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CALCULATION OF EQUIVALENT DOSE FOR AUGER ELECTRON EMITTING RADIONUCLIDES DISTRIBUTED IN HUMAN ORGANS

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Radionuclides that emit Auger electrons can be extremely radiotoxic depending on the subcellular distribution of the radiochemical. Despite this, ICRP 60 provides no guidance in the calculation of equivalent dose H_T for Auger electrons. The recent report by the American Association of Physicists in Medicine recommends a radiation weighting factor w_R of 20 for stochastic effects caused by Auger electrons, along with a method of calculating the equivalent dose that takes into account the subcellular distribution of the radionuclide. In view of these recommendations, it is important to reevaluate equivalent doses from Auger electron emitters. The mean absorbed dose per unit cumulated activity (S-value) from Auger electrons and other radiations is calculated for ninety Auger-electron-emitting radionuclides distributed in human ovaries, testes and liver. Using these S-values, and the formalism given in the recent AAPM report, the dependence of the organ equivalent doses on subcellular distribution of the Auger electron emitters is examined. The results show an increase in the mean equivalent dose for Auger electron emitters when a significant fraction of the organ activity localizes in the DNA.

Many radionuclides used in nuclear medicine (e.g., ^{67}Ga, ^{99m}Tc, ^{111}In, ^{123}I, ^{201}Tl), as well as radionuclides found in the environment from natural and man-made sources (e.g., ^{40}K, ^{55}Fe), decay by electron capture (EC) and/or internal conversion (IC). These decay processes result in the creation of a vacancy in their inner atomic shell which initiates a cascade of electron transitions (1, 2). As a result, a large number of low energy electrons having ranges of subcellular dimensions are emitted. These electrons are properly referred to as Auger, Coster-Kronig, and super Coster-Kronig electrons, depending on the nature of the atomic transition. However, for convenience, these electrons are often collectively called Auger electrons, and the radionuclides from which they emanate are known as Auger electron emitters.

When Auger electron emitters are incorporated into tissue, the biological damage caused by them can be severe, depending on the subcellular distribution of the radiochemical (3–6). For example, when the prolific Auger electron emitter ^{125}I is incorporated into DNA in the cell nucleus (e.g., ^{125}IUdR), the effects are as severe as high linear energy transfer (LET) α-particles emitted by incorporated ^{210}Po (7, 8). In contrast, when the same radionuclide localizes in the cytoplasm, the effects are equivalent to those caused by low-LET radiations (6, 9, 10). Similar radiotoxicity has been observed for the Auger electron emitters ^{77}Br (11, 12) and ^{123}I, when similarly incorporated into the DNA. Other Auger electron emitting radiochemicals that localize in the cell nucleus have also been found to be highly radiotoxic including ^{125}Iodoproflavine (13), ^{111}In oxine (5), and trans-^{195m}Pt (14). These data provide ample evidence that the biological effects of Auger electron emitters can be severe, depending on the subcellular distribution of the radionuclide.

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In view of the highly radiotoxic nature of Auger electron emitters, it is important to develop risk assessment methods. The ICRP recently published a comprehensive set of recommendations to aid in assessing risk from radiation exposure (15). In their report, the equivalent dose H_T to tissue T is defined as the product of the mean absorbed dose D_T to tissue T and the radiation weighting factor w_R, a factor based on the observed relative biological effectiveness (RBE) of the radiation. A radiation weighting factor of 1 was recommended for all electrons except those emitted by DNA bound Auger electron emitters (15). However, no guidance was provided with regard to estimating the equivalent dose from Auger electron emitters despite the fact that DNA incorporated Auger electron emitters have been shown to be as radiotoxic as incorporated alpha emitters (7, 8). Recently, Howell et al. (16) used the mouse testes model to show that there is a linear relationship between relative biological effectiveness (RBE) of ^{125}I and the fraction of organ activity bound to DNA. Based on these findings, the following expression for the equivalent dose was derived for Auger electron emitters (16),

$$H_T = H_{T,R_{Auger}} + H_{T,R_{other}} = [1 + f_0(w_{R_{Auger}} - 1)]D_{T,R_{Auger}} + D_{T,R_{other}} \quad [1]$$

where f_0 is the fraction of organ activity bound to DNA, $w_{R_{Auger}}$ is the radiation weighting factor for Auger electrons, $H_{T,R_{Auger}}$ and $D_{T,R_{Auger}}$ are the equivalent dose and absorbed dose from Auger electrons, and $H_{T,R_{other}}$ and $D_{T,R_{other}}$ are the equivalent dose and absorbed dose from other radiations. This expression allows calculation of the equivalent dose for Auger electron emitters given the mean tissue doses from the different types of radiations and the subcellular distribution of the radionuclide in the tissue. This approach was recently adopted by the American Association of the Physicists in Medicine (AAPM) in their recent report on the dosimetry of Auger electron emitters (17). The AAPM also reviewed the effects of Auger electrons in several biological systems and recommended a radiation weighting factor of 20 for stochastic effects (17).

