exposure that the patient will induce to the public will be below the acceptable limits of 1 mSv/yr or 0.02 mSv in any 1-hour period.[16-18]

Radiation Exposure to Patients

Although most PET/CT studies are performed on patients who already have cancer, the issue of radiation safety is still pertinent. Patients with cancer often undergo multiple PET/CT examinations over the course of several years, and the long-term survival of cancer patients is increasing.[19]

Radiation dose to the patient from a PET/CT scan is equal to the sum of the combined dose from the PET and the CT components of the scan. The radiation dose of the FDG PET component of the scan has been thoroughly investigated by many researchers. Table 2 shows the radiation dose estimates to different organs in the body as well as the total effective dose equivalent (EDE). Doses to different organs are reported in mGy/MBq, whereas the EDE is reported in the mSv/MBq. The mGy is the unit for dose and corresponds to the amount of energy deposited per gram of tissue, whereas mSv is the unit used to measure radiation-specific biological damage in human beings. In an FDG PET scan, the amount of injected activity usually ranges between 85 and 740 MBq (5-20 mCi), depending on the scanner and the protocol. With these levels of injected activity, the maximum dose to any organ from an FDG examination does not exceed 141 mGy and the maximum EDE to the whole body does not exceed 22.2 mSv.

The radiation dose from the CT largely 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,[21] making the effective dose for the CT component of the PET/CT equal to 24 mSv (excluding the legs). The total effective dose to the patient for a FDG combined PET/CT scan is the sum of the PET and CT components, giving a total of 22 + 24 = 46 mSv. This is in comparison with an annual effective dose from natural background radiation of approximately 3 mSv.[21]

There are several strategies that can be used to minimize the radiation dose to the patient undergoing a PET/CT scan. For the PET component, the best way to reduce dose is by reducing the injected activity. However, reducing the injected activity would result in a reduction in image quality. One method of reducing the injected activity while maintaining image quality is by increasing scan duration. However, this would come at the cost of decreased scanner throughput as well as increased patient motion which leads to increased image blur. Another method to improve the image quality while still reducing the injected dose (hence reducing patient radiation) is by improving the scanner sensitivity. This can be achieved by scanning in 3D rather than 2D mode, by increasing the axial extent of the scanner, or, most recently, by acquiring PET data in time-of-flight (TOF) mode.

The first 2 approaches allow more γ rays to be detected per unit time for a preset injected amount of activity. For example, if an acceptable image quality requires 1 million counts in total, then a scanner which is more sensitive than another can achieve this goal by either shortening the scan duration or injecting a smaller amount of radioactivity. For the last approach, TOF systems are characterized by higher contrast with noise ratio than non-TOF systems which directly affect image quality. Therefore, the injected activity in a TOF system can be reduced while still achieving a contrast with noise

Table 2 Radiation Dose Estimates for F-18 FDG[20]*

Organ	Adult	15 Years	10 Years	5 Years	1 Year
Adrenals	1.2 E-02	1.5 E-02	2.4 E-02	3.8 E-02	7.2 E-02
Bladder	1.6 E-02	2.1 E-02	2.8 E-02	3.2 E-02	5.9 E-02
Bone surfaces	1.1 E-02	1.4 E-02	2.2 E-02	3.5 E-02	6.6 E-02
Brain	2.8 E-02	2.8 E-02	3.0 E-02	3.4 E-02	4.8 E-02
Breast	8.6 E-02	1.1 E-02	1.8 E-02	2.9 E-02	5.6 E-02
Stomach	1.1 E-02	1.4 E-02	2.2 E-02	3.6 E-02	6.8 E-02
Small intestine	1.3 E-02	1.7 E-02	2.7 E-02	4.1 E-02	7.7 E-02
Colon	1.3 E-02	1.7 E-02	2.7 E-02	4.0 E-02	7.4 E-02
Heart	6.2 E-02	8.1 E-02	1.2 E-02	2.0 E-02	3.5 E-02
Kidneys	2.1 E-02	2.5 E-02	3.6 E-02	5.4 E-02	9.6 E-02
Liver	1.1 E-02	1.4 E-02	2.2 E-02	3.7 E-02	7.0 E-02
Lungs	1.0 E-02	1.4 E-02	2.1 E-02	3.4 E-02	6.5 E-02
Muscles	1.1 E-02	1.4 E-02	2.1 E-02	3.4 E-02	6.5 E-02
Ovaries	1.5 E-02	2.0 E-02	3.0 E-02	4.4 E-02	8.2 E-02
Pancreas	1.2 E-02	1.6 E-02	2.5 E-02	4.0 E-02	7.6 E-02
Red marrow	1.1 E-02	1.4 E-02	2.2 E-02	3.2 E-02	6.1 E-02
Skin	8.0 E-02	1.0 E-02	1.6 E-02	2.7 E-02	5.2 E-02
Testes	1.2 E-02	1.6 E-02	2.6 E-02	3.8 E-02	7.3 E-02
Thymus	1.1 E-02	1.5 E-02	2.2 E-02	3.5 E-02	6.8 E-02
Thyroid	1.0 E-02	1.3 E-02	2.1 E-02	3.5 E-02	6.8 E-02
Uterus	2.1 E-02	2.6 E-02	3.9 E-02	5.5 E-02	1.0 E-02
Effective dose (mSv/MBq)	1.9 E-02	2.5 E-02	3.6 E-02	5.0 E-02	9.5 E-02

