PATIENT ORGANS DOSE CALCULATIONS IN NUCLEAR MEDICINE

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ABSTRACT

Radionuclides are used in nuclear medicine in a variety of diagnostic and therapeutic procedures. Two types of risk are identified following the administration of a radiopharmaceutical to a patient: the risk to the patient and the risk to critical groups exposed to the patient. 1) For the scope of risk assessment in protection against diagnostic ionizing radiation, it is necessary to determine the internal radiation dose to specific body organs and tissues of patients. For this purpose, absorbed dose from intravenously administered ^{99m}Tc-MDP, ^{99m}Tc-MIBI, and ^{111}In- Ibritumomab Tiuxetan were calculated using the MIRDose model version 3.0. 2) Patients who have administered radiopharmaceuticals could be a source of radiation to their relatives, medical nurses and people who have contact them. In this study, the dose rates at various distances of 5 cm, 10 cm, 50 cm, 1 m and 2 m from patient who administered diagnostic amounts of ^{131}I-NaI, ^{99m}Tc-MIBI and ^{201}Tl-Chloride radiopharmaceuticals at five different interval times were calculated using RADAR software. Finally, the dose rate have been calculated for nuclear medicine staff exposed to 2 patients performed 2 different scans with different radiopharmaceuticals.

1. INTRODUCTION

The administration of radioactive substances to humans for diagnostic, therapy or research purposes is a well established and developing branch of medical practice. New methods and new radiopharmaceuticals are being introduced continually. Accurate dosimetry for representative groups of patients for each specific investigation is needed in order to optimize use of the various alternative radiodiagnostic techniques, and to estimate the collective radiation exposure and risk from nuclear medicine investigations [1]. There are three major elements involved in successfully meeting a performance standard of maintaining exposure of members of the public to released nuclear medicine patients to fewer than 5 mSv (500 mrem): The first is an evaluation of the patient's living and working conditions to ascertain whether or not a given patient can be safely released. The second step is the appropriate performance of a patient-specific dose calculation to ensure that no individual member of the public will likely be exposed to a dose in excess of 5 mSv (500 mrem). The third step to provide written instructions that are simple in order for the patient to limit the radiation dose to others to as low as reasonably achievable (ALARA) [2].

This study represents the risks associated with diagnostic applications of radiopharmaceuticals. Firstly, the radioactivity administered presents a risk to the patient who should be balanced against the benefit from obtaining a diagnosis or carrying out treatment. Secondly, contact with radioactive tissue from the patient or exposure to radiation emitted from radioactivity retained by the patient presents a risk to hospital staff and to members of the patient's family, particularly young children and breast-fed infants are of particular concern, and their associated risks require careful assessment.

2. CURRENT NUCLEAR MEDICINE APPLICATIONS

Nuclear medicine is the medical specialty using small amounts of radioisotopes as tracers to diagnostic disease, or larger amounts for therapy. Tracers are substances that are attracted to special organs bones or tissues, like iodine to the thyroid gland. After being injected into the body, tracers emit characteristic radiations. Special electronic instruments such as scintillation or a gamma camera, which displays these emissions into images, can detect these emissions. The images yield information about the anatomy and the function of the body organ being imaged. The nuclear medicine physician interprets the image to determine the cause of a given disease [3].

Nuclear medicine is also used for therapeutic purposes such as the treatment of hyperthyroidism, thyroid cancer, blood imbalances and pain relief from certain bone cancers. It is a safe and effective way of obtaining information that would otherwise be unavailable, or can only be obtained by intrusive riskier techniques such as surgery and biopsies. Nuclear medicine tests are extremely sensitive to abnormalities in body organs structure and function. Tests using nuclear medicine techniques are more sensitive and specific for disease detection than most tests because they identify abnormalities very early in the progression of a disease, long before the medical problem would be apparent with other diagnostic tests. Nuclear medicine continues to employ radionuclides such as ^{99m}Tc,

^{18}F, ^{111}In, ^{123}I, ^{131}I, ^{201}Tl,..etc in diagnostic procedures. Such procedures are used to scan bone, cardiovascular system, thyroid and to scan liver, spleen and lung [4].

