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CONTEMPORARY ISSUES IN RADIATION PROTECTION IN MEDICAL IMAGING SPECIAL FEATURE: REVIEW ARTICLE

Cumulative radiation doses from recurrent PET–CT examinations

[1]MAKOTO HOSONO, MD, PhD, [2]MAMORU TAKENAKA, MD, PhD, [3]HAJIME MONZEN, PhD, [3]MIKOTO TAMURA, PhD, [2]MASATOSHI KUDO, MD, PhD and [1]YASUMASA NISHIMURA, MD, PhD

[1]Department of Radiation Oncology, Faculty of Medicine, Kindai University, 377-2 Ohno-Higashi, Osaka-Sayama, Osaka, Japan
[2]Department of Gastroenterology, Faculty of Medicine, Kindai University, Ohno-Higashi, Osaka-Sayama, Osaka, Japan
[3]Department of Medical Physics, Graduate School of Medical Sciences, Kindai University, Ohno-Higashi, Osaka-Sayama, Osaka, Japan

Address correspondence to: Prof Makoto Hosono
E-mail: *hosono@med.kindai.ac.jp*

ABSTRACT

Positron emission tomography (PET–CT) is an essential imaging modality for the management of various diseases. Increasing numbers of PET–CT examinations are carried out across the world and deliver benefits to patients; however, there are concerns about the cumulative radiation doses from these examinations in patients. Compared to the radiation exposure delivered by CT, there have been few reports on the frequency of patients with a cumulative effective radiation dose of ≥100 mSv from repeated PET–CT examinations. The emerging dose tracking system facilitates surveys on patient cumulative doses by PET–CT because it can easily wrap up exposure doses of PET radiopharmaceuticals and CT. Regardless of the use of a dose tracking system, implementation of justification for PET–CT examinations and utilisation of dose reduction measures are key issues in coping with the cumulative dose in patients. Despite all the advantages of PET/MRI such as eliminating radiation exposure from CT and providing good tissue contrast in MRI, it is expensive and cannot be introduced at every facility; thus, it is still necessary to utilise PET–CT with radiation reduction measures in most clinical situations.

INTRODUCTION

Positron emission tomography (PET–CT), in which 2-deoxy-2-[^{18}F]flu-D-glucose (FDG) is the most frequently used PET pharmaceutical, is now an essential imaging modality in various clinical circumstances, especially in the management of oncology patients.[1] Individualised application of therapy that is customised via PET–CT imaging is actually becoming an indispensable process especially in the strategy of oncological management strategies, such as initial diagnosis and staging, treatment selection, planning of external beam radiation therapy when applied, response evaluation to therapy, and follow-up and detection of recurrence after therapy. PET–CT offers reliable guides also for patient management in cardiology, neurology, and some other specialties. Notably, such wide application of PET–CT will require standardisation and sufficient quality assurance of the imaging.

While increasing numbers of PET–CT examinations are being carried out across the world and deliver benefits to patients, concerns have been arising regarding cumulative radiation doses of patients from repeated PET–CT examinations in patients. Countermeasures of radiation protection for both patients and staff members should evolve to sustain the application of this modality in medical practice. We are in an era where the medical radiation exposure of patients has been increasing, and there is a growing interest in how to deal with medical exposure as radiological procedures have become indispensable in various clinical circumstances.

Multiple radiological and nuclear medicine examinations lead to a substantial cumulative effective dose (CED) of radiation in individual patients, *e.g.* a CED of ≥100 mSv. One of the largest man-made radiation sources to humans is CT, and despite all efforts and focus on reduction in radiation dose per CT, patients undergoing multiple CT examinations and receiving a CED of ≥100 mSv are not uncommon lately.[2–4] This cut-off CED of ≥100 mSv could be used because at this level many organs might receive doses of ≥100 mGy, a range at which a statistically significant excess of certain cancers has

been demonstrated in studies and there is a reasonable degree of agreement among official international and national organisations on potential stochastic radiation effects.[2] Rehani et al reported that of the 2.5 million patients who underwent 4.8 million CT examinations during the period between 1 and 5 years in 324 hospitals in the USA and Europe, 1.33% of patients received a CED of ≥100 mSv with an overall median CED of 130.3 mSv and maximum of 1,185 mSv.[2] In another study, the first estimates of the number of patients likely receiving a CED of ≥100 mSv through recurrent CT examinations in 35 OECD countries indicate that 2.5 million patients reach this level in 5 years.[3] Moreover, Rehani et al reported in another paper that there were 0.8% of 3.9 million patient-days with ≥50 mSv and one-third of them were of patients aged 50 or younger,[5] which spreads the ripples among stakeholders in radiation protection in medicine.