In the present work, the recommendations of the AAPM (17) are used to examine the equivalent dose to the human liver, testes, and ovaries from Auger electron emitters. The mean organ dose from Auger electrons and other low-LET radiations are tabulated separately for 90 radionuclides. Using these values, assumed subcellular distributions of the radionuclides, and the recommended $w_{R_{Auger}} = 20$, the equivalent dose per unit cumulated activity (S_H) is calculated for several radionuclides distributed in human testes, and liver.

Material and Methods

Absorbed dose per unit cumulated activity

The mean self-absorbed dose per unit cumulated activity S (18) was calculated for 90 different Auger electron emitting radionuclides uniformly distributed in three different human organs, namely, liver, testes and ovaries. The mean self-absorbed dose per unit cumulated activity $S_{T\leftarrow T}$ to tissue T (18) is given by

$$S_{T\leftarrow T} = \sum_{R_{Auger}} S_{T\leftarrow T,R_{Auger}} + \sum_{R_{other}} S_{T\leftarrow T,R_{other}} = \frac{1}{m_T}\left\{\sum_{R_{Auger}} \Delta_{R_{Auger}}\phi_{T\leftarrow T,R_{Auger}} + \sum_{R_{other}} \Delta_{R_{other}}\phi_{T\leftarrow T,R_{other}}\right\} \quad [2]$$

where $\Sigma_{R_{Auger}} S_{T\leftarrow T,R_{Auger}}$ and $\Sigma_{R_{other}} S_{T\leftarrow T,R_{other}}$ are the mean self-absorbed dose per unit cumulated activity in tissue T from Auger electrons and other radiations respectively. The quantity m_T is the mass of the tissue T, $\Delta_{R_{Auger}}$ and $\phi_{T\leftarrow T,R_{Auger}}$ are the mean energy emitted per nuclear transition and self-absorbed fraction for the Rth Auger electron component respectively (18). The quantities $\Delta_{R_{other}}$ and $\phi_{T\leftarrow T,R_{other}}$ are the mean energy emitted per nuclear transition and self-absorbed fraction for the Rth radiation component other than Auger electrons. The organ masses were taken as 1.8, 0.035, 0.011 kg for the liver, testes, and ovaries respectively (19). A computer code (20) was used to calculate the S-values with some modifications to separately calculate the S values for Auger electrons and other radiations including conversion electrons, β-rays, and photons. The organs were assumed to be homogeneous spheres of density 1 g/cm^3, and the activity was distributed uniformly in these organs.

Radiation spectra

All the radionuclides chosen for these calculations undergo nuclear transitions involving substantial EC or IC probabilities and therefore are Auger electron emitters. The complete radiation spectra of Eckerman et al. (21) were used for all radionuclides. The full logarithmically binned β-spectra were used for all radionuclides involving β^- or β^+ decay (21). Some of the spectra contained in excess of one thousand different radiations for a given radionuclide, many of which are insignificant with respect to internal dosimetry because of their low yields. Accordingly, only those radiations which contributed greater than 0.1% to the total Δ for that particular radiation-type were retained. The different radiation-types considered separately in this manner were photons, beta particles, conversion electrons, and Auger electrons.

Equivalent dose per unit cumulated activity

Although the absorbed dose D is a useful dosimetric quantity in radiological protection, the biological effects of radiation also are known to depend on the radiation type and energy of the radiation. Therefore, in order to predict the biological effect of a given radiation compared with a

standard radiation (e.g., 250 kVp x-rays), the absorbed dose is modified by a radiation weighting factor which is related to the observed RBE values for the given radiation type and energy (15). This weighted absorbed dose, known as the equivalent dose (15), is given by Eq. [1] for Auger electron emitters. Similarly, we define the equivalent dose to tissue T per unit cumulated activity $S^H_{T\leftarrow T}$ in tissue T as

$$S^H_{T\leftarrow T} = [1 + f_0(w_{R_{Auger}} - 1)] \sum_{R_{Auger}} S_{T\leftarrow T,R_{Auger}} + \sum_{R_{other}} w_{R_{other}} S_{T\leftarrow T,R_{other}} \quad [3]$$

As recommended by the AAPM (17), a preliminary radiation weighting factor of $w_{R_{Auger}} = 20$ was used in the calculation of $S^H_{T\leftarrow T}$.

Absorbed dose and equivalent dose

The mean self-absorbed dose to tissue T from activity in tissue T is simply (18):

$$D_{T\leftarrow T} = \tilde{A}_T S_{T\leftarrow T} \quad [4]$$

The quantity $\tilde{A}_T$ is the cumulated activity in tissue T (18),

$$\tilde{A}_T = \int A(t)dt \quad [5]$$

where A(t) is the instantaneous activity in tissue T at time t. In terms of the equivalent dose per unit cumulated activity, the equivalent dose to tissue T from activity in tissue T is simply:

$$H_{T\leftarrow T} = \tilde{A}_T S^H_{T\leftarrow T} \quad [6]$$

Results

The mean self-absorbed dose per unit cumulated activity in human liver, testes, and ovaries is given in Table 1 for 90 Auger electron emitters. The quantities $\Sigma_{R_{Auger}} S_{T\leftarrow T,R_{Auger}}$ and $\sum_{R_{other}} S_{T\leftarrow T,R_{other}}$ are tabulated separately for each organ. For all 90 radionuclides presented here, R_{other} corresponds to low-LET radiations including photons, β^+, β^-, and conversion electrons. Separation of S into two components, $\sum_{R_{Auger}} S_{T\leftarrow T,R_{Auger}}$ and $\Sigma_{R_{other}} S_{T\leftarrow T,R_{other}}$, facilitates calculation of the equivalent dose per unit cumulated activity for Auger electron emitters as described by Eq. [3]. It is important to reiterate that the S values given in Table 1 are only the mean self-absorbed dose per unit cumulated activity (i.e., dose from the activity distributed within the target organ). The cross-dose contribution (i.e., dose to target organ from activity in non-target organs) must be obtained separately. The cross-dose S-values for different radionuclides may be obtained from MIRD Pamphlet 11 (19). For more accurate assessment of the radiation risk one should always account for the cross-dose from all other organs. It should be noted that the cross-dose contribution from Auger electrons is zero because of their extremely short range in biological tissues. When the cross-dose contribution is taken into account, the equivalent dose may be rewritten as

$$H_T = H_{T\leftarrow T} + \sum_{NT} H_{T\leftarrow NT} = \tilde{A}_T S^H_{T\leftarrow T} + \sum_{NT} \tilde{A}_{NT} S^H_{T\leftarrow NT} \quad [7]$$

where, $\tilde{A}_{NT}$ represents the cumulated activity in a non-target tissue (NT) and $S^H_{T\leftarrow NT}$ is the equivalent dose to target tissue (T) per unit cumulated activity in the non-target tissue. An example involving the use of Eq. [7] is given in the appendix for the prolific Auger electron emitter ^{201}Tl.

To demonstrate the effect of the radiation weighting factor for Auger electrons on the equivalent dose, Table 2 gives the equivalent dose to tissue T per unit cumulated activity $S^H_{T\leftarrow T}$ for various radionuclides commonly used in medicine (^{67}Ga, ^{103}Pd, ^{123}I, ^{125}I, ^{111}In, ^{99m}Tc and ^{201}Tl). The quantities $S^H_{Testes\leftarrow Testes}$ and $S^H_{Liver\leftarrow Liver}$ are tabulated and compared with $S_{Testes\leftarrow Testes}$ and $S_{Liver\leftarrow Liver}$. Two values of f_0 are considered, 0.5 and 1.0, and the ratio of $S^H_{Testes\leftarrow Testes}/S_{Testes\leftarrow Testes}$ and $S^H_{Liver\leftarrow Liver}/S_{Liver\leftarrow Liver}$ are presented. These ratios are related to the expected relative biological effectiveness (RBE) for the stated values of f_0.

Discussion

Radionuclides emit a variety of radiations, some of which are low-LET (photons, β, conversion electrons) and others are high-LET (α, n). When low-LET emitters are incorporated into tissue, the mean absorbed dose to the tissue is generally adequate to predict biological response and assess the risk associated with the exposure. However, for radionuclides which emit high-LET alpha particles, the biological response for a given mean absorbed dose is considerably greater than that for low-LET radiations. In view of these considerations, the ICRP has recommended the mean absorbed dose be multiplied by the radiation weighting factor w_R to obtain the equivalent dose (15). For alpha particles, the recommended $w_R = 20$ (15). Auger electron emitters fall into a different class of radionuclides in that their biological effects depend strongly on their subcellular distribution in tissue. When Auger electron emitters are incorporated into the DNA of the cell nucleus, they are as radiotoxic as high-LET alpha particles, whereas they are only as radiotoxic as low-LET radiations when they are localized outside the cell nucleus (6–8, 10, 22). In view of these data, the AAPM (17) recently recommended a radiation weighting factor of 20 for Auger electrons and a method to calculate the equivalent dose for these radionuclides which utilizes the subcellular distribution and mean absorbed dose to the tissue (see Eq. [1]).

In view of the highly localized energy deposition of Auger electron emitters, the appropriateness of utilizing mean organ doses and a radiation weighting factor of 20 to calculate the equivalent dose for these radionuclides

Table 1*

Mean absorbed dose per unit cumulated activity distributed in different human organs from Auger electrons and other radiations

