Nuclear Medicine Dose Equivalent: A Method for Determination of Radiation Risk

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Conventional nuclear medicine dosimetry involves specifying individual organ doses. The difficulties that can arise with this approach to radiation dosimetry are discussed. An alternative scheme is described that is based on the ICRP effective dose equivalent, H_E, and which is a direct estimate of the average radiation risk to the patient. The mean value of H_E for seven common ^{99m}Tc nuclear medicine procedures is 0.46 rem and the average radiation risk from this level of exposure is estimated to be comparable to the risk from smoking ~ 28 packs of cigarettes or driving ~ 1,300 miles.

Conventional radiation dosimetry in nuclear medicine is concerned with the mean absorbed dose to individual organs and tissues. This paper discusses the problems associated with this approach to dosimetry and introduces the effective dose equivalent (H_E), which is directly proportional to the estimate of the radiation risk to the patient undergoing a nuclear medicine examination. Calculations of the value of H_E for a range of nuclear medicine procedures are presented and these radiation risk estimates are compared with the risks of death associated with smoking cigarettes and driving automobiles.

PROBLEMS OF CONVENTIONAL DOSIMETRY

Table 1 presents the typical type of radiation dosimetry information associated with a diagnostic procedure that is currently available to the nuclear medicine community. There are a number of problems with expressing radiation doses in this manner. These all relate to the fact that the dose distribution is not uniform and the fundamental parameter that is generally required is the overall risk to the patient, which is not directly obtainable from information of the type shown in Table 1. Examples of these difficulties include the large differences in the radiosensitivities of different organs and the problems of the additivity of differing types of procedures that involve ionizing radiation. Furthermore, it is very difficult to make meaningful intercomparison between the radiation risks of differing types of procedures and to compare these risks with, for example, the whole-body dose limits for atomic radiation workers and members of the public or other types of risks encountered in everyday life, when presented only with the data in Table 1.

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TABLE 1. Radiation Dose Estimates for Renal ^{99m}Tc Complexes (rem/mCi)

Item	DMSA	GHA	Iron ascorbate	DTPA	Gluconate
Renal cortices	0.76	0.20	–	–	–
Whole kidneys	0.62	0.17	0.27	0.042	0.21
Bladder mucosa	0.28	0.80	–	0.55	0.12
Liver	0.02	0.01	–	–	–
Ovaries	0.022	0.020	–	0.019	–
Blood	0.019	0.010	–	–	–
Total body	0.016	0.007	0.008	0.016	0.006

RADIATION RISKS ESTIMATES

The principal radiation risks in diagnostic nuclear medicine studies are the nonstochastic processes of carcinogenesis and genetic effects. In addition, there are also fetal risks (embryonic death, malformation during organogenesis, and elevated incidence of childhood cancer) because of the very small number of cases of pregnant women undergoing nuclear medicine studies. From a radiation risks perspective, it is important to note that there is generally no possibility of nonstochastic (dose threshold) effects, such as skin erythema and epilalation, that would require explicit knowledge of individual organ doses.

The human evidence for carcinogenesis, which is the major risk of concern in diagnostic nuclear medicine, is shown in summary form in Table 2. Collectively, these data demonstrate a causal relationship between ionizing radiation dose and cancer for doses in excess of the order of 50 rem. (For the low-LET radiation encountered in nuclear medicine, rads are equivalent to rems, and the latter term is employed throughout this paper.) This human-based information has been reviewed by a number of international organizations, such as the International Commission on Radiological Protection (ICRP) (*1*), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (*2,3*), and the U.S. National Academy of Sciences (BEIR) (*4*). The uncertainties associated with the radiation risks at low doses are significant and the data in Table 3 show a summary (*5*) of the currently available radiation risk estimates from the ICRP, UNSCEAR, and BEIR. These data show that the typical differences

TABLE 2. Human Data on Carcinogenesis

Exposed group	Comments
Early radiologists/physicists	Small number of individuals.
Uranium miners	Inhalation of alpha-emitting aerosols.
Radium dial painters	Ingestion of radium-226, which deposits in bone.
Thorotrast patients	Elevated incidence of liver cancer.
A-Bomb survivors	Largest group studies to date—very important for quantitative risk estimates.
Ankylosing spondylitis patients	Radiotherapy patients—high doses.
Enlarged thymus patients (children)	Radiotherapy patients—elevated incidence of thyroid cancer.
Fluoroscopy (TB) patients	Elevated incidence of breast cancer in women.
Tinea capitis patients	Radiotherapy patients—scattered radiation to thyroid.
Prenatal x-ray exposure	United Kingdom study—interpretation of results problematic.

between the different risk models and extrapolation models are factors of 2–3. In using radiation risk estimates, it is important to note that the figures summarized in Table 3 are average risk estimates and there may be sizable differences depending on the age and sex of the exposed individual. Furthermore, there is a latent period which may be of the order of decades before the expression of the radiation induced cancer.

THE EFFECTIVE DOSE EQUIVALENT (H_E)

Table 4 shows the ICRP (*1*) radiation risk coefficients for individual organs. The risk value for the gonads relates to serious genetic effects in the first two generations and is an average value for a typical adult working population. The remaining tissues have a cumulative radiation risk of 50×10^{-6} per rem with no individual organ or tissue being assigned a risk value of $> 10 \times 10^{-6}$ per rem and no more than 5 organs or tissues being taken into consideration. Thus, the total whole body risk is 165×10^{-6} rem^{-1}, with a weighting factor of 1.00. From these data, the relative risk of any irradiated organ i can be readily evaluated and is given by the term W_i in the last column of Table 4. The effective dose equivalent, H_E, is then defined as:

$$H_E = \sum W_i H_i \qquad \text{Eq. 1}$$

where W_i is the weighting factor for organ i, and H_i is the radiation dose (equivalent) to organ i.