Compared to patient radiation exposure delivered by CT, there have been very few comprehensive reports on patient exposure from repeated PET–CT examinations. Therefore, this review will discuss the cumulative exposure of patients to radiation from PET–CT examinations and present how it should be dealt with in clinical circumstances where PET–CT serves as a highly efficient tool in the management of patients with various diseases.

PATIENT RADIATION EXPOSURE DELIVERED BY PET–CT

Combined positron PET–CT imaging has become a routine procedure in diagnostic radiology and nuclear medicine that benefits from the fusion of functional and anatomical information.[6] Radiation exposure from PET–CT consists of contributions from PET radiopharmaceuticals[7] and from X-ray CT.[8] In the earlier days of the introduction of PET–CT, a report showed that the average effective dose of patients from whole-body FDG-PET–CT examinations was approximately 25 mSv.[9] PET radiopharmaceuticals typically deliver several mSv of effective doses.[10] The dose of PET radiopharmaceuticals can be reduced by using a PET–CT scanner equipped with a recent high-sensitivity PET detector that incorporates technologies such as semi-conductor detector, time of flight, point spread function, and novel reconstruction algorithms.[11–13]

The radiation dose to the patient from CT examinations generally depends on parameters such as scan length, tube current, tube current modulation, tube voltage, collimation, pitch, and slice thickness.[14] The radiation dose from CT is principally measured by using a dedicated cylindrical phantom and expressed as a volume-averaged CT dose index (CTDI). The parameter volume CTDI (CTDIvol) indicates the average absorbed dose at a point with the scan volume for a particular scan protocol for a standardised phantom.[14] CT scans of PET–CT examinations are acquired based on three purposes.[15] They are: (1) attenuation correction of the PET images, (2) anatomical localisation of PET radiopharmaceutical in the patient's body, and (3) diagnostic interpretation of CT images themselves. Such purposes are often mixed with others in the real clinical settings. Prieto et al reported that a significant radiation dose reduction of 28.7% was reached by reducing administered FDG activity from 5.18 MBq/kg to 3.70–4.44 MBq/kg and CT current–time–product from 120 mAs to 80–100 mAs, with image readers reporting unchanged clinical confidence.[16]

Although surveys have reported on the cumulative radiation dose of CT examinations in patients, there have been no comprehensive reports on that of PET–CT examinations. Among the recent reports on cumulative doses of patients in various radiological examinations, actual findings regarding PET–CT have been reported at an IAEA symposium.[17] In a single hospital, 10,838 PET–CT examinations were performed for 8029 patients (1.3 examinations per patient) in 44 months (January 2017–September 2020). For malignant lymphoma, 1117 examinations were performed for 718 patients (1.56 examinations per patient), and for cardiac sarcoidosis, 146 examinations in 92 patients (1.59 examinations per patient). Among the high dose patients, 18 of 8029 patients (0.22%) for all PET–CT examinations, 4 of 718 patients (0.56%) for malignant lymphoma, and 1 of 92 patients (1.1%) for cardiac sarcoidosis were recorded as having received CED of ≥100 mSv. Further surveys are needed to clarify the frequency of patients with a high CED due to PET–CT.

JUSTIFICATION OF FDG-PET–CT

Many studies have demonstrated the impact of FDG-PET–CT on the management of patients including staging and suspected disease recurrence in various malignancies and the role of FDG-PET–CT has been clarified well.[1,18,19] And through this process, referral criteria or appropriateness guidelines have been established well, and thus, justification can be implemented by following them. In addition, through accumulated evidence on the role of FDG-PET–CT, the health insurance coverage can clearly be defined as compared to those for other imaging modalities in nations.[20,21] For example, the Centers for Medicare and Medicaid Services in the USA determine when and how FDG-PET–CT examinations are performed under the health insurance coverage.[20] Such strictly defined health insurance coverage may generally suppress overuse of FDG-PET–CT, and this situation of more limited indication of FDG-PET–CT than that of CT may be common worldwide.[22–24] Such measures may reduce the overall cumulative radiation dose from FDG-PET–CT by limiting the cases of overly repeated examinations.

DOSE TRACKING SYSTEM

Recently, dose tracking systems have become widespread in clinical practices. Hospitals and health-care professionals can see all of a patient's dose information in one place, which will allow them to justify their radiological procedures and optimise radiation dose to improve patient radiological protection.[25–27] Seuri et al reported that the availability of previous imaging studies and radiation dose figures helped to avoid additional new CT examinations by providing required information from previously performed CT examinations.[28] PET, PET–CT, single photon emission computed tomography (SPECT), SPECT/CT, and some of nuclear medicine examinations have become the focus of attention as high-dose examinations, even though they are less frequently performed. The spread of the dose tracking system will facilitate a survey on radiation exposure doses from PET–CT in patients because it can easily wrap up exposure doses of PET radiopharmaceuticals and X-ray CT.