3. SELECTION OF ORGANS AND TISSUES FOR DOSE CALCULATIONS

Absorbed doses are calculated for a large number of organs and tissues (called the target organs or tissues). These absorbed doses may arise as a result of radioactive decays occurring in other regions (called the source regions). Thus, absorbed doses in a particular organ or tissue are typically the sum of contributions from various sources, usually including the target organ or tissue itself. The International Commission on Radiological Protection (ICRP) introduced the parameter *effective dose equivalent* (H_e or EDE). Certain organs or organ systems were assigned dimensionless weighting factors (table 1) which are a function of their assumed relative radiosensitivity for expressing fatal cancers or genetic defects [5].

In this respect, an overall cancer risk can be computed for a situation in which different organs receive different doses, with or without external irradiation of the whole body. The ICRP developed this method for use in a risk-based system of occupational radiation protection and not for application to patient dosimetry in nuclear medicine procedures. However, if we wish to compare procedures and the resulting patient doses for assessment of risk versus benefit, effective dose equivalent is a more appropriate parameter than whole body dose, because it takes into account the different sensitivities of the organs, as will be seen later [6].

Table 1: Tissue weighing factors recommended by the ICRP for the derivation of effective dose

Tissue	Weighting Factor
Lung	0.12
Gonads	0.25*
Thyroid	0.03
Red marrow	0.12
Bone surfaces	0.03
Breast	0.15
Remainder†	0.06

*Includes the risk of genetic effects. †The five remainder organs (chosen from a defined list) receiving the highest absorbed doses are each assigned a weighting factor of 0.06.

4. DOSE CALCULATIONS METHODS AND RESOURCES

The principal quantity of interest in internal dosimetry is the absorbed dose, or the dose equivalent. Absorbed dose, *D*, is defined as [7]:

$$D = \frac{d\varepsilon}{dm}$$

Where $d\varepsilon$ is the mean energy imparted by ionizing radiation to matter of mass dm. The units of absorbed dose are typically erg/g or J/Kg. the special units are rad (100 erg/g) or gray (Gy) (1 J/Kg = 100 rad = 10^4 erg/g). the dose equivalent, *H*, is the absorbed dose multiplied by a quality factor, *Q*, the later account for the effectiveness of different types of radiation in causing biological effects:

$$H = DQ$$

Because the quality factor is in principle dimensionless, the pure units of this quantity are the same as absorbed dose (i.e. erg/g or J/kg). However the special units have unique names, specifically the rem and sievert (Sv). Values for the quality factor have changed as new information about radiation effectiveness has become available. Current values, recommended by ICRP (30), are given in Table 2.

Table 2. Quality factors recommendedIn ICRP 30 [8].

Radiation type	Quality factor, Q
Alpha particle	20
Beta particles	1
Gamma rays	1
X-rays	1

The quantity dose equivalent was originally derived for use in radiation protection programs. The development of the effective dose equivalent by the ICRP in 1979, and of the effective dose in 1991, however, allowed non-uniform internal doses to be expressed as a single value, representing an equivalent whole body dose. A generic equation for the absorbed dose rate in an organ can be shown as:

$$D = \frac{k\tilde{A}\sum_{i} n_i E_i \varphi_i}{m}$$

Where:

D is the absorbed dose (rad or Gy);
Ã is the cumulated activity (μCi.h or MBq.s)
n is the number of radiations with energy E emitted per nuclear transition;
ϕ is fraction of energy absorbed in the target;
m is the mass of the target region (g orkg);
k is the proportionality constant (rad.g.$\mu Ci^{-1}.h^{-1}.MeV^{-1}$ or Gy.kg.$MBq^{-1}.s^{-1}.MeV^{-1}$).

It is extremely important that the proportionality constant be properly calculated and applied. The application of quality factors to this equation to calculate the dose equivalent rate is a trivial matter; for most of this section only absorbed doses are considered.

5. MIRDOSE SOFTWARE AND RADAR SYSTEM

A computer program called MIRDose [9], has been developed and distributed by M.G. Stabin, Radiation Internal Dose Information Center, Oak Ridge Institute for Science and Education. P.O.BOX 117, Oak Ridge, TN 37831-0117, USA. The program contains tables of the S factors for the common radionuclides; the user must provide the biokinetic data in the form of residence times for the source organs. The program then generates tables of organ doses per unit administered activity in the traditional and SI units (rad/mCi and mGy/MBq). A samples Mirdose computer for ^{99m}Tc-MDP, ^{99m}Tc-MIBI and ^{111}In- Ibritumomab Tiuxetan are shown in tables 4, 5 and 6.

