RADIOPHARMACEUTICAL RENAL DOSIMETRY USING SNYDER / CRISTY-ECKERMAN / SEGARS ANTHROPOMORPHIC REPRESENTATIONS

DOSIMETRÍA RENAL DE RADIOFÁRMACOS UTILIZANDO REPRESENTACIONES ANTROPOMÓRFICAS DE SNYDER / CRISTY-ECKERMAN / SEGARS

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(Received: May/2023. Accepted: Aug./2023)

Abstract

Absorbed doses to the kidneys of adult patients are estimated using the Medical Internal Radiation Dosimetry (MIRD) methodology and the anthropomorphic representations of Snyder, Cristy-Eckerman, and Segars. The radiopharmaceuticals $^{99m}Tc(DTPA)$, $^{99m}Tc(DMSA)$, and $^{99m}Tc(MAG3)$ are used to perform renal function studies in adults. The dose results found for these radiopharmaceuticals and their representations will allow exploring their dosimetric impact on each other. The relative difference in total renal dose by using the Snyder/Segars and Cristy-Eckerman/Segars anthropomorphic-representations was 3.6 % and 0.3 % when using $^{99m}Tc(DMSA)$; 2.9 % and 3.0 % when using $^{99m}Tc(MAG3)$; 5.0 % and 1.5 % when using $^{99m}Tc(DTPA)$. Regardless of the radiopharmaceutical selected, the substitution of Segars phantoms for Snyder

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or Cristy-Eckerman phantoms does not reflect significant changes in the estimated absorbed dose to the kidneys.

Keywords: MIRD dosimetry, Snyder/Cristy-Eckerman /Segars representations for kidneys.

Resumen

Se estiman las dosis absorbidas por los riñones de pacientes adultos utilizando la metodología Medical Internal Radiation Dosimetry (MIRD) y las representaciones antropomórficas de Snyder, Cristy-Eckerman, y de Segars. Los radiofármacos $^{99m}Tc(DTPA)$, $^{99m}Tc(DMSA)$ y $^{99m}Tc(MAG3)$ se utilizan para realizar estudios de función renal en adultos. Los resultados de dosis encontrados para estos radiofármacos y sus representaciones permitirán explorar su impacto dosimétrico entre ellas. La diferencia relativa en la dosis renal total al utilizar las representaciones antropomórficas de Snyder/Segars y Cristy-Eckerman/Segars fue del 3,6 % y del 0,3 % al utilizar $^{99m}Tc(DMSA)$; 2,9 % y 3,0 % cuando se usa $^{99m}Tc(MAG3)$; 5,0 % y 1,5 % cuando se utiliza $^{99m}Tc(DTPA)$. Independientemente del radiofármaco seleccionado, la sustitución de los fantomas de Segars por los fantomas de Snyder o Cristy-Eckerman no refleja cambios significativos en la dosis absorbida estimada en los riñones.

Palabras clave: dosimetría MIRD, representaciones de riñones Cristy-Eckerman/Segars.

Introduction

The radiopharmaceutical compound diethylenetriaminepentaacetic -$^{99m}Tc(DTPA)$ is a chelate that is eliminated almost exclusively by glomerular filtration. Dimercaptosuccinic-^{99m}Tc (DMSA) has a high affinity for the renal cortex and is primarily taken up by proximal tubular cells.

Mercaptoacetyltriglycine-^{99m}Tc (MAG3) is excreted mainly through tubular secretion. These radiopharmaceuticals are used

in adult male patients during renal function studies; they are distributed in the organs according to their biokinetics. Dosimetric estimation is related to residence time, which in turn is related to differences in the biological and physical mechanisms of excretion [1]. The biokinetic data related to radiopharmaceuticals were published by the International Commission on Radiological Protection (ICRP), publication 53 [2], updated in ICRP 128 [3] and ICRP-80 [4].

