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Investigation of Impact of Using the ICRP 110 Adult Reference Phantoms and ICRP 103 Tissue Weighting Factors on the Radiopharmaceutical's Effective Dose

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ABSTRACT

The effective dose is an important tool in the radiation protection community. This is because it represents the health risk associated with different procedures involving ionizing radiation, and therefore it allows comparing them. Therefore, accurate determination of the effective dose for nuclear medicine procedures is important. In this study, the effective dose per unit activity administered was calculated for some of the ^{99m}Tc-based radiopharmaceuticals. The MIRD method was used for the calculation of the organ's absorbed doses using the ICRP 110 adult male and female reference phantoms. The biokinetic data was taken from ICRP Publications 128 and 53. Then, the effective doses were calculated using the ICRP 103 tissue weighting factors. The results show that with some exceptions, the calculated effective doses based on new phantoms and tissue weighting factors are lower than the ICRP published data. This reduction is significant in some cases and can significantly reduce the collective effective dose of patients.

***Keywords*:** Radiopharmaceutical; MIRD Method; Time Integrated Activity; S-value; Effective Dose

1. Introductions

The effective dose indicates the potential risk from the stochastic effects of radiation. It is intended for use as a protection quantity for planning and optimization in radiological protection, and demonstration of compliance with dose limits for regulatory purposes [1]. It allows one to compare different nuclear medicine procedures [2, 3].

The application of radiopharmaceuticals in nuclear medicine for therapy and diagnosis has increased in recent years. This leads to an increase in the number of individuals that receive a radiation dose. The calculation of effective dose can be used to compare the risk associated with the application of different radiopharmaceuticals and if possible, choose the radiopharmaceuticals with lower effective doses. The collective effective dose of the patients can be optimized as a result.

The ICRP published several documents about radiation doses to patients from radiopharmaceuticals

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in publications 53 [4], 80 [5], 106 [6] and then published a compendium of biokinetic data for frequently used radiopharmaceuticals in the ICRP 128 [7]. These documents include the biokinetic data for important radiopharmaceuticals. Also, the absorbed and effective dose per unit activity administered was calculated. The ICRP revised its formalism for the calculation of effective dose in ICRP 103. Also, the ICRP developed more realistic voxelized phantoms as reference adults in publication 110 [8]. However, in all of its publications about radiation dose to patients, it used ICRP 60 or ICRP 26 formalism for effective dose calculation and stylized phantoms of Cristy and Eckerman [9]. Therefore, recalculation of effective dose using new reference phantoms and new calculation method is necessary. The purpose of this study is to investigate the effects of new phantoms and new calculation method on the effective dose of radiopharmaceuticals. ^{99m}Tc is the most important radioisotope used in nuclear medicine. Therefore, some 99mTc-based radiopharmaceuticals were calculated.

2. Methods

Phantoms

ICRP adult reference male and female voxel phantoms are based on the medical images of two individuals that are consistent with the data given in the ICRP 89. The adult male phantom consists of 220 slices of 256 × 256 pixels. The original voxel size is 8 mm in height with an in-plane resolution of 2.08 mm, resulting in a voxel volume of 34.6 mm. The adult female phantom consists of 346 slices of 256 × 256 pixels. The voxel size is then 5 mm in height with an in-plane resolution of 1.875 mm, resulting in a voxel volume of 17.6 mm. These phantoms accommodate all organs and tissues that are relevant to the assessment of effective dose based on the recommendations in the ICRP 103. A detailed description of the phantoms (organs ID numbers, elemental composition, etc.) can be found in annexes A and B of the ICRP 110 [8].

MIRD method

The Medical Internal Radiation Dose (MIRD) committee of society of nuclear medicine developed a method that is the most commonly used method for internal radiation dosimetry. In this method, the mean absorbed dose $D(r_T,T_D)$ to the target tissue r_T over a defined dose-integration period T_D after administration of the radioactive material to the subject is given as [10]:

$$D(r_T,T_D)=\sum_{r_S}\tilde{A}(r_S,T_D)\,S(r_T\leftarrow r_S) \quad (1)$$

where $\tilde{A}(r_S,T_D)$ is the time-integrated activity or the total number of nuclear transformations in the source tissue, r_S and given as:

$$\tilde{A}(r_S,T_D)=\int_0^{T_D}A(r_S,t)dt \quad (2)$$

Due to short physical half-life of the radionuclides commonly used in nuclear medicine, T_D is usually taken to be infinity. The time-integrated activities for radiopharmaceuticals were taken from ICRP publications 128 and 53.

