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Invited Paper

MATHEMATICAL PROCEDURES FOR ESTIMATING DOSE FROM AN INTERNALLY DEPOSITED EMITTER

Walter S. Snyder, Health Physics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830, USA

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Human Studies Project

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Abstract

The estimate of dose delivered by a radionuclide will depend on its decay scheme and the related dosimetry data available, on its distribution and retention in the body, and on the characteristics of the individual who incorporates the activity. Dillman and Blichert-Toft have provided decay scheme data for most radionuclides, and Spiers has greatly advanced our knowledge of the dose to red bone marrow and to endosteal cells. The new point kernel of Berger offers the possibility of better dosimetry for beta-like radiation. Finally, the methods presented in MIRD Pamphlet Nos. 3, 5, and 8 have made it possible to take account of dose delivered by sources of photons anywhere within the body. The impact of the new ICRP lung model and of identification of endosteal cells as the sensitive cells of bone demands more detailed information on retention and distribution of a radionuclide and its daughters if the corresponding doses are to be computed. The model of Marshall for the metabolism of the alkaline earths (Health Physics, in press) is a first step in this direction, providing estimates of the material present in trabecular and cortical bone. Finally, attention is being given to the importance of individual characteristics (of fetus, infant, child, adult), both as regards uptake and retention (Lloyd et al., Nature 220, 1029, 1968) and with respect to dosimetry (W. S. Snyder, ORNL-4720), although there is an abundance of problems centering about the fetus and younger age groups which will challenge our ingenuity in the future.

Introduction

Estimates of doses to organs and tissues of the body require a considerable amount of information, physical as well as biological. There is no substitute for data, and to ask for dose to certain tissues of the body--even to certain cells--when one has only general ideas about the distribution of the radionuclide within the body is to ask for the impossible. Radiobiologists who accumulate data frequently only measure activity in a few bones of

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the skeleton and yet would like an estimate of dose to endosteal cells! In the past, the criteria for protection have been phrased in terms of an average dose to an organ, and for this an organ burden is perhaps sufficient, but barely. Refinements in estimation of dose generally will be possible only if experimenters provide more detailed data on the distribution of the nuclide with respect to the tissues for which dose is to be estimated. In this paper, we review some of the recent advances in dosimetry that have been made, beginning with the biological data, and point out many of the gaps where more detailed data are necessary. Then we shall discuss the physical factors which are involved in our estimates of dose.

Discussion of Dosimetric Models

The ICRP has indicated the endosteal cells as the radiosensitive tissue of bone and the active bone marrow as a tissue of interest for exposure of the hematopoietic system. The limits on occupational exposure of these tissues are 15 rem/yr and 5 rem/yr, respectively. The Task Group on the Radiosensitivity of the Tissues in Bone[1] advises that the endosteal cells lie within about 10 μm of the bone surfaces, and thus data on the distribution of beta emitters and alpha emitters are needed for distances from these cells comparable with the range of the radiation emitted. At present only a barest beginning has been attempted.

Marshall[2] has elaborated a model for metabolism of the alkaline earths which provides for retention in cortical and trabecular bone as well as for deposition in hot spots and soft tissue. The model appears to fit all the human data for adults and thus provides us with some information for four elements--calcium, strontium, barium, and radium. One has an estimate of average deposition and retention in these two broad types of bone and, hence, can estimate in an average sense the dose to the endosteal cells lying near the bone surfaces of these two categories of bone.

