DOSIMETRIC ASPECTS OF A FORTHCOMING REPORT OF ICRP ON INTERNAL EMITTERS*

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Abstract

The International Commission on Radiological Protection (ICRP) has recommended maximum permissible annual doses (MPAD) as a basis for protection of radiation workers. Committee 2 of ICRP attempts to provide secondary standards on annual intake which are based on these MPAD. This committee plans to issue a new handbook with complete text, but the first edition will contain only the radionuclides of some twenty elements which have been selected partly on the basis of their importance and partly to illustrate the method of calculation.

Some new features of the publication are the following: (1) If an intake of radioactivity occurs in a certain year, the total dose from this intake is attributed to this year, and this principle of dose commitment insures that workers do not become "unemployable" in radiation work due to early intake of a long-term emitter. (2) A new lung model provides more detailed information on the deposition and clearance rates of inhaled particulates and includes an adjustment of deposition with the activity median aerodynamic diameter. (3) Doses to active bone marrow and to endosteal cells are estimated for beta and gamma emitters depositing in bone. The methods of Spiers are used for these estimates. For alpha emitters, the Committee will continue to use the relative damage factor N pending more detailed information on the distribution of such emitters in the skeleton. (4) Dose from photons released in a large cloud of radioactivity is estimated by computing depth dose within the body by Monte Carlo techniques. (5) The report will use more accurate decay scheme data and improved retention models, and dose from photons will be estimated more accurately than in the old report.

To predict the course a committee may take is to predict the unpredictable, and this is especially true when one can only offer his own judgments. Nevertheless, my topic is that of expounding the dosimetric methods developed for the new report of ICRP Committee 2. Of course, the Committee can always change its direction or use a new bit of data that comes along, and thus it should not be cause for surprise if the judgments offered here turn out to be wrong sometimes. However, many of the dosimetric techniques the Committee plans to use have been developed at Oak Ridge National Laboratory by me and my colleagues, and this is what I will be speaking of for the most part.

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Present plans call for the Committee to publish an initial volume early in 1974 which is to contain a complete text and the procedure for dosimetry. This same report will contain recommendations on a certain number of radionuclides which will be chosen to illustrate the principles given in the text but which also are the more important ones for radiation protection. First of all, let us review the new recommendations that will be embodied in the report. These are:

(1) The principle of dose commitment is used as the controlling factor for occupational exposure to radionuclides of long half-time in the body. This principle is implicit in ICRP Publications 1 and 2,[1-2] but its use explicitly results in greater simplicity in that it allots to the year during which an intake occurred all the dose to be received from that intake during the worker's remaining life span (conventionally taken as 50 years). This is a simple recognition of the fact that the consequences of an early accumulation of a long-term body burden should be attributed to the operation which led to this intake. The principle that such intakes are not to be considered as routine is a healthy one for radiation protection.

(2) The total body as an organ supposedly uniformly exposed is de-emphasized, because this rarely, if ever, occurs. The average dose equivalent to the active bone marrow and the dose equivalent to endosteal cells lying near bone surfaces have been indicated as criteria for exposure of bone. In effect, these tissues replace bone insofar as one can implement the recommendation. The technical difficulties of estimating dose to these tissues will be discussed further below.

(3) The use of 1 as the value of Q for electrons and beta rays of low energy instead of 1.7 as used formerly is a simplification. Now electrons are on a par with photons since, for all these, dose is numerically equal to dose equivalent.

(4) Dose equivalent to pulmonic lymph nodes is not considered at this time. This decision of the Commission is based on biological evidence which, at present, indicates that exposure by inhalation appears to produce many more malignancies of lung tissue than malignancies associated with lymphatic tissue. Undoubtedly, experiments now in progress will be watched to assess more accurately the hazard to the lymph nodes.

There are other changes in the basic recommendations, and some of them will be referred to below; but none of these is as closely involved in the dosimetry of internally deposited emitters as are the foregoing. There will be many changes in retention models as will be seen, these applying for the most part to the early period postintake and, hence, being important principally for interpretation of excretion data or for radionuclides of short radiological decay times. Fortunately, relatively easy access to a whole body counter has made it possible in many cases for the health physicist to feel that he can determine intake and even retention to some extent, and this is a great help in meeting the recommendations which place considerable emphasis on control of intake. Unhappily, there are still radionuclides which cannot be measured with sufficient accuracy for the routine cases, and these offer considerable challenge to health physicists who must deal with them.

Several ICRP recommendations on internal emitters have been published since ICRP Publication 2 appeared in 1959, the most extensive being those in ICRP Publication 6.[3] Also, ICRP Publications 10[4] and 10A[5] provide some help in meeting practical problems. However, it is a tribute to Publication 2 that it has served so well for so many years.