Radionuclide	Ovaries		Testes		Liver	
	$\Sigma S_{O \leftarrow O,R_{Auger}}$ (Gy per Bq s)	$\Sigma S_{O \leftarrow O,R_{other}}$ (Gy per Bq s)	$\Sigma S_{T \leftarrow T,R_{Auger}}$ (Gy per Bq s)	$\Sigma S_{T \leftarrow T,R_{other}}$ (Gy per Bqs)	$\Sigma S_{L \leftarrow L,R_{Auger}}$ (Gy per Bq s)	$\Sigma S_{L \leftarrow L,R_{other}}$ (Gy per bq s)
Ag-109m	6.14E – 14	1.10E – 12	1.93E – 14	3.48E – 13	3.75E – 16	7.04E – 15
Ar-37	2.86E – 14	2.96E – 15	8.98E – 15	9.31E – 16	1.75E – 16	1.82E – 17
As-73	1.73E – 13	8.35E – 13	5.43E – 14	2.63E – 13	1.06E – 15	5.24E – 15
Au-195	2.58E – 13	5.72E – 13	8.10E – 14	1.87E – 13	1.58E – 15	5.00E – 15
Au-195m	1.45E – 13	1.67E – 12	4.57E – 14	5.41E – 13	8.88E – 16	1.31E – 14
Ba-128	9.82E – 14	1.05E – 13	3.09E – 14	4.32E – 14	6.01E – 16	2.12E – 15
Ba-131m	1.09E – 13	1.54E – 12	3.42E – 14	4.94E – 13	6.65E – 16	1.09E – 14
Ba-133	1.66E – 13	8.69E – 13	5.21E – 14	3.12E – 13	1.01E – 15	1.18E – 14
Bi-204	1.90E – 13	2.25E – 12	5.96E – 14	9.06E – 13	1.16E – 15	4.87E – 14
Bi-206	2.12E – 13	3.19E – 12	6.67E – 14	1.23E – 12	1.30E – 15	5.91E – 14
Br-77	7.69E – 14	2.60E – 13	2.42E – 14	1.05E – 13	4.70E – 16	5.83E – 15
Br-80m	1.15E – 13	8.71E – 13	3.61E – 14	2.77E – 13	7.03E – 16	5.82E – 15
Cd-109	1.44E – 13	1.17E – 12	4.54E – 14	3.78E – 13	8.84E – 16	8.02E – 15
Ce-134	1.05E – 13	7.23E – 14	3.30E – 14	3.00E – 14	6.41E – 16	1.42E – 15
Ce-139	1.16E – 13	5.14E – 13	3.63E – 14	1.78E – 13	7.07E – 16	5.99E – 15
Co-57	1.17E – 13	2.64E – 13	3.67E – 14	9.14E – 14	7.14E – 16	3.41E – 15
Co-58	5.44E – 14	9.43E – 13	1.71E – 14	3.66E – 13	3.32E – 16	1.79E – 14
Cr-48	5.57E – 14	2.88E – 13	1.75E – 14	1.22E – 13	3.41E – 16	7.80E – 15
Cr-51	5.53E – 14	3.13E – 14	1.74E – 14	1.22E – 14	3.38E – 16	6.29E – 16
Cs-129	1.34E – 13	3.23E – 13	4.22E – 14	1.30E – 13	8.20E – 16	6.55E – 15
Cs-131	9.58E – 14	5.61E – 14	3.01E – 14	2.48E – 14	5.86E – 16	1.21E – 15
Cs-132	9.49E – 14	4.96E – 13	2.98E – 14	2.12E – 13	5.80E – 16	1.25E – 14
Cs-134m	1.26E – 13	1.54E – 12	3.95E – 14	4.89E – 13	7.67E – 16	1.00E – 14
Dy-157	1.24E – 13	2.70E – 13	3.89E – 14	1.13E – 13	7.57E – 16	6.79E – 15
Dy-159	1.42E – 13	1.06E – 13	4.45E – 14	4.02E – 14	8.66E – 16	1.88E – 15
Er-165	1.17E – 13	4.49E – 14	3.67E – 14	1.93E – 14	7.14E – 16	1.24E – 15
Fe-55	6.11E – 14	2.20E – 14	1.92E – 14	6.92E – 15	3.73E – 16	1.35E – 16
Ga-67	9.36E – 14	5.38E – 13	2.94E – 14	1.80E – 13	5.72E – 16	5.44E – 15
Gd-153	1.73E – 13	5.19E – 13	5.44E – 14	1.76E – 13	1.06E – 15	5.47E – 15
Ge-68	7.12E – 14	5.07E – 14	2.24E – 14	1.59E – 14	4.35E – 16	3.10E – 16
Hg-195	2.30E – 13	8.53E – 13	7.24E – 14	2.83E – 13	1.41E – 15	8.09E – 15
Hg-195m	3.08E – 13	2.00E – 12	9.68E – 14	6.46E – 13	1.88E – 15	1.52E – 14
Hg-197	2.17E – 13	8.28E – 13	6.82E – 14	2.66E – 13	1.33E – 15	6.29E – 15
Hg-197m	1.91E – 13	3.01E – 12	5.99E – 14	9.56E – 13	1.17E – 15	1.99E – 14
I-123	1.09E – 13	4.45E – 13	3.42E – 14	1.59E – 13	6.66E – 16	5.74E – 15
I-125	1.79E – 13	2.32E – 13	5.62E – 14	8.75E – 14	1.09E – 15	3.00E – 15
I-129	8.96E – 14	9.18E – 13	2.82E – 14	2.96E – 13	5.48E – 16	6.54E – 15
In-109	9.18E – 14	9.65E – 13	2.89E – 14	3.58E – 13	5.61E – 16	1.48E – 14
In-111	1.02E – 13	6.68E – 13	3.21E – 14	2.47E – 13	6.24E – 16	1.02E – 14
Ir-190	1.72E – 13	1.64E – 12	5.41E – 14	6.25E – 13	1.05E – 15	2.99E – 14
Ir-190m	9.51E – 14	2.80E – 13	2.99E – 14	8.79E – 14	5.81E – 16	1.71E – 15
Ir-190n	2.70E – 13	2.35E – 12	8.48E – 14	8.53E – 13	1.65E – 15	3.51E – 14
Ir-191m	1.97E – 13	1.27E – 12	6.20E – 14	4.06E – 13	1.21E – 15	9.01E – 15
Kr-79	7.21E – 14	4.54E – 13	2.27E – 14	1.62E – 13	4.41E – 16	6.08E – 15
Kr-81	7.28E – 14	5.13E – 14	2.29E – 14	1.69E – 14	4.45E – 16	4.61E – 16
Kr-83m	5.81E – 14	5.27E – 13	1.83E – 14	1.66E – 13	3.55E – 16	3.22E – 15
Mn-54	5.83E – 14	4.16E – 13	1.83E – 14	1.89E – 13	3.57E – 16	1.27E – 14
Os-190m	1.49E – 13	2.33E – 12	4.68E – 14	8.50E – 13	9.10E – 16	3.53E – 14
Os-191	1.97E – 13	1.83E – 12	6.20E – 14	5.81E – 13	1.21E – 15	1.24E – 14
Os-191m	1.02E – 13	8.68E – 13	3.22E – 14	2.74E – 13	6.26E – 16	5.45E – 15
Pb-201	1.64E – 13	1.04E – 12	5.15E – 14	3.83E – 13	1.00E – 15	1.63E – 14
Pb-203	1.65E – 13	7.69E – 13	5.19E – 14	2.66E – 13	1.01E – 15	9.29E – 15
Pd-103	8.52E – 14	8.10E – 14	2.68E – 14	3.25E – 14	5.21E – 16	1.01E – 15
Pm-145	1.13E – 13	1.21E – 13	3.55E – 14	4.44E – 14	6.90E – 16	1.72E – 15
Pt-195m	3.18E – 13	2.44E – 12	9.99E – 14	7.74E – 13	1.94E – 15	1.62E – 14
Rb-83	9.85E – 14	4.19E – 13	3.10E – 14	1.68E – 13	6.02E – 16	9.01E – 15
Rh-103m	4.03E – 14	5.09E – 13	1.27E – 14	1.61E – 13	2.46E – 16	3.17E – 15