These actual estimates must also use the data which Spiers has accumulated over a number of years on dose to endosteal cells and to active bone marrow. Generally, Spiers has produced these estimates for specific portions of bone contaminated at a uniform level. A number of such estimates are shown in Table 1 which is taken from Spiers[3] and

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Table 1. Values of $\bar{D}_m/D_o$ and $\bar{D}_s/D_o$ Averaged over Adult Skeleton[a]

Groups of Bones	$\bar{D}_m/D_o$ for active marrow: Marrow fraction, f_m	$\bar{D}_m/D_o$	$f_m\bar{D}_m/D_o$	$\bar{D}_s/D_o$ for trabecular endosteum: Endosteal fraction, f_s	$\bar{D}_s/D_o$	$f_s\bar{D}_s/D_o$
1. Cranium	0.119	0.392	0.047	0.140	0.472	0.066
Mandible	0.012	0.274	0.003	0.014	0.364	0.005
2. Clavicles Scapulae Hip bones	0.287	0.218	0.063	0.304	0.334	0.102
3. Sternum Ribs	0.102	0.274	0.028	0.120	0.365	0.044
4. Humeri Femora	0.057	0.176	0.010	0.060	0.300	0.018
5. Vertebrae Sacrum	0.423	0.124	0.052	0.362	0.258	0.093
Totals for trabecular bone:			0.203			0.328
$\bar{D}_s/D_o$ for endosteal tissues in bone shafts:						0.50
Average values D_m/D_o and D_s/D_o for whole skeleton:			0.203			0.42

[a]Data from Spiers[3]

includes his estimate of an average dose to endosteal cells and to active bone marrow for ^{90}Sr-^{90}Y. These estimates are expressed as ratios of the average dose to active bone marrow, $\bar{D}_m$, to D_o, which is the dose computed with complete absorption of energy in bone, and, likewise, the ratio of the average dose to endosteal cells, $\bar{D}_s$, to D_o. It will be noted that the dose to marrow or to endosteal cells varies considerably from one portion of bone to another, and thus one needs a retention function for each portion of bone if the doses are to be estimated accurately. However, Marshall's model only provides an estimate for the total in trabecular bone and the total in cortical bone. For other radionuclides one has at most only a retention function for bone as a whole. In such a case, one can assume it is all in trabecular bone and thus maximize his estimate of dose to the active marrow. Since endosteal surfaces on trabecular bone and on cortical

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bone are about equal, one hopes this may have relatively little effect on the estimate. Clearly one needs much better data to make a reasonably accurate estimate of dose--or dose commitment--for either tissue. Experimenters are beginning to make some estimates of deposition and retention on or near bone surfaces, but we have far to go before we will have all the data that are needed.

The story is much the same for the lungs and for the gastrointestinal (GI) tract. Models have been proposed[4,5] which provide estimates of deposition and retention. In the case of lungs, these do provide for the effects of particle size and shape on deposition, although retention is essentially independent of size and shape. These data suffice to compute an average deposition and residence in the pulmonary region and in the tracheobronchial region. For the GI tract, the situation is similar; from the model one can compute an average dose to the four sections of the tract, but it is well known that the range of uncertainty involved here is much greater. Hayes[6] has shown, from his data on human patients, that dose in sections of the GI tract may vary by a factor of 10 on either side of the model estimates. There have been a few studies of distribution of material within the sections of the tract. For example, Fish[7] has shown that microspheres ingested by rats tend to be distributed preferentially in certain regions of the tract of rats, and data of Wade et al.[8] on sheep which ingested sand tend to support the assumption of inhomogeneity of this material within the tract. If one is content with an average dose within the sections of the tract, this may be tolerable, but it would not be a good basis for estimation of dose in depth within the wall. For example, there is little data available on the thickness of the mucous layer which may provide some protection for the wall itself. One needs data on its relative thickness around the villi which protrude into the contents of the tract and also the extent to which various radionuclides may interpenetrate the mucous layer.

Similar difficulties may be mentioned concerning the dose in a variety of organs and for dose from an external cloud (immersion dose). However, the examples cited should suffice to make the point: If great accuracy is to be required in estimating dose, one will require a corresponding degree of accuracy in our knowledge of the distribution of the radionuclide in the organs and in the body.

