

THE MIRD METHOD OF ESTIMATING ABSORBED DOSE

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ABSTRACT

The estimate of absorbed radiation dose from internal emitters provides the information required to assess the radiation risk associated with the administration of radiopharmaceuticals for medical applications. The MIRD (Medical Internal Radiation Dose) system of dose calculation provides a systematic approach to combining the biologic distribution data and clearance data of radiopharmaceuticals and the physical properties of radionuclides to obtain dose estimates. This tutorial presents a review of the MIRD schema, the derivation of the equations used to calculate absorbed dose, and shows how the MIRD schema can be applied to estimate dose from radiopharmaceuticals used in nuclear medicine.

INTRODUCTION

The MIRD Committee, organized within the Society of Nuclear Medicine in the 1960's, has been and remains a group active in; 1) preparing absorbed dose estimate reports based on radionuclide distribution kinetics in humans, 2) compiling, processing and publishing physical factors needed for dose calculations and 3) developing and publishing methods of dose computation, for the nuclear medicine community. Beginning with its first publication of the original MIRD Schema in 1968 (1), the committee has worked on methods of dose calculation over the last 23 years. During this time, the committee has prepared 13 MIRD pamphlets, 2 revised pamphlets, and 2 monographs concerned with methods of dose calculation, units, symbols, models and decay schemes (1-17). The most recent major publications of the committee are the MIRD Primer for Absorbed Dose Calculations published in 1988 (16) and the MIRD: Radionuclide Decay Data and Decay Schemes monograph published in 1989 (17). The primer details the derivation and explanation of the MIRD schema with examples that show application of the methodology and the decay scheme monograph provides the physical half-life, decay constant, mode of decay, and information on the energies and intensities of the radiations emitted by 242 radionuclides of interest in diagnostic or therapeutic nuclear medicine.

Since 1973, the committee has published 14 dose estimate reports in the Journal of Nuclear Medicine that provide absorbed dose estimates for selected radiopharmaceuticals based on biologic distribution and clearance data collected in human subjects. The first 12 of these dose estimates were compiled for inclusion in the MIRD Primer for Absorbed Dose Calculations (16). These include dose estimates for Se-75-L-selenomethionine, Ga-66-, Ga-67-, Ga-68-, and Ga-72-citrate, Tc-99m-sulfur colloid, Au-198-colloidal gold, I-123, I-124, I-125, I-126, I-130, and I-131 as sodium iodide, Hg-197- and Hg-203-labeled chloromerodrin, I-123, I-124, I-126, I-130, and

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I-131 as sodium rose bengal, Tc-99m as sodium pertechnetate, Xe-127, Xe-129m, Xe-131m, and Xe-133 as the elemental gas or in saline, Tc-99m labeled albumin microspheres, Fe-52, Fe-55, and Fe-59 as chloride, citrate or sulfate, and Tc-99m diethylenetriaminepentaacetic acid. The two latest dose estimate reports on Tc-99m-MDP, Tc-99m-HMDP, Tc-99m-HEDP, and Tc-99m-PP_i and on Tc-99m-labeled red blood cells were published recently in the Journal of Nuclear Medicine (18,19).

BACKGROUND

Direct measurements of absorbed dose and dose distributions in vivo for administered radiopharmaceuticals are difficult to perform and are infrequently made. The MIRDO schema provide a systematic and a well documented means of calculating estimated absorbed dose. The schema use the fraction of photon energy emitted from a source organ that is deposited in a target organ as the basis for calculating dose from the biodistribution and clearance of administered activity and the decay properties of the radionuclide. The tabular values of the fraction of energy deposited in target organs, termed the absorbed fraction in MIRDO terminology, are based on Monte Carlo calculations of photon histories for photons emitted from source organs and photons deposited in target organs in a mathematically defined adult anthropomorphic phantom (6).

DOSE ESTIMATE

Basic Assumptions and Derivation of the Dose Equation

The absorbed dose from internal emitters refers to the amount of energy from ionizing radiation that is deposited per unit mass of tissue. The dose to different tissues is dependent on the biological distribution of the activity and the physical properties of the particles emitted by a radionuclide. The MIRDO schema provides the methodology to combine these quantities to estimate dose. An outline of the derivation of the MIRDO schema follows. A complete discussion can be found in the MIRDO primer (16).

