MIRD Dose Estimate Report No. 17: Radiation Absorbed Dose Estimates from Inhaled Krypton-81m Gas in Lung Imaging

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The estimated absorbed doses from ^{81m}Kr gas administered by inhalation are given in Table 1. The data and assumptions used for the calculations follow.

TABLE 1
Estimated Absorbed Dose from Inhaled ^{81m}Kr Gas*

Target organ	rad/mCi-min in lungs	mGy/MBq-min in lungs
Tracheal mucosa (surface)	4.6×10^{-1}	1.2×10^{-1}
Tracheal mucosa (mean)	2.1×10^{-3}	5.7×10^{-4}
Lungs	2.5×10^{-3}	6.7×10^{-4}
Liver	5.2×10^{-5}	1.4×10^{-5}
Spleen	4.9×10^{-5}	1.8×10^{-5}
Red marrow	3.9×10^{-5}	1.0×10^{-5}
Muscle	3.5×10^{-5}	9.3×10^{-6}
Kidneys	2.7×10^{-5}	7.2×10^{-6}
Ovaries	1.6×10^{-5}	4.2×10^{-6}
Testes	1.1×10^{-5}	2.9×10^{-6}
Total body	6.7×10^{-5}	1.8×10^{-5}

*Assumes equilibrium in the lung is attained, which requires inhalation of the gas for at least 2 min.

RADIOPHARMACEUTICAL

Krypton-81m, a daughter product of the radioactive decay of ^{81}Rb, is used for ventilation lung imaging, primarily as an aid in diagnosing pulmonary embolism. The radionuclide is commercially supplied as a ^{81}Rb/^{81m}Kr generator system. The rubidium is retained on the column and the ^{81m}Kr is eluted by flowing air or oxygen through the generator. Therefore, only the ^{81m}Kr need be considered in this dose estimate.

NUCLEAR DATA

Krypton-81m decays with a half-life of 13 sec by isomeric transition (99.99%) to ^{81}Kr or by electron capture (0.01%) to stable ^{81}Br. Krypton-81 undergoes electron capture with a half-life of 2.13×10^5 yr to ^{81}Br. Physical data are given in Table 2 (*1*).

BIOLOGIC DATA

The extremely short physical half-life of ^{81m}Kr precludes obtaining biologic data directly for an absorbed dose estimate. However, studies performed with ^{79}Kr and ^{127}Xe at Brookhaven National Laboratory (16 subjects) and with ^{85}Kr at the Institute of Biophysics of the Ministry of Health in Moscow (15 subjects) have produced data providing fractional distribution functions and biologic disappearance constants (*2,3*). Biologic parameters are given in Table 3. The various components are associated with plasma [1], hemoglobin [2], muscle [3] and fat [4,5]. References for these associations are given by Ellis et al. (*2*). These data are similar to those obtained for xenon except that for components with longer half-times, the disappearance of krypton is more rapid because of its lower solubility in fat (*4*). The longer-lived components have a minimal effect on the absorbed dose estimate because of the extremely short physical half-life (13 sec) of ^{81m}Kr. The fractional distribution function for body components 3, 4 and 5 are those from the publication by Ellis et al. (*2*). The fractional distribution function for components 1 and 2 are derived from their ratios as determined in the absorbed dose estimate for xenon (*5*), but their sum total is based on the difference between 100% and the total of the values for krypton for the other components.

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TABLE 2
Nuclear Data (1)

Radionuclide	^{81m}Kr	^{81}Kr
Physical half-life (h)	3.61×10^{-3}	1.87×10^{9}
Decay constant (h^{-1})	192.0	3.71×10^{-10}
Mode of decay	E.C. (0.01%) I.T. (99.99%)	E.C.