A new model for deposition and retention, or clearance of particulates from the respiratory system, was formulated by the ICRP Task Group on Lung Dynamics (chaired by P. E. Morrow), and this was first published in Health Physics in 1966.[6] Although some of the parameters of the model have been revised several times since its first appearance, the model remains basically the same. The most notable of these revisions affects the clearance from lymph nodes. This had been conservatively chosen so that 90% of the deposition in these organs was eliminated only by radioactive decay and 10% with a long biological clearance time, as was indicated by the biological data available at that time. Since then, the long-term studies of dogs exposed to an aerosol of natural uranium[7] have given an indication that there is clearance from the lymph nodes, and the model has been revised so that now the situation is just the reverse--90% clearing with a long biological half-time and 10% eliminated only by radioactive decay. This is a striking example of how ICRP models are formed and changed as new data accumulate. At the moment, the Committee intends to average dose over the lungs as formerly. No doubt when the question of the lymph nodes is reconsidered and when the model is complete for gases and vapors, as well as for particulates, the question of reassessing doses to subregions of the lung will be reconsidered also.

A procedure for computing the time integral of activity (μCi-days) of the nuclide and of its daughters in the various subregions of the lung is derived, and the dose equivalent, H_k, to organ k is calculated by the formula

$$H_k = \sum_i \sum_j U_{ij} \times (SEE)_i (k \leftarrow j) \quad \text{rem}/\mu\text{Ci intake} \qquad (1)$$

where U_{ij} is the time integral of activity of daughter i in the lung or other source organ indexed by j, and $(SEE)_i (k \leftarrow j)$ is the specific effective energy for the i^{th} daughter with source organ j and target organ k, that is, the energy absorbed per gram in the target organ k per disintegration of the i^{th} daughter in the source organ j. In computing the $(SEE)_i (k \leftarrow j)$, the absorbed fractions of photon energy are computed as in MIRD Pamphlet No. 5.[8] In principle, j may be any organ of the body, and it is one of the unusual features of this dosimetry that cross irradiation of an organ by photons emitted in other organs is taken into account. The decay scheme information has been processed by the methods of Dillman[9] so full account is taken of internal conversion, Auger electrons, and other particles emitted. The U_{ij} are computed assuming the aerodynamic mean activity diameter (AMAD) is 1 μm, but a procedure is indicated which makes it possible to adjust the dose to any desired particle size in the respirable range. The dose equivalent per μCi inhaled will be given in the projected report for all organs for which the dose equivalent is 10% or more of its annual dose limit when the critical organ just attains its dose limit. An attempt will be made to list genetic dose especially, even though it may be only 1% of its limit, but the adequacy of the model will be taken into account also, that is, one requires that the biological information be reasonably adequate for activity contained in the gonads as well as for the surrounding organs.

The Committee intends to list also the maximum permissible annual intake (MPAI) by inhalation and the derived working level (DWL) which is the former $(MPC)_a$ in disguise. The reason for these changes is to emphasize that it is the annual intake and the dose commitment due to it that are basic in the Commission's recommendations, while there is no clear violation involved if the DWL is exceeded by a factor of 10 for a day or so. The report also will contain estimates of MPAI for intake by oral ingestion. However, no equivalent of the $(MPC)_w$ will be given, since the situation where the supply of drinking water is contaminated significantly rarely occurs in occupational exposure. In any case, the MPAI is the criterion for protection, and an equivalent concentration is easily obtained if it is wanted.

It will be noted that formula (1) only involves two variables, the U_{ij} and $(SEE)_i(k \leftarrow j)$. The estimation of the first of these involves the model for retention and is computed for each daughter element and for each source organ, here indexed by i and j, respectively. This requires that one have a retention model for each daughter element as well as for the parent. Biological data on these daughter elements is sparse indeed, and for many elements one will be reduced to guessing the behavior of the daughter, usually assuming it will remain in the organ where it is produced subject to elimination as would material recently deposited in the organ. Thus, if

$$\sum_i a_i e^{-\lambda_i t} \tag{2}$$

is the retention function for a daughter element in bone or liver or some other organ when the element is injected into blood, then

$$\sum_i a_i e^{-\lambda_i t} \Big/ \sum_i a_i \tag{3}$$

will be the retention function for that element when it is produced in the organ as a daughter element. There are a few elements where some biological data indicate exceptions to this, but they are very few. In fact, the question has hardly begun to be explored by the biologists. For most daughter elements, formula (3) is the basis for the dosimetry of that element when it is produced in an organ.

The estimation of $(SEE)_i(k \leftarrow j)$ involves a chapter of its own, beginning with the Task Group on Revision of Reference Man. This report, which is in press, gives organ weights and other biological data needed for dose estimation. Most of these data are embodied in a mathematical phantom which has been used to estimate absorbed fractions of photon energy for various source and target organs.[8] The phantom representation approximates the size, shape, density, position, and elemental composition of the various organs. A computer code uses this information to produce the specific effective energy, and in a sense the use of SEE values replaces the effective energies and F values of Publication 2. The decay scheme data used have been produced by the method of Dillman as was noted above.

