

Cellular Dosimetry: Absorbed Fractions for Monoenergetic Electron and Alpha Particle Sources and S-Values for Radionuclides Uniformly Distributed in Different Cell Compartments

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The importance of cellular dosimetry in both diagnostic and therapeutic nuclear medicine is becoming increasingly recognized. **Methods:** Experimental range-energy relations for electrons and alpha particles, along with derived geometric reduction factors, are used to calculate cellular absorbed fractions for these radiations. The resulting absorbed fractions are employed to calculate cellular S-values for several radionuclides. **Results:** Cellular absorbed fractions for monoenergetic electron sources with energies ranging from 0.1 keV to 1 MeV, distributed uniformly in the source region, are calculated for several target-source combinations including cell-cell, cell-cell surface, nucleus-nucleus, nucleus-cytoplasm and nucleus-cell surface. Similar data are also provided for monoenergetic alpha particle sources with energies ranging from 3 to 10 MeV. S-values are also conveniently tabulated for ^{32}P , ^{35}S , ^{86}Rb , ^{88}Sr , ^{90}Y , ^{91}Y , $^{114\text{m}}\text{In}$, ^{131}I , Auger-electron-emitters ^{51}Cr , ^{67}Ga , $^{99\text{m}}\text{Tc}$, ^{111}In , ^{123}I , ^{125}I , ^{201}Tl , ^{203}Pb and the alpha emitter ^{210}Po . In addition, S-values are given for radionuclides in the ^{212}Pb decay series, including ^{212}Pb , ^{212}Bi and ^{212}Po . Both absorbed fractions and S-values are supplied for a number of different size cells and cell nuclei. **Conclusions:** With the absorbed fractions and S-values in hand, along with experimentally determined information on the biokinetics and subcellular distribution of the radionuclides, the cellular self-absorbed dose can be conveniently calculated.

Key Words: cellular dosimetry; absorbed fractions; S-values; electrons; alpha particles

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The use of incorporated radionuclides to fight cancer takes on new dimensions as the current therapeutic

techniques are improved upon to enhance efficacy and improve safety. Such improvements require more reliable dose calculations to assist in treatment planning, prediction of therapeutic outcome and assessment of risk to normal cells. The standard dosimetric approach is to calculate mean absorbed doses to normal organs and bulk tumor using the wealth of information available in the MIRD publications (1-4). However, in some instances it is more relevant to determine the absorbed dose received by individual cells as opposed to the mean organ/tumor dose (5-9), particularly when radionuclides concentrate in cells and/or emit radiations whose ranges are comparable to cell dimensions (10-12). For example, it is of interest to know the absorbed dose to the bone marrow cells, blood components and isolated cells. However, although limited general data on energy deposition in cells containing radioactivity are available (11,13), cellular absorbed fractions or S-values (absorbed dose per unit cumulated activity) (1) required to calculate cell doses are not readily available in the literature.

In the present work, cellular absorbed fractions ϕ are calculated for sources of monoenergetic electrons and alpha particles distributed uniformly in various cell compartments. The cells are assumed to be spherically symmetric with the radii of the cell and cell nucleus ranging from 2 to 10 μm . Different target-source combinations including cell-cell, cell-cell surface, nucleus-nucleus, nucleus-cytoplasm, and nucleus-cell surface, are considered. Similarly, S-values are tabulated for cells containing various radionuclides with very different radiation characteristics. With knowledge of the biokinetics and subcellular distribution of the radiopharmaceutical, these data greatly simplify calculation of absorbed doses at the cellular level.

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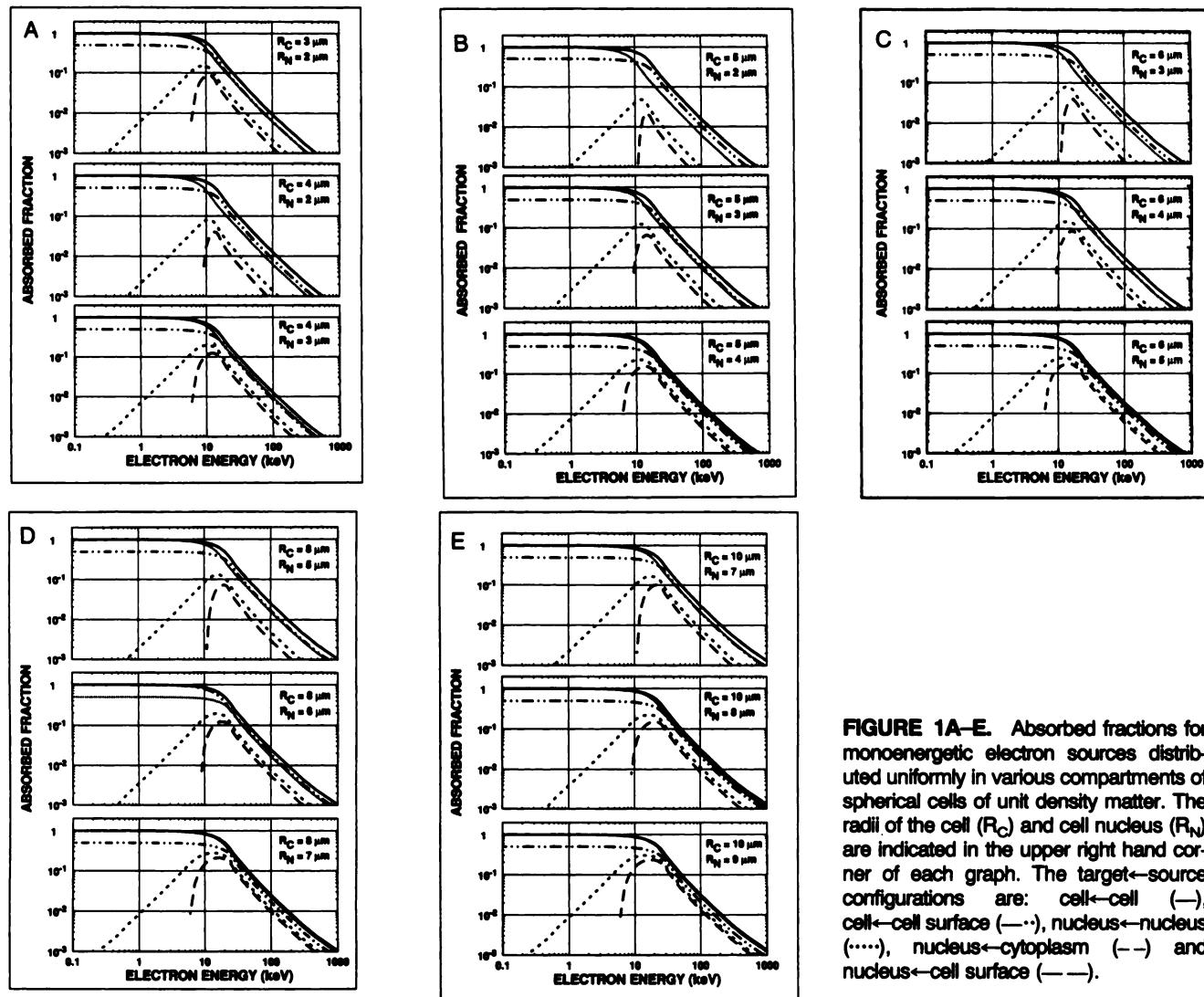


FIGURE 1A–E. Absorbed fractions for monoenergetic electron sources distributed uniformly in various compartments of spherical cells of unit density matter. The radii of the cell (R_C) and cell nucleus (R_N) are indicated in the upper right hand corner of each graph. The target–source configurations are: cell–cell (—), cell–cell surface (—·—), nucleus–nucleus (···), nucleus–cytoplasm (—·—) and nucleus–cell surface (——).