A unified system is developed on a web site for rapid electronic access. This site, called the Radiation Dose Assessment Resource (RADAR), provides decay data for over 800 radionuclides, absobed fractions for all available stylized phantoms and some voxel phantoms, kinetic data, dose factors (for all phantoms and nuclides), risk information and other data via electronic transfer to users worldwide. The resources have several features that make it easier to understand and use than existing resources in these areas [10].

6. RESULTS AND DISCUSSIONS

The ultimate goal of radiopharmaceutical internal dosimetry is to develop a method whereby the radiation doses to the organs of a specific patient may be estimated, rather than those of a standard phantom. As more and more therapeutic applications of radiopharmaceuticals are developed, patient-specific dosimetry will be needed to estimate both the probabilities of tumor control and of complications arising in normal tissues, as is standard practice in external beam radiation therapy. Radiation exposures from diagnostic medical examinations are generally low and are almost always justified by the benefits of accurate diagnosis of possible disease conditions. In this study, we represent patients' organ doses after administration of ^{99m}Tc-MDP, ^{99m}Tc-MIBI and ^{111}In- Ibritumomab Tiuxetan radiopharmaceuticals. Table 3 shows some typical doses from nuclear medicine exam [11].

Table 3: Typical Doses from Nuclear Medicine exam used in this study [11].

Typical Doses from Nuclear Medicine Exams		
Nuclear Medical Scans	Radiopharmaceulicals	Activity (mCi)
Bone	^{99m}Tc-MDP	25
Heart	^{99m}Tc-MIBI	30
Heart	^{111}In- Ibritumomab Tiuxetan	20
Heart	^{201}Tl-Cl	2
Thyroid	^{131}I-NaI	5

The first case handled in this study will be for a patient has administered intravenous injection with 17 mCi of ^{99m}Tc-MDP, the source organs included: cortical bone, cancellous bone, kidneys, urinary bladder and remainder of the body.

Tables 4 and 5 show the organ doses and the effective dose estimates generated by MIRDOSE software for the reference adult man (70 kg) after intravenous injection of ^{99m}Tc-MIBI and ^{111}In- Ibritumomab Tiuxetan radiopharmaceuticals consequently.

Table 4: Radiation Dose Estimates for the Reference Adult for ^{99m}Tc-MDP using MIRDose software

Target organ	**mGy/MBq**	**Rad/mCi**
Adrenals	2.23E-04	8.25E-04
Brain	2.23E-04	8.25E-04
Breasts	2.23E-04	8.25E-04
Gallbladder wall	2.23E-04	8.25E-04
LLI wall	2.23E-04	8.25E-04
Small intestine	2.23E-04	8.25E-04
Stomach	2.23E-04	8.25E-04
ULI wall	2.23E-04	8.25E-04
Heart wall	2.23E-04	8.25E-04
Kidneys	4.59E-03	1.70E-02
Liver	2.23E-04	8.25E-04
Lungs	2.23E-04	8.25E-04
Muscle	2.23E-04	8.25E-04
Ovaries	2.23E-04	8.25E-04
Pancreas	2.23E-04	8.25E-04
Red marrow	2.48E-03	9.18E-03
Bone surfaces	**2.88E-02**	**1.07E-01**
Skin	2.23E-04	8.25E-04
Spleen	2.23E-04	8.25E-04
Testes	2.23E-04	8.25E-04
Thymus	2.23E-04	8.25E-04
Thyroid	2.23E-04	8.25E-04
Urinary bladder wall	1.73E-02	6.40E-02
Uterus	2.23E-04	8.25E-04
Total body	5.86E-04	2.17E-03
EDE	2.64E-03	9.76E-03
ED	1.75E-03	6.46E-03
Source organ	**Residence Time (hr) (12)**	
Kidneys	1.48E-01	
Cort. Bone	1.36E+00	
Trab, bone	1.36E+00	
Urinary Bl. Content	7.82E-01	
Remainder	1.64E+00	

Residence time (τ), as used here, refers to the area under the time-activity curve for the organ of interest, divided by the activity injected as intravenous radiopharmaceuticals at time zero. The residence times that form the basis for the calculations in this work were derived from different sources and will referred to below. Absorbed doses were calculated using MIRDOSE software. Performing such calculations is not difficult and requiring not much effort. It may apply as a standardized method for performing patient internal dose calculations among different institutions. It has success in predicting organ/tissue response and with the use of radiation dose calculation provides positive benefit that justifies extra effort and coast.