Explicit formulae are given for the time integrals of retention in the gastrointestinal tract. The basis for this procedure is the report of Eve[10] which is almost unchanged except for new data on the masses of the small intestine and contents. Then dose is given by formula (1) as before. For photons, the absorbed fractions are computed using the anthropomorphic phantom described above, and dose from electrons and from alpha particles represents only a surface dose as in ICRP Publication 2. The inclusion of a modifying factor of 0.01 for alpha radiation originating in the contents of the tract is continued, since it rests on rather firm biological evidence indicating that the hazard of irradiation by alpha particles emitted in the contents of the tract is very small.[11] The Committee plans to give a dose per μCi of intake to organs with the same limitations on dose equivalent as for inhalation.

The dose equivalent for other organs is given by the same formula (1) as before, although the time integral of activities for the source organs will depend on the retention functions adopted. These retention functions are being completely re-examined and revised by the Committee. No attempt is being made to reduce them to a common form since each element will be treated separately on a few pages of the report, and thus the retention models will be independently developed. In each case there will be tables indicating the time integrals of retention and the SEE values for various source and target organs, and these will be given for the radionuclide and for each daughter element as required.

The only organ where the dosimetry has considerable novelty is the skeleton with its intricate intermixture of bone and bone marrow. Here the Committee is adopting the methods developed by Spiers for beta emitters.[12] Spiers has supplied to the Committee his latest estimates of the dose received by active bone marrow and by endosteal cells near cancellous bone or near cortical bone from a number of beta emitters of a variety of mean energies.[13] For other betas and electrons, the Committee will interpolate on the mean energy or unique energy of the particle to estimate the dose.

Unfortunately, Spiers' estimates are rather different when the source is in cancellous bone and when it is in cortical bone, and thus one should have independent estimates of the time integrals of activity in these two types of bone. There are very few radionuclides which deposit in bone for which we have this data, and these are nearly all due to the efforts of John Marshall, Chairman of the ICRP Task Group on Alkaline Earth Metabolism in Adult Man.[14] Marshall and his task group have supplied to the Committee their estimates of the time integrals of activity for all the isotopes of Ca, Sr, Ra, and Ba. This is a notable contribution and represents years of work, yet it is only a beginning. Clearly such estimates are needed for all bone-seekers, and this puts the burden squarely on the shoulders of the experimental biologist who must undertake the arduous task of documenting the distribution of the radionuclide in bone in considerable detail. In the absence of this data, the Committee is planning to consider all the activity to be present in cancellous bone. For most radionuclides of short radioactive decay time, this may not be far from the truth, but, clearly, better data are needed.

For alpha emitters depositing in bone, the Committee is forced, for lack of adequate data on distribution of the radionuclide in bone, to give up for the moment any attempt to calculate dose to the endosteal cells. Thus the dosimetry of the alpha emitters remains essentially that of ICRP Publication 2--namely, average dose equivalent in bone and use the N factor for the various radionuclides. The value $N = 5$ used previously still seems reasonably adequate and is retained. The ICRP Task Group on Metabolism of Plutonium and Related Elements and Their Compounds, chaired by Arthur Lindenbaum, has altered considerably the distribution of activity by recommending that deposition in the liver and in skeleton be considered as being equal. This may result in making liver the critical organ for some radionuclides.

In Publication 2 the modifying factor N has been given the value $N = 1$ for radium when it is the parent. This is because ^{226}Ra was considered a standard for bone-seeking radionuclides, and the carcinogenic potency was thought to be related to the distribution of dose within the skeletal system. However, the human data of Spiess and Mays,[15] as well as the animal data of Hug,[16] indicate that ^{224}Ra is a more effective carcinogen than is ^{226}Ra. The Committee plans to use the factor $N = 5$ for the radiums of short radioactive decay times when they are the parent radionuclide.

There remains immersion dose, that is, the dosimetry associated with a person exposed to a semi-infinite cloud of a radionuclide. Here the essential step is due to Dillman[17] who has estimated the energy spectrum of the photons in such a cloud and has also given us the depth dose from the electrons and from beta rays.[18] Finally, he has developed the spectrum of bremsstrahlung produced by the betas. All of these spectra are allowed to impinge on the anthropomorphic phantom developed by the Oak Ridge group, and so for the first time we have dose distributed in depth in such a phantom from a cloud source and also estimates of dose to the various organs.

There are many other facets of the report as planned which remain much the same as previously, and the fact that they are not mentioned here is not to be construed to mean they

are omitted. Clearly in the allotted time, one can only mention principal points, and one can only hope the new report will serve health physicists as well as did ICRP Publication 2.

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