RADIATION HAZARDS FROM INTERNAL EMITTERS: CALCULATION OF ABSORBED DOSE AND EFFECTIVE DOSE EQUIVALENT

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Introduction

The absorbed dose from radioactive material incorporated in man is rarely, if ever, uniform throughout the body. The true non-uniform radiation exposure can be converted mathematically to an equivalent whole body dose without changing the risk of damage induced by radiation. It would be more logical to calculate the risk caused by radiation directly. However, the absolute risk factors of the late effects are not known accurately; the uncertainty may even be of the order of magnitude. Thus it is preferable to approach the risk assessment with relative risk factors or weighting factors (w). The International Commission on Radiological Protection, ICRP, has used this technique to convert the dose equivalents H_T (Sv) of single organs to the effective dose equivalent $H_E = \sum_T w_T H_T$.

Detailed information on the harmful effects of the different types of radiation is needed to convert the doses absorbed by the organs to the dose equivalents or to the risk of somatic and genetic harm. At present, however, there is no unambiguous way to compare the hazard of one type of radiation with another; the comparison depends on the biological end point. The ability to kill growing cells and the effectiveness of malignant transformation depend greatly and in different ways, on the radiation quality, e.g. on LET. In addition to the absorbed dose, many other factors - biological and environmental variables - have a great influence on the risk of clinical cancer.

Dose Calculation

The present system of dose calculation makes good use of precalculated S factors (the absorbed doses per unit cumulative activity) on the basis of the work of the MIRD committee.[2] The S factors are presently available only for the reference man (70 kg). Extensive additional Monte Carlo calculations would be required to give individual, or nearly individual S factors. In some special cases, however, the S factors calculated for the reference man can be converted fairly easily to individual values. For for the thyroid, a simple correction, proportional to the cube root of the mass of the gland, gives results nearly equal to those of more sophisticated methods; however, a discrepancy is detected in cases of enlarged thyroids.[3]

In the following formulation, different quality factors (Q_{np}, Q_p) are used for non-penetrating and penetrating radiation; however, they are omitted from the computer program because no reliable information is available. In fact, the method gives an effective absorbed dose rather than an effective dose equivalent. The goal is to avoid the direct calculation of any index for the biological hazard which contains too many poorly known or even unknown factors.

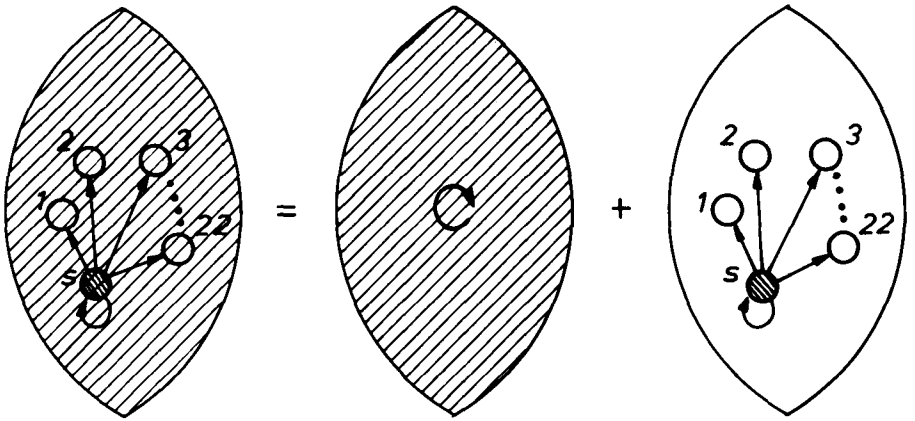

Fig. 1. Calculation of the effective dose equivalent (see Eq. (1)). The dose is obtained in two parts: from the uniform distribution of the activity and from the source organ(s) s.

Let us assume that the residence time τ_s (the cumulative activity per unit intake of radioactive material) in the source organ s and the residence time τ_{WB} in the whole body are known (measured). The activity outside the source organs is assumed to be uniformly distributed throughout the body. The effective dose equivalent is now calculated from the contribution of the uniform activity in the body and from the activity of the source organs:

$$H_E = \tau_u \left[Q_{np} S_{np}(WB \leftarrow WB) + Q_p S_p(WB \leftarrow WB) \right] + \sum_s \sum_i w_i \tau_s^* \left[Q_{np} S_{np}(i \leftarrow s) + Q_p S_p(i \leftarrow s) \right] \quad (1)$$

The residence times τ_s have to be corrected; otherwise part of the activity would be included in the equation twice:

$$\tau_s^* = \tau_s - \frac{m_s}{m_{RB}} \tau_{RB} \quad (2)$$

where the subscript RB refers to the remaining body, with residence time

$$\tau_{RB} = \tau_{WB} - \sum_s \tau_s \quad (3)$$

The residence time for the uniform activity in the whole body is simply

$$\tau_u = \tau_{RB} \frac{m_{WB}}{m_{RB}} \qquad (4)$$

In addition to the 23 organs considered in the program, other parts of the body are also exposed to radiation from the source organs. The contribution of this component - the remaining part (RP) of the body - could be assessed as follows:

$$D(RP) = \sum_s \tau_s^* S_p(RP \leftarrow s) \qquad (5)$$

An expression for the factor $S_p(RP \leftarrow s)$ was derived by Toivonen.[3] However, the contribution of Eq. (5) to the effective dose equivalent is small and can thus be excluded from the dose calculation.

