Estimates of Radiation Dose to the Embryo from Nuclear Medicine Procedures

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These phantom studies and computer calculations provide a direct means of estimating the radiation dose to the embryo resulting from the administration of a radiopharmaceutical to the mother during organogenesis. The specific absorbed fractions to the embryo from 19 source organs were computed for 12 monoenergetic photon energies. Tables of absorbed dose per unit cumulated activity, S, for the embryo as a target organ have been assembled for ^{99m}Tc, ^{111}In, ^{113m}In, ^{123}I, ^{131}I, and ^{133}Xe. In addition, the dose to the embryo was calculated for several of the radiopharmaceuticals for which the MIRD Committee has published dose estimate reports.

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The estimate of the radiation absorbed dose to the embryo is essential when a radiopharmaceutical has been intentionally or unknowingly administered to a woman at the beginning of her pregnancy (*1*). Currently there are no direct methods of calculating the dose to the embryo unless it is assumed to be equivalent to the dose to the uterus. The latter may be calculated by using the MIRD Committee's formalism and the data contained in *MIRD Pamphlet No. 11* (*2*) and the revision of MIRD Pamphlet No. 5 (*3*).

MATERIALS AND METHODS

Anatomic model. A sphere of radius 0.13 cm and mass 9.2 mg is the geometric model chosen to represent the embryo (*4*) during the period of organogenesis, i.e., 10–41 days after conception. Although the weight and physical dimensions of the embryo vary significantly during this period, these changes will have little effect on the dose estimates since specific absorbed fractions are relatively insensitive to mass and shape, especially when the target organ is distant from the source organ (*2,3*). The sphere representing the embryo is located at the origin of the semiaxes of a 66-cm^3 ellipsoid, representing the uterus in the heterogeneous adult phantom (*3*). The semiaxes of the ellipsoid representing the uterus are 2.5, 5.0, and 1.5 cm; a plane truncates the y axis of the ellipsoid anteriorly. Figures 1A and 1B are computer plots of sections through the adult hermaphrodite phantom illustrating the shape of the uterus and its position relative to other organs.

Specific absorbed fractions. The specific absorbed fractions Φ were calculated for 12 monoenergetic photon energies and various source organs (Table 1), as described in the revision of MIRD Pamphlet No. 5 (*3*) with the exceptions noted below. To reduce the computing time, the embryo was taken as the source organ and the source organs listed in Table 1 were taken as the target organs with the exception of bone, lungs, and red marrow. To reduce computer time further, the Build-Up Factor Code was used rather than the Monte Carlo Code. When used appropriately, the agreement between the two codes is good (*5*). A linear extrapolation was made to obtain Φ for 10 keV. After Φ was calculated with the embryo as the source organ, the reciprocity theorem was used to calculate Φ for the embryo as the target organ.

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TABLE 1. SPECIFIC ABSORBED FRACTIONS* OF PHOTON ENERGY Φ(embryo←r_h), (gm^{-1})
FOR THE EMBRYO AS THE TARGET ORGAN FROM VARIOUS SOURCE ORGANS r_h