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Turning now to the physical side, we may consider the needs of the health physicist for estimation of dose, assuming he knows the location of the source with reasonable accuracy. Of course, he will need accurate data on decay schemes, and several compilations are available. The usual decay scheme does not provide what the health physicist needs, namely, a listing of the particles produced per decay with their yields and average energies or energies. Usually there are a number of tedious calculations which must be made to obtain the average energies of the betas and the energies of internal conversion electrons, Auger electrons, x-rays, etc. Some years ago we asked Dillman, a specialist in this field, to code this computation for us. As a result our Information Center for Internal Exposure has over 300 decay schemes on file which contain this information, and they are revised from time to time. There are three separate MIRD pamphlets which give this information for radionuclides of interest for nuclear medicine,[9, 10, 11] and Blichert-Toft[12] has issued a similar compilation. If the decay scheme for the radionuclide of interest is not in this published literature, a note to our Information Center will probably produce the data you need.

Regarding dose from alpha emitters and beta emitters, there is little to be said if all one requires is an average dose in large organs. However, the capability now exists to do more than this if only the data on the retention of the nuclide warrant the effort. An approximate curve for the dissipation of energy by an alpha particle at various distances along its tract has been available for some time[13] and could be used. Recently, Berger[14] has published a point kernel for monoenergetic electrons and for many beta particles. This published data makes it possible to estimate dose to a wide variety of structures ranging from the cell nucleus to depth dose within the skin from an external source.

There remains the problem of dose from photons and the problem of irradiation of one organ, the target organ, by a source in another organ, the source organ. There are several papers which treat the problem generally,[15, 16] that is, for sources in homogeneous ellipsoids of various sizes. A number of years ago, the author and his colleagues began the development of an anthropomorphic phantom which would simulate the body structure and its major inhomogeneities. The general outline of the phantom and a view of some of the major internal organs are shown in Figs. 1a and 1b. Computer runs have been

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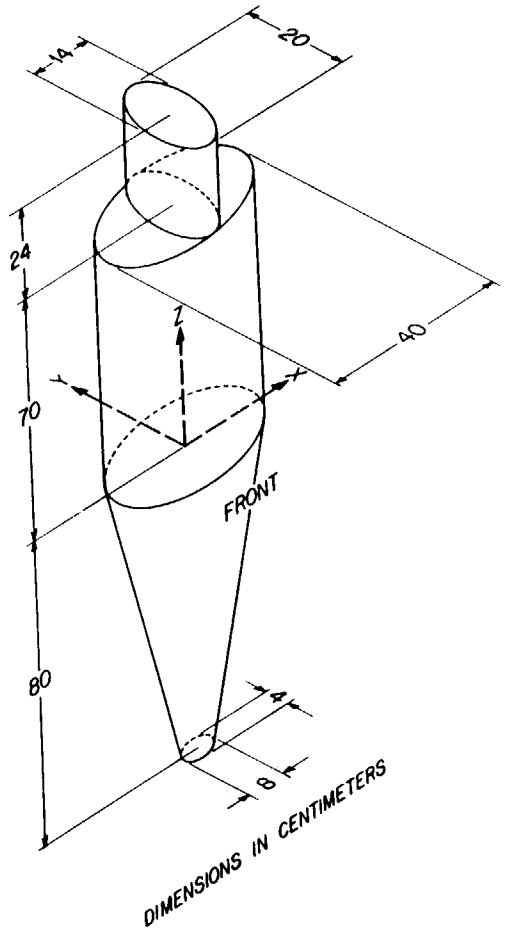
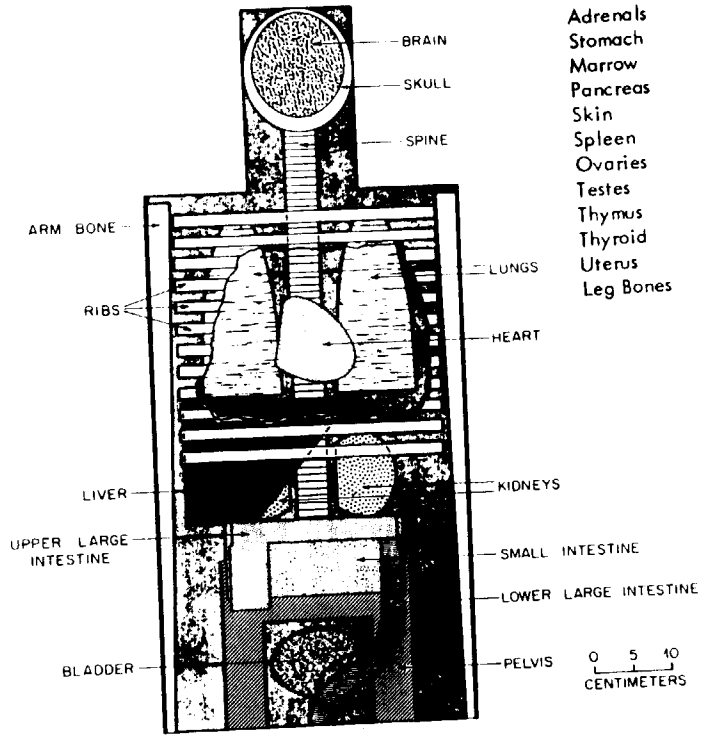