Table 1 (continued)

Radionuclide	Ovaries		Testes		Liver	
	$\Sigma S_{O \leftarrow O, R_{Auger}}$ (Gy per Bq s)	$\Sigma S_{O \leftarrow O, R_{other}}$ (Gy per Bq s)	$\Sigma S_{T \leftarrow T, R_{Auger}}$ (Gy per Bq s)	$\Sigma S_{T \leftarrow T, R_{other}}$ (Gy per Bqs)	$\Sigma S_{L \leftarrow L, R_{Auger}}$ (Gy per Bq s)	$\Sigma S_{L \leftarrow L, R_{other}}$ (Gy per bq s)
Ru-97	8.68E − 14	2.97E − 13	2.73E − 14	1.16E − 13	5.31E − 16	5.36E − 15
Sb-118m	1.67E − 13	1.70E − 12	5.24E − 14	7.18E − 13	1.02E − 15	4.17E − 14
Se-72	1.08E − 13	3.01E − 13	3.38E − 14	9.87E − 14	6.57E − 16	2.58E − 15
Se-75	8.48E − 14	3.51E − 13	2.66E − 14	1.38E − 13	5.18E − 16	7.54E − 15
Sm-145	1.94E − 13	3.46E − 13	6.10E − 14	1.21E − 13	1.19E − 15	4.04E − 15
Sn-113	8.95E − 14	8.13E − 14	2.81E − 14	3.34E − 14	5.47E − 16	1.23E − 15
Sr-82	7.83E − 14	5.75E − 14	2.46E − 14	1.81E − 14	4.79E − 16	3.54E − 16
Sr-85	7.95E − 14	3.56E − 13	2.50E − 14	1.49E − 13	4.86E − 16	8.78E − 15
Sr-85m	3.21E − 14	2.67E − 13	1.01E − 14	9.96E − 14	1.96E − 16	4.63E − 15
Ta-177	1.45E − 13	2.62E − 13	4.56E − 14	8.89E − 14	8.87E − 16	2.92E − 15
Ta-178a	1.60E − 13	4.07E − 13	5.01E − 14	1.37E − 13	9.75E − 16	4.26E − 15
Ta-179	1.18E − 13	4.00E − 14	3.70E − 14	1.60E − 14	7.20E − 16	9.41E − 16
Tc-95	8.31E − 14	4.76E − 13	2.61E − 14	2.10E − 13	5.08E − 16	1.29E − 14
Tc-95m	8.37E − 14	5.61E − 13	2.63E − 14	2.32E − 13	5.12E − 16	1.27E − 14
Tc-97m	6.96E − 14	1.25E − 12	2.19E − 14	3.98E − 13	4.26E − 16	7.94E − 15
Tc-99m	1.48E − 14	2.83E − 13	4.66E − 15	9.85E − 14	9.07E − 17	3.60E − 15
Te-123	4.14E − 14	2.18E − 15	1.30E − 14	6.90E − 16	2.53E − 16	1.45E − 17
Te-123m	8.90E − 14	1.50E − 12	2.80E − 14	4.87E − 13	5.44E − 16	1.16E − 14
Tl-200	1.48E − 13	1.02E − 12	4.66E − 14	4.11E − 13	9.07E − 16	2.22E − 14
Tl-201	2.03E − 13	5.12E − 13	6.36E − 14	1.69E − 13	1.24E − 15	4.72E − 15
Tl-202	1.43E − 13	4.44E − 13	4.49E − 14	1.75E − 13	8.74E − 16	9.22E − 15
Tm-167	1.94E − 13	1.76E − 12	6.08E − 14	5.70E − 13	1.18E − 15	1.34E − 14
W-177	3.16E − 13	1.58E − 12	9.92E − 14	5.65E − 13	1.93E − 15	2.20E − 14
W-178	1.06E − 13	2.87E − 14	3.34E − 14	1.04E − 14	6.50E − 16	4.55E − 16
W-181	1.32E − 13	1.12E − 13	4.15E − 14	3.93E − 14	8.08E − 16	1.52E − 15
Xe-122	9.96E − 14	1.38E − 13	3.13E − 14	5.45E − 14	6.09E − 16	2.35E − 15
Xe-127	1.13E − 13	5.47E − 13	3.54E − 14	1.99E − 13	6.89E − 16	7.88E − 15
Xe-129m	1.73E − 13	2.60E − 12	5.45E − 14	8.33E − 13	1.06E − 15	1.77E − 14
Y-87a	8.00E − 14	3.11E − 13	2.51E − 14	1.31E − 13	4.89E − 16	7.83E − 15
Y-88a	7.98E − 14	1.21E − 12	2.51E − 14	5.45E − 13	4.88E − 16	3.63E − 14
Yb-169	3.18E − 13	1.67E − 12	1.00E − 13	5.54E − 13	1.95E − 15	1.58E − 14
Zn-62	7.49E − 14	6.70E − 13	2.35E − 14	2.44E − 13	4.58E − 16	9.97E − 15
Zn-65	6.80E − 14	3.35E − 13	2.14E − 14	1.44E − 13	4.16E − 16	8.77E − 15

