

**DOSYMMETRIC ESTIMATES OF ^{99m}Tc (MAA) and ^{133}Xe
IN NEWBORN LUNGS USING CRISTY-ECKERMAN/
SEGARS REPRESENTATIONS**

**ESTIMACIONES DOSIMÉTRICAS DEL ^{99m}Tc (MAA) y
 ^{133}Xe EN LOS PULMONES DE RECIÉN NACIDOS
UTILIZANDO LAS REPRESENTACIONES DE
CRISTY-ECKERMAN/SEGARS**

**Marcial Vasquez-Arteaga¹, Héctor Vega-Carrillo²,
Gustavo Montalvo-Soberon¹, Juan Rivera-Vásquez¹,
Pedro Jaramillo-Arica¹, Marcela Vasquez-Silva³,
Carlos Cabrera-Salvatierra⁴, Roberto Rojas-Alegría⁴**

¹ Universidad Señor de Sipán, Chiclayo, Perú.

² Unidad Académica de Estudios Nucleares, Universidad Autónoma de Zacatecas, México.

³ Universidad Privada del Norte, Trujillo, Perú.

⁴ Universidad Nacional de Trujillo, Perú.

(Recibido: 10/2021. Aceptado: 11/2021)

Abstract

Using the Cristy-Eckerman (C-E)/Segars anatomical representations and the MIRD formalism, the Absorbed doses in lungs of newborn patients scanned with radiopharmaceuticals ^{133}Xe (ventilation) and ^{99m}Tc (MAA) (perfusion) are estimated. These representations are phantoms used in Monte Carlo calculations to determine specific absorbed fractions, which, associated with the pharmaceutical residence time, determine the absorbed dose. Concerns about the dosimetric impact of using these ventilation / perfusion agents, as well as the use of different phantoms, were explored in newborn patients. When the lungs were scanned with ^{99m}Tc (MAA), the relative difference in total dose between the C-E / Segars anatomical representations was 1.0 %. When the lungs were scanned with ^{133}Xe , the relative difference in total dose

between the anthropomorphic representations of C-E / Segars was 0.5 %. Regardless of the radiopharmaceutical used for the pulmonary studies of a newborn patient, the substitution of the C-E representation for that of Segars does not reflect very significant changes in the calculation of the absorbed dose in the lungs, where the greatest dosimetric contribution is its self-dose, which is supplied mainly by the electrons produced during the ^{99m}Tc and ^{133}Xe decay.

Keywords: MIRDo dosimetry, Cristy-Eckerman /segars representations, lungs.

Resumen

Usando las representaciones anatómicas de Cristy-Eckerman (C-E) / Segars y el formalismo MIRDo, se estiman las dosis absorbidas en pulmones de pacientes recién nacidos explorados con radiofarmacos ^{133}Xe (Ventilación) y ^{99m}Tc (MAA) (perfusión). Estas representaciones son fantasmas utilizados en los cálculos de Monte Carlo en la determinación de fracciones absorbidas específicas, que asociadas al tiempo de residencia farmacéutica determinan la dosis absorbida. Preocupaciones sobre el impacto dosimétrico de usar estos agentes ventilación /perfusión, así como el uso de diferentes fantasmas, se exploraron en pacientes recién nacidos. Cuando a los pulmones se exploran con ^{99m}Tc (MAA), la diferencia relativa en la dosis total entre las representaciones anatómicas de C-E/Segars fue de 1,0%. Cuando a los pulmones se exploran con ^{133}Xe , la diferencia relativa en la dosis total entre las representaciones antropomórficas de C-E/Segars fue de 0,5%. Independientemente del radiofármaco utilizado para los estudios pulmonares de un paciente recién nacido, la sustitución de la representación de C-E por la de Segars no refleja cambios muy significativos en el cálculo de la dosis absorbida en los pulmones, donde la mayor contribución dosimétrica es su autodosis que es suministrada principalmente por los electrones producidos a lo largo de la desintegración del ^{99m}Tc y ^{133}Xe .

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

Introduction

Radiopharmaceuticals ^{99m}Tc (MAA), and ^{133}Xe used in newborn patients with suspected pulmonary embolism are distributed in their organs according to their biokinetics. Dosimetric behavior is related to residence time, which in turn is related to differences in biological and physical excretion mechanisms. The use of radiopharmaceuticals in these patients is exposed to radiation emitted by ^{99m}Tc and ^{133}Xe [1–3].