Table 5: Radiation Dose Estimates for the Reference Adult for ^{99m}Tc-MIBI using MIRDose software

Target organ	**mGy/MBq**	**Rad/mCi**
Adrenals	5.13E-04	1.90E-03
Brain	5.13E-04	1.90E-03
Breasts	5.13E-04	1.90E-03
Gallbladder wall	6.12E-01	2.26E+00
LLI wall	5.13E-04	1.90E-03
Small intestine	5.13E-04	1.90E-03
Stomach	5.13E-04	1.90E-03
ULI wall	5.13E-04	1.90E-03
Heart wall	1.56E-01	5.76E-01
Kidneys	8.99E-02	3.33E-01
Liver	9.03E-03	3.34E-02
Lungs	4.54E-02	1.68E-01
Muscle	5.13E-04	1.90E-03
Ovaries	5.13E-04	1.90E-03
Pancreas	5.13E-04	1.90E-03
Red marrow	5.13E-04	1.90E-03
Bone surfaces	5.13E-04	1.90E-03
Skin	5.13E-04	1.90E-03
Spleen	1.22E-01	4.50E-01
Testes	5.13E-04	1.90E-03
Thymus	5.13E-04	1.90E-03
Thyroid	5.13E-04	1.90E-03
Urinary bladder	**1.72E-01**	**6.35E-01**
Uterus	5.13E-04	1.90E-03
Total body	2.94E-03	1.09E-02
EDE	7.48E-02	2.77E-01
ED	1.69E-02	6.26E-02
Source organ	**Residence Time (hr) (13)**	
Gall Bl. Wall	7.35E+00	
Heart wall	5.30E+00	
Kidneys	2.90E+00	
Liver	1.86E+00	
Lungs	4.90E+00	
Spleen	2.40E+00	
Urinary Bl. Content	7.80E+00	
Remainder	3.86E+00	

The availability of the short lived technetium-99m (a half-life of 6.6 hours) is one of the major factors which have promoted the universal use of this radioisotope. Technetium-99m-MDP (methylene diphosphonate) is a widely used radiopharmaceutical to detect bone metastasis associated with many forms of cancer. It has also been discovered that some of the technetium-99m radiopharmaceuticals used for renal (^{99m}Tc-DTPA) and cardiac (^{99m}Tc- MIBI) studies also accumulate in some forms of primary cancer, which has led to the use of technetium-99m radiopharmaceuticals for imaging primary cancer other than that of the thyroid.

Table 6: Radiation Dose Estimates for the Reference Adult for ^{111}In using MIRDose software

Target organ	**mGy/MBq**	**Rad/mCi**
Adrenals	1.51E-02	5.57E-02
Brain	1.51E-02	5.57E-02
Breasts	1.51E-02	5.57E-02
Gallbladder wall	1.51E-02	5.57E-02
LLI wall	1.51E-02	5.57E-02
Small intestine	1.51E-02	5.57E-02
Stomach	1.51E-02	5.57E-02
ULI wall	1.51E-02	5.57E-02
Heart wall	7.48E-02	2.77E-01
Kidneys	9.37E-02	3.47E-01
Liver	1.35E-01	5.0E-01
Lungs	2.82E-02	1.04E-01
Muscle	1.51E-02	5.57E-02
Ovaries	1.51E-02	5.57E-02
Pancreas	1.51E-02	5.57E-02
Red marrow	1.18E-01	4.37E-01
Bone surfaces	7.24E-02	2.68E-01
Skin	1.51E-02	5.57E-02
Spleen	1.78E-01	6.60E-01
Testes	8.35E-02	3.09E-01
Thymus	1.51E-02	5.57E-02
Thyroid	1.51E-02	5.57E-02
Urinary bladder wall	1.51E-02	5.57E-02
Uterus	1.51E-02	5.57E-02
Total body	2.23E-02	8.26E-02
EDE	7.31E-02	2.71E-01
ED	5.60E-02	2.07E-01
Source organ	**Residence Time (hr) (14)**	
Heart wall	1.18E+00	
Kidneys	1.40E+00	
Liver	1.29E+01	
Lungs	1.41E+00	
Red marrow	1.17E+01	
spleen	1.63E+00	
tests	1.63E-01	
Remainder	5.18E+01	