	^{81m}Kr		Δ_i		^{81}Kr		Δ_i	
Principal radiation	E_i(keV)	n_i	rad g/µCi h	Gy kg/Bq s	E_i(keV)	n_i	rad g/µCi h	Gy kg/Bq s
Photons	190.4	0.671	0.272	2.05×10^{-14}	276.0	0.039	0.0229	1.73×10^{-15}
	12.6–14.1	0.164	0.004	3.35×10^{-16}	11.9–13.5	0.505	0.0130	9.78×10^{-16}
Nonpenetrating			0.126	9.44×10^{-15}			0.0109	8.19×10^{-16}

E_i is mean energy per particle or photon; n_i is number of particles or photons per nuclear transition; Δ_i is mean energy emitted per nuclear transition.
Nonpenetrating radiation from ^{81m}Kr includes conversion and Auger electrons ranging in energy from 0.149 keV to 190.2 keV. Nonpenetrating radiation from ^{81}Kr includes conversion and Auger electrons ranging in energy from 0.126 keV to 274.2 keV. Only photons with a mean yield per nuclear transition greater than 0.01 are included.
Note: Complete decay of 1 unit of activity of ^{81m}Kr produces 1.93×10^{-12} units of activity of ^{81}Kr.

Krypton-81m is introduced into the lungs by means of inhalation of air or oxygen continuously flowing at 2–3 liters per min through the ^{81}Rb/^{81m}Kr generator into a mask covering the patient's nose and mouth. Inhalation is typically continued for 2–3 min for each projection of the lungs in order to permit acquisition of an image. From 1 to 6 views may be acquired, depending on the clinical situation.

The dose calculations are based on the model that the equilibrium level of activity is present in each source tissue for 1 min. In effect, this is equivalent to assuming that equilibrium is attained instantaneously in the lungs and that in the other tissues, the delay in washin is made up for by an equal delay in washout. The washin curve has the form $E(1 - e^{-\lambda t})$, and the washout curve has the form $Ee^{-\lambda t}$, where E is the equilibrium concentration, so that the integrated sum of these two equations is essentially equal to E, provided that in each case t is sufficiently long so that $e^{-\lambda t}$ approaches zero. Since the uptake and disappearance curves are dominated by the 13-sec physical half-life, 99% of equilibrium is attained in 86 sec or less and the assumptions made are within the errors of measurement.

RADIATION ABSORBED DOSE

In calculating the absorbed dose, it is assumed the patient inhales ^{81m}Kr at a constant rate of delivery and at "equilibrium" 37 MBq (1 mCi) of the gas are in the lung spaces. The delivery of radioactivity is abruptly stopped after acquisition of the image and the ^{81m}Kr washes out of the lungs.

The trachea was modeled as a right circular cylinder with an inside diameter of 1.1 cm and a mucosal (wall) thickness of 0.2 cm. The radionuclide was assumed to mix uniformly with air at a pressure of 1 atmosphere and to fill the inner cylinder at the same concentration as that in the lung. Calculations of the radiation absorbed dose to the

TABLE 3
Biologic Parameters for Inhaled Krypton Gas

Component	Fractional distribution coefficient α_i	Biologic disappearance constant, λ_i (h^{-1})	Biologic disappearance half-time, T_i (h)	Residence time, τ_i, for ^{81m}Kr* (h)
Lungs				1.7×10^{-2}
1 Plasma	0.744	116.06	0.00597	2.7×10^{-3}
2 Hemoglobin	0.0734	8.77	0.079	2.7×10^{-4}
3 Muscle	0.112	2.10	0.33	4.1×10^{-4}
4 Fat†	0.0536	0.288	2.41	2.0×10^{-4}
5 Fat‡	0.0170	0.099	6.99	6.3×10^{-5}

*Tau(τ) is computed for a 1-min inhalation period using a factor of 0.2215 based on the body-to-lung Kr content (from Table 4 of ref. 2, i.e., τ_i = 0.017 hr × 0.2215 × α_i).
†Nonadipose fat.
‡Adipose tissue.

mucosa were accomplished using the computer code EGS4 (electron-gamma shower), a coupled photon-electron Monte Carlo transport code (*6*). Because the range of the conversion electrons emitted from the ^{81m}Kr transitions is less than 0.35 mm, the dose to the tracheal mucosa surface (depth 0.01 mm) as well as the mean dose to the entire mucosa was calculated.

The residence times for the various components of the washout were calculated from the ratio of body content to lung content as determined by Ellis et al. (*2*). Because separate S values are not available for plasma, hemoglobin and fat, the residence times for these tissues were considered to be distributed throughout the body and calculated as "remainder of the body" (*7*). The S values for muscle in *MIRD Pamphlet No. 11* were used with the residence time in muscle for estimating the absorbed dose (*8*).

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