The calculations of absorbed dose is fundamentally a two step process in which activity is converted into energy emitted and, this in turn, is converted into energy absorbed in the target per unit mass. In a source containing activity, A , all nuclear transitions that occur within the source are summed; this is termed cumulated activity, \tilde{A} . The energy emitted by the radionuclide is calculated for each discrete nuclear transition in its decay as:

$$\Delta_i = n_i E_i \quad (1)$$

where Δ = mean energy emitted per nuclear transition

n = number of particles per transition

E = mean energy per particle

i = index to designate type of radiation transition

Depending on the energy and type of particles emitted, the size and shape of the source and target, and the distance between the source and target, a variable fraction of the emitted energy contributes to energy absorbed in the target. This fraction is the absorbed fraction, Φ_i . The product of \bar{A} , Δ_i and Φ_i yields the energy absorbed in the target:

$$\text{Energy Absorbed} = \bar{A} \Delta_i \Phi_i \quad (2)$$

Introducing the term absorbed fraction/unit mass, ϕ_i / m , defined as the specific absorbed fraction Φ_i , the absorbed dose to the target from radiation i is calculated as:

$$\bar{D}_i = \bar{A} \Delta_i \phi_i / m \quad (3)$$

$$= \bar{A} \Delta_i \Phi_i \quad (4)$$

Tabulation of the product of $\Delta_i \Phi_i$ assigned the symbol S_i , reduces the equation for dose to

$$\bar{D}_i = \bar{A} S_i \quad (5)$$

Expressing the dose in terms of dose per administered activity, an additional quantity, residence time τ , is introduced. The residence time in the source is defined as

$$\tau = \bar{A} / A_0 \quad (6)$$

where A_0 is the administered activity. The mean dose to the target per unit administered activity from radiation i then becomes

$$\bar{D} / A_0 = \tau S_i \quad (7)$$

Extending these equations to account for a variable number of source organs contributing to the dose in a target organ, and to include more than one radiation emitted from a radionuclide, yields the MIRD equations to calculated dose. The source and target organs in these equations are identified as h and k , respectively. The absorbed fraction of radiation type i in target r_k for source r_h is expressed as $\phi_i(r_k \leftarrow r_h)$; and the specific absorbed fraction of radiation type i in target r_k from source r_h is expressed as $\Phi_i(r_k \leftarrow r_h)$. Using a summation sign (Σ) to indicate the addition of a various types of radiation and sources, the mean absorbed dose in target r_k from source r_h can be written:

$$\bar{D}(r_k \leftarrow r_h) = \bar{A}_h \sum_i \Delta_i \phi_i(r_k \leftarrow r_h) / m_k \quad (8)$$

$$= \bar{A}_h \sum_i \Delta_i \Phi_i(r_k \leftarrow r_h) \quad (9)$$

$$\text{With } S(r_k \leftarrow r_h) = \sum_i \Delta_i \Phi_i(r_k \leftarrow r_h)$$

$$\bar{D}(r_k \leftarrow r_h) = D_k = \bar{A}_h S(r_k \leftarrow r_h) \quad (10)$$

where \bar{A}_h = cumulated activity in source organ r_h

m_k = mass of target organ r_k

Δ_i = equilibrium dose constant

$\phi_i(r_k \leftarrow r_h)$ = absorbed fraction for target organ r_k for i -type radiation emitted from source organ r_h

$\Phi_i(r_k \leftarrow r_h)$ = specific absorbed fraction for target organ r_k for i -type radiation emitted from source organ r_h

S = mean absorbed dose to target organ r_k per unit cumulated activity in source organ r_h

To account for more than one source organ r_h contributing to dose in the target organ r_k , the summation of the individual source to target doses are obtained as follows:

$$\bar{D}(r_k) = \sum_h \bar{D}(r_k \leftarrow r_h) \quad (11)$$

Expressed as a mean absorbed dose to target r_k per unit administered activity A_0 , equation 11 becomes

$$\bar{D}(r_k) / A_0 = \sum_h \tau_h S(r_k \leftarrow r_h) \quad (12)$$

The notation is sometimes further simplified and the equation is written in the form,

$$\bar{D}_k / A_0 = \sum_h \tau_h S(k \leftarrow h) \quad (13)$$

Dose Calculations

Several publications of the MIRD committee, in addition to the MIRD Primer, can provide assistance in the performance of dose calculations using the MIRD schema. The tabulation of absorbed fractions and specific absorbed fractions for 25 target organs and 16 source organs for 12 monoenergetic photon source energies ranging from 10 keV to 4 MeV can be found in MIRD Pamphlets No. 5 and No. 5R (6,7). A mathematical description of the adult anthropomorphic phantom with internal organs and the elemental composition and density of the phantom and organs used in the Monte Carlo calculation of absorbed fractions are described in the same publication. A similar compilation of ϕ_i and Φ_i for small spheres, cylinders, ellipsoids and other basic shapes are computed and tabulated in pamphlets No. 3 and No. 8 (4,10).