The Adult Human Phantom.

Fig. 1a.



Organs Not Shown in this View

- Adrenals
- Stomach
- Marrow
- Pancreas
- Skin
- Spleen
- Ovaries
- Testes
- Thymus
- Thyroid
- Uterus
- Leg Bones

ANTERIOR VIEW OF THE PRINCIPAL ORGANS IN THE HEAD AND TRUNK OF THE PHANTOM

Fig. 1b.

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made corresponding to sources distributed uniformly in some 16 different organs of the body and for 12 monoenergetic sources of photons. A comprehensive tabulation of the absorbed fractions found has been published in MIRD Pamphlet No. 5,[17] except that no value was listed when the coefficient of variation (C of V = 100 σ/m) exceeded 50%. Thus there are a number of blanks in the published tables which should be filled. These data have the merit that they do take account of the gross shape of organs and the major inhomogeneities of the body (i.e., lungs, soft tissue, bone). However, it is clear that values corresponding to individuals will differ depending on the configuration of their organs and their general bodily structure.

We have made a number of efforts to fill these gaps in the data, that is, those cases where the C of V is 50% or higher. We have studied the validity of the reciprocity theorem, and this will suffice to fill some of them--but not all. We have found that by computing the specific absorbed fraction (fraction of energy absorbed per gram) by use of the buildup factor for an infinite homogeneous medium,[17] the results agree within a factor of 2 or better than those obtained in the anthropomorphic phantom. This amounts to computing the six-dimensional integral

$$\frac{1}{|T|\,|S|} \int_S dy \int_T dx \; \frac{\mu_{ab}\, e^{-\mu|X-Y|}}{4\pi\,|X-Y|^2}\; B(\mu|X-Y|) \qquad (1)$$

where S and T are a pair of source and target organs; μ_{ab} and μ are mass absorption and mass attenuation coefficients; X and Y are variable points selected in the regions T and S, respectively; and B is the buildup factor tabulated by Berger for an infinite homogeneous medium.[18] Some of the comparisons of the data are shown in Figs. 2 and 3 where results at one high energy of 0.5 Mev and results at a low energy, 50 kev, are shown. Of course, these are only test cases, that is, cases where the Monte Carlo calculation provides us with a reasonably precise answer. The organs and energies of interest are not these shown, but these are the cases where a comparison is possible. Some adjustments need to be made. For example, one should be careful to use $\mu_{ab}^{(bone)}$ in the formula if bone is the target organ, for at low energies, this will change the points by about a factor of 3 or more. Similarly, if lungs is the source organ, one should multiply by a factor of 3.3 since lungs in the homogeneous space have a weight of about 3000 g instead of the customary 1000 g.