It should be noted that installing a dose tracking system, although if encouraged, is costly and may not always be possible

Table 1. Examples of effective doses for PET radiopharmaceuticals[10]

	Effective dose per unit activity administered (mSv/MBq)				
Pharmaceutical	Adult	15 years	10 years	5 years	1 year
[^{18}F]FDG	1.9E-02	2.4E-02	3.7E-02	5.6E-02	9.5E-02
[^{18}F]choline	2.0E-02	2.4E-02	3.7E-02	5.7E-02	1.0E-01
[^{18}F]fluoride	1.7E-02	2.0E-02	3.3E-02	5.6E-02	1.1E-01
[^{18}F]fluorothymidine	1.5E-02	1.9E-02	2.9E-02	4.6E-02	8.8E-01
[^{11}C]methionine	8.2E-03	1.1E-02	1.6E-02	2.5E-02	4.7E-02
[^{15}O]water	1.1E-03	1.4E-03	2.3E-03	3.8E-03	7.7E-03
^{82}Rb-chloride	1.1E-03	1.4E-03	3.0E-03	4.9E-03	8.5E-03
[^{124}I]iodide	3.0E-01	4.2E-01	6.3E-01	1.2*E* + 00	2.2*E* + 00

PET, positron emission tomography

in hospitals even in high-income countries and particularly in low- and middle-income countries.[25] Regardless of the use of such a dose tracking system, implementation of justification through evidence-based clinical guides and utilisation of dose reduction measures are key issues in coping with the cumulative dose of radiation exposure in patients.[27,29]

PET RADIOPHARMACEUTICALS

The majority of PET–CT examinations in daily practices are performed using FDG,[15] which visualises glucose metabolism and has a wide range of applications. However, various PET radiopharmaceuticals have been developed and introduced into the clinical stages (Table 1). Moreover, as a theranostics approach is currently used, it is important to be aware of radiation exposure of patients delivered by PET radiopharmaceuticals in the course of a theranostics approach. Examples of using PET radiopharmaceuticals other than FDG in PET–CT include ^{68}Ga-labeled somatostatin analogs for therapy with ^{177}Lu-labeled somatostatin analogs against neuroendocrine tumours.[30] In addition, ^{68}Ga-labeled or ^{18}F-labeled PSMA ligands for therapy with ^{177}Lu-labeled or ^{225}Ac-labeled PSMA ligands against castration-resistant prostate cancer have received a lot of attention.[31–34] With the increasing use of PET radiopharmaceuticals in theranostic approaches, cumulative radiation doses in patients should be recorded in consideration with PET radiopharmaceuticals.

POTENTIALS OF PET/MRI

The development of integrated PET/MRI scanners has been a technological challenge because the PET detectors should function in the high magnetic fields of MRI and attenuation correction of PET should be applied based on MR images.[35,36] The advantages of PET/MRI over PET–CT include high soft tissue resolution on MRI and no CT radiation exposure. PET/MRI scanners have recently been introduced in clinical sites despite their high price, and findings on diagnostic accuracy and roles in patient management have been accumulated.[37–41]

When we consider the reduction of radiation exposure associated with the CT part of PET–CT, MRI may be a good alternative that provides anatomical information without using ionising radiation. One of the major benefits of PET/MRI for patient care is the significant reduction in radiation exposure while presenting a similar diagnostic performance. Martin et al reported that the results confirmed the potential for a mean dose reduction of 83.2% when compared with full-dose PET–CT imaging. The estimated mean effective dose for whole-body PET–CT amounted to 17.6 ± 8.7 mSv, in comparison to 3.6 ± 1.4 mSv for PET/MRI, resulting in a potential dose reduction of 79.6%; 83.2% for full-dose PET–CT to PET/MRI, and 36.1% for low-dose PET–CT to PET/MRI.[42] The potential risks to patients from exposure to magnetic fields may be negligible.[43] Moreover, simultaneous exposure to ionising radiation and electromagnetic fields did not result in a significant synergistic outcome of double-strand breaks in lymphocyte DNA.[44] The advantage of PET/MRI regarding radiation exposure in paediatric patients is being recognised in comparison to PET–CT.[42,45] Despite all the advantages of PET/MRI, PET/MRI is expensive and cannot be introduced at every facility; therefore, it is still necessary to utilise PET–CT with radiation reduction measures in most clinical situations.

CONCLUSIONS

The cumulative radiation dose from PET–CT in patients has not been as discussed as the cumulative radiation dose from CT. This is probably partly due to the lower total number of examinations, the narrower coverage of insurance, and the lower frequency of examinations for individual patients. The spread of the dose tracking system will facilitate surveys on patient exposure doses by PET–CT because it can easily wrap up exposure doses of PET radiopharmaceuticals and X-ray CT. Regardless of the use of such a dose tracking system, implementation of justification through evidence-based clinical guides and utilisation of dose reduction measures are key issues in coping with the cumulative radiation dose in patients.

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