Biological effects due to radiopharmaceuticals are estimated by measuring their absorbed dose. Medical Internal Radiation Dosimetry (MIRD) is a methodology used to estimate the absorbed dose in a target organ from one or several source organs [5]. In the MIRD methodology, the absorbed dose is based on specific absorbed fractions (SAF), which represent the fraction of energy emitted by an organ source that is absorbed by the organ target per unit mass of the target. These are calculated on anthropomorphic computational phantoms using Monte Carlo methods [6]. The SAF, along with the incorporation of the residence time of the radiopharmaceutical, determines the absorbed dose. MIRD phantoms are mathematical representations of the human body. Here, the organs are defined by stylized geometric bodies that describe their sizes and shapes [7, 8].

In 1969, Snyder et al. [9] introduced a stylized phantom, the MIRD-5 phantom, based on reference data from the International Commission on Radiological Protection (ICRP) publication 23 [10]. Snyder's MIRD-5R phantom was reported by the ORNL group in 1978, which includes SAF values [11]. In 1980, Cristy and Eckerman [12] introduced a new series of stylized phantoms of various ages, including newborn, 1, 5, 10, 15-year old, and adult phantoms based on anthropomorphic reference data from the ICRP-23 publication [10]. This work was published in the ORNL/TM-8381 report in 1987 [13]. The report contained a full compilation of SAFs calculated from the ORNL phantom series. MIRD phantoms were enhanced with more realistic body models using digital image-based voxels [14]. Their use is accompanied by modified organ masses according to the ICRP data [15]. Segars [16] developed enhanced adult male

and female phantoms. Segars'phantoms were based on non-uniform rational b-spline (NURBS) modeling techniques that define male and female reference models [17, 18]. This new set of phantoms was included in the Radiation Dose Assessment resource (RADAR) [19], where SAF photons (in addition to electrons) were also included.

The replacement of the Snyder and Cristy-Eckerman phantoms with the Segars phantom, an updated and improved phantom, raises concerns about the dosimetric impact of these radiopharmaceuticals when applied in studies of renal function. Vasquez et al. [1] indicate that the relative differences in the total dose due to the use of the Stabin and Segars representations are relatively small for radiopharmaceuticals used during renal studies for a woman with early pregnancy. While the relative differences in the total doses in the uterine wall when using the Stabin and Segars phantoms are high, it depends on the representation of Stabin or Segars. It is also indicated that, regardless of the radiopharmaceutical used for pulmonary studies of a newborn patient, the substitution of the Cristy-Eckerman anthropomorphic representation for the Segars representation does not reflect very significant changes in the calculation of the absorbed dose in the lungs [20].

Zankl et al. [14] report that when comparing calculations using voxel phantoms with calculations using stylized phantoms, deviations between 50 and 100 % can be obtained. To investigate the dosimetric implications generated by the substitution of the Snyder and Cristy-Eckerman anthropomorphic phantoms by the Segars phantom during renal function studies, their absorbed doses must be compared in each of these representations.

Using the MIRD formalism and the anthropomorphic representations of Snyder, Cristy-Eckerman, and Segars in adult kidneys that use radiopharmaceuticals ^{99m}Tc $(DTPA)$, ^{99m}Tc $(DMSA)$, and ^{99m}Tc $(MAG3)$ in their studies, the objective of the work is to determine whether the relative difference in the total dose of the Cristy-Eckerman/Segars and Snyder/Segars representations found is significant.

Materials and Methods

The ^{99m}Tc undergoes an isomeric transition through gamma emission, with an energy of 140 keV and a half-life of 6 hours. Gamma radiation can transfer energy directly to one of the more tightly bound electrons through internal conversion [21].

