What should be done for radiation protection in a department with PET/CT camera and cyclotron

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Positron emission tomography (PET) allows accurate imaging of the distribution of radiopharmaceuticals labelled with positron emitting radionuclides such as $^{18}$F (the most widely used), $^{13}$N, $^{11}$C and $^{15}$O. The combination of CT and PET modalities in the same scanner allows to acquire both anatomic (CT) and metabolic (PET) information that can be displayed in an unique fused image. The physical characteristics of positron emitters could result in a higher radiation risk for staff in comparison to conventional nuclear medicine because:

1. the penetrating ability of the high-energy 511 keV $\gamma$-rays produced by annihilation reaction of a positron and a electron is greater than that of all the radionuclides used in conventional nuclear medicine;
2. the specific $\gamma$-ray dose constants for the $b^+$ emitters, i.e. the dose rate in air for 1 MBq at a distance of 1 m, are about 6 and 3 times higher than for $^{99m}$Tc and $^{131}$I respectively.

Many other variables involved in clinical routine, such as shielding, workload, injected activity, time between injection and imaging and time spent by the operator close to the patient, should be considered to optimize the procedures from a radiation protection point of view.

Workload and injected activity

Every working day a medium size nuclear medicine department with 3 SPECT gammacameras and 1 PET scanner on average performs 30 conventional nuclear medicine and 7 PET examinations administering about 15000 MBq of $^{99m}$Tc and 2500 MBq of $^{18}$F (ratio $^{18}$F and $^{99m}$Tc activity = 1/6). The mean administered activity per study is about 520 and 350 MBq for $^{99m}$Tc and $^{18}$F respectively. The introduction of the new technology of 3D high sensitivity PET/CT scanners brought to a decreasing of about 20% of $^{18}$F-FDG injected activity per study but the number of daily patients increased because acquisition times are shortened so the two effects balance out. Some already published works agree about that the technologist daily dose in PET is proportional to the daily injected activity with an average effective dose of 22 nSv/MBq. When the daily injected activity increases it is necessary to adopt shielding devices and to enroll more exposed workers. Particular care must be paid also to the cases of slow infusion during dynamic studies: if many of this kind of studies are performed the use of an automatic injector is advisable.

Shielding and facility layout

All radionuclide manipulations should be done in shielded cells that for $b^+$ emitters must have at least 50 mm of lead, many air changes per hour and be in depressed status. Usually $^{18}$F-FDG is delivered in a multi-dose vial of about 37 GBq and automated fractionaters are now available to limit body exposure, however attention must be paid to hand exposure due to activity stagnating into unshielded tubes inside the cell. When no automatic fractionaters are available exposure can be reduced by dividing the radiopharmaceutical during the synthesis into multiple vials to use at different times; the vials should be put in lead boxes and a spinal needle (10 cm long) inserted through the cap allows to fill the syringe without touching the vial with the hands. The syringe with the activity must be transported from the hotlab to the injection room in lead-shielded container. No heavy syringe shields (about 350 g) are usually applied during injection because these devices slow down the injection on already endangered veins of oncological patients. At $\gamma$ energies of 511 keV a short time for injection is more effective for radiation protection than few mm of lead shielding. It must be remembered that exposure linearly depends on time.

Room shielding, department layout and patient ways must be correctly set during the planning phase. Injected patients should have minimum contact with staff members and should be at the maximum possible distance. Exposure inversely depends on the square of the distance for point source geometry and...
on distance for extended sources such as patients. The scanner room should be as wide as possible and the control room set outside at the maximum distance from the scanner couch where patient lays. From a radiation protection point of view it was demonstrated that the best position for the control room is at the feet side of the scanner couch. Patients must be controlled through a lead glass window and videocameras; further vocal instructions can be given by means of an interphone system. If available spaces are not so wide it is necessary to add shield to the walls. Attention must be paid even to doors position. Ways must be studied so that injected patients have separate access to hot waiting areas, toilets and diagnostic room. PET scanners equipped with $^{64}$Ge rods (about 500 MBq) for transmissive acquisitions need shielding for the presence of these radioactive sources. With PET/CT scanners CT produces a low energy but high intensity beam that requires shielding considerations also for scatter radiation.

**Time between injection and imaging and time spent by the operator close to the patient**

With $^{18}$F-FDG acquisitions are usually performed 1 h after injection. After this time the activity in the patient body is slightly more than half of the administered activity because of the physical decay with a short half-time and the biological excretion with urine. The positioning of the patient on the scanner couch and his/her centering in the scanner field of view correspond to the major contact between technologist and injected patient. With PET/CT scanners a faster patient positioning should be expected being controlled by software on CT topogram.

**Staff education and employment**

All staff members must be correctly instructed about the good practice procedures in PET areas including the radiation protection aspects and be aware about the differences with conventional nuclear medicine. A constant daily workload of about 7 PET patients implies a greater dose than for conventional nuclear medicine investigations, so a rotation of the personnel is suggested to avoid an overexposure of a limited number of fellows. Technologists must remember to give any kind of instruction to patients before the injection so that after the administration patient care can be limited to what strictly necessary depending on the patients health conditions.

**Cyclotron**

Not all the PET centers are equipped with their own cyclotron facility however the number of these particle accelerators is increasing due to the growth of the demand of positron emitting radionuclides. PET center cyclotrons usually accelerates protons up to 18 MeV with a current of about 30 mA; they must be located in vaults with shielding of about 2 m of concrete. It is absolutely forbidden to stay inside the vaults during the bombardment because dose rate can be higher than 200 mSv/h and safety devices are present to avoid this possibility. After bombardment activity inside the vault is due to activation of materials such as beam transport system, target assembly and shielding structures directly bombarded by the accelerated charged particles or exposed to the secondary neutron field induced by the charged particle reactions. Secondary neutrons also activate the air inside the vault. Only a few of these activation products are long-lived, therefore it is recommended to wait for some hours from the end of bombardment before getting inside the vaults for any maintenance intervention in order to minimize the dose rate. Next to the cyclotron vault usually there are the radiochemistry laboratories: in a typical production cycle the cyclotron irradiation is followed by the delivery of the radionuclides through sealed and shielded delivery lines to the hot cells where the automated synthesis modules perform the preparation of the desired radiopharmaceutical. Hot cells are usually shielded at least with 50 mm of lead. Some steps in the complex radiosynthetic procedures may lead to volatile radioactive by-products. Unfortunately hot cell trapping features such as chemical absorbers are not completely effective with all these compounds. If this gaseous exhaust is repeatedly released into the environment it can represent an hazard for the population living close to the facility system. If the facility is close to a busy residential area it is strongly recommended to install an air compressing station which is a compressing pump that stores the contaminated gas at high pressure into a series of cylinders for the time necessary to let the gas to decay (about 24 h) before releasing it into the environment trough a chimney.

As the synthesis yield can be as low as 0.5, half of the activity remains in the hot cells and so any intervention on the synthesis modules should be performed after about 10 physical decay half-times (for $^{18}$F about 24 h) after the last synthesis. It is reported that not optimized interventions in radiopharmaceutical and cyclotron areas give rise to high personnel doses.
References

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