USE OF TISSUE-TO-AIR RATIO IN COMPUTATION OF SPECIFIC ABSORBED FRACTION

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This paper describes a new approach for computing specific absorbed fractions that can be used for estimating doses that result from the internal administration of radiopharmaceuticals. This approach uses the concept of the tissue-to-air ratio (TAR) which can either be calculated or experimentally determined for the radionuclides of interest. Good agreement exists between the specific absorbed fraction values obtained using measured and computed values of TAR. This implies that the measured values of TAR can be used to obtain specific absorbed fractions for all radionuclides.

The estimation of dose from internally administered radiopharmaceuticals is at present based on the concepts of absorbed fraction and specific absorbed fraction, Φ (*1*). Brownell, et al (*2*) have used the Monte Carlo technique for such dose computations. Berger (*3*) has used the Moments method to solve the energy transport equations to obtain energy absorption buildup factors that, in turn, were used to calculate the dose. The present paper deals with a different approach wherein the concept of the tissue-to-air ratio (TAR) is used to obtain specific absorbed fraction.

RELATIONSHIP BETWEEN TAR AND Φ

TAR is extensively used for the dose computations in beam therapy (*4*). For point isotropic source, the tissue-to-air ratio can be defined as TAR = dose to a small mass of tissue in phantom from a point isotropic source/dose to the same mass of the tissue in free space from the source.

TAR can be calculated from energy absorption buildup factors as shown below and can also be experimentally measured. From the definition of TAR, it is evident that the dose rate, D_m, in tissue at a point distance X cm from the point isotropic source of 1 mCi activity is:

$$D_m = \frac{\mathrm{TAR}\ (X)}{X^2} \sum_{i=1}^{N} \tau_i \cdot f_i \quad \text{rad/mCi-hr} \qquad (1)$$

where TAR (X) is tissue-to-air ratio at a distance X cm from a point isotropic source that emits N photons per disintegration, τ is specific gamma-ray emission constant in R-cm^2/mCi-hr, and f is roentgen-to-rad conversion factor in rad/R.

It should be noted that TAR as used in Eq. (1) is the experimental value and when the theoretical value is used, it must be weighted for all the energies emitted by the isotope.

The energy rate, E_m, emitted by the source is given by:

$$E_m = 2.134 \times 10^3 \sum_{i=1}^{N} n_i E_i \quad \text{g-rad/mCi-hr} \qquad (2)$$

where n_i is the average number of the ith photon of energy E_i megavolt emitted per disintegration.

By definition, the ratio D_m/E_m is the specific absorbed fraction Φ (X). Hence,

$$\Phi\ (X) = \frac{4.686 \times 10^{-4} \cdot \mathrm{TAR}\ (X) \sum_{i=1}^{N} \tau_i \cdot f_i}{X^2 \sum_{i=1}^{N} n_i \cdot E_i}\ g^{-1} \qquad (3)$$

COMPUTATION OF TAR

From first principles, it can easily be shown that the general expression for TAR is given by the following expression:

$$\mathrm{TAR}\ (X) = \frac{\sum_{i=1}^{N} n_i \cdot E_i \cdot (\mu_{en}/\rho)_{air,\,i} \cdot f_i \cdot B_{en}\ (\mu_i x) \cdot e^{-\mu_i x}}{\sum_{i=1}^{N} n_i \cdot E_i \cdot (\mu_{en}/\rho)_{air,\,i} \cdot f_i} \qquad (4)$$

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TABLE 1. SPECIFIC ABSORBED FRACTION Φ (X) FOR POINT-ISOTROPIC SOURCE OF ^{198}Au IN WATER

Photon energies* (6): $E_1 = 1.0877$ (0.2%), $E_2 = 0.6759$ (0.98%), and $E_3 = 0.4118$ (95.8%) MeV. $f_1 = 0.966$, $f_2 = 0.968$, and $f_3 = 0.967$.

X (cm)	TAR (X)	Φ (X), g^{-1} based on Eqs. 4 and 5	Φ (X), g^{-1} based on Shalek, et al (5) TAR values and Eq. 4
1	1.00272	2.620E–03	2.664E–03
2	1.00665	6.590E–04	6.622E–04
5	0.99889	1.040E–04	1.039E–04
8	0.96630	3.930E–05	3.884E–05
10	0.93490	2.434E–05	2.345–05
12	0.89354	1.615E–05	—
15	0.82238	9.515E–06	—
18	0.74368	5.975E–06	—
20	0.68710	4.472E–06	—
25	0.55137	2.297E–06	—
30	0.42824	1.239E–06	—

The digits following the symbol E indicate the powers of 10 by which each number is to be multiplied.
* X-ray energies used in the calculation of Φ (X) are not listed here but can be obtained from (6).