Photons and charged particles ionize and excite matter with which they interact through different mechanisms that govern the absorbed dose in tissues. In the MIRD methodology, the kidneys are assumed as the target organ and the absorbed dose per unit of activity of the administered radiopharmaceutical was calculated using equation (1) [22]:

$$\frac{D_{\text{phot}}(\text{kidney})}{A_0} = \left\{ \sum_{i \neq \text{kidney}} \sum_j \Delta_j \Phi_j(\text{kidney} \leftarrow i)\tau_i + \sum_j \Delta_j \Phi_j(\text{kidney} \leftarrow \text{kidney})\tau_{\text{kidney}} \right\} \times 270 \text{ mGy/MBq} \quad (1)$$

On the right side of the equation, the absorbed dose represents the dose to the kidneys due to the source organ i (i: bladder, whole body, liver, and spleen); Δ_j is the average energy of the photon j emitted by ^{99m}Tc per decay.

$\Phi_j(\text{kidney} \leftarrow i)$ is the fraction of energy emitted by organ i that is absorbed by the kidney per unit mass of the kidney, also known as SAF. Such SAFs for the Snyder, Cristy-Eckerman, and Segars representations are given in [11], [13], and [19], respectively.

τ_i is the residence time of the radiopharmaceutical in source organ i. The residence times for ^{99m}Tc (DTPA), ^{99m}Tc (DMSA), and ^{99m}Tc (MAG-3) of organs due to biokinetic features are indicated in Table 1 [4].

For charged particles, the absorbed doses to the kidneys were calculated using equation 2 [22]:

$$\frac{D_{\text{particle}}(\text{kidney} \leftarrow \text{kidney})}{A_o} = \bar{E}_{\text{partic}} \left[\frac{\tau_{\text{kidneys}}}{m_{\text{kidneys}}} + \frac{\tau_{TB}}{m_{\text{TB}}} \right] \times 2.13 \times 270 \,\text{mGy/MBq} \quad (2)$$

Organ	τ $^{99m}Tc - MAG3$	τ $^{99m}Tc - DMSA$	τ $^{99m}Tc - DTPA$ (nonpregnant)
Kidneys (cortex)	0.065	3.7	0.073
Urinary Bladder contents	2.70	0.40	1.5
TB (bladder excluded)	0.23	6.8	2.0
Liver	-	0.42	-
Spleen	-	0.042	-

TB: Whole Body

TABLE 1. *Residence time in adults by hours used as parameters for organs biokinetic [4]*

$\bar{E}_{\text{particle}}$ is the average energy of the particle τ_{TB}, and τ_{kidney} are the residence time of the radiopharmaceutical in the total body and the kidney, respectively; while, m_{TB} and m_{kidney} are the mass of total body and the mass of kidney, respectively.

For dosimetric calculations, the kidney and total body (TB) masses used in adult males are given by: 284 g for kidneys and 69,900 g for TB, for Snyder's phantom [11]; 299 g for kidneys and 73,700 g for TB (current phantom), for Cristy-Eckerman phantom [13]; finally, 310 g for kidneys and 73,000 g for TB, for Segars phantom [15].

Tables 2 and 3 show the photon characteristics, as well as particles emitted in the ^{99m}Tc decay [23] that were used in the dose calculations. Tables 2 and 3 determine the Δk and $\overline{E}_{\text{particle}}$ values of the ^{99m}Tc radioisotope used in the estimated absorbed dose, given by equations (1) and (2).

	Photons	E_k (MeV)	n_k part/dis	$\Delta_k = 2.13 n_k E_k$ (rad – g) $\mu Ci - h$
^{99m}Tc	Gamma	0.1405	0.8906	0.2665
	Radiation	0.1426	0.0002	0.0001
	Characteristic radiation	0.0183	0.021	0.0008
		0.0184	0.040	0.0016
		0.0206	0.012	0.0005

TABLE 2. *Nuclear data of the most significant photons emitted by ^{99m}Tc (MeV) [23]*