In the MIRD methodology, anatomical models (phantoms) are used to calculate specific absorbed fractions (SAF) using Monte Carlo methods [4]. MIRD phantoms are mathematical representations of the human body. Here, the organs are defined by stylized geometric bodies that describe the sizes and shapes of the organs.

Cristy and Eckermann developed male and female reference phantoms, including newborns, children aged 1, 5, 10, and 15 years, and adults [5]. Phantoms of adult women (nonpregnant and pregnant) were developed by Stabin et al. [6]. The height, body weight, and organ mass of MIRD phantoms are consistent according to the ICRP data [7].

The MIRD phantoms were enhanced by more realistic body models with the use of voxels [8]. Enhanced adult male and female phantoms were developed by Segars [9]. The use of voxels is accompanied by the modified organ masses according to the ICRP data [10]. The Segars model phantoms were based on non-uniform rational b-spline modeling (NURBS) techniques that define a new generation of adult male and female reference models [11, 12]. This new set of phantoms was included in the Radiation Dose Assessment (RADAR) resource [13], where the photon SAFs were also included (besides the electrons).

The replacement of MIRD phantoms with updated and improved phantoms raises the question of whether the absorbed dose to the

organs also changes. According to Kramer et al. [14], the doses to the organs depend on the geometric similarity of the anatomy of the human body, the elemental composition and density of organs and tissues, and the method of radiation transport used. Therefore, it is necessary to investigate the dosimetric impact of using different phantoms, as well as to evaluate the internal dose administered by available radiopharmaceuticals. Vasquez-Arteaga et al. [15] indicate that “radiopharmaceuticals used during renal studies for a woman with early pregnancy using the Stabin / Segars representations, do not impact the dose absorbed by the kidneys. While the dose absorbed by the uterine wall depends on the representation of Stabin or Segars”. Therefore, it is necessary to investigate the dosimetric impact of using different phantoms, as well as to evaluate the internal dose administered by available radiopharmaceuticals.

In neonates, ^{133}Xe is used to assess pulmonary ventilation (distribution of air in the respiratory passages), and ^{99m}Tc -labeled albumin macroaggregate (MAA) is used to assess blood flow distribution in the lungs. For diagnostic purposes in newborn patients with suspected pulmonary embolism, the study should combine pulmonary ventilation/perfusion [3, 16].

The objective of this work is to determine the absorbed doses in the lungs of newborn patients using ^{99m}Tc (MAA) and ^{133}Xe radiopharmaceuticals, the MIRD formalism as well as the Cristy-Eckerman and Segars anatomical representations. The results obtained will be useful to evaluate if there are differences in the use of the SAFs obtained from the anatomical representations of Cristy-Eckerman/Segars.

Materials and methods

The ^{99m}Tc disintegrates by isometric transition by 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. The ^{133}Xe is essentially a β -emitter that decays emitting γ radiation of 81 keV fundamentally, and a half-life of 5.2 d. [17, 18].

Photons and charged particles ionize and excite matter with which they interact through different mechanisms that govern the absorbed dose in tissues. In the MIRDO procedure, the lungs are assumed as the target organ and the absorbed dose per unit of activity of the administered radiopharmaceutical was calculated using equation 1.

$$\frac{D_{photons(lungs)}}{A_o} = \left\{ \sum_{i \neq lung} \sum_j \Delta_j \Phi_j (lungs \leftarrow i) \tau_i + \sum_j \Delta_j \Phi_j (lungs \leftarrow lungs) \tau_{lung} \right\} \times 270 mGy/MBq \quad (1)$$

On the right side of the equations, the absorbed dose represents the dose to the lung, due to the source organ i , Δ_j is the average energy of the photon j emitted by ^{99m}Tc and ^{133}Xe per decay; $\Phi_j (lung \leftarrow i)$ is the fraction of energy emitted by organ i that is absorbed by the lung per unit mass of the lung. It is also known as the specific absorbed fraction [19], and τ_i is the residence time of the radiopharmaceutical in source organ i .