METHODS

Radionuclides

Radionuclides that emit energetic beta particles are considered to be prime candidates for treating bulk tumors (14). Accordingly, S-values are calculated for several beta-emitting radionuclides (^{32}P , ^{35}S , ^{86}Rb , ^{89}Sr , ^{90}Y , ^{91}Y , $^{114\text{m}}\text{In}$, ^{131}I). Recently, there has been considerable interest in employing alpha emitters for radioimmunotherapy (15–17). Hence, calculations are also done for ^{210}Po , and the members of the ^{212}Pb decay series including ^{212}Pb , ^{212}Bi and ^{212}Po (^{208}Tl has not been included in view of its minor contribution to the total cellular dose). Also of interest are radionuclides commonly used in diagnostic nuclear medicine that decay by electron capture and/or internal conversion. These radionuclides emit many low-energy electrons known as Auger electrons (11,18) which have very short ranges and therefore deposit their energy in a highly localized fashion around the decay site (11). Consequently, the biological effects of Auger emitters are highly dependent on the subcellular distribution of the radio-

pharmaceutical (6,9,10,19,20). Furthermore, it has been shown that when Auger emitters localize in the cell nucleus and bind to DNA, their lethal effects can be as severe as alpha particles of high linear energy transfer (LET) (21–23). Hence, in view of the extensive use of Auger emitters in diagnosis and growing interest to employ them in therapy (24–26), S-values are presented for several radionuclides in this class including ^{51}Cr , ^{67}Ga , $^{99\text{m}}\text{Tc}$, ^{111}In , ^{123}I , ^{125}I , ^{201}Tl and ^{203}Pb .

Radiation Spectra

The complete radiation spectra for alpha and beta emitters are taken from Weber et al. (27). However, for cellular dosimetry it is essential to use radiation spectra that reflect the continuous nature of the beta spectrum because cellular absorbed fractions for electrons are highly energy dependent (Fig. 1). More specifically, our calculations indicate that use of the average beta particle energy instead of the beta spectrum leads to errors of about 20% in the S-values. Browne et al. (28) have conveniently binned the beta particle spectra in a logarithmic manner with respect to energy for all

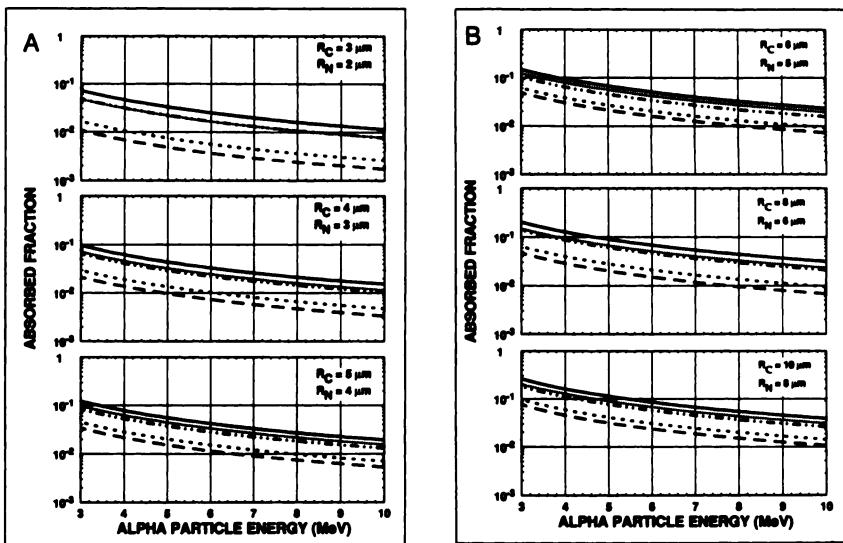


FIGURE 2A–B. Absorbed fractions for monoenergetic alpha particle sources distributed uniformly in various compartments of spherical cells of unit density matter. The radii of the cell (R_C) and cell nucleus (R_N) are indicated in the upper right hand corner of each graph. The target–source configurations are: cell–cell (—), cell–cell surface (—·—), nucleus–nucleus (···), nucleus–cytoplasm (—·—) and nucleus–cell surface (—·—).

radionuclides. Hence, beta particle components of the spectra of Weber et al. (27) are replaced with these. For the Auger electron emitters, the radiation spectra are taken from the recent American Association of Physicists in Medicine Task Group report (18).

Source and Target Volumes

Typical cell dimensions encountered in practice vary anywhere from 6 μm to 20 μm in diameter with the corresponding diameters of the cell nucleus ranging from 4 μm to 18 μm (29,30). Therefore for the sake of convenience, absorbed fractions for both monoenergetic electrons and alpha particles and S-values for various radionuclides are calculated for spherical cells of different radii (see Appendix for details). The cellular radioactivity is assumed to be uniformly distributed in one of the following regions of the cell: throughout the cell (C), cytoplasm (Cy), cell surface (CS) or cell nucleus (N). Two different target regions are considered; the entire cell and the cell nucleus. It is generally recognized that the radiosensitive sites are associated with DNA in the cell nucleus, although their specific location is not well known. Therefore, the absorbed dose to the cell nucleus, as opposed to the entire cell, is perhaps more meaningful in this context.

Cellular Absorbed Fraction and S-Value Calculations

Theoretical details of the calculations are presented in the Appendix. Absorbed fractions are calculated for monoenergetic electrons with energies ranging from 0.1 keV to 1 MeV, whereas the alpha particle energy is varied from 3 MeV to 10 MeV. S-values are calculated for the radionuclides listed above. It should be noted that the contributions of photon radiations to the S-values have been ignored because they are negligible compared to the contributions of the particulate radiations.

RESULTS AND DISCUSSION

The calculated electron absorbed fractions are plotted in Figure 1 as a function of initial particle energy, for different cell sizes and configurations of source and target volumes.

Similarly, alpha particle absorbed fractions are shown in Figure 2 for a limited number of cell size configurations. These absorbed fractions may be used to calculate the mean absorbed dose to the cell or cell nucleus from radionuclides distributed in various cell compartments provided that the radiation spectra of the radionuclides are known. This is a formidable task for radionuclides with a large number of emitted radiations, hence S-values are provided for a number of radionuclides of interest in Tables 1–17. It should be noted that the tabulated S-values are in SI units (Gy/Bq · s). For those more familiar with traditional units, the SI values may be divided by a conversion factor of 7.508E-05 to obtain S-values in units of rad/pCi · h. Care should be taken using the S-values for the radionuclides in the ^{212}Pb decay series. The S-value for the short-lived daughter ^{212}Po must be multiplied by its branching ratio which is given in Weber et al. (27). Conversely, the $^{114\text{m}}\text{In}$ daughter radiations have been included in the $^{114\text{m}}\text{In}$ S-value.

In conclusion, the development of safe and effective radiopharmaceuticals for diagnosis and therapy depends in part on our ability to calculate and verify absorbed doses to organs as well as to critical cells within the organ and to targeted cancer cells. The absorbed fractions and tabulated S-values presented in this work may be used to conveniently calculate cellular self-absorbed doses provided that the appropriate biological data is available including the biokinetics and subcellular distribution of the radionuclide. Such calculations may play an important role in evaluating the relative merits of different radionuclides and pharmaceuticals as we attempt to improve the safety and efficacy of radiopharmaceuticals used in diagnostic and therapeutic nuclear medicine.