	Particles	E_k (MeV)	n_k part/dis	$n_k E_k$ MeV/dis	$E_{particle} = \Sigma\ n_k\ E_k$ MeV/dis
^{99m}Tc	Conversion electrons	0.1195	0.0880	0.01052	0.01446
		0.1216	0.0055	0.00067	
		0.1375	0.0107	0.0015	
		0.1396	0.0017	0.00024	
		0.1400	0.0019	0.00026	
		0.1404	0.0004	0.00006	
		0.1421	0.0003	0.00004	
		0.0016	0.7460	0.00120	
	Auger electrons	0.0022	0.102	0.00022	0.00054
		0.0155	0.0207	0.00032	

TABLE 3. *Nuclear data of the particles emitted by ^{99m}Tc (MeV) [23]*

Compound	**Emissions**	**D(Kidney←Kidney)/A$_0$ mGy/MBq**		**Organs the Biokinetic**	**D(Kidney←i)/A$_0$ (mGy/MBq)**		**TOTAL Cristy-Eckerman /Segars mGy/MBq**
		Cristy-Eckerman	**Segars**		**Cristy-Eckerman**	**Segars**	
Tc^{99m} (DTPA)	Photons	1.336 (28.8 %)	1.430 (26.1 %)	Bladder	0.100 (2.16 %)	0.230 (2.9 %)	**(4.64/4.57) * 1.5 %**
	Electrons	2.334 (50.3 %)	2.290 (47.8 %)	Total Body	0.870 (18.75 %)	0.620 (21.7 %)	
	Self-dose	3.670 (79.1 %)	3.720 (81.4 %)	Σ Dose Org Biokinetics	0.970 (20.9 %)	0.850 (18.6 %)	
Tc^{99m} (MAG3)	Photons	1.200 (35.7 %)	1.284 (34.8 %)	Bladder	0.187 (5.56 %)	0.430 (11.8 %)	**(3.360/3.62) * 3.0 %**
	Electrons	1.870 (55.65 %)	1.840 (52.2 %)	Total Body	0.102 (3.036 %)	0.072 (2.0 %)	
	Self-dose	3.070 (91.4 %)	3.124 (86.2 %)	Σ Dose Org. Biokinetics	0.289 (8.6 %)	0.502 (13.8 %)	
Tc^{99m} (DMSA)	Photons	68.20 (38.04 %)	72.80 (40.4 %)	Bladder	0.027 (0.015 %)	0.062 (0.035)	**(179.3/179.7)* 0.3 %**
	Electrons	107.50 (60.0 %)	104.0 (57.7 %)	Total Body	3.012 (1.68 %)	2.120 (1.18 %)	
				Liver	0.44 (0.25 %)	0.630 (0.35 %)	
				Spleen	0.090 (0.050 %)	0.130 (0.07 %)	
	Self-dose	175.70 (98.0 %)	176.80 (98.4 %)	Σ Dose Org. Biokinetics	3.569 (2.0 %)	2.94 (1.64 %)	

* Indicates the relative difference in the total dose of the Cristy-Eckerman / Segars representations

TABLE 4. *Radiation dose $\times 10^{-3}$ mGy/MBq in male adult kidney during renal function studies using ^{99m}Tc(DPTA), ^{99m}Tc(DMSA), ^{99m}Tc(MAG3) and Cristy-Eckerman /Segars representations*

Results

Tables 4 and 5 show the absorbed dose in the kidneys of male adult patients from photons and particles emitted by radiopharmaceuticals during studies conducted with ^{99m}Tc (MAG3, DTPA, DMSA) for the reference phantoms of Segars, Cristy-Eckerman, and Snyder.