For charged particles, the absorbed doses to the lungs were calculated using equation 2:

$$\frac{D_{particle(lungs \leftarrow lungs)}}{A_o} = \left(2.13 \bar{E}_{particle} \frac{\tau_{lungs}}{m_{lungs}} \right) \times 2.70 mGy/MBq \quad (2)$$

$\bar{E}_{particle}$ is the average energy of the particle, τ_{lungs} residence time of the ^{133}Xe and ^{99m}Tc (MAA), in the lungs; while m_{lungs} is the mass of the lungs of a newborn.

Target organ and source organ-specific absorbed fractions for C-E and Segars representations in neonates were obtained from Cristy-Eckerman [20], and from RADAR/Stabin et al., [13, 21] respectively.

The residence times for ^{99m}Tc (MAA) and ^{133}Xe of organs used in the calculations are shown in Table 1 [22, 23].

Tables 2 and 3 show the characteristics of the photons and particles emitted in the ^{99m}Tc and ^{133}Xe decay [24] that were used in the dose calculation.

The mass of the organs included in the newborn biokinetics used in the calculations indicates that the lungs mass of the newborn is 50.6 g, approximate value, according to the ICRP data [10] (does not affect the calculation of particle dose); and the mass of the whole body (TB) is 3600 g [22].

^{99m}Tc (MAA)	TB (excl. bladder)	Lung	Liver	Kidney	Bladder content
	7.610	4.890	1.040	0.018	0.217
^{133}Xe (5 minutes)	Lungs	Remain tissue			
	0.013	0.533			

TB: Whole Body.

TABLE 1. Residence time in hours used as organs of biokinetic [22, 23].

	Photons	E_k (MeV)	n_k part/dis	$\Delta_k = 2.13 n_k \cdot E_k$ $\frac{(rad - g)}{\mu Ci - h}$
^{99m}Tc	Gamma Radiation	0.1405	0.8906	0.2665
		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
^{133}Xe	Gamma Radiation	0.1606	0.0007	0.0002
		0.0796	0.0027	0.0004
	Characteristic radiation	0.0810	0.3800	0.0656
		0.0306	0.1410	0.0092
		0.0310	0.2620	0.0173
		0.0350	0.0940	0.0070

TABLE 2. Nuclear data of emitted photons (MeV) of ^{99m}Tc and ^{133}Xe more significant [24].

	Particles	E_k (MeV)	n_k part/dis	$n_k E_k$ Mev/dis	$E_{particle=}$ $\sum n_k E_k$ 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		
Beta	0.0750	0.0081	0.00061	0.1001	
	0.1005	0.9900	0.09949		
^{133}Xe	Conversion electrons	0.0436	0.0041	0.00018	0.03284
		0.0450	0.5510	0.02479	
		0.0753	0.0820	0.00617	
		0.0798	0.0169	0.00135	
		0.0808	0.0044	0.00035	
Auger electrons	0.0035	0.5100	0.00178	0.00326	
	0.0255	0.0582	0.00148		

TABLE 3. Nuclear data emitted particles (MeV) of ^{99m}Tc and ^{133}Xe [24].

For diagnostic purposes in newborns with suspected pulmonary embolism, the study should combine pulmonary ventilation/perfusion (V/P) agents [25–27].

Results

Table 4 shows the absorbed dose in the lungs of newborns, due to photons and particles of radiopharmaceuticals during perfusion and ventilation studies explored with radiopharmaceuticals ^{133}Xe and ^{99m}Tc (MAA), for the reference phantoms of Segars and Cristy-Eckerman.