In this study, the estimated effective dose for ^{99m}Tc-MDP, ^{99m}Tc-MIBI and ^{111}In- Ibritumomab Tiuxetan radiopharmaceuticals is generally higher than total body dose by a factor of 2-3. The organs receiving the highest absorbed dose from ^{99m}Tc-MDP were bone surfaces (2.88E-02), urinary bladder wall (1.73E-02) and kidneys (4.59E-03). For ^{99m}Tc-MIBI, the organs receiving the highest absorbed dose are gallbladder wall (6.12E-01), heart wall (1.56E-01), and urinary bladder (1.72E-01). Finally, for ^{111}In-DTPA, the organs receiving the highest absorbed dose are: liver (1.35E-01), red marrow (1.18E-01) and spleen (1.78E-01).

Routine implementation of MIRDOSE approach are in the best interests of the patient' treated and are in the economic interests of the institution administering the treatment. Such information can be used to estimate the internal dose associated with the presence of ^{99m}Tc-MDP, ^{99m}Tc-MIBI and ^{111}In- Ibritumomab Tiuxetan administered in nuclear medicine patients. Thus the final goal of this work was to provide basic information to improve the quality of the radiopharmaceuticals used in nuclear medicine and avoid an unnecessary radiation dose to the patients.

7. ABSORBED DOSE FOR NUCLEAR MEDICINE STAFF

Generally speaking, direct external radiation from the patient and exhalation of different radiopharmaceuticals are possible sources of significant dose in other persons. Exposure to these sources should be prevented or reduced as

far as is reasonably possible. Absorbed dose from patients or any other radiation source depends on contact time, distance and intensity of radiation. The possible pathways for staff exposure are:

- Receipt of radiopharmaceuticals
- In-house preparations of radiopharmaceuticals
- Patient transport
- Specimen transport
- Cleaning-up spills
- Holding and lifting patients
- Standing next to the treadmill
- Patient excreta-vomitus and urine
- CT with SPECT and PET
- Treating I-131 thyroid patients, specially large doses

For determination of external radiation to nuclear medicine staff, the radiations in five different interval times were calculated: 1) 10 min. after injection, 2) 20 minutes later, 3) after 30 minutes of injection, 4) after 1 hr. of injection and 5) after 2 hrs. of injection. This is calculated at 5 cm, 10 cm, 50 cm 1 meter and 2 meters from the patient. Tables 7, 8 and 9 show the calculated absorbed dose for I-131, Tc-99m and Tl-201 using the RADAR software. Figure 1 shows the relation between distances from the injected patient and the corresponding absorbed dose for the mentioned radiopharmaceuticals.

Table 7: absorbed dose to medical staff after 5 mCi of ^{131}I injection to a nuclear medicine patient.

Radiopharmaceuticals	Activity (mCi)	Distance	Time	Absorbed dose (m Sv)
^{131}I- NaI	5	5 cm	10 min.	0.75
		10 cm	20 min.	0.36
		50 cm	30 min.	0.022
		1 m	1 hr.	0.011
		2 m	2 hrs.	0.0022

Table 8: absorbed dose to medical staff after 20 mCi of ^{99m}Tc injection to a nuclear medicine patient.

Radiopharmaceuticals	Activity (mCi)	Distance	Time	Absorbed dose (m Sv)
^{99m}Tc-MIBI	20	5 cm	10 min.	1
		10 cm	20 min.	0.5
		50 cm	30 min.	0.03
		1 m	1 hr.	0.015
		2 m	2 hrs.	0.0033

Table 9: absorbed dose to medical staff after 2 mCi of ^{201}Tl injection to a nuclear medicine patient.

Radiopharmaceuticals	Activity (mCi)	Distance	Time	Absorbed dose (m Sv)
^{201}Tl-chloride	2	5 cm	10 min.	0.64
		10 cm	20 min.	0.31
		50 cm	30 min.	0.019
		1 m	1 hr.	0.093
		2 m	2 hrs.	0.047

From the absorbed dose and occupancy data (i.e. time and distance from the patient), it was found that: The absorbed dose per ^{131}I diagnostic procedure to nuclear medicine imaging staff varied from o.75 to 0.0022 mSv as shown in table 7. Using ^{99m}Tc in diagnostic procedure, the nuclear medicine staff may expose to absorbed dose ranged from 1 to 0.0033 mSv, table 8. Finally, the nuclear medicine staff may to expose 0.64 to 0.047 mSv per ^{201}Tl diagnostic procedure.