	Photon energy E (MeV)										
Source organs	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.00	1.50	2.00	4.00
Adrenals	7.00E-34	1.29E-21	7.51E-13	1.56E-08	5.05E-07	1.42E-06	1.67E-06	1.67E-06	1.62E-06	1.56E-06	1.51E-06	1.32E-06
Bladder content	3.00E-08	1.82E-06	3.45E-05	1.24E-04	1.19E-04	7.71E-05	6.51E-05	5.84E-05	5.19E-05	4.70E-05	4.37E-05	3.55E-05
Bone (total)	1.40E-16	7.64E-12	1.84E-08	8.38E-07	2.64E-06	3.00E-06	2.73E-06	2.43E-06	2.21E-06	2.07E-06	1.95E-06	1.65E-06
GI tract (stom. cont.)	9.80E-24	6.51E-16	2.52E-10	1.93E-07	2.04E-06	3.68E-06	3.69E-06	3.37E-06	3.10E-06	2.89E-06	2.73E-06	2.32E-06
GI tract (SI and cont.)	2.00E-08	9.04E-07	1.40E-05	5.30E-05	5.96E-05	4.27E-05	3.62E-05	3.20E-05	2.84E-05	2.58E-05	2.38E-05	1.95E-05
GI tract (UU cont.)	6.10E-13	2.06E-09	6.82E-07	1.29E-05	2.79E-05	2.49E-05	2.10E-05	1.79E-05	1.57E-05	1.42E-05	1.32E-05	1.08E-05
GI tract (LU cont.)	4.60E-13	2.33E-09	1.03E-06	1.88E-05	3.67E-05	3.08E-05	2.57E-05	2.19E-05	1.93E-05	1.74E-05	1.63E-05	1.33E-05
Kidneys	7.20E-24	6.54E-16	3.17E-10	2.53E-07	2.53E-06	4.41E-06	4.37E-06	3.90E-06	3.57E-06	3.30E-06	3.13E-06	2.64E-06
Liver	9.00E-25	1.16E-16	7.19E-11	8.41E-08	1.16E-06	2.40E-06	2.56E-06	2.41E-06	2.27E-06	2.14E-06	2.05E-06	1.76E-06
Lungs	1.90E-40	9.66E-26	3.07E-15	6.16E-10	5.56E-08	2.67E-07	3.98E-07	4.85E-07	5.36E-07	5.51E-07	5.59E-07	5.28E-07
Marrow (red)	5.90E-16	3.22E-11	7.76E-08	3.25E-06	9.29E-06	9.19E-06	7.93E-06	6.72E-06	5.93E-06	5.44E-06	5.07E-06	4.19E-06
Other tissues (muscle)	1.62E-06	8.95E-06	1.46E-05	1.86E-05	1.26E-05	1.01E-05	8.83E-06	8.29E-06	7.59E-06	6.54E-06	6.25E-06	5.02E-06
Ovaries	1.10E-09	3.69E-07	2.28E-05	1.19E-04	1.23E-04	7.99E-05	6.72E-05	5.97E-05	5.32E-05	4.81E-05	4.46E-05	3.62E-05
Pancreas	2.80E-28	1.71E-18	1.66E-11	6.23E-08	1.13E-06	2.49E-06	2.68E-06	2.52E-06	2.37E-06	2.24E-06	2.13E-06	1.83E-06
Salivary glands	8.50E-40	3.70E-30	2.89E-24	2.00E-13	5.27E-10	9.99E-09	2.81E-08	5.90E-08	9.16E-08	1.12E-07	1.26E-07	1.46E-07
Skin	8.40E-15	5.46E-11	2.89E-08	7.26E-07	2.25E-06	2.75E-06	2.56E-06	2.27E-06	2.10E-06	1.95E-06	1.85E-06	1.56E-06
Spleen	4.00E-29	5.03E-19	8.21E-12	3.95E-08	8.26E-07	1.96E-06	2.17E-06	2.09E-06	2.00E-06	1.90E-06	1.82E-06	1.58E-06
Thyroid	8.50E-40	3.70E-30	2.89E-24	2.00E-13	5.27E-10	9.99E-09	2.81E-08	5.90E-08	9.16E-08	1.12E-07	1.26E-07	1.46E-07
Total body	1.20E-06	6.64E-06	1.10E-05	1.49E-05	1.10E-05	8.98E-06	7.86E-06	7.31E-06	6.72E-06	5.82E-06	5.54E-06	4.48E-06

* The digits following the symbol E indicate the power of 10 by which the initial number is to be multiplied, e.g., 7.00E-34 = 7.00×10^{-34}.

Since the reciprocity theorem is not valid when the target and source organs have different elemental compositions, direct Monte Carlo Code calculations were made for bone, lungs, and red marrow as source organs. To improve the statistics of these calculations, the embryo was assumed to be a sphere with a mass of 10 gm. This change should not affect the accuracy of the calculations since Φ is relatively insensitive to the mass of the target organ as long as the two organs are not adjacent.

Absorbed dose per unit cumulated activity. The values of absorbed dose per unit cumulated activity, S, were calculated as described in *MIRD Pamphlet No. 11* (*2*) using the values of Φ given in Table 1. The results are given in Table 2.

Absorbed dose calculations. The values given in Table 3 were obtained by using the general MIRD dose calculations:

$$\bar{D}(\text{embryo}) = \sum_h \bar{D}(\text{embryo} \leftarrow r_h)$$

$$= \sum_h \sum_i \tilde{A}_h(0,\infty)\Delta_i\Phi_i(\text{embryo} \leftarrow r_h) \quad \text{(rads)},$$

$$S(\text{embryo} \leftarrow r_h) = \sum_i \Delta_i\Phi_i(\text{embryo} \leftarrow r_h) \quad (\text{rads}/\mu\text{Ci-hr}),$$

$$\bar{D}(\text{embryo}) = \sum_h \tilde{A}_h(0,\infty)S(\text{embryo} \leftarrow r_h) \quad \text{(rads)},$$

where $\bar{D}$(embryo) is the total mean dose to the embryo (rads); $\bar{D}$(embryo←r_h) is the mean dose to the embryo from source organ r_h (rads); $\tilde{A}_h(0,\infty)$ is the cumulated activity in source organ r_h from $t = 0$ to $t = \infty$ (μCi-hr); Δ_i is the mean energy emitted per nuclear transformation for i-type radiations (gm-rad/μCi-hr); Φ_i(embryo←r_h) is the specific absorbed fraction of energy for the target organ, the embryo, for i-type radiations emitted in source organ r_h (gm^{-1}); and S(embryo←r_h) is the absorbed dose to the embryo per unit cumulated activity in source organ r_h (rads/μCi-hr).