Compound	Emissions	D (Lungs ← Lungs)/A0 (mGy/MBq)		Organs the Biokinetics	D (Lungs ← i)/A0 mGy/MBq		TOTAL C-E /Segars mGy/MBq	
		C-E	Segars		C-E	Segars		
^{99m}Tc (MAA)	Photons	0,143 (14,23 %)	0,132 (13,2 %)	Kidneys	0,00006 (0,01 %)	0,00004 (0,004 %)	1,009/ 0,999 (1 %)	
	Electrons	0,834 (82,98 %)	0,834 (83,6 %)	Total	0,0260 (2,58 %)	0,0260 (2,60 %)		
				Body				
	Self-dose	0,977 (96,8 %)	0,966 (96,7 %)	Liver	0,00603 (0,60 %)	0,00637 (0,64 %)		
				Bladder cont.	0,00011 (0,01 %)	0,00007 (0,007 %)		
				∑ Dose Org. Biokinet	0,0322 (3,2 %)	0,0325 (3,3 %)		
^{133}Xe	Photons	0,00029 (1,33 %)	0,00027 (1,23 %)	Bladder	0,0000	0,0000	0,021 8/0,0 219 (0.5 %)	
	Electrons	0,0202 (92,66 %)	0,0202 (92,24 %)	Total	0,0013			
				Body	(2,74 %)	0,00142 (2,66 %)		
	Self-dose	0,02049 (94,0 %)	0,02047 (93,5 %)	∑ Dose	0,0013	0,00142		
				Org. Biokinet	(6,0 %)	(6,5 %)		

TABLE 4. Absorbed dose per unit of activity administered in the lungs of the newborn patient using ^{99m}Tc (MAA) and ^{133}Xe for Segars and Cristy-Eckerman reference phantoms.

Discussion

The anatomical phantoms of the new generation of Segars clearly represent a significant improvement in the anatomical realism of the organs and it is better modeled in the proximity of the organs,

while in stylized models of C-E, the separation of spaces of organs occurs by the simplicity of the forms used to model them [27].

From Table 4, can be noticed that the higher dose absorbed by the lungs in newborn patients explored with ^{99m}Tc (MAA) when using the C-E/Segars representations, is mainly due to its autodose with 96.8 % / 96.7 % contribution. The dosimetric contribution due to the organs of biokinetics: kidneys (0.01 % / 0.004 %), total body (2.58 % / 2.60 %), liver (0.60 % / 0.64 %), and bladder (0.01 % / 0.007 %), are small.

It is observed that the highest dosimetric contribution of the biokinetic organs due to the total body (2.58 % / 2.60 %) is associated with their residence time.

When the lungs are scanned with ^{99m}Tc (MAA), the relative difference in the total dose when using CE and Segars anatomical representations was 1.0 %.

The higher dose absorbed by the lungs in newborn patients scanned with ^{133}Xe when using the C-E/Segars representations, is mainly due to its autodose with of 94 % / 93.5 % contribution. The dosimetric contribution due to its biokinetic organ, the total body (TB), is 6 % / 6.5 % of the total contribution.

When the lungs were scanned with ^{133}Xe , the relative difference in total dose when using C-E and Segars anatomical representations was 0.5 %.

The highest dose to the lungs for a newborn is due to his self-dose delivered primarily by electrons released by ^{99m}Tc and ^{133}Xe .

The use of the C-E or Segars representation is not very sensitively affected by the calculated doses to the lungs of the newborn.

The probable explanation for the behavior of the representations is due to:

The geometric and anatomical differences presented by the CE and Segars representations make the SAF due to the x and γ photons

of ^{99m}Tc and ^{133}Xe to be slightly the same, generating insignificant relative differences in the total dose and in the dose of the biokinetic organs.

Conclusions

The absorbed dose in the lungs of newborn patients scanned with radiopharmaceuticals ^{133}Xe (ventilarian) and ^{99m}Tc (MAA) (perfusion) is estimated using the MIRD formalism for anatomical representations of Cristy-Eckerman and Segars.

The total dose in the lungs of newborns is due in large part to its self-dose, supplied mainly by the electrons produced during the decay of ^{99m}Tc and ^{133}Xe .

For the Cristy-Eckerman and Segars anatomical representations, the relative difference in the total dose between both representations is 1.0%, when the lungs are explored with ^{99m}Tc (MAA).

For the anatomical representations of Cristy-Eckerman and Segars, the relative difference in the total dose between both representations is 0.5%, when the lungs are explored with ^{133}Xe .

Regardless of the radiopharmaceutical used for pulmonary examinations of a newborn patient, the substitution of the Cristy-Eckerman representation for the Segars representation does not reflect significant changes in the calculation of the absorbed dose in the lungs.