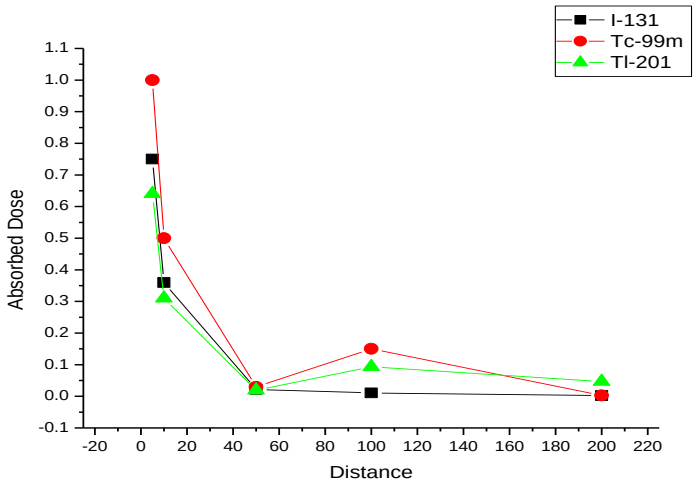

Fig. 1: External Dose

From the above figure, the external radiation dose rate from I-131 fell gradually. For injection of Tc-99m a rising of the external dose at 1 hour (due to deposition of the activity in the heart) was seen. The decrease in dose rate from patients administered Tl-201 is significant from point of view of the radiation protection. The main part of the effective dose on staff is related to Tc-99m. According to ICRP maximum allowable for one day for nuclear medicine staff is 55 µSv [2].

Nuclear Medicine Scan

Tc-99m Neurolite also know n as ECD and Bicisate
Tc-99m Pentetate also know n as Tc-99m DTPA
Tc-99m Pyrophosphate
Tc-99m Red Blood Cells
Tc-99m Sestamibi also know n as Cardiolite, Rest

Activity (mCi): 20

Tc-99m Technegas
Tc-99m Tetrofosmin also know n as Myoview - Rest
Tc-99m Tetrofosmin also know n as Myoview - Stress
Tc-99m White Blood Cells
Tl-201 Thallous Chloride (w ith contaminants)

Activity (mCi): 2

Total effective dose: 18.5 mSv, or 1850 mrem

This research study involves exposure to radiation from a Tc-99m Sestamibi also know n as Cardiolite, Rest, Tl-201 Thallous Chloride (w ith contaminants). The total amount of radiation that one w ill receive in this study is about 18.5 mSv or 1850 mrem, and is approximately equivalent to a w hole body exposure of 2251 days (6.166 years) of exposure to natural background radiation. This use involves minimal risk and is necessary to obtain the research information desired.

8. CONCLUSION

Radiation dose calculations for radiopharmaceulicles have been standardized by implementation and dissemination of tools like MIRDOSE and RADAR softwares. The Mirdose software greatly facilitates the calculation of internal radiation dose estimates by the MIRD techniques. The program makes use of standard and most up-to-date models in internal dosimetry. The quantities effective dose equivalent and effective dose were also calculated and added to the list of dose estimation given by the program. In theory, these quantities permit the representation of a non-uniform internal dose as a single value, which is the dose equivalent to that which the whole body could uniformly receive that would result in the same overall risk as the actual non-uniform dose distribution received.

In this work we have evaluated the effective dose (E) of the most common nuclear medicine radiopharmaceuticals using the MIRdose software, based on the ICRP-103 weighing factors and the latest dosimetry data. Also, we relate the calculated dose with the natural background radiation using RADAR software. The radiation dose equivalent estimates are given in mSv per MBq administered. The radiation dose equivalent calculations used the most recent values of quality factor (Q) given in ICRP 30 to convert absorbed doses in mGy to dose equivalents in mSv. Also, the effective dose equivalent for each pharmaceutical is given, based on the definition and tissue weighting factors (wT) given in ICRP 30.

In this part, RADAR software gives radiation dose estimates for certain radiographic and nuclear medicine procedures. Individual organ doses and total body effective doses are given for these specified examinations, and some combinations of examinations.

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