The present computer program has been developed on the basis of the CAMIRD/III program.[1] CAMIRD/III is written in FORTRAN IV and was originally implemented on IBM 370/168. Using CAMIRD/III, the S factors were calculated (UNIVAC 1100) for 22 nuclides important in nuclear medicine. These results were transferred to an ECLIPSE S-140 computer. A PASCAL program (SMIRD) was developed to cope with the dose calculation. SMIRD makes use of files containing precalculated S factors for each radionuclide. A file comprises about 6500 ASCII characters. SMIRD is an interactive program including various types of checking of the input data. The absorbed dose is calculated by SMIRD for the desired target organ and the result is given separately for each source organ. In addition, the total absorbed doses of all organs are calculated and, for clear reporting, they are printed in descending order. The effective dose equivalent is calculated with the aid of ICRP weighting factors. These, however, have been normalized to give a weight of one for all the somatic effects; the gonad doses are calculated separately but they are not included in the effective dose equivalent. SMIRD is a fairly small program, about 450 PASCAL lines, and it can be easily implemented on different types of computer systems (available for VAX-11, PDP-11, PC-325, PC-350, CP/M-86, CP/M-80; Mimarobe Ltd, Tampere).

Application to ^{131}I with Stable Iodine

The residence times of a radionuclide in the source organs are the input data needed by the SMIRD program. The kinetics of the nuclides vary widely in different persons; the individual variability can be taken into account only by the direct measurement of the behaviour of the radioactive material in the body. However, the model studies can provide useful information to compare completely different exposure situations or to assess quantitatively the effect of different treatments or protection schedules. In the present study the kinetics of ^{131}I were simulated by a set of differential equations (the model can be used for all isotopes of iodine). The details of the model are given by Turai and Toivonen.[4]

Table 1 shows an example of the calculations of the prophylactic efficacy of 30 mg of potassium iodide (KI) given 0.5 h after the intake of ^{131}I. The model studies show that although the thyroid

gland can be protected effectively with KI (ratio 0.062), the total number of nuclear disintegrations in the body is reduced much less drastically (ratio 0.239). The reduced total risk of late effects is not described by the thyroid doses but rather by the effective dose equivalents. However, it is not at all clear, using the present weighting factors, that the effective dose equivalent is the true indicator of the radiation hazard.

Table 1. Residence times and radiation doses of different organs for ^{131}I; (a) unperturbed kinetics, (b) 30 mg potassium iodide given 0.5 h after the intake of radioiodine.

	(a)	(b)	Ratio (b/a)	
Residence times (h):				
thyroid	63.69	3.940	0.062	
blood (inorganic)	9.073	11.75	1.295	1.039
blood (organic)	2.377	0.147	0.062	
bladder	1.906	2.464	1.293	
lungs	0.164	0.164	1.	
total	77.21	18.47	0.239	
Radiation doses (μGy/MBq):				
thyroid	374000	23100	0.062	
bladder	646	831	1.286	
blood	330	283	0.858	
thymus	225	30.2	0.134	
lungs	82.2	36.5	0.444	
muscle	80.4	20.3	0.252	
red marrow	59.7	21.3	0.357	
skeleton	52.9	17.8	0.336	
skin	49.2	11.5	0.234	
uterus	39.3	45.7	1.163	
ovaries	25.6	28.4	1.109	
testes	20.5	23.0	1.122	
effective somatic dose equivalent (μSv/MBq)	15100	1040	0.069	

References:

1. Bellina C.R. and Gruzzardi R., CAMIRD/III: A Revised Version of the CAMIRD/II and MIRD S Packages for Internal Dose Calculation: Concise Communication. J. Nucl. Med. 1980(21), 379-383.
2. Snyder W.S., Ford M.R., Warner G.G. and Watson S.B., "S", Absorbed Dose per Unit Cumulated Activity for Selected Radionuclides and Organs. Medical Internal Radiation Dose Committee, MIRD pamphlet No. 11, N.Y., Society of Nuclear Medicine, 1975.
3. Toivonen H., Calculation of Patient Doses from Radioisotopes. Institute of Radiation Protection: STL-B47, Helsinki, 1983 (in Finnish).
4. Turai I. and Toivonen H., Radiohygiene of Fission Isotopes of Iodine: Experiments in Rats and Model Studies in Man. Institute of Radiation Protection: STL-A42, Helsinki, 1983.