TABLE 1
S-values for Intracellular ^{32}P and $^{90}\text{Y}^*$

R_C (μm)	R_N (μm)	C←C (Gy/Bq · s)	C←CS (Gy/Bq · s)	N←N (Gy/Bq · s)	N←Cy (Gy/Bq · s)	N←CS (Gy/Bq · s)
3	2	6.87E-04	4.58E-04	1.56E-03	5.23E-04	3.34E-04
3	1	6.87E-04	4.58E-04	6.32E-03	6.87E-04	3.07E-04
4	3	3.86E-04	2.56E-04	6.87E-04	2.78E-04	1.96E-04
4	2	3.86E-04	2.56E-04	1.56E-03	3.34E-04	1.80E-04
5	4	2.46E-04	1.63E-04	3.86E-04	1.72E-04	1.28E-04
5	3	2.46E-04	1.63E-04	6.87E-04	1.98E-04	1.18E-04
5	2	2.46E-04	1.63E-04	1.56E-03	2.33E-04	1.13E-04
6	5	1.70E-04	1.13E-04	2.46E-04	1.17E-04	9.07E-05
6	4	1.70E-04	1.13E-04	3.86E-04	1.30E-04	8.35E-05
6	3	1.70E-04	1.13E-04	6.87E-04	1.49E-04	7.94E-05
7	6	1.25E-04	8.29E-05	1.70E-04	8.44E-05	6.76E-05
7	5	1.25E-04	8.29E-05	2.46E-04	9.20E-05	6.23E-05
7	4	1.25E-04	8.29E-05	3.86E-04	1.02E-04	5.91E-05
8	7	9.53E-05	6.33E-05	1.25E-04	6.40E-05	5.25E-05
8	6	9.53E-05	6.33E-05	1.70E-04	6.86E-05	4.84E-05
8	5	9.53E-05	6.33E-05	2.46E-04	7.50E-05	4.59E-05
9	8	7.52E-05	5.00E-05	9.53E-05	5.02E-05	4.19E-05
9	7	7.52E-05	5.00E-05	1.25E-04	5.32E-05	3.88E-05
9	6	7.52E-05	5.00E-05	1.70E-04	5.73E-05	3.67E-05
10	9	6.08E-05	4.05E-05	7.52E-05	4.05E-05	3.44E-05
10	8	6.08E-05	4.05E-05	9.53E-05	4.25E-05	3.18E-05
10	7	6.08E-05	4.05E-05	1.25E-04	4.53E-05	3.02E-05

*The S-values for ^{32}P and ^{90}Y are within 2%.

TABLE 2
S-values for Intracellular ^{35}S

R_C (μm)	R_N (μm)	C←C (Gy/Bq · s)	C←CS (Gy/Bq · s)	N←N (Gy/Bq · s)	N←Cy (Gy/Bq · s)	N←CS (Gy/Bq · s)
3	2	3.14E-03	2.03E-03	7.56E-03	2.07E-03	1.23E-03
3	1	3.14E-03	2.03E-03	3.54E-02	2.71E-03	1.14E-03
4	3	1.70E-03	1.09E-03	3.14E-03	1.12E-03	7.56E-04
4	2	1.70E-03	1.09E-03	7.56E-03	1.32E-03	7.41E-04
5	4	1.05E-03	6.67E-04	1.70E-03	6.68E-04	4.76E-04
5	3	1.05E-03	6.67E-04	3.14E-03	7.82E-04	4.56E-04
5	2	1.05E-03	6.67E-04	7.56E-03	9.35E-04	4.66E-04
6	5	7.03E-04	4.45E-04	1.05E-03	4.36E-04	3.23E-04
6	4	7.03E-04	4.45E-04	1.70E-03	4.92E-04	3.01E-04
6	3	7.03E-04	4.45E-04	3.14E-03	5.79E-04	2.88E-04
7	6	5.00E-04	3.17E-04	7.03E-04	3.05E-04	2.34E-04
7	5	5.00E-04	3.17E-04	1.05E-03	3.34E-04	2.14E-04
7	4	5.00E-04	3.17E-04	1.70E-03	3.79E-04	1.99E-04
8	7	3.73E-04	2.37E-04	5.00E-04	2.26E-04	1.78E-04
8	6	3.73E-04	2.37E-04	7.03E-04	2.41E-04	1.62E-04
8	5	3.73E-04	2.37E-04	1.05E-03	2.66E-04	1.49E-04
9	8	2.89E-04	1.85E-04	3.73E-04	1.75E-04	1.41E-04
9	7	2.89E-04	1.85E-04	5.00E-04	1.83E-04	1.28E-04
9	6	2.89E-04	1.85E-04	7.03E-04	1.97E-04	1.17E-04
10	9	2.31E-04	1.49E-04	2.89E-04	1.41E-04	1.17E-04
10	8	2.31E-04	1.49E-04	3.73E-04	1.45E-04	1.06E-04
10	7	2.31E-04	1.49E-04	5.00E-04	1.53E-04	9.66E-05

TABLE 3
S-values for Intracellular ^{51}Cr

R_C (μm)	R_N (μm)	C \leftarrow C (Gy/Bq · s)	C \leftarrow CS (Gy/Bq · s)	N \leftarrow N (Gy/Bq · s)	N \leftarrow Cy (Gy/Bq · s)	N \leftarrow CS (Gy/Bq · s)
3	2	4.74E-03	2.44E-03	1.53E-02	9.18E-04	6.47E-08
3	1	4.74E-03	2.44E-03	1.05E-01	1.32E-03	5.96E-08
4	3	2.04E-03	1.04E-03	4.74E-03	3.15E-04	3.78E-08
4	2	2.04E-03	1.04E-03	1.53E-02	3.12E-04	3.46E-08
5	4	1.06E-03	5.39E-04	2.04E-03	1.44E-04	2.49E-08
5	3	1.06E-03	5.39E-04	4.74E-03	1.19E-04	2.28E-08
5	2	1.06E-03	5.39E-04	1.53E-02	1.49E-04	2.17E-08
6	5	6.19E-04	3.14E-04	1.06E-03	7.71E-05	1.76E-08
6	4	6.19E-04	3.14E-04	2.04E-03	5.77E-05	1.62E-08
6	3	6.19E-04	3.14E-04	4.74E-03	6.18E-05	1.54E-08
7	6	3.92E-04	1.99E-04	6.19E-04	4.60E-05	1.32E-08
7	5	3.92E-04	1.99E-04	1.06E-03	3.22E-05	1.21E-08
7	4	3.92E-04	1.99E-04	2.04E-03	3.14E-05	1.15E-08
8	7	2.64E-04	1.33E-04	3.92E-04	2.97E-05	1.02E-08
8	6	2.64E-04	1.33E-04	6.19E-04	1.98E-05	9.46E-09
8	5	2.64E-04	1.33E-04	1.06E-03	1.81E-05	8.98E-09
9	8	1.86E-04	9.39E-05	2.64E-04	2.02E-05	8.19E-09
9	7	1.86E-04	9.39E-05	3.92E-04	1.30E-05	7.58E-09
9	6	1.86E-04	9.39E-05	6.19E-04	1.14E-05	7.21E-09
10	9	1.36E-04	6.86E-05	1.86E-04	1.44E-05	6.70E-09
10	8	1.36E-04	6.86E-05	2.64E-04	9.00E-06	6.22E-09
10	7	1.36E-04	6.86E-05	3.92E-04	7.64E-06	5.92E-09

TABLE 4
S-values for Intracellular ^{67}Ga

R_C (μm)	R_N (μm)	C \leftarrow C (Gy/Bq · s)	C \leftarrow CS (Gy/Bq · s)	N \leftarrow N (Gy/Bq · s)	N \leftarrow Cy (Gy/Bq · s)	N \leftarrow CS (Gy/Bq · s)
3	2	7.61E-03	4.16E-03	2.25E-02	3.47E-03	1.31E-03
3	1	7.61E-03	4.16E-03	1.26E-01	5.05E-03	2.35E-04
4	3	3.45E-03	1.86E-03	7.61E-03	1.30E-03	5.14E-04
4	2	3.45E-03	1.86E-03	2.25E-02	1.45E-03	1.29E-04
5	4	1.86E-03	9.94E-04	3.45E-03	6.32E-04	2.64E-04
5	3	1.86E-03	9.94E-04	7.61E-03	6.12E-04	8.43E-05
5	2	1.86E-03	9.94E-04	2.25E-02	7.45E-04	7.90E-05
6	5	1.12E-03	5.96E-04	1.86E-03	3.59E-04	1.58E-04
6	4	1.12E-03	5.96E-04	3.45E-03	3.22E-04	5.97E-05
6	3	1.12E-03	5.96E-04	7.61E-03	3.50E-04	5.62E-05
7	6	7.25E-04	3.87E-04	1.12E-03	2.26E-04	1.05E-04
7	5	7.25E-04	3.87E-04	1.86E-03	1.94E-04	4.48E-05
7	4	7.25E-04	3.87E-04	3.45E-03	1.98E-04	4.22E-05
8	7	4.99E-04	2.67E-04	7.25E-04	1.53E-04	7.41E-05
8	6	4.99E-04	2.67E-04	1.12E-03	1.28E-04	3.49E-05
8	5	4.99E-04	2.67E-04	1.86E-03	1.26E-04	3.30E-05
9	8	3.59E-04	1.92E-04	4.99E-04	1.09E-04	5.51E-05
9	7	3.59E-04	1.92E-04	7.25E-04	9.03E-05	2.80E-05
9	6	3.59E-04	1.92E-04	1.12E-03	8.88E-05	2.65E-05
10	9	2.68E-04	1.43E-04	3.59E-04	8.12E-05	4.26E-05
10	8	2.68E-04	1.43E-04	4.99E-04	6.67E-05	2.30E-05
10	7	2.68E-04	1.43E-04	7.25E-04	6.32E-05	2.18E-05