* Radiations emitted by radioactive daughters are not included in the calculations.

Table 2

Ratio of equivalent dose and mean absorbed dose per unit cumulated activity distributed in different human organs from Auger electron emitters

Radionuclide	Human testes					Human liver				
	$S_{T \leftarrow T}$ Gy/Bq s	50% in DNA		100% in DNA		$S_{T \leftarrow T}$ Gy/Bq s	50% in DNA		100% in DNA	
		$S^H_{T \leftarrow T}$ Sv/Bq s	$\frac{S^H_{T \leftarrow T}}{S_{T \leftarrow T}}$ $\frac{Sv}{Gy}$	$S^H_{T \leftarrow T}$ Sv/Bq s	$\frac{S^H_{T \leftarrow T}}{S_{T \leftarrow T}}$ $\frac{Sv}{Gy}$		$S^H_{T \leftarrow T}$ Sv/Bq s	$\frac{S^H_{T \leftarrow T}}{S_{T \leftarrow T}}$ $\frac{Sv}{Gy}$	$S^H_{T \leftarrow T}$ Sv/Bq s	$\frac{S^H_{T \leftarrow T}}{S_{T \leftarrow T}}$ $\frac{Sv}{Gy}$
Ga-67	2.10E − 13	4.89E − 13	2.3	7.68E − 13	3.7	6.01E − 15	1.14E − 14	1.9	1.69E − 14	2.8
I-123	1.93E − 13	5.19E − 13	2.7	8.44E − 13	4.4	6.41E − 15	1.27E − 14	2.0	1.91E − 14	3.0
I-125	1.44E − 13	6.78E − 13	4.7	1.21E − 12	8.4	4.09E − 15	1.45E − 14	3.5	2.49E − 14	6.1
In-111	2.79E − 13	5.83E − 13	2.1	8.88E − 13	3.2	1.08E − 14	1.68E − 14	1.6	2.27E − 14	2.1
Pd-103	5.92E − 14	3.13E − 13	5.3	5.68E − 13	9.6	1.53E − 15	6.47E − 15	4.2	1.14E − 14	7.5
Tc-99m	1.03E − 13	1.47E − 13	1.4	1.92E − 13	1.9	3.69E − 15	4.55E − 15	1.2	5.41E − 15	1.5
Tl-201	2.32E − 13	8.37E − 13	3.6	1.44E − 12	6.2	5.96E − 15	1.77E − 14	3.0	2.95E − 14	5.0