To simplify dose calculations for most routine applications, the MIRD committee has prepared tables of S values for 120 radionuclides based on the specific absorbed fraction calculations using the adult anthropomorphic phantom. These S-value tables for 20 target-organ and source-organ pairs for 120 radionuclides are published in MIRD Pamphlet No. 11 (13). Using these tables, dose calculations are a relatively simple multiplication requiring the user to only supply the residence time, τ_h , or cumulated activity, \tilde{A} , for the source organs of interest. The reader is referred to the MIRD Primer for a detailed discussion on the various approaches to calculating cumulative activity, \tilde{A} , and residence time, τ_h , and for examples of dose calculations that demonstrate the use of the MIRD schema.

SUMMARY

The MIRD schema provide a systematic and dependable approach to estimating absorbed radiation dose from internal emitters in nuclear medicine. Continuing work by the MIRD committee on the development of new dosimetric models is expected to lead to improvements in the accuracy of the methodology. Revised absorbed fraction and S-value tabulations that are now being developed by the MIRD committee include data based on additional organ models. The committee continues to consider small scale dosimetry at the cellular level to better define focal regional energy deposition, however, the formalism of the MIRD schema has not been extended to do these calculations. The MIRD schema as presented here remain the primary approach to calculating estimated absorbed dose for radiopharmaceuticals in nuclear medicine.

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REFERENCES

1. Loevinger R, Berman M (1968) The Society of Nuclear Medicine: MIRD Pamphlet 1. *J Nucl Med* 9(suppl 1):7-14
2. Loevinger R, Berman M (1976) The Society of Nuclear Medicine: MIRD Pamphlet 1, revised
3. Berger MJ (1968) The Society of Nuclear Medicine: MIRD Pamphlet 2. *J Nucl Med* 9 (suppl 1):15-25
4. Brownell GL, Ellen WH, Reddy AR (1968) The Society of Nuclear Medicine: MIRD Pamphlet 3. *J Nucl Med* 9(suppl 1):27-39
5. Dillman LT (1969) The Society of Nuclear Medicine: MIRD Pamphlet 4. *J Nucl Med* 10(suppl 2):5-32
6. Snyder WS, Ford MR, Warner GG, Fisher HL, Jr (1969) The Society of Nuclear Medicine: MIRD Pamphlet 5. *J Nucl Med* 10(suppl 3):5-52
7. Snyder WS, Ford MR, Warner GG (1978) The Society of Nuclear Medicine: MIRD Pamphlet 5, revised
8. Dillman LT (1970) The Society of Nuclear Medicine: MIRD Pamphlet 6. *J Nucl Med* 11(suppl 4):5-32
9. Berger MJ (1971) The Society of Nuclear Medicine: MIRD Pamphlet 7. *J Nucl Med* 12 (suppl 5):5-23
10. Ellen WH, Humes RM (1971) The Society of Nuclear Medicine: MIRD Pamphlet 8. *J Nucl Med* 12(suppl 5):25-32
11. Lathrop KA, Johnston RE, Blau M, Rothschild EO (1972) The Society of Nuclear Medicine: MIRD Pamphlet 9. *J Nucl Med* 13(suppl 6):7-30
12. Dillman LT, Von der Lage FC (1975) The Society of Nuclear Medicine: MIRD Pamphlet 10
13. Snyder WS, Ford MR, Warner GG, Watson SB (1975) The Society of Nuclear Medicine: MIRD Pamphlet 11
14. Berman M (1977) The Society of Nuclear Medicine: MIRD pamphlet 12
15. Coffey JL, Cristy M, Warner GG (1981) The Society of Nuclear Medicine: MIRD Pamphlet 13. *J Nucl Med* 22:65-71
16. Loevinger R, Budinger TF, Watson EE (1988) MIRD Primer for Absorbed Dose Calculations. The Society of Nuclear Medicine, New York. pp 128
17. Weber DA, Eckerman KF, Dillman LT, Ryman JC (1989) MIRD: Radionuclide Data and Decay Schemes. The Society of Nuclear Medicine, New York. pp 447
18. Weber DA, Makler PT, Watson EE, Coffey JL, Thomas SR, London J (1989) *J Nucl Med* 30:1117-1122
19. Atkins HL, Thomas SR, Buddemeyer U, Chervu LR (1990) *J Nucl Med* 31:378-380