TABLE 5
S-values for Intracellular ^{86}Rb , ^{89}Sr , $^{91}\text{Y}^*$

R_C (μm)	R_N (μm)	C←C (Gy/Bq · s)	C←CS (Gy/Bq · s)	N←N (Gy/Bq · s)	N←Cy (Gy/Bq · s)	N←CS (Gy/Bq · s)
3	2	7.97E-04	5.29E-04	1.82E-03	5.95E-04	3.78E-04
3	1	7.97E-04	5.29E-04	7.54E-03	7.81E-04	3.48E-04
4	3	4.45E-04	2.95E-04	7.97E-04	3.17E-04	2.23E-04
4	2	4.45E-04	2.95E-04	1.82E-03	3.81E-04	2.07E-04
5	4	2.83E-04	1.87E-04	4.45E-04	1.95E-04	1.45E-04
5	3	2.83E-04	1.87E-04	7.97E-04	2.25E-04	1.34E-04
5	2	2.83E-04	1.87E-04	1.82E-03	2.67E-04	1.30E-04
6	5	1.95E-04	1.29E-04	2.83E-04	1.32E-04	1.02E-04
6	4	1.95E-04	1.29E-04	4.45E-04	1.48E-04	9.42E-05
6	3	1.95E-04	1.29E-04	7.97E-04	1.69E-04	8.97E-05
7	6	1.42E-04	9.41E-05	1.95E-04	9.53E-05	7.61E-05
7	5	1.42E-04	9.41E-05	2.83E-04	1.04E-04	7.00E-05
7	4	1.42E-04	9.41E-05	4.45E-04	1.16E-04	6.62E-05
8	7	1.08E-04	7.18E-05	1.42E-04	7.21E-05	5.89E-05
8	6	1.08E-04	7.18E-05	1.95E-04	7.72E-05	5.42E-05
8	5	1.08E-04	7.18E-05	2.83E-04	8.45E-05	5.12E-05
9	8	8.54E-05	5.66E-05	1.08E-04	5.65E-05	4.70E-05
9	7	8.54E-05	5.66E-05	1.42E-04	5.98E-05	4.34E-05
9	6	8.54E-05	5.66E-05	1.95E-04	6.44E-05	4.10E-05
10	9	6.90E-05	4.59E-05	8.54E-05	4.56E-05	3.86E-05
10	8	6.90E-05	4.59E-05	1.08E-04	4.77E-05	3.57E-05
10	7	6.90E-05	4.59E-05	1.42E-04	5.08E-05	3.37E-05

*The S-values for ^{86}Rb , ^{89}Sr and ^{91}Y are within 2%.

TABLE 6
S-values for Intracellular ^{99m}Tc

R_C (μm)	R_N (μm)	C←C (Gy/Bq · s)	C←CS (Gy/Bq · s)	N←N (Gy/Bq · s)	N←Cy (Gy/Bq · s)	N←CS (Gy/Bq · s)
3	2	3.58E-03	1.85E-03	1.17E-02	3.33E-04	1.19E-04
3	1	3.58E-03	1.85E-03	8.85E-02	4.56E-04	1.10E-04
4	3	1.55E-03	8.05E-04	3.58E-03	1.54E-04	7.47E-05
4	2	1.55E-03	8.05E-04	1.17E-02	1.72E-04	7.23E-05
5	4	8.16E-04	4.23E-04	1.55E-03	8.68E-05	4.76E-05
5	3	8.16E-04	4.23E-04	3.58E-03	9.44E-05	4.63E-05
5	2	8.16E-04	4.23E-04	1.17E-02	1.13E-04	4.76E-05
6	5	4.82E-04	2.50E-04	8.16E-04	5.38E-05	3.17E-05
6	4	4.82E-04	2.50E-04	1.55E-03	5.72E-05	3.00E-05
6	3	4.82E-04	2.50E-04	3.58E-03	6.67E-05	2.96E-05
7	6	3.09E-04	1.61E-04	4.82E-04	3.60E-05	2.23E-05
7	5	3.09E-04	1.61E-04	8.16E-04	3.72E-05	2.06E-05
7	4	3.09E-04	1.61E-04	1.55E-03	4.21E-05	1.95E-05
8	7	2.11E-04	1.10E-04	3.09E-04	2.55E-05	1.64E-05
8	6	2.11E-04	1.10E-04	4.82E-04	2.58E-05	1.50E-05
8	5	2.11E-04	1.10E-04	8.16E-04	2.83E-05	1.38E-05
9	8	1.50E-04	7.83E-05	2.11E-04	1.89E-05	1.26E-05
9	7	1.50E-04	7.83E-05	3.09E-04	1.88E-05	1.13E-05
9	6	1.50E-04	7.83E-05	4.82E-04	2.01E-05	1.03E-05
10	9	1.11E-04	5.80E-05	1.50E-04	1.45E-05	9.93E-06
10	8	1.11E-04	5.80E-05	2.11E-04	1.42E-05	8.90E-06
10	7	1.11E-04	5.80E-05	3.09E-04	1.50E-05	8.05E-06

TABLE 7
S-values for intracellular ^{111}In

R_C (μm)	R_N (μm)	C \leftarrow C (Gy/Bq · s)	C \leftarrow CS (Gy/Bq · s)	N \leftarrow N (Gy/Bq · s)	N \leftarrow Cy (Gy/Bq · s)	N \leftarrow CS (Gy/Bq · s)
3	2	6.03E-03	3.20E-03	1.91E-02	1.03E-03	4.25E-04
3	1	6.03E-03	3.20E-03	1.38E-01	1.40E-03	3.95E-04
4	3	2.70E-03	1.45E-03	6.03E-03	4.92E-04	2.65E-04
4	2	2.70E-03	1.45E-03	1.91E-02	5.57E-04	2.45E-04
5	4	1.47E-03	8.03E-04	2.70E-03	3.03E-04	1.94E-04
5	3	1.47E-03	8.03E-04	6.03E-03	3.18E-04	1.78E-04
5	2	1.47E-03	8.03E-04	1.91E-02	3.70E-04	1.69E-04
6	5	8.96E-04	4.94E-04	1.47E-03	2.06E-04	1.41E-04
6	4	8.96E-04	4.94E-04	2.70E-03	2.19E-04	1.38E-04
6	3	8.96E-04	4.94E-04	6.03E-03	2.40E-04	1.40E-04
7	6	5.91E-04	3.25E-04	8.96E-04	1.44E-04	1.02E-04
7	5	5.91E-04	3.25E-04	1.47E-03	1.55E-04	1.00E-04
7	4	5.91E-04	3.25E-04	2.70E-03	1.73E-04	1.02E-04
8	7	4.12E-04	2.25E-04	5.91E-04	1.03E-04	7.44E-05
8	6	4.12E-04	2.25E-04	8.96E-04	1.10E-04	7.24E-05
8	5	4.12E-04	2.25E-04	1.47E-03	1.24E-04	7.29E-05
9	8	2.99E-04	1.63E-04	4.12E-04	7.56E-05	5.56E-05
9	7	2.99E-04	1.63E-04	5.91E-04	8.02E-05	5.32E-05
9	6	2.99E-04	1.63E-04	8.96E-04	8.96E-05	5.23E-05
10	9	2.24E-04	1.21E-04	2.99E-04	5.71E-05	4.25E-05
10	8	2.24E-04	1.21E-04	4.12E-04	5.97E-05	4.00E-05
10	7	2.24E-04	1.21E-04	5.91E-04	6.57E-05	3.85E-05