Compound	**Emissions**	**D(Kidn←Kidn)/A$_0$ mGy/MBq**		**Organs the Biokinetics**	**D(Kidney←i)/A$_0$ (mGy/MBq)**		**TOTAL Snyder /Segars mGy/MBq**
		Snyder	**Segars**		**Snyder**	**Segars**	
	Photons	1.370 (28.5 %)	1.430 (26.1 %)	Bladder	0.108 (2.9 %)	0.230 (2.9 %)	
Tc^{99m} (DTPA)	Electrons	2.450 (50.9 %)	2.290 (47.8 %)	Total Body	0.880 (22.9 %)	0.620 (21.7 %)	**(4.81/4.57)*** 5,0 %
	Self-dose	**3.820 (79.42 %)**	**3.720 (81.4 %)**	**Σ Dose Org Biokinetics**	**0.988 (20.54 %)**	**0.850 (18.6 %)**	
	Photons	1.224 (33.8 %)	1.284 (34.8 %)	Bladder	0.197 (5.6 %)	0.430 (11.8 %)	
Tc^{99m} (MAG3)	Electrons	2.0 (55.24 %)	1.840 (52.2 %)	Total Body	0.102 (2.9 %)	0.720 (2.0 %)	**(3.523/3.626)*** 2.9 %
	Self-dose	**3.224 (91.5 %)**	**3.124 (86.2 %)**	**Σ Dose Org. Biokinetics**	**0.299 (8.5 %)**	**0.502 (13.8 %)**	
	Photons	69.68 (37.38 %)	72.80 (40.4 %)	Bladder	0.029 (0.015 %)	0.062 (0.035)	
Tc^{99m} (DMSA)	Electrons	113.2 (60.73 %)	104.0 (57.7 %)	Total Body Liver Spleen	3.012 (1.615 %) 0.459 (0.246 %) 0.104 (0.055 %)	2.120 (1.18 %) 0.630 (0.35 %) 0.130 (0.07 %)	**(186.5/179.7)*** 3.6 %
	Self-dose	**182.9 (98.0 %)**	**176.80 (98.4 %)**	**Σ Dose Org. Biokinetics**	**3.604 (1.93 %)**	**2.94 (1.64 %)**	

* Indicates the Relative difference in the total dose of the Snyder/ Segars representations.

TABLE 5. *Radiation dose $\times 10^{-3}$ mGy/MBq in male adult kidney during renal function studies using ^{99m}Tc-DPTA, ^{99m}Tc-DMSA, ^{99m}Tc-MAG3 and Snyder/ Segars representations*

Discussion

Absorbed doses to the kidneys of adult patients are estimated using the MIRD formalism and the anthropomorphic representations of Snyder/Cristy-Eckerman/Segars. The radiopharmaceuticals ^{99m}Tc (DTPA), ^{99m}Tc (DMSA), and ^{99m}Tc (MAG) were used in their

studies. From Tables 4 and 5, it is evident that regardless of the radiopharmaceutical and its corresponding representations, the primary contribution to the total dose in the kidneys of adults comes from the self-dose. This is predominantly supplied by the electrons produced during the decay of ^{99m}Tc, which, in turn, are linked to the residence time values presented in both the kidneys and the entire body (Table 1).

The relative difference in the total dose between the Snyder/Segars and C-E/Segars representations, for each of the utilized radiopharmaceuticals, is small. This indicates that the calculated doses in adult kidneys are very sensitively affected. The probable explanation lies in the slight variations of the Specific Absorbed Fractions (SAFs) observed between the Segars, Snyder, and Cristy-Eckerman representations in the kidneys and organs within their biokinetics when using ^{99m}Tc. Also, due to the mass, shape, and total body mass of the kidneys in the anthropomorphic representations, they have minimal effect on the calculated doses [11], [13], [19].

Conclusions

The relative difference in total renal dose by using the Snyder/Segars and Cristy-Eckerman/Segars anthropomorphic-representations was 3.6 % and 0.3 % when using ^{99m}Tc (DMSA); 2.9 % and 3.0 % when using ^{99m}Tc (MAG3); and 5.0 % and 1.5 % when using ^{99m}Tc (DTPA).

Regardless of the radiopharmaceuticals selected, substituting Snyder or Cristy-Eckerman phantoms for Segars phantoms does not reflect significant changes in the estimated absorbed dose to the kidneys.

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