TABLE 3. Estimated Excess Mortality per Million Persons per rem from All Forms of Cancer*

Source of risk estimate	Absolute risk model	Relative risk model	Comments	
BEIR (1980)	10	28	Quadratic	Based on 10 rem exposure
	77	226	Linear-quadratic	
	167	501	Linear	
ICRP (1977)	126	—	—	
UNSCEAR (1977)	75–175	—	—	

*The "natural" cancer mortality rate is ~160,000 per million.

DISCUSSION

The interpretation of H_E for a partial body irradiation is that it corresponds to the same risk as a uniform whole-body radiation dose of H_E. The advantages of using H_E are that it is a direct estimate of risk and is therefore additive, and is directly comparable to the H_E value of other procedures involving ionizing radiations. Furthermore, it can be directly compared to current legal radiation dose limits of 5 rem/yr for atomic radiation workers in Canada and 0.5 rem/yr for members of the public. These risk estimates can also be used directly to compare the radiation risks with other types of risks to which individuals are exposed. Some rough estimates of the risk of smoking are 1.37×10^{-7} deaths per cigarette, and the risk of dying in an automobile accident in North America are 5.6×10^{-8} deaths per mile driven (*6*). The radiation risk from an effective dose equivalent of 1 rem is 165×10^{-6} (*1*) and is therefore comparable to the risk of dying from smoking a pack of 20 cigarettes each day for 2 mo (1,200 cigarettes) or the risk of dying in an automobile from the miles driven by an average individual in ~ 3 mo (2,900 miles).

H_E FOR TYPICAL NUCLEAR MEDICINE PROCEDURES

From the knowledge of the biodistribution of radioactivity

TABLE 4. Summary of Risk Coefficients

Organ	Risk coefficient rem^{-1} ($\times 10^{-6}$)	Weighting factor W_i
Gonads	40	0.25
Breast	25	0.15
Red bone marrow	20	0.12
Lung	20	0.12
Thyroid	5	0.03
Bone surfaces	5	0.03
Remaining tissues	50	5 @ 0.06*

*A value of $W_i = 0.06$ is assigned to five organs of remaining tissues with the highest doses.

TABLE 5. Calculation of H_E—the Effective Dose Equivalent—for ^{99m}Tc-DMSA*

Organ	Radiation dose rads/mCi (H_i)	Weighting factor (W_i)	$W_i \times H_i$
Renal cortices	0.76	0.06	0.046
Whole kidneys	0.62	0.06	0.037
Bladder mucosa	0.28	0.06	0.017
Liver	0.02	0.06	0.001
Ovaries	0.022	0.25	0.006
Blood	0.019	0.06	0.001
Total body	0.016	1.00	0.016

*Total $H_E = \sum W_i H_i = 0.124$ rem/mCi.

of any given radiopharmaceutical, it is relatively straightforward to obtain the radiation dose values for any given organ (*7*) and to generate radiation dosimetry data of the type shown in Table 1. On the basis of individual organ dose data, one can readily generate an effective dose equivalent (H_E) value as shown by the example in Table 5 for ^{99m}Tc-labeled DMSA using the organ dose data given in Table 1. In this example, the renal cortices and kidneys have been treated as separate organs, and the blood has also been treated as a separate organ. The value of H_E in this example is 0.12 rem/mCi injected activity. Using radiation dosimetry data available in the literature (*8*), the values of H_E for routine nuclear medicine procedures are shown in Table 6. The most common procedures are those involving ^{99m}Tc-labeled radionuclides, and the mean value of H_E for the seven ^{99m}Tc studies listed in Table 6 is 0.46 rem, which is comparable to the 0.5 rem annual whole-body dose limit for the general public (*1*). The average radiation risk from this level of exposure is thus estimated to be comparable to the risk from smoking ~ 28 packs of cigarettes or driving ~ 1,300 miles. This value can also be compared to the H_E dose equivalents associated with CT examinations, in which a typical head CT scan has a H_E of 0.084 rem, a chest CT scan 0.48 rem, and an abdominal CT scan 0.26 rem (*9*).

TABLE 6. H_E Values for Nuclear Medicine Procedures

Nuclide	Chemical form	Activity injected	H_E rem
^{99m}Tc	Pertechnetate	20 mCi	0.82
^{99m}Tc	Pyrophosphate	20 mCi	0.44
^{99m}Tc	Gluconate	20 mCi	0.74
^{99m}Tc	DTPA	20 mCi	0.46
^{99m}Tc	Red blood cells	20 mCi	0.52
^{99m}Tc	Sulphur colloid	3 mCi	0.14
^{99m}Tc	MAA	3 mCi	0.13
^{67}Ga	Citrate	3 mCi	3.4
^{201}Tl	Chloride	2 mCi	0.7
^{111}In	White blood cells	500 μCi	1.2
^{111}In	DTPA (CSF)	500 μCi	0.047
^{131}I	Orthoiodohippuric acid (hippurate)	200 μCi	0.09
^{131}I	Sodium—Iodide (15%) (oral)	5 μCi	0.12
^{131}I	Sodium—Iodide (35%) (oral)	5 μCi	0.30
^{123}I	Sodium—Iodide (15%) (oral)	200 μCi	0.054
^{123}I	Sodium—Iodide (35%) (oral)	200 μCi	0.13

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