The quantity S is the mean absorbed dose in the target tissue, r_T, per nuclear transformation in the source tissue, r_S and given as:

$$S(r_T\leftarrow r_S)=\frac{1}{M(r_T)}\sum_i E_i Y_i \varphi(r_T\leftarrow r_S,E_i)=\frac{1}{M(r_T)}\sum_i \Delta_i \varphi(r_T\leftarrow r_S,E_i) \quad (3)$$

where E_i is the mean (or individual) energy of ith nuclear transition, Y_i is the number of ith nuclear transition per nuclear transformation, Δ_i is their product that defines the mean energy of ith nuclear transition per nuclear transformation, ϕ is the absorbed fraction (defined as the fraction of emitted energy from the source tissue, r_S, that is

absorbed in the target tissue, r_T), and $M(r_T)$ is the mass of target tissue, r_T.

3. Calculation of S values

The S-values of ^{99m}Tc for source organs of interest were calculated using the GATE Monte Carlo package (version 8.2). The DoseActor was used to calculate the deposited energy in the target organs of interest. Based on these values, the S-values were calculated. The energy and intensity of different transitions per nuclear transformation of ^{99m}Tc are listed in Table 1. For each source organ, the S-values were calculated for 27 target organs and tissues that are listed in Table 2. The uncertainty of the calculated S-values is below 5%. The Penelope model was used in the simulations. This model has been specifically developed for Monte Carlo simulation, and great care was given to the low energy description. Penelope processes are efficient between 250 eV and 1 GeV [11].

Table 1. Energy and intensity of different transitions per nuclear transformation of ^{99m}Tc [12].

Transition type	E_i (MeV)	Y_i
Internal conversion electrons	0.0016	0.7460
	0.1195	0.0880
	0.1216	0.0055
	0.1375	0.0107
	0.1396	0.0017
	0.1400	0.0019
	0.1404	0.0004
	0.1421	0.0003
Auger Electrons	0.0022	0.1020
	0.0155	0.0207
X-rays	0.0024	0.0048
	0.0183	0.0210
	0.0184	0.0402
	0.0206	0.0120
Gamma rays	0.1405	0.8906
	0.1426	0.0002
Beta	-	-

Based on the calculated S-values and the time-integrated activities taken from the ICRP publications, the organ's absorbed doses were calculated using equation (1) for eight different ^{99m}Tc based radiopharmaceuticals (10 biokinetic models). Then the effective doses were calculated using the ICRP 103 and ICRP 60 tissue weighting factors based on the following formula:

$$E = \sum_T w_T \sum_R w_R \frac{D(r_T, T_D)^{Male} + H(r_T, T_D)^{Female}}{2} \quad (4)$$

Where w_T and w_R are the tissue and radiation weighting factors, respectively. w_R is equal to 1 for beta and gamma radiations.

4. Results and Discussion

Table 3 shows the calculated effective dose for radiopharmaceuticals of interest in this study and compares the results with the data published by the ICRP.

The results show that the effective doses calculated using the ICRP 110 adult reference phantoms and the ICRP 103 tissue weighting factors are generally lower than the ICRP published data except for some radiopharmaceuticals. Only for two radiopharmaceuticals, ^{99m}Tc-(MAA and Albumin microspheres), the calculated effective dose using the ICRP 110 phantoms and the ICRP 103 formalism is higher than the ICRP published data. The difference between the results is, on average (-21 ± 23)%. The effective doses for ^{99m}Tc-(Gluconate and Penicillamine) are 47% and 46% lower than ICRP published data, respectively. On the other hand, the effective dose for ^{99m}Tc-MAA is 22% higher than ICRP published data. These differences can be due to the following reasons:

- Anatomical differences between the ICRP 110 phantoms and the Cristy-Eckerman phantoms.
- The calculation method: The ICRP assumes that all electrons absorb in the source organ, but in this study, the electron transport was taken into account.
- The differences in the formalism and the tissue weighting factors used for effective dose calculation.

Table 2. the ID numbers, medium no, and mass of the source and target organs of interest [8]