References

- [1] E. E. Watson, M. G. Stabin, and J. A. Siegel, *Med. Phys.* **20**, 511 (1993).
- [2] J. Bevelacqua and B. Resources, *Radiation Protection Management* **22**, 7 (2005).
- [3] M. Vasquez-Arteaga, H. Vega-Carrillo, C. Rodriguez-Benites,

- C. Castillo, H. Rodriguez, R. Chanduvi, and C. Chirinos, *MOMENTO* **63**, 22–33 (2021).
- [4] M. Stabin, *Internal dose assessment: extrapolation from animal species to human*. (Springer, 2004) p. 77.
- [5] M. Cristy, *Mathematical phantoms representing children at various ages for use in estimates of internal dose* (Oak Ridge National Laboratory Rep. ORNL/TM-8377, 1980).
- [6] M. Stabin, E. Watson, M. Cristy, J. Ryman, K. Eckerman, J. Davis, D. Marshall, and M. Gehlen, *Mathematical models and specific absorbed fractions of photon energy in the nonpregnant adult female and at the end of each trimester of pregnancy* (Oak Ridge National Lab. (ORNL), Oak Ridge, 1995).
- [7] W. S. Snyder and et al., *Report on the Task Group on Reference Man. ICR Publication 23* (Pergamon Press, 1975).
- [8] N. Petoussi, M. Zankl, U. Fill, and D. Regulla, *Phys. Med. Biol.* **47**, 89 (2001).
- [9] W. Segars, *Development of a new dynamic NURBS-based cardiac-torso (NCAT) phantom* (Chapel Hill, NC: University of North Carolina, 2001).
- [10] J. Valentin, Pergamon. *ICRP Publication 89* **32**, 1 (2002).
- [11] T. C. Chao and X. G. Xu, *Phys. Med. Biol.* **46**, 901 (2001).
- [12] X. G. Xu, C. Shi, M. G. Stabin, and V. Taranenkov, *Handbook of Anatomical Models for Radiation Dosimetry - Chapter: Pregnant Female/Fetus Computational Phantoms and the Latest RPI-P Series Representing 3, 6, and 9 Month Gestational Periods* (CRC Press, 2009) p. 32.
- [13] M. G. Stabin and J. A. Siegel, *J. Nucl. Med.* **59**, 154 (2018).
- [14] R. Kramer, J. W. Vieira, H. J. Khoury, E. C. M. Loureiro, F. R. A. Lima, and G. Hoff, *IRPA* **11** (2004).
- [15] M. Vasquez -Arteaga and et al., *Appl. Radiat. Isotopes* **176**, 109888 (2021).
- [16] G. Nicolas and et al., *J. Nucl. Med.* **59**, 516 (2018).
- [17] K. Eckerman and K. Endo, *MIRD: Radionuclide Data and Decay Schemes* (The Society of Nuclear Medicine, 2007).

- [18] J. Parker and et al., J. Nucl. Med. **37**, 1906 (1996).
- [19] M. Cristy and K. F. Eckerman, *Specific absorbed fractions of energy at various ages from internal photon sources: 1, Methods*, Vol. 1 (Oak Ridge National Lab. (ORNL), Oak Ridge, 1987).
- [20] M. Cristy and K. F. Eckerman, *Specific absorbed fractions of energy at various ages from internal photon sources: 6, Newborn*, Vol. 6 (Oak Ridge National Lab. (ORNL), Oak Ridge, 1987).
- [21] M. Stabin and J. Siegel, Health Physics **85**, 294 (2003).
- [22] S. Mattsson and et al., Annals of the ICRP - Publication 128 **44(2_suppl)**, 7 (2015).
- [23] H. P. Society, Kinetic models used as the basic for the dose estimates (2013)(Reviewed on March 2021).
- [24] H. P. Society, Kinetic models used as the basic for the dose estimates (2013)(Reviewed on March 2021).
- [25] M. Ferrari, P. De Marco, D. Origi, and G. Pedroli, Clin. Transl. Imaging **2**, 557 (2014).
- [26] J. Parker, R. Coleman, B. Siegel, H. Sostman, K. McKusick, H. Royal, and J. Wilson, J. Nucl. Med. **37**, 1906 (1996).
- [27] M. Stabin, S. Kost, J. Clark, and D. Pickens, Vanderbilt University, Nashville, TN, USA (2015).