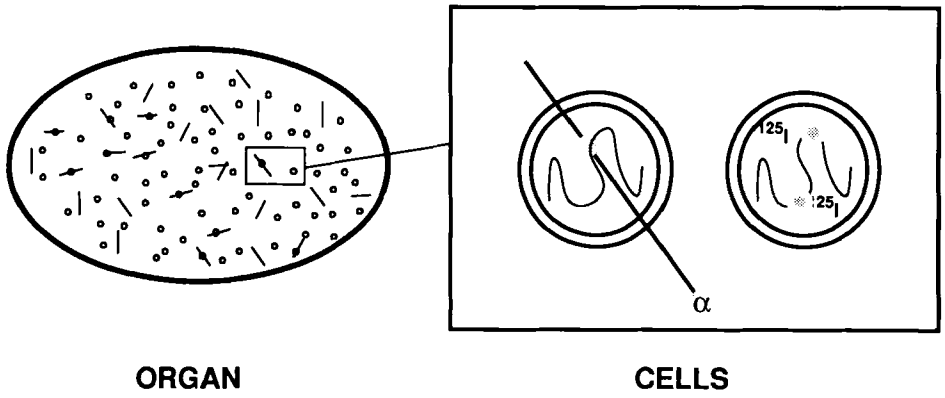

Fig. 1. a) Alpha particle tracks in an organ. The straight lines represent alpha particle tracks, whereas the circles represent cells within the organ. The deposition of energy is highly nonuniform across the organ at mean absorbed doses that are relevant for stochastic effects. b) Enlargement of cells. An alpha particle passes through the cell on the left and undergoes interactions with the DNA. For a mean absorbed dose of 0.01 Gy there is an average of one interaction with the DNA in each cell. There will be more interactions in some cells and none in others. Similarly, the cell on the right illustrates the average of two interactions (decays) in each cell that are produced by ^{125}I for the same mean absorbed dose. Some cells will have more ^{125}I decays and some cells will have none. In both cases, the energy deposition at the organ, cellular, and DNA level is highly nonuniform.

should be addressed. In doing so, it is instructive to review and compare the energy deposition patterns of Auger electron and alpha particle emitters, keeping in mind that the ICRP presently uses the mean absorbed dose to calculate the equivalent dose for alpha particle emitters. The energy density in the immediate vicinity of a decay site (<10 nm) of an Auger electron emitter is extremely high and falls off sharply as one moves away from the decay site (2). In contrast, alpha particles deposit their energy along a track with increasing energy density as the particle slows down. Despite these differences in energy deposition patterns, the observed biological effects for a given absorbed dose are about the same for alpha and Auger electron emitters (7, 8, 22). Consider a tissue that receives a mean absorbed dose of 0.01 Gy (stochastic range) from either ^{210}Po which emits one 5.3 MeV alpha particle per decay, or ^{125}IUdR which releases a total electron energy of about 20 keV per decay. Hence, about 1.2×10^7 decays of ^{210}Po and 3.1×10^9 decays of ^{125}I are required to deliver 0.01 Gy to one gram of tissue (6.24×10^7 MeV/g). Given that a gram of tissue contains about 1.4×10^9 cells of diameter 10 μm in close packed geometry, there is only about one ^{210}Po decay per 100 cells. Recognizing that the 5.3 MeV alpha particle can traverse through about five cells, an alpha particle will hit one cell out of every 20 cells (Fig. 1a). In contrast, there are about two ^{125}I decays per cell on the average. Hence, for mean absorbed doses that are relevant for stochastic effects, the energy deposition in tissue is highly non-uniform for alpha as well as Auger electron emitters. A similar analysis can be performed at the cellular and DNA level (Fig. 1b). Barendsen (23) has suggested that a complete traversal (i.e. maximum chord-length) by an alpha particle through a cell nucleus undergoes about 60 interactions with the DNA. As indicated above, a 5.3 MeV alpha particle will travel about 5 cell diameters. However, given the packing density of the cells (0.74 for close packed geometry), and the fact that the cell nucleus typically occupies only about one half of the cell volume, a 5.3 MeV alpha particle will only pass through the equivalent of about two complete nuclear diameters. (~ 12 μm). Hence, each ^{210}Po decay will result in about 100 traversals through the DNA per 100 cells, or about one traversal through the DNA per cell on the average. In comparison, there are about two ^{125}I decays in the DNA per cell on the average. Given that the track structure of an alpha particle traversal through the DNA and its subsequent radical chemistry is similar to that for an ^{125}I decay (24), this analysis suggests that the energy deposition is equally non-uniform at the cellular and DNA level for both alpha and Auger electron emitters. Considering that ICRP 60 recommends calculating the equivalent dose for alpha emitters by simply taking the product of the mean absorbed dose and the radiation weighting factor of 20 (15), it is reasonable to take a similar approach for Auger electron emitters given that their energy deposition characteristics and biological effects are similar to those of alpha particle emitters.

In this work, the mean absorbed doses per unit cumulated activity presented in Table 1 for numerous Auger electron emitters are provided to assist in calculating the equivalent dose when these radionuclides are distributed in human ovaries, testes, and liver. Following the AAPM recommendations, the equivalent dose per unit cumulated activity was calculated for some commonly used Auger electron emitters (Table 2). These calculations show that the equivalent dose per unit cumulated activity in the testes can be as much as ten times (^{103}Pd) the mean absorbed dose per unit cumulated activity in the testes when 100% of the activity is bound to DNA. The data in Table 2 also show that the equivalent dose is highly dependent on the

fraction of activity bound to DNA, illustrating the importance of subcellular distribution of Auger electron emitters in assessing the equivalent dose.