TABLE 8
S-values for intracellular $^{114\text{m}}\text{In}$

R_C (μm)	R_N (μm)	C \leftarrow C (Gy/Bq · s)	C \leftarrow CS (Gy/Bq · s)	N \leftarrow N (Gy/Bq · s)	N \leftarrow Cy (Gy/Bq · s)	N \leftarrow CS (Gy/Bq · s)
3	2	5.27E-03	2.94E-03	1.57E-02	1.57E-03	8.30E-04
3	1	5.27E-03	2.94E-03	1.05E-01	2.11E-03	7.65E-04
4	3	2.48E-03	1.41E-03	5.27E-03	7.88E-04	4.91E-04
4	2	2.48E-03	1.41E-03	1.57E-02	9.26E-04	4.52E-04
5	4	1.40E-03	8.09E-04	2.48E-03	4.78E-04	3.29E-04
5	3	1.40E-03	8.09E-04	5.27E-03	5.32E-04	3.02E-04
5	2	1.40E-03	8.09E-04	1.57E-02	6.28E-04	2.89E-04
6	5	8.85E-04	5.18E-04	1.40E-03	3.23E-04	2.36E-04
6	4	8.85E-04	5.18E-04	2.48E-03	3.51E-04	2.20E-04
6	3	8.85E-04	5.18E-04	5.27E-03	3.96E-04	2.10E-04
7	6	6.04E-04	3.56E-04	8.85E-04	2.32E-04	1.76E-04
7	5	6.04E-04	3.56E-04	1.40E-03	2.48E-04	1.64E-04
7	4	6.04E-04	3.56E-04	2.48E-03	2.75E-04	1.58E-04
8	7	4.35E-04	2.57E-04	6.04E-04	1.73E-04	1.35E-04
8	6	4.35E-04	2.57E-04	8.85E-04	1.84E-04	1.26E-04
8	5	4.35E-04	2.57E-04	1.40E-03	2.01E-04	1.22E-04
9	8	3.26E-04	1.94E-04	4.35E-04	1.34E-04	1.07E-04
9	7	3.26E-04	1.94E-04	6.04E-04	1.40E-04	9.95E-05
9	6	3.26E-04	1.94E-04	8.85E-04	1.52E-04	9.54E-05
10	9	2.52E-04	1.51E-04	3.26E-04	1.06E-04	8.61E-05
10	8	2.52E-04	1.51E-04	4.35E-04	1.10E-04	8.03E-05
10	7	2.52E-04	1.51E-04	6.04E-04	1.18E-04	7.67E-05

TABLE 9
S-values for Intracellular ^{123}I

R_C (μm)	R_N (μm)	C \leftarrow C (Gy/Bq · s)	C \leftarrow CS (Gy/Bq · s)	N \leftarrow N (Gy/Bq · s)	N \leftarrow Cy (Gy/Bq · s)	N \leftarrow CS (Gy/Bq · s)
3	2	6.64E-03	3.48E-03	2.12E-02	1.10E-03	3.39E-04
3	1	6.64E-03	3.48E-03	1.53E-01	1.52E-03	3.14E-04
4	3	2.93E-03	1.55E-03	6.64E-03	4.81E-04	2.05E-04
4	2	2.93E-03	1.55E-03	2.12E-02	5.34E-04	1.89E-04
5	4	1.56E-03	8.36E-04	2.93E-03	2.72E-04	1.40E-04
5	3	1.56E-03	8.36E-04	6.64E-03	2.81E-04	1.30E-04
5	2	1.56E-03	8.36E-04	2.12E-02	3.34E-04	1.24E-04
6	5	9.44E-04	5.12E-04	1.56E-03	1.79E-04	1.07E-04
6	4	9.44E-04	5.12E-04	2.93E-03	1.78E-04	9.80E-05
6	3	9.44E-04	5.12E-04	6.64E-03	1.98E-04	9.34E-05
7	6	6.19E-04	3.38E-04	9.44E-04	1.29E-04	8.36E-05
7	5	6.19E-04	3.38E-04	1.56E-03	1.28E-04	8.00E-05
7	4	6.19E-04	3.38E-04	2.93E-03	1.36E-04	7.69E-05
8	7	4.31E-04	2.36E-04	6.19E-04	9.59E-05	6.53E-05
8	6	4.31E-04	2.36E-04	9.44E-04	9.65E-05	6.31E-05
8	5	4.31E-04	2.36E-04	1.56E-03	1.03E-04	6.28E-05
9	8	3.13E-04	1.72E-04	4.31E-04	7.29E-05	5.12E-05
9	7	3.13E-04	1.72E-04	6.19E-04	7.38E-05	4.98E-05
9	6	3.13E-04	1.72E-04	9.44E-04	7.93E-05	4.97E-05
10	9	2.35E-04	1.29E-04	3.13E-04	5.64E-05	4.05E-05
10	8	2.35E-04	1.29E-04	4.31E-04	5.72E-05	3.92E-05
10	7	2.35E-04	1.29E-04	6.19E-04	6.15E-05	3.90E-05

TABLE 10
S-values for Intracellular ^{125}I

R_C (μm)	R_N (μm)	C \leftarrow C (Gy/Bq · s)	C \leftarrow CS (Gy/Bq · s)	N \leftarrow N (Gy/Bq · s)	N \leftarrow Cy (Gy/Bq · s)	N \leftarrow CS (Gy/Bq · s)
3	2	1.50E-02	7.85E-03	4.79E-02	2.60E-03	6.28E-04
3	1	1.50E-02	7.85E-03	3.42E-01	3.63E-03	5.83E-04
4	3	6.60E-03	3.47E-03	1.50E-02	1.09E-03	3.80E-04
4	2	6.60E-03	3.47E-03	4.79E-02	1.18E-03	3.52E-04
5	4	3.51E-03	1.86E-03	6.60E-03	5.94E-04	2.62E-04
5	3	3.51E-03	1.86E-03	1.50E-02	5.96E-04	2.42E-04
5	2	3.51E-03	1.86E-03	4.79E-02	7.13E-04	2.32E-04
6	5	2.10E-03	1.13E-03	3.51E-03	3.80E-04	1.98E-04
6	4	2.10E-03	1.13E-03	6.60E-03	3.67E-04	1.83E-04
6	3	2.10E-03	1.13E-03	1.50E-02	4.07E-04	1.75E-04
7	6	1.37E-03	7.43E-04	2.10E-03	2.69E-04	1.56E-04
7	5	1.37E-03	7.43E-04	3.51E-03	2.58E-04	1.49E-04
7	4	1.37E-03	7.43E-04	6.60E-03	2.73E-04	1.43E-04
8	7	9.52E-04	5.17E-04	1.37E-03	1.98E-04	1.23E-04
8	6	9.52E-04	5.17E-04	2.10E-03	1.92E-04	1.18E-04
8	5	9.52E-04	5.17E-04	3.51E-03	2.03E-04	1.18E-04
9	8	6.90E-04	3.76E-04	9.52E-04	1.50E-04	9.78E-05
9	7	6.90E-04	3.76E-04	1.37E-03	1.47E-04	9.48E-05
9	6	6.90E-04	3.76E-04	2.10E-03	1.55E-04	9.40E-05
10	9	5.18E-04	2.83E-04	6.90E-04	1.17E-04	7.94E-05
10	8	5.18E-04	2.83E-04	9.52E-04	1.14E-04	7.64E-05
10	7	5.18E-04	2.83E-04	1.37E-03	1.21E-04	7.54E-05

