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

Harold L. Atkins, James S. Robertson and Gamal Akabani

Medical Department, Brookhaven National Laboratory, Upton, New York; Department of Radiology, Health Sciences Center, State University of New York, Stony Brook, New York; and Dosimetry Research Division, Health Physics Department, Battelle-Pacific Northwest Laboratories, Richland, Washington

TABLE 1
Estimated Absorbed Dose from Inhaled 81mKr Gas

<table>
<thead>
<tr>
<th>Target organ</th>
<th>rad/mCi-min in lungs</th>
<th>mGy/mBq-min in lungs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracheal mucosa</td>
<td>4.6 × 10⁻¹</td>
<td>1.2 × 10⁻¹</td>
</tr>
<tr>
<td>(surface)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracheal mucosa</td>
<td>2.1 × 10⁻³</td>
<td>5.7 × 10⁻⁴</td>
</tr>
<tr>
<td>(mean)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lungs</td>
<td>2.5 × 10⁻³</td>
<td>6.7 × 10⁻⁴</td>
</tr>
<tr>
<td>Liver</td>
<td>5.2 × 10⁻⁵</td>
<td>1.4 × 10⁻⁵</td>
</tr>
<tr>
<td>Spleen</td>
<td>4.9 × 10⁻⁵</td>
<td>1.8 × 10⁻⁵</td>
</tr>
<tr>
<td>Red marrow</td>
<td>3.9 × 10⁻⁵</td>
<td>1.0 × 10⁻⁵</td>
</tr>
<tr>
<td>Muscle</td>
<td>3.5 × 10⁻⁵</td>
<td>9.3 × 10⁻⁶</td>
</tr>
<tr>
<td>Kidneys</td>
<td>2.7 × 10⁻⁵</td>
<td>7.2 × 10⁻⁶</td>
</tr>
<tr>
<td>Ovaries</td>
<td>1.6 × 10⁻⁵</td>
<td>4.2 × 10⁻⁶</td>
</tr>
<tr>
<td>Testes</td>
<td>1.1 × 10⁻⁵</td>
<td>2.9 × 10⁻⁵</td>
</tr>
<tr>
<td>Total body</td>
<td>6.7 × 10⁻⁸</td>
<td>1.8 × 10⁻⁸</td>
</tr>
</tbody>
</table>

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

NUCLEAR DATA

Krypton-81m decays with a half-life of 13 sec by isomeric transition (99.99%) to 81Kr or by electron capture (0.01%) to stable 81Br. Krypton-81m undergoes electron capture with a half-life of 2.13 × 10⁵ yr to 81Br. Physical data are given in Table 2 (f).

BIOLGIC DATA

The extremely short physical half-life of 81mKr precludes obtaining biologic data directly for an absorbed dose estimate. However, studies performed with 79Kr and 127Xe at Brookhaven National Laboratory (16 subjects) and with 85Kr 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 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 81mKr. 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.
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 $^{81m}$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.

### TABLE 2
Nuclear Data ($\gamma$)

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>$^{81m}$Kr</th>
<th>$^{81}$Kr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical half-life (h)</td>
<td>$3.61 \times 10^{-3}$</td>
<td>$1.87 \times 10^{6}$</td>
</tr>
<tr>
<td>Decay constant (h$^{-1}$)</td>
<td>192.0</td>
<td>$3.71 \times 10^{-10}$</td>
</tr>
<tr>
<td>Mode of decay</td>
<td>E.C. (0.01%)</td>
<td>E.C.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta t$</th>
<th>$\Delta t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal radiation</td>
<td>$E_i$ (keV)</td>
</tr>
<tr>
<td>Photons</td>
<td>190.4</td>
</tr>
<tr>
<td></td>
<td>12.6–14.1</td>
</tr>
<tr>
<td>Nonpenetrating</td>
<td>0.126</td>
</tr>
</tbody>
</table>

$E_i$ is mean energy per particle or photon; $n_\gamma$ is number of particles or photons per nuclear transition; $\Delta t$ 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 $1.93 \times 10^{-12}$ units of activity of $^{81}$Kr.

### TABLE 3
Biologic Parameters for Inhaled Krypton Gas

<table>
<thead>
<tr>
<th>Component</th>
<th>Fractional distribution coefficient, $\alpha_i$</th>
<th>Biologic disappearance constant, $\lambda_i$ (h$^{-1}$)</th>
<th>Biologic disappearance half-time, $T_i$ (h)</th>
<th>Residence time, $\tau_i$ for $^{81m}$Kr$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lungs</td>
<td>1.7 $\times 10^{-2}$</td>
<td>116.06</td>
<td>0.00597</td>
<td>1.7 $\times 10^{-2}$</td>
</tr>
<tr>
<td>1 Plasma</td>
<td>0.744</td>
<td>116.06</td>
<td>0.00597</td>
<td>1.7 $\times 10^{-2}$</td>
</tr>
<tr>
<td>2 Hemoglobin</td>
<td>0.0734</td>
<td>8.77</td>
<td>0.079</td>
<td>2.7 $\times 10^{-3}$</td>
</tr>
<tr>
<td>3 Muscle</td>
<td>0.112</td>
<td>2.10</td>
<td>0.33</td>
<td>4.1 $\times 10^{-4}$</td>
</tr>
<tr>
<td>4 Fat$^+$</td>
<td>0.0536</td>
<td>0.288</td>
<td>2.41</td>
<td>2.0 $\times 10^{-4}$</td>
</tr>
<tr>
<td>5 Fat$^+$</td>
<td>0.0170</td>
<td>0.089</td>
<td>6.99</td>
<td>6.3 $\times 10^{-5}$</td>
</tr>
</tbody>
</table>

* $\tau_i$ 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., $\tau_i = 0.017$ hr $\times 0.2215 \times \alpha_i$).

$^*$Nonadipose tissue.

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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).

REFERENCES