The dose calculations were made for a 70-kg reference adult as described in Refs. *2* and *3*. It was assumed that the uterus was not enlarged and that the presence of the placenta could be neglected. The embryo weighed 9.2 mg and was implanted centrally in the uterus. The embryo was assumed not to be irradiated by any particulate radiations except when the activity is uniformly distributed in the total body. In this case the embryo contains its proportionate share of activity and S(embryo←total body) reflects this. The bladder was assumed to contain 200 ml of urine. All assumptions used in the appropriate MIRD Dose Estimate Reports (*6–9*) were also assumed in the dose estimates given in Table 3.

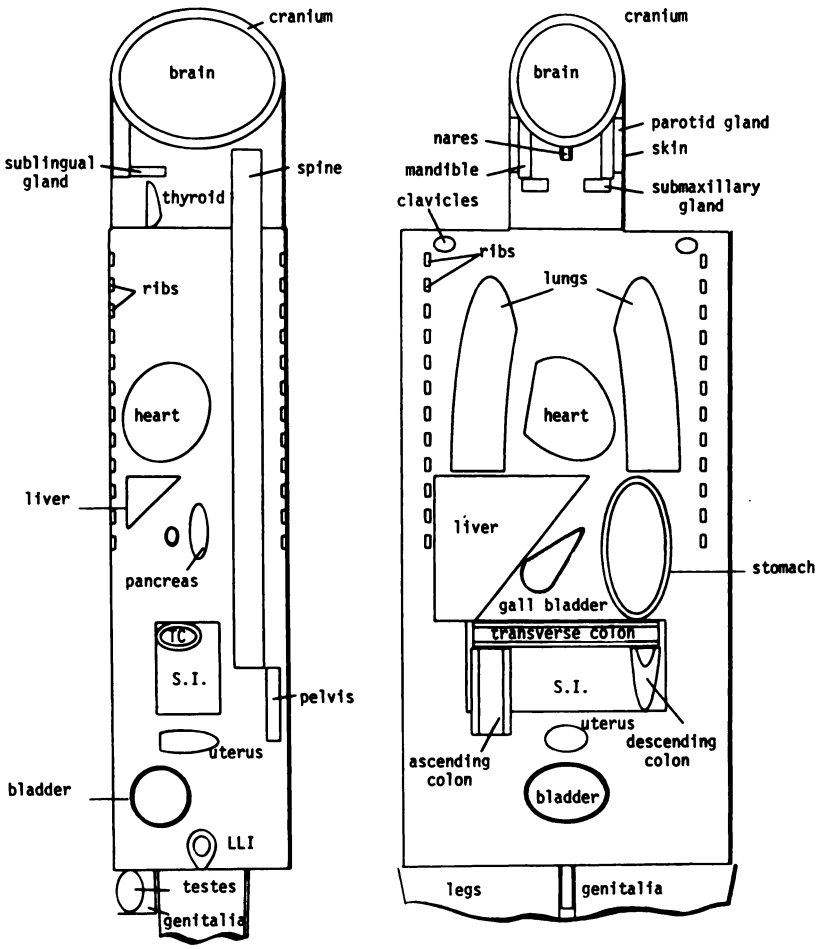

FIG. 1. Computer plots of sections through adult hermaphrodite phantom illustrating shape of uterus and its position relative to other organs.

TABLE 2. S(embryo←r_h), ABSORBED DOSE PER UNIT CUMULATED ACTIVITY (rads/μCi-hr), FOR SEVERAL RADIONUCLIDES AND VARIOUS SOURCE ORGANS r_h WITH THE EMBRYO AS THE TARGET ORGAN*