TABLE 11
S-values for Intracellular ^{131}I

R_C (μm)	R_N (μm)	C \leftarrow C (Gy/Bq · s)	C \leftarrow CS (Gy/Bq · s)	N \leftarrow N (Gy/Bq · s)	N \leftarrow Cy (Gy/Bq · s)	N \leftarrow CS (Gy/Bq · s)
3	2	1.99E-03	1.26E-03	4.98E-03	1.21E-03	7.35E-04
3	1	1.99E-03	1.26E-03	2.53E-02	1.59E-03	6.78E-04
4	3	1.06E-03	6.73E-04	1.99E-03	6.44E-04	4.40E-04
4	2	1.06E-03	6.73E-04	4.98E-03	7.66E-04	4.17E-04
5	4	6.50E-04	4.13E-04	1.06E-03	3.91E-04	2.83E-04
5	3	6.50E-04	4.13E-04	1.99E-03	4.52E-04	2.66E-04
5	2	6.50E-04	4.13E-04	4.98E-03	5.37E-04	2.62E-04
6	5	4.36E-04	2.78E-04	6.50E-04	2.61E-04	1.97E-04
6	4	4.36E-04	2.78E-04	1.06E-03	2.91E-04	1.83E-04
6	3	4.36E-04	2.78E-04	1.99E-03	3.37E-04	1.74E-04
7	6	3.12E-04	1.99E-04	4.36E-04	1.86E-04	1.46E-04
7	5	3.12E-04	1.99E-04	6.50E-04	2.03E-04	1.34E-04
7	4	3.12E-04	1.99E-04	1.06E-03	2.27E-04	1.26E-04
8	7	2.34E-04	1.50E-04	3.12E-04	1.40E-04	1.13E-04
8	6	2.34E-04	1.50E-04	4.36E-04	1.49E-04	1.03E-04
8	5	2.34E-04	1.50E-04	6.50E-04	1.84E-04	9.69E-05
9	8	1.82E-04	1.18E-04	2.34E-04	1.09E-04	8.99E-05
9	7	1.82E-04	1.18E-04	3.12E-04	1.15E-04	8.26E-05
9	6	1.82E-04	1.18E-04	4.36E-04	1.24E-04	7.74E-05
10	9	1.45E-04	9.46E-05	1.82E-04	8.85E-05	7.40E-05
10	8	1.45E-04	9.46E-05	2.34E-04	9.18E-05	6.81E-05
10	7	1.45E-04	9.46E-05	3.12E-04	9.74E-05	6.38E-05

TABLE 12
S-values for Intracellular ^{201}Tl

R_C (μm)	R_N (μm)	C \leftarrow C (Gy/Bq · s)	C \leftarrow CS (Gy/Bq · s)	N \leftarrow N (Gy/Bq · s)	N \leftarrow Cy (Gy/Bq · s)	N \leftarrow CS (Gy/Bq · s)
3	2	1.72E-02	9.38E-03	5.14E-02	6.09E-03	2.79E-03
3	1	1.72E-02	9.38E-03	3.23E-01	8.82E-03	1.65E-03
4	3	7.83E-03	4.26E-03	1.72E-02	2.50E-03	1.26E-03
4	2	7.83E-03	4.26E-03	5.14E-02	2.95E-03	7.09E-04
5	4	4.24E-03	2.29E-03	7.83E-03	1.29E-03	6.91E-04
5	3	4.24E-03	2.29E-03	1.72E-02	1.38E-03	4.29E-04
5	2	4.24E-03	2.29E-03	5.14E-02	1.66E-03	3.72E-04
6	5	2.56E-03	1.38E-03	4.24E-03	7.55E-04	4.20E-04
6	4	2.56E-03	1.38E-03	7.83E-03	7.66E-04	2.65E-04
6	3	2.56E-03	1.38E-03	1.72E-02	8.63E-04	2.35E-04
7	6	1.67E-03	8.94E-04	2.56E-03	4.81E-04	2.76E-04
7	5	1.67E-03	8.94E-04	4.24E-03	4.68E-04	1.75E-04
7	4	1.67E-03	8.94E-04	7.83E-03	5.06E-04	1.51E-04
8	7	1.15E-03	6.15E-04	1.67E-03	3.27E-04	1.93E-04
8	6	1.15E-03	6.15E-04	2.56E-03	3.08E-04	1.23E-04
8	5	1.15E-03	6.15E-04	4.24E-03	3.21E-04	1.04E-04
9	8	8.28E-04	4.43E-04	1.15E-03	2.34E-04	1.42E-04
9	7	8.28E-04	4.43E-04	1.67E-03	2.16E-04	9.16E-05
9	6	8.28E-04	4.43E-04	2.56E-03	2.18E-04	7.66E-05
10	9	6.17E-04	3.30E-04	8.28E-04	1.74E-04	1.08E-04
10	8	6.17E-04	3.30E-04	1.15E-03	1.58E-04	7.09E-05
10	7	6.17E-04	3.30E-04	1.67E-03	1.57E-04	5.93E-05

TABLE 13
S-values for Intracellular ^{203}Pb

R_C (μm)	R_N (μm)	C←C (Gy/Bq · s)	C←CS (Gy/Bq · s)	N←N (Gy/Bq · s)	N←Cy (Gy/Bq · s)	N←CS (Gy/Bq · s)
3	2	1.13E-02	6.06E-03	3.40E-02	3.95E-03	1.70E-03
3	1	1.13E-02	6.06E-03	2.13E-01	5.86E-03	8.76E-04
4	3	5.03E-03	2.67E-03	1.13E-02	1.49E-03	6.53E-04
4	2	5.03E-03	2.67E-03	3.40E-02	1.79E-03	2.45E-04
5	4	2.67E-03	1.40E-03	5.03E-03	7.14E-04	3.21E-04
5	3	2.67E-03	1.40E-03	1.13E-02	7.38E-04	1.10E-04
5	2	2.67E-03	1.40E-03	3.40E-02	9.10E-04	4.49E-05
6	5	1.59E-03	8.30E-04	2.67E-03	3.97E-04	1.83E-04
6	4	1.59E-03	8.30E-04	5.03E-03	3.74E-04	6.18E-05
6	3	1.59E-03	8.30E-04	1.13E-02	4.08E-04	2.93E-05
7	6	1.02E-03	5.31E-04	1.59E-03	2.44E-04	1.15E-04
7	5	1.02E-03	5.31E-04	2.67E-03	2.17E-04	3.98E-05
7	4	1.02E-03	5.31E-04	5.03E-03	2.19E-04	2.11E-05
8	7	6.95E-04	3.61E-04	1.02E-03	1.62E-04	7.77E-05
8	6	6.95E-04	3.61E-04	1.59E-03	1.38E-04	2.79E-05
8	5	6.95E-04	3.61E-04	2.67E-03	1.32E-04	1.62E-05
9	8	4.95E-04	2.57E-04	6.95E-04	1.13E-04	5.54E-05
9	7	4.95E-04	2.57E-04	1.02E-03	9.34E-05	2.07E-05
9	6	4.95E-04	2.57E-04	1.59E-03	8.69E-05	1.28E-05
10	9	3.65E-04	1.89E-04	4.95E-04	8.22E-05	4.11E-05
10	8	3.65E-04	1.89E-04	6.95E-04	6.67E-05	1.60E-05
10	7	3.65E-04	1.89E-04	1.02E-03	6.06E-05	1.05E-05