Target Organ	Medium no.	ID number(s)	Mass (g)	
			Male	Female
Adrenals	43	1, 2	14.00	13.00
Brain	32	61	1450.00	1300.00
Breasts	49 (adipose tissue) 48 (glandular tissue)	62-65	24.98	500.02
Gallbladder Wall	45	70	13.92	10.24
Small Intestine wall	37	74	650.00	599.99
Stomach Wall	36	72	149.99	140.00
Colon	38	76, 78, 80, 82, 84, 86	369.97	360.00
Heart Wall	33	87	329.98	250.00
Kidneys	35	89-94	310.04	275.01
Liver	30	95	1800.01	1400.00
Lungs	28 (blood) 50 (tissue)	96-99	1208.37	950.01
Muscle	29	106-109	29000.13	17500.00
Pancreas	31	113	140.00	120.01
Red Marrow	3, 7-9, 13-21	[a]	1170.00	899.10
Bone Surfaces	3-25	[b]	544.40	407.50
Skin	27	122-125	3278.01	2721.46
Spleen	39	127	149.99	130.00
Ovaries	42	111, 112	N. A.	11.00
Testes	42	129, 130	35.00	N. A.
Thymus	45	131	24.99	19.99
Thyroid	40	132	19.99	17.00
Urinary Bladder Wall	41	137	50.01	40.00
Urinary Bladder Contents (as source organ)	52	138	200.00	200.00
Salivary Glands	45	120, 121	84.98	70.00
Prostate	46	115	17.01	N. A.
Oesophagus	44	110	40.01	34.99
ET region	45	3, 4	39.44	18.61
Oral Mucosa	29	5, 6	35.83	22.45
Lymph Nodes	47	102-105	129.31	73.94
Total Body	-	1–70, 72, 74, 76, 78, 80, 82, 84, 86–137, 139	71845.89	58924.24

[a] Red bone marrow fraction[c] in organ IDs 14, 25, 27, 29, 40, 42, 44, 46, 48, 50, 52, 54, 56.

[b] Endosteum fraction[c] in organ IDs 14, 15, 17, 18, 20, 21, 23, 25, 27, 29, 30, 32, 33, 35, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56.

Table 3. Comparison of calculated effective dose (mSv/Bq) in this study (based on the ICRP 103) with the data published by the ICRP.

Radiopharmaceuticals[a]	ICRP	This study (ICRP 103)[b]	RD %[c]	This study (ICRP 60)[d]	RD %[c]
Tc-99m DMSA	8.80E-03	7.55E-03	-14.22	9.88E-03	12.27
Tc-99m DTPA (Normal[e])	4.90E-03	3.36E-03	-31.40	4.01E-03	-18.16
Tc-99m DTPA (Abnormal[e])	4.60E-03	4.49E-03	-2.35	4.72E-03	2.61
Tc-99m MAA	1.10E-02	1.35E-02	22.31	1.30E-02	18.18
Tc-99m Q12 (Resting subject)	1.00E-02	7.20E-03	-28.04	7.06E-03	-29.40
Tc-99m Q12 (Exercise)	8.90E-03	6.80E-03	-23.55	6.66E-03	-25.17
Tc-99m Citrate complex	8.30E-03	5.01E-03	-39.63	6.03E-03	-27.35
Tc-99m Gluconate	9.00E-03	4.71E-03	-47.66	5.90E-03	-34.44
Tc-99m Penicillamine	1.30E-02	6.98E-03	-46.30	8.62E-03	-33.69
Tc-99m Albumin Microspheres	1.10E-02	1.15E-02	4.63	1.12E-02	1.82

[a] For the first six radiopharmaceuticals (up to Q12 Exercise), the biokinetic data was given from the ICRP 128, and for the rest of the radiopharmaceuticals, the biokinetic data was given from the ICRP 53.

[b] Calculated effective dose using the ICRP 110 phantoms and ICRP 103 formalism

[c] $RD\% = (E_{This\ study} - E_{ICRP})/E_{ICRP} \times 100$

[d] Calculated effective dose using the ICRP 110 phantoms and ICRP 60 formalism

[e] Normal and abnormal represent normal and abnormal renal function, respectively.

Table 3 also shows the comparison of the calculated effective doses using the ICRP 110 phantoms and ICRP 60 formalism with the data published by the ICRP (column 6 of Table 3). The results show that even with the ICRP 60 formalism, the calculated effective doses for the ICRP adult reference phantoms are generally lower than the corresponding published data except for ^{99m}Tc-(DMSA, DTPA-Abnormal, and Albumin microspheres). The difference between the results is, on average (-13 ± 20) %.

These results are in agreement with the data published by Hadid et al. [3] that investigated the impact of different parameters on the effective dose values. The two major factors influencing the dose calculation were the transport of electrons, especially for small and walled organs, and the use of a realistic voxel phantom instead of stylized phantoms. Both of these factors lead to a reduction in the calculated effective dose.

5. Conclusions

According to the results, the application of ICRP 110 adult reference phantoms and the ICRP 103 tissue weighting factors, generally leads to a reduction in the calculated effective dose except for some radiopharmaceuticals. This reduction is significant in some cases. This can lead to a reduction in the collective effective dose of patients undergoing different diagnostic nuclear medicine procedures. Therefore, the effective dose of radiopharmaceuticals should recalculate using the new phantoms and new tissue weighting factors.

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