It should be noted that Auger electron emitters that are localized in the nucleus and not bound to DNA can also produce high-LET type effects, although to a lesser degree (i.e. RBE ~4) (5, 13, 14, 22, 25–29). Therefore, despite the somewhat lower RBE values observed in these instances, it may be prudent to take the same approach in calculating the equivalent dose for Auger electron emitting radiochemicals that localize in the nucleus (16, 17). As more experimental data becomes available on the stochastic effects of Auger electron emitting radiochemicals, the methods to calculate the equivalent dose may be refined.

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Appendix

Example on the Use of Tabulated Values of $\sum_{R_{Auger}} S_{T \leftarrow T,R_{Auger}}$ and $\sum_{R_{other}} S_{T \leftarrow T,R_{other}}$:

Calculation of mean equivalent dose to the testes

Problem. A male patient who is undergoing a cardiac imaging procedure is intravenously injected with 92.5 MBq (2.5 mCi) of ^{201}Tl-Thallous chloride. Assume that the non-testicular activity is distributed uniformly throughout the body. Also assume that 50% of the testicular activity is associated with the DNA ($f_0 = 0.5$, this assumption is justified by the RBE of ~ 3 obtained for ^{201}Tl in mouse testes (26)). Calculate the mean equivalent dose to the testes using a radiation weighting factor $w_{R_{Auger}} = 20$. Compare this value to the mean absorbed dose.

Solution. From Rao et al. (30), the cumulated activity in the body and testes are 3.0×10^{11} and 1.37×10^{9} Bq s per MBq and of injected activity respectively. Hence, for a 92.5 MBq injection, $\tilde{A}_{Body}$ and $\tilde{A}_{Testes}$ are 2.78×10^{13} and 1.27×10^{11} Bq s respectively. From Snyder et al. (19), $S_{Testes \leftarrow Body} = 1.73 \times 10^{-16}$ Gy/Bq s. Hence, the mean equivalent dose to the testes from body activity is

$$\sum_{NT} H_{Testes \leftarrow NT} = \tilde{A}_{Body} S^{H}_{Testes \leftarrow Body} = \tilde{A}_{Body} S_{Testes \leftarrow Body} w_R$$
$$= (2.78 \times 10^{13}\ \text{Bq s}) \left(1.73 \times 10^{-16} \frac{\text{Gy}}{\text{Bq s}}\right)(1)$$
$$= 4.8 \times 10^{-3}\text{Sv}$$

From Table 1, one obtains $\sum_{R_{Auger}} S_{Testes \leftarrow Testes,R_{Auger}} = 6.36 \times 10^{-14}$ Gy/Bq s and $\sum_{R_{other}} S_{Testes \leftarrow Testes,R_{other}} = 1.69 \times 10^{-13}$ Gy/Bq s. Hence, the mean equivalent dose to the testes from testicular activity is

$$H_{Testes \leftarrow Testes} = \tilde{A}_{Testes} S^{H}_{Testes \leftarrow Testes}$$
$$= \tilde{A}_{Testes} \left\{ [1 + f_0(w_{R_{Auger}} - 1)] \sum_{R_{Auger}} S_{T \leftarrow T,R_{Auger}} + \sum_{R_{other}} w_{R_{other}} S_{T \leftarrow T,R_{other}} \right\}$$
$$= (1.27 \times 10^{11}\ \text{Bq s}) \left\{ [1 + 0.5(20 - 1)] \times \left(6.36 \times 10^{-14} \frac{\text{Gy}}{\text{Bq s}}\right) + (1)\left(1.69 \times 10^{-13} \frac{\text{Gy}}{\text{Bq s}}\right) \right\}$$
$$= 0.106\ \text{Sv}.$$

Finally, the mean equivalent dose to the testes is therefore $H_{Testes} = H_{Testes \leftarrow Body} + H_{Testes \leftarrow Testes} = 0.11$ Sv.

The mean absorbed dose is given by $D_{Testes} = D_{Testes \leftarrow Body} + D_{Testes \leftarrow Testes}$.

$$D_{Testes \leftarrow Testes} = \tilde{A}_{Testes} S_{Testes \leftarrow Testes}$$
$$= (1.27 \times 10^{11}\ \text{Bq s}) \left(6.36 \times 10^{-14} \frac{\text{Gy}}{\text{Bq s}} + 1.69 \times 10^{-13} \frac{\text{Gy}}{\text{Bq s}}\right) = 0.03\ \text{Gy}$$

$$D_{Testes \leftarrow Body} = \tilde{A}_{Body} S_{Testes \leftarrow Body}$$
$$= (2.78 \times 10^{13}\ \text{Bq s}) \left(1.73 \times 10^{-16} \frac{\text{Gy}}{\text{Bq s}}\right)$$
$$= 4.8 \times 10^{-3}\text{Gy}$$

Hence, the ratio of the equivalent dose per unit cumulated activity to the mean absorbed dose per unit cumulated activity is 0.11 Sv/(0.035 Gy) = 3.1 Sv/Gy.