TABLE 14
S-values for Intracellular ^{210}Po

R_C (μm)	R_N (μm)	C←C (Gy/Bq · s)	C←CS (Gy/Bq · s)	N←N (Gy/Bq · s)	N←Cy (Gy/Bq · s)	N←CS (Gy/Bq · s)
3	2	2.26E-01	1.51E-01	5.06E-01	1.74E-01	1.13E-01
3	1	2.26E-01	1.51E-01	2.02E+00	2.29E-01	1.04E-01
4	3	1.28E-01	8.54E-02	2.26E-01	9.31E-02	6.63E-02
4	2	1.28E-01	8.54E-02	5.06E-01	1.12E-01	6.08E-02
5	4	8.19E-02	5.49E-02	1.28E-01	5.80E-02	4.38E-02
5	3	8.19E-02	5.49E-02	2.26E-01	6.66E-02	4.03E-02
5	2	8.19E-02	5.49E-02	5.06E-01	7.85E-02	3.84E-02
6	5	5.71E-02	3.84E-02	8.19E-02	3.98E-02	3.13E-02
6	4	5.71E-02	3.84E-02	1.28E-01	4.42E-02	2.88E-02
6	3	5.71E-02	3.84E-02	2.26E-01	5.03E-02	2.74E-02
7	6	4.21E-02	2.83E-02	5.71E-02	2.90E-02	2.35E-02
7	5	4.21E-02	2.83E-02	8.19E-02	3.16E-02	2.17E-02
7	4	4.21E-02	2.83E-02	1.28E-01	3.51E-02	2.07E-02
8	7	3.24E-02	2.18E-02	4.21E-02	2.22E-02	1.83E-02
8	6	3.24E-02	2.18E-02	5.71E-02	2.38E-02	1.70E-02
8	5	3.24E-02	2.18E-02	8.19E-02	2.59E-02	1.62E-02
9	8	2.57E-02	1.73E-02	3.24E-02	1.75E-02	1.48E-02
9	7	2.57E-02	1.73E-02	4.21E-02	1.86E-02	1.37E-02
9	6	2.57E-02	1.73E-02	5.71E-02	2.00E-02	1.31E-02
10	9	2.09E-02	1.41E-02	2.57E-02	1.42E-02	1.21E-02
10	8	2.09E-02	1.41E-02	3.24E-02	1.49E-02	1.13E-02
10	7	2.09E-02	1.41E-02	4.21E-02	1.59E-02	1.08E-02

TABLE 15
S-values for Intracellular $^{212}\text{Pb}^*$

R_C (μm)	R_N (μm)	C←C (Gy/Bq · s)	C←CS (Gy/Bq · s)	N←N (Gy/Bq · s)	N←Cy (Gy/Bq · s)	N←CS (Gy/Bq · s)
3	2	6.63E-03	3.94E-03	1.78E-02	3.54E-03	1.89E-03
3	1	6.63E-03	3.94E-03	9.61E-02	4.88E-03	1.63E-03
4	3	3.29E-03	1.95E-03	6.63E-03	1.67E-03	1.00E-03
4	2	3.29E-03	1.95E-03	1.78E-02	2.01E-03	8.50E-04
5	4	1.90E-03	1.13E-03	3.29E-03	9.38E-04	6.04E-04
5	3	1.90E-03	1.13E-03	6.63E-03	1.06E-03	5.09E-04
5	2	1.90E-03	1.13E-03	1.78E-02	1.28E-03	4.69E-04
6	5	1.22E-03	7.22E-04	1.80E-03	5.94E-04	4.04E-04
6	4	1.22E-03	7.22E-04	3.29E-03	6.42E-04	3.38E-04
6	3	1.22E-03	7.22E-04	6.63E-03	7.38E-04	3.05E-04
7	6	8.37E-04	4.99E-04	1.22E-03	4.08E-04	2.90E-04
7	5	8.37E-04	4.99E-04	1.90E-03	4.28E-04	2.44E-04
7	4	8.37E-04	4.99E-04	3.29E-03	4.72E-04	2.19E-04
8	7	6.06E-04	3.64E-04	8.37E-04	2.98E-04	2.19E-04
8	6	6.06E-04	3.64E-04	1.22E-03	3.06E-04	1.86E-04
8	5	6.06E-04	3.64E-04	1.90E-03	3.28E-04	1.68E-04
9	8	4.58E-04	2.76E-04	6.06E-04	2.27E-04	1.72E-04
9	7	4.58E-04	2.76E-04	8.37E-04	2.30E-04	1.47E-04
9	6	4.58E-04	2.76E-04	1.22E-03	2.43E-04	1.34E-04
10	9	3.57E-04	2.17E-04	4.58E-04	1.79E-04	1.39E-04
10	8	3.57E-04	2.17E-04	6.06E-04	1.80E-04	1.20E-04
10	7	3.57E-04	2.17E-04	8.37E-04	1.87E-04	1.10E-04

*Contribution to the absorbed dose from the ^{212}Pb daughters (^{212}Bi , ^{212}Po) must be taken into account. The contribution of ^{208}Tl is small. Branching ratios may be found in Weber et al. (27).

TABLE 16
S-values for Intracellular $^{212}\text{Bi}^*$

R_C (μm)	R_N (μm)	C←C (Gy/Bq · s)	C←CS (Gy/Bq · s)	N←N (Gy/Bq · s)	N←Cy (Gy/Bq · s)	N←CS (Gy/Bq · s)
3	2	7.82E-02	5.21E-02	1.76E-01	5.96E-02	3.85E-02
3	1	7.82E-02	5.21E-02	7.16E-01	7.82E-02	3.55E-02
4	3	4.40E-02	2.94E-02	7.82E-02	3.18E-02	2.26E-02
4	2	4.40E-02	2.94E-02	1.76E-01	3.83E-02	2.07E-02
5	4	2.82E-02	1.88E-02	4.40E-02	1.98E-02	1.49E-02
5	3	2.82E-02	1.88E-02	7.82E-02	2.27E-02	1.37E-02
5	2	2.82E-02	1.88E-02	1.76E-01	2.68E-02	1.31E-02
6	5	1.96E-02	1.31E-02	2.82E-02	1.35E-02	1.06E-02
6	4	1.96E-02	1.31E-02	4.40E-02	1.51E-02	9.79E-03
6	3	1.96E-02	1.31E-02	7.82E-02	1.71E-02	9.32E-03
7	6	1.44E-02	9.68E-03	1.96E-02	9.88E-03	7.99E-03
7	5	1.44E-02	9.68E-03	2.82E-02	1.08E-02	7.38E-03
7	4	1.44E-02	9.68E-03	4.40E-02	1.19E-02	7.02E-03
8	7	1.11E-02	7.44E-03	1.44E-02	7.54E-03	6.23E-03
8	6	1.11E-02	7.44E-03	1.96E-02	8.08E-03	5.78E-03
8	5	1.11E-02	7.44E-03	2.82E-02	8.82E-03	5.50E-03
9	8	8.79E-03	5.90E-03	1.11E-02	5.95E-03	5.01E-03
9	7	8.79E-03	5.90E-03	1.44E-02	6.31E-03	4.66E-03
9	6	8.79E-03	5.90E-03	1.96E-02	6.79E-03	4.44E-03
10	9	7.14E-03	4.80E-03	8.79E-03	4.82E-03	4.11E-03
10	8	7.14E-03	4.80E-03	1.11E-02	5.06E-03	3.84E-03
10	7	7.14E-03	4.80E-03	1.44E-02	5.40E-03	3.66E-03

*Contribution to the absorbed dose from the ^{212}Bi daughter ^{212}Po must be taken into account. The contribution of ^{208}Tl is small. Branching ratios may be found in Weber et al. (27).