*Values are given as absorbed dose per unit activity administered (mGy/MBq).

ratio comparable to a non-TOF system. Combining the effects of 3D vs 2D, increased axial extent, and TOF capability could result in a dose reduction to the patient by more than 50%-75%.

For the CT component, several approaches also exist to minimize radiation dose to the patient. As described in the article on CT in this edition, a reduction in kilovolt peak, milliampere, tube rotation speed, detector configuration efficiency, as well as an increase in helical pitch, all lead to decreasing the effective dose to the patient. However, a reduction in patient dose will affect the image quality for diagnostic evaluation, particularly when dealing with large patients. Careful consideration of the acquisition parameters should be performed to achieve a balance between patient dose and image quality. One such application is to use x-ray tube current modulation which minimizes patient exposure while maintaining image quality. This approach is currently available on most PET/CT commercially available scanners and should be used whenever possible to reduce patient dose.

Another strategy to reduce patient dose from the CT is the decision to use the CT component of the PET/CT scan solely for attenuation correction and anatomical land marking rather than for diagnostic evaluation. In this regard, the CT acquisition parameters can be further manipulated to further reduce patient dose because the use of CT for attenuation correction and anatomical land marking do not necessitate a high quality CT scan. Finally, the use of bismuth shields is an additional technique which reduces the dose to the patient's breast by a maximum of 20%. Bismuth breast shields are effective in decreasing radiation dose to the breast without degrading image quality.[22]

It is important to note that although the total effective dose from a PET/CT scan is relatively high (Table 3; it shows a comparison of different diagnostic procedures), the maximum annual additional risk because of a single PET/CT scan averaged over the general US population (gender and age) for incidence of any solid tumors except thyroid cancer or nonmelanoma skin cancer is 0.019%.

The CT portion of the PET/CT examination should be customized on the basis of the clinical situation and whether the patient's evaluation necessitates a diagnostic quality CT or simply a lower dose CT for localization and attenuation correction. Patients who have already had a contrast-enhanced, diagnostic CT as part of their work-up can usually be evaluated with a PET/CT that incorporates a low-dose CT. A low-dose CT may be sufficient in patients undergoing long-term surveillance of treated cancer with a low suspicion of active disease.[23]

^{18}F-FDG has renal excretion, and the bladder is the critical organ that accumulates ^{18}F. Patients should be instructed to increase fluid intake and frequently empty their bladder after the study to decrease the radiation dose to bladder.[9]

Table 3 Adult Effective Doses for Various Radiologic and Nuclear Medicine Procedures[21]

Examination	Average Effective Dose (mSv)
PA and lateral CXR	0.1
Mammography	0.4
Barium enema	8
Chest CT	7
Chest CT for pulmonary embolism	15
Abdominal CT	8
Pelvic CT	6
Three-phase liver CT	15
Virtual colonoscopy	10
TIPS placement	70
99mTc bone scan	6.0
18F-FDG PET	14.1

Pregnant Patients

There is limited data regarding the use of PET/CT in pregnant patients. A combined PET/CT results in a relatively high radiation dose to an embryo.[24] This is a function of ^{18}F-FDG uptake as well as the CT dose, which varies depending on the scan parameters. Every female patient referred for PET/CT should be carefully screened for pregnancy, and the study is usually canceled if there is a question of pregnancy. There may be instances in which the benefits of a PET/CT would outweigh the risks to a fetus. The principle of "as low as reasonable achievable" should be applied, and in most cases, sufficient diagnostic information can be acquired by other imaging modalities which result in a lower radiation dose, and the PET/CT can be postponed until after the pregnancy.