Source organs	Radionuclides					
	^{99m}Tc	^{111}In	^{113m}In	^{123}I	^{131}I	^{133}Xe
Adrenals	4.0E–07	1.4E–06	8.6E–07	4.9E–07	1.3E–06	7.0E–08
Bladder contents	1.9E–05	5.7E–05	3.2E–05	2.7E–05	4.9E–05	9.8E–06
Bone (total)	7.6E–07	2.3E–06	1.3E–06	9.0E–07	2.0E–06	2.1E–07
GI tract (stom. cont.)	9.7E–07	3.0E–06	1.8E–06	1.1E–06	2.8E–06	2.1E–07
GI tract (SI and cont.)	1.1E–05	3.1E–05	1.8E–05	1.4E–05	2.7E–05	4.8E–06
GI tract (ULI cont.)	6.1E–06	1.8E–05	9.9E–06	7.4E–06	1.5E–05	2.1E–06
GI tract (LLI cont.)	7.6E–06	2.2E–05	1.2E–05	9.2E–06	1.9E–05	2.7E–06
Kidneys	1.2E–06	3.6E–06	2.1E–06	1.4E–06	3.3E–06	2.5E–07
Liver	6.5E–07	2.1E–06	1.3E–06	7.7E–07	2.0E–06	1.3E–07
Lungs	8.4E–08	3.2E–07	2.4E–07	1.1E–07	3.6E–07	1.2E–08
Marrow (red)	2.3E–06	6.6E–06	3.7E–06	2.7E–06	5.8E–06	7.0E–07
Other tissues (muscle)	2.6E–06	8.0E–06	4.6E–06	3.8E–06	6.9E–06	1.3E–06
Ovaries	2.0E–05	5.8E–05	3.3E–05	2.7E–05	5.0E–05	9.9E–06
Pancreas	6.8E–07	2.2E–06	1.3E–06	8.0E–07	2.1E–06	1.3E–07
Salivary glands	4.5E–09	2.4E–08	2.5E–08	7.3E–09	3.9E–08	4.2E–10
Skin	7.0E–07	2.1E–06	1.2E–07	8.3E–07	1.9E–06	1.9E–07
Spleen	5.4E–07	1.8E–06	1.1E–06	6.5E–07	1.7E–06	1.0E–07
Thyroid	4.5E–09	2.4E–08	2.5E–08	7.3E–09	3.9E–08	4.2E–10
Total body	2.8E–06	8.2E–06	8.4E–06	4.1E–06	1.2E–05	5.3E–06

* The digits following the symbol E indicate the power of 10 by which the initial number is to be multiplied, e.g., 4.0E–07 = 4.0×10^{-7}.

TABLE 3. DOSE ESTIMATES FOR THE EMBRYO

Radiopharmaceutical	Rads per millicurie administered
^{99m}Tc-sulfur colloid (normal) (6)	0.007
^{99m}Tc-sodium pertechnetate (7):	
resting population	0.037
non-resting population	0.039
^{123}I-sodium iodide (15%) (8)	0.032
^{123}I-sodium iodide (15%) (8)	0.10
^{123}I-sodium rose bengal (9)	0.13
^{123}I-sodium rose bengal (9)	0.68

RESULTS AND DISCUSSION

The values for $\Phi(\text{embryo} \leftarrow r_h)$ and $\Phi(\text{uterus} \leftarrow r_h)$ were compared for six source organs. In general, $\Phi(\text{embryo} \leftarrow r_h)$ is greater than $\Phi(\text{uterus} \leftarrow r_h)$ for energies 30 keV or greater, sometimes approaching twice the value of $\Phi(\text{uterus} \leftarrow r_h)$. These ratios fluctuate considerably.

To ascertain the variability of $\Phi(\text{embryo} \leftarrow r_h)$, additional studies should be performed to investigate the effects that the implantation site of the embryo and the relative location of the uterus to other abdominal organs have on $\Phi(\text{embryo} \leftarrow r_h)$. The effect of the variable size of the bladder and its contents is of even greater importance to the calculation of $\Phi(\text{embryo} \leftarrow r_h)$.

Since radioactivity was assumed not to cross the placenta, nonpenetrating radiation is not included in these calculations except for activity uniformly distributed in the total body. If, for example, ^{99m}Tc-pertechnetate did cross the placenta, and the concentration in the placenta equaled that in a 70-kg woman in whom ^{99m}Tc is uniformly distributed and has an infinite biologic half-time, the dose to the embryo from nonpenetrating radiations would be 0.0044 rads per millicurie administered. This is approximately an order of magnitude less than the value given in Table 3 for this radiopharmaceutical, which does include the fraction of ^{99m}Tc uniformly distributed in the total body in the dose estimate.

Before the values given in Tables 1–3 are used, the user should be fully aware of all the assumptions and limitations inherent in these values. The assumptions include the use of the S values (Table 2), which specify the anatomic model, a uniform distribution of activity in the source organ, a bladder containing 200 ml of urine, and the nuclear data.

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