TABLE 2. SPECIFIC ABSORBED FRACTION Φ (X) FOR POINT-ISOTROPIC SOURCES OF ^{137}Cs AND ^{60}Co IN WATER

Cobalt-60 energies (6): $E_1 = 1.1732$ (99.8%), and $E_2 = 1.3325$ (100%) MeV. Cesium-137 energy* (6): $E = 0.6616$ MeV (84%).

	Specific absorbed fraction Φ (X), g^{-1}			
X	^{137}Cs		^{60}Co	
(cm)	a†	b‡	a†	b‡
1	2.574E–03	2.596E–03	2.304E–03	2.312E–03
2	6.377E–04	6.423E–04	5.674E–04	5.709E–04
3	2.805E–04	2.482E–04	2.496E–04	2.496E–04
4	1.559E–04	1.567E–04	1.373E–04	1.377E–04
5	9.848E–05	9.886E–05	8.631E–05	8.617E–05
6	6.739E–05	6.755E–05	5.882E–05	5.841E–05
7	4.872E–05	4.872E–05	4.235E–05	4.184E–05
8	3.666E–05	3.653E–05	3.174E–05	3.123E–05
9	2.842E–05	2.819E–05	2.452E–05	2.407E–05
10	2.256E–05	2.223E–05	1.938E–05	1.905E–05

The digits following the symbol E indicate the powers of 10 by which each number is to be multiplied.
* X-ray energies used in the calculation of Φ (X) are not listed here but can be obtained from (6).
† Φ (X) calculated using TAR values completed with the help of Eq. 5.
‡ Φ (X) computed using TAR values of Shalek, et al (5).

where $(\mu en/\rho)_{air}$ is mass energy absorption coefficient in air, in cm^2/gm; μ is linear attenuation coefficient in tissue at the source energy, in cm^{-1}; and Ben(μx) is energy absorption buildup factor at a distance X cm from a point isotropic source in units of mean free path.

RESULTS AND DISCUSSION

Tissue-to-air ratios for radionuclides commonly used in nuclear medicine are not available. We have attempted to compare specific absorbed fractions of ^{198}Au, ^{60}Co, and ^{137}Cs as obtained by using experimentally determined TAR and calculated TAR in order to establish that measured TAR can as well be used for the estimation of Φ (X). For computations, the energy absorption buildup factors for specific photon energies of radionuclides were obtained by appropriate interpolations of Berger's results.

Shalek, et al (5) have published TAR values for a number of isotopes commonly used in brachytherapy. The values are available only up to 10 cm depth and they are the mean of all experimental data and theoretical values computed by them. The coefficients of a third-degree polynomial fitting TAR values thus obtained have also been published by these authors.

Φ (X) values obtained by substituting TAR values derived from these coefficients and calculated theoretically are compared for ^{198}Au in Table 1 and for ^{60}Co and ^{137}Cs in Table 2. The close agreement between the experimental and the theoretical results demonstrates that the measured TAR values can be successfully used to compute Φ (X).

Φ (X) values for other radionuclides used in nuclear medicine have also been computed. As an example, Table 3 gives Φ (X) values for ^{99m}Tc which

TABLE 3. SPECIFIC ABSORBED FRACTION Φ (X) FOR POINT-ISOTROPIC SOURCE OF ^{99m}Tc IN WATER

Photon energies (6): $E_1 = 0.1405$ (88.3%) and $E_2 = 0.1427$ (0.03%) MeV. $f_1 = 0.9575$ and $f_2 = 0.9601$.*

X	TAR (X)	Φ (X), g^{-1} based on Eqs. 4 and 5
1	1.09499	2.374E–03
2	1.18140	6.403E–04
5	1.35408	1.174E–04
8	1.40946	4.774E–05
10	1.38721	3.007E–05
12	1.33377	2.007E–05
15	1.19772	1.154E–05
18	1.04264	6.976E–06
20	0.93743	5.080E–06
25	0.67661	2.347E–06
30	0.46245	1.114E–06

The digits following the symbol E indicate the powers of 10 by which each number is to be multiplied.
* X-ray energies used in the calculation of Φ (X) are not listed here but can be obtained from (6).

is a commonly used isotope in nuclear medicine procedures. These Φ (X) values are based on computed TAR values as measured values of TAR are not available at present. Once such measured TAR values become available, this approach will not require the use of computed values of energy absorption buildup factors. Experiments are in progress to obtain the TAR values for this and the other commonly used radionuclides.

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