In cases of accidental exposure of a pregnant patient to PET/CT, the estimated dose to the fetus should be calculated by a medical physicist. According to the National Council on Radiation Protection and Measurements, the risk "is considered to be negligible at 50 mGy or less when compared to other risks of pregnancy, and the risk of malformations is significantly increased above control levels only at doses above 150 mGy. Therefore, exposure of the fetus to radiation arising from diagnostic procedures would very rarely be cause, by itself, for terminating a pregnancy."[25,26] The estimated dose to the uterus from ^{18}F-FDG is 2.3×10^{-2} mGy/MBq, and to reach 50 mGy from the PET component would require an injection of 58.7 mCi of ^{18}F-FDG, a dose which would be unheard of in clinical practice.

Lactating Patients

Given the increasing use of PET/CT, it is not uncommon for a currently breastfeeding woman to be referred for PET/CT. Lactating patients demonstrate significantly increased uptake of radiotracer in their breasts compared with nonlactating patients.[27] This is predominantly because of uptake of ^{18}F-FDG by active glandular tissue. A relatively low level of radiotracer is excreted into the actual breast milk.[28] Consequently, the main source of radiation exposure for a nursing infant would be close proximity to the mother's breast soon after the examination, rather than ingestion of breast milk. When radiopharmaceuticals are secreted into breast milk, the recommended guideline is to cease breastfeeding until

the effective dose to the child would be ≤1 mSv.[17] This guideline dictates an interruption of breastfeeding for varying lengths of time, depending on the physical half-life of the radiopharmaceutical. The International Commission on Radiological Protection recommendation for ^{18}F-FDG is "no interruption" of breastfeeding.[17] Cessation of breastfeeding is unnecessary, given the short half-life of ^{18}F and low-level of excretion of FDG into the breast milk. However, as a precaution, expression of breast milk and bottle-feeding by a third party for the first feeding after a PET/CT examination could minimize exposure to the infant.[28]

Pediatric Patients

PET/CT has proven utility in pediatric oncology and can significantly change clinical management in many pediatric malignancies.[29] Concern over the radiation dose to pediatric patients undergoing CT examinations has heightened in recent years, and increased awareness and education has led to significant improvements in this regard.[30,31] PET/CT faces similar concerns given the ever-increasing number of pediatric patients referred for examinations. Both the CT and the PET portions of the examination contribute significantly to the radiation dose from a PET/CT examination.

The CT dose can vary greatly depending on the CT acquisition parameters. The CT parameters should be tailored to the patient's size, similar to the adjustments made for a diagnostic CT of a pediatric patient.[32] The CT scan parameters are also determined by the clinical setting and whether evaluation of the patient requires diagnostic quality images, lower quality "localization" images, or merely attenuation correction images.[33] For example, if the patient has already undergone a recent diagnostic-quality CT scan, the PET/CT could be performed using a low-dose CT strictly for anatomical correlation, reducing the patient's radiation dose by a factor of 2- or 3-fold.[34]

For the PET portion of the examination, the effective dose is determined by the administered activity of ^{18}F-FDG and the age of the patient.[35] Optimized protocols can reduce the effective radiation dose without comprising on image quality. A reduction in the amount of activity administered can be balanced by an increase in the amount of time per bed position (at the cost of increased patient motion during the scan time), and also by the use of the more sensitive 3D mode as compared with 2D mode.[35]

Parents of pediatric patients often wish to remain with their children during procedures. The calculated radiation exposure to a parent staying within 1 m of a patient during a 1-hour uptake period and a 1-hour imaging period of a typical PET/CT examination has been reported to be no more than 5.5 mR, which is an acceptable level.[29] Parents may be allowed to accompany pediatric patients, but they should be instructed keep as much distance as is possible from the patient.

Summary

PET/CT has become an indispensable modality in clinical imaging, particularly in the management of oncology patients, and is becoming the study of choice for many indications.[36,4] PET/CT is accurate and quick, and is becoming increasingly available in various practice settings.[37] The use of ^{18}F-FDG, a positron-emitting radionuclide, poses special hazards in a PET/CT facility. The radiation exposure to patients undergoing PET/CT is of concern as the dose is a combination of internal and external exposures, from the PET portion and the CT portion, respectively.[7] Physicians supervising PET/CT examinations should be familiar with the unique radiation safety issues associated with PET/CT. There are many available resources to assist with the design of a PET/CT facility and to guide implementation of protective measures and workflow patterns to minimize occupational exposure. Careful screening of patients referred for PET/CT based on documented indications supported by current published data and Centers for Medicare and Medicaid Services coverage decisions, and optimization of scanning protocols can protect the safety of patients.

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