TABLE 17
S-values for Intracellular ^{212}Po

R_C (μm)	R_N (μm)	C-C (Gy/Bq · s)	C-CS (Gy/Bq · s)	N-N (Gy/Bq · s)	N-Cy (Gy/Bq · s)	N-CS (Gy/Bq · s)
3	2	1.74E-01	1.17E-01	3.92E-01	1.34E-01	8.69E-02
3	1	1.74E-01	1.17E-01	1.56E+00	1.77E-01	8.00E-02
4	3	9.83E-02	6.57E-02	1.74E-01	7.15E-02	5.08E-02
4	2	9.83E-02	6.57E-02	3.92E-01	8.63E-02	4.66E-02
5	4	6.30E-02	4.21E-02	9.83E-02	4.45E-02	3.35E-02
5	3	6.30E-02	4.21E-02	1.74E-01	5.11E-02	3.07E-02
5	2	6.30E-02	4.21E-02	3.92E-01	6.02E-02	2.93E-02
6	5	4.38E-02	2.93E-02	6.30E-02	3.04E-02	2.38E-02
6	4	4.38E-02	2.93E-02	9.83E-02	3.38E-02	2.19E-02
6	3	4.38E-02	2.93E-02	1.74E-01	3.85E-02	2.08E-02
7	6	3.23E-02	2.16E-02	4.38E-02	2.21E-02	1.78E-02
7	5	3.23E-02	2.16E-02	6.30E-02	2.41E-02	1.65E-02
7	4	3.23E-02	2.16E-02	9.83E-02	2.68E-02	1.56E-02
8	7	2.47E-02	1.66E-02	3.23E-02	1.68E-02	1.39E-02
8	6	2.47E-02	1.66E-02	4.38E-02	1.81E-02	1.28E-02
8	5	2.47E-02	1.66E-02	6.30E-02	1.97E-02	1.22E-02
9	8	1.96E-02	1.31E-02	2.47E-02	1.32E-02	1.11E-02
9	7	1.96E-02	1.31E-02	3.23E-02	1.40E-02	1.03E-02
9	6	1.96E-02	1.31E-02	4.38E-02	1.51E-02	9.82E-03
10	9	1.59E-02	1.07E-02	1.96E-02	1.07E-02	9.13E-03
10	8	1.59E-02	1.07E-02	2.47E-02	1.13E-02	8.49E-03
10	7	1.59E-02	1.07E-02	3.23E-02	1.20E-02	8.09E-03

APPENDIX

The mean absorbed dose \bar{D}_k to target region r_k from source region r_h is given by (1):

$$\bar{D}(r_k \leftarrow r_h) = \bar{A}_h S(r_k \leftarrow r_h), \quad \text{Eq. A1}$$

where \bar{A}_h is the cumulated activity in the source region, and the S-value is the dose to the target region per unit cumulated activity in the source region, defined by:

$$S(r_k \leftarrow r_h) = \sum_i \frac{\Delta_i \phi_i(r_k \leftarrow r_h)}{m_k}. \quad \text{Eq. A2}$$

The parameter m_k is the mass of the target region, Δ_i and ϕ_i are the mean energy emitted per nuclear transition and the fraction of energy emitted from the source region that is absorbed in the target region for the i th radiation component, respectively (1). The absorbed fraction $\phi_i(r_k \leftarrow r_h)$ for particulate radiations may be written as (8):

$$\phi_i(r_k \leftarrow r_h) = \int_0^{\infty} \psi_{r_k \leftarrow r_h}(x) \frac{1}{E_i} \frac{dE}{dx} \Big|_{X(E_i) - x} dx, \quad \text{Eq. A3}$$

where E_i is the initial energy. The quantity dE/dx can be obtained from experimental range-energy relationships. For electrons, Cole (31) experimentally determined that the electron energy E_e (keV) and range X (μm) in unit density matter are related by:

$$E_e = 5.9(X + 0.007)^{0.565} + 0.00413X^{1.33} - 0.367. \quad \text{Eq. A4}$$

Differentiation of Equation A4 yields the energy loss expression for electrons,

$$dE_e/dX = 3.333(X + 0.007)^{-0.435} + 0.0055X^{0.33}. \quad \text{Eq. A5}$$

Hence, $dE/dX|_{X(E_i) - x}$ is the energy loss expression (Equation A5) evaluated at $X(E_i) - x$, the residual range of the particle after passing a distance of x through the medium. The empirical range-energy relationship for alpha particles in air given by Kaplan (32)

was extrapolated to tissue (33) assuming that the ranges are related by the ratio of the densities of the media (1.3×10^{-3}). The relationship thus obtained for tissue is: $E_\alpha = 390 X^{2/3}$, with E_α being the alpha particle energy in keV. Similarly, differentiation yields the alpha particle energy loss expression $dE_\alpha/dX = 260 X^{-1/3}$ (22). Integration of Equation A3 using the above energy loss expressions for electrons and alpha particles insures that the changes in LET of the particle as it tracks through the cell are taken into account.

The geometric factor $\psi_{r_k \leftarrow r_h}$ is the mean probability that a randomly directed vector of length x that starts from a random point within the source region r_h ends within the target region r_k . This quantity is highly dependent on the geometry and dimensions of the source and target regions. In this work the cell and cell nucleus are taken to be concentric spheroids of unit density matter. The annular shell between the cell nucleus and the cell surface (i.e., cell membrane) is the cytoplasm. Let CS, Cy, N and C denote the regions corresponding to the cell surface, cytoplasm, nucleus and entire cell, respectively. The geometric factor $\psi_{N \leftarrow CS}$ for radioactivity distributed uniformly on the cell surface and the cell nucleus as the target region is (8):

$$\psi_{N \leftarrow CS}(x)$$

$$= \begin{cases} 0 & \text{when } 0 \leq x \leq R_C - R_N \\ \frac{2xR_C - R_C^2 - x^2 + R_N^2}{4xR_C} & \text{when } R_C - R_N \leq x \leq R_C + R_N \\ 0 & \text{when } x \geq R_C + R_N, \end{cases} \quad \text{Eq. A6}$$

where R_C and R_N are the radii of cell and cell nucleus, respectively (8). Similarly, when the nucleus is the target, the geometric factors for radioactivity distributed uniformly in the cytoplasm $\psi_{N \leftarrow Cy}$ or nucleus $\psi_{N \leftarrow N}$ are given by Equations A7 and A8, respectively (8).

$$\psi_{N \leftarrow C}(x) = \begin{cases} Qx^2 \left(R_N^2 - \frac{1}{12}x^2 \right) & \text{when } R_C \leq 3R_N \text{ and } 0 \leq x \leq R_C - R_N \\ Q \left[\frac{1}{2}(R_C^2 - R_N^2)(R_N^2 - x^2) + \frac{2x}{3}(R_C^3 - R_N^3) - \frac{1}{4}(R_C^4 - R_N^4) \right] & \text{when } R_C \leq 3R_N \text{ and } R_C - R_N \leq x \leq 2R_N \\ \frac{R_N^3}{R_C^3 - R_N^3} & \text{when } R_C \geq 3R_N \\ \frac{Q}{12} [x^4 - 3(R_C^4 + R_N^4) + 6(R_C^2 R_N^2 - x^2 R_N^2 - x^2 R_C^2) \\ + 8x(R_C^3 + R_N^3)] & \text{when } R_C \leq 3R_N \text{ and } 2R_N \leq x \leq R_C + R_N \\ 0 & \text{when } R_C \geq 3R_N \text{ and } R_C - R_N \leq x \leq R_C + R_N \\ 0 & \text{when } x \geq R_C + R_N, \end{cases}$$

where $Q = \frac{3}{4x(R_C^3 - R_N^3)}$ Eq. A7

$$\psi_{N \leftarrow N}(x) = \begin{cases} 1 - \frac{3}{4} \left(\frac{x}{R_N} \right)^2 + \frac{1}{16} \left(\frac{x}{R_N} \right)^3 & \text{when } 0 \leq x \leq 2R_N \\ 0 & \text{when } x > 2R_N. \end{cases}$$

Eq. A8

When the cell as a whole is taken as the target region, the geometric factors for radioactivity distributed uniformly on the cell surface $\psi_{C \leftarrow CS}$ and within the cell $\psi_{C \leftarrow C}$ may be obtained by substituting R_C for R_N in Equations A6 and A8, respectively (8).

Finally, numerical integration of Equation A3 is carried out on a UNIX-based Hewlett Packard 9000, 800 series computer. The program was written in FORTRAN 77 with some VAX FORTRAN extensions employed. The longest run-time to generate an S-value table for one radionuclide is 1 min.

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