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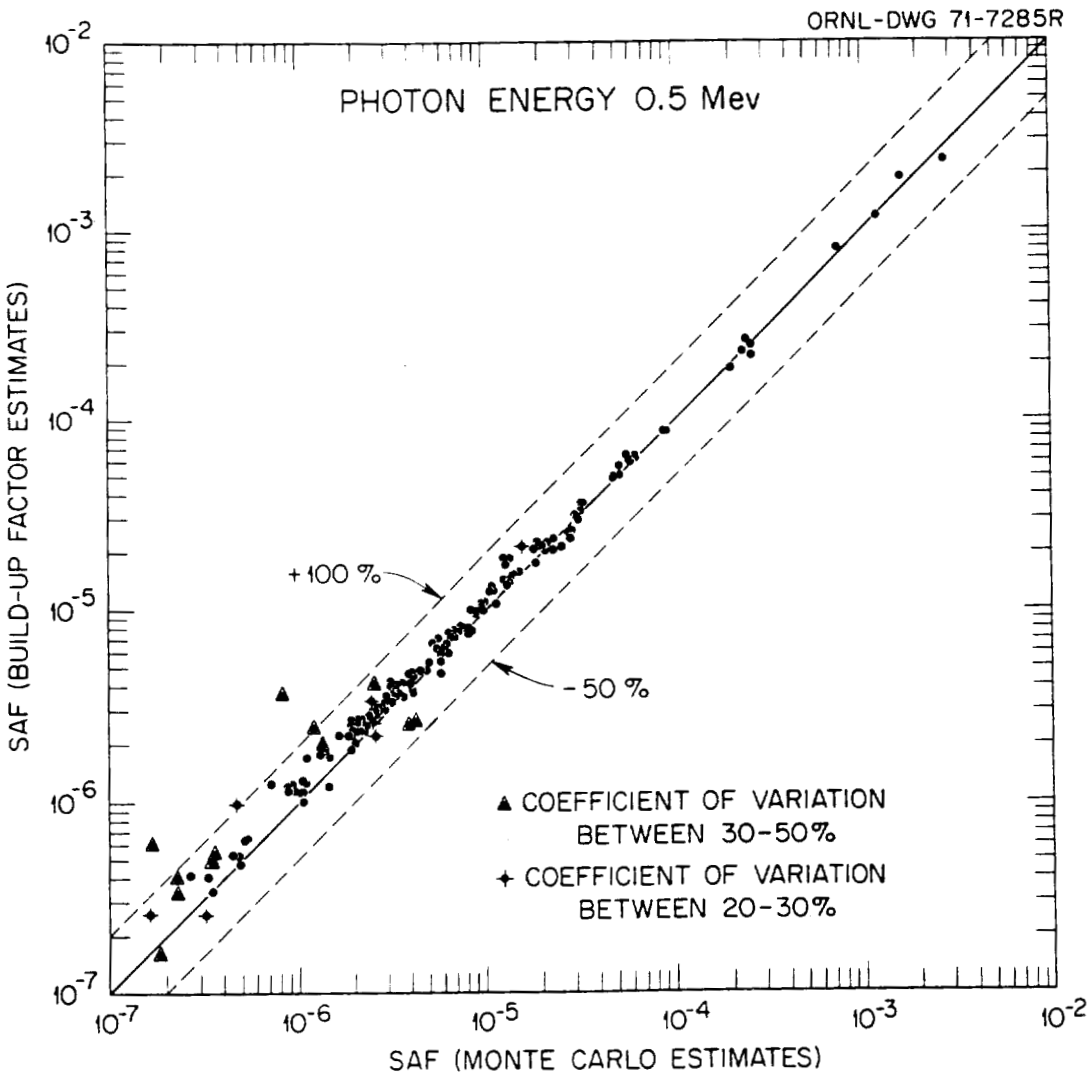

Monte Carlo Estimates of Specific Absorbed Fractions Compared with Build-up Factor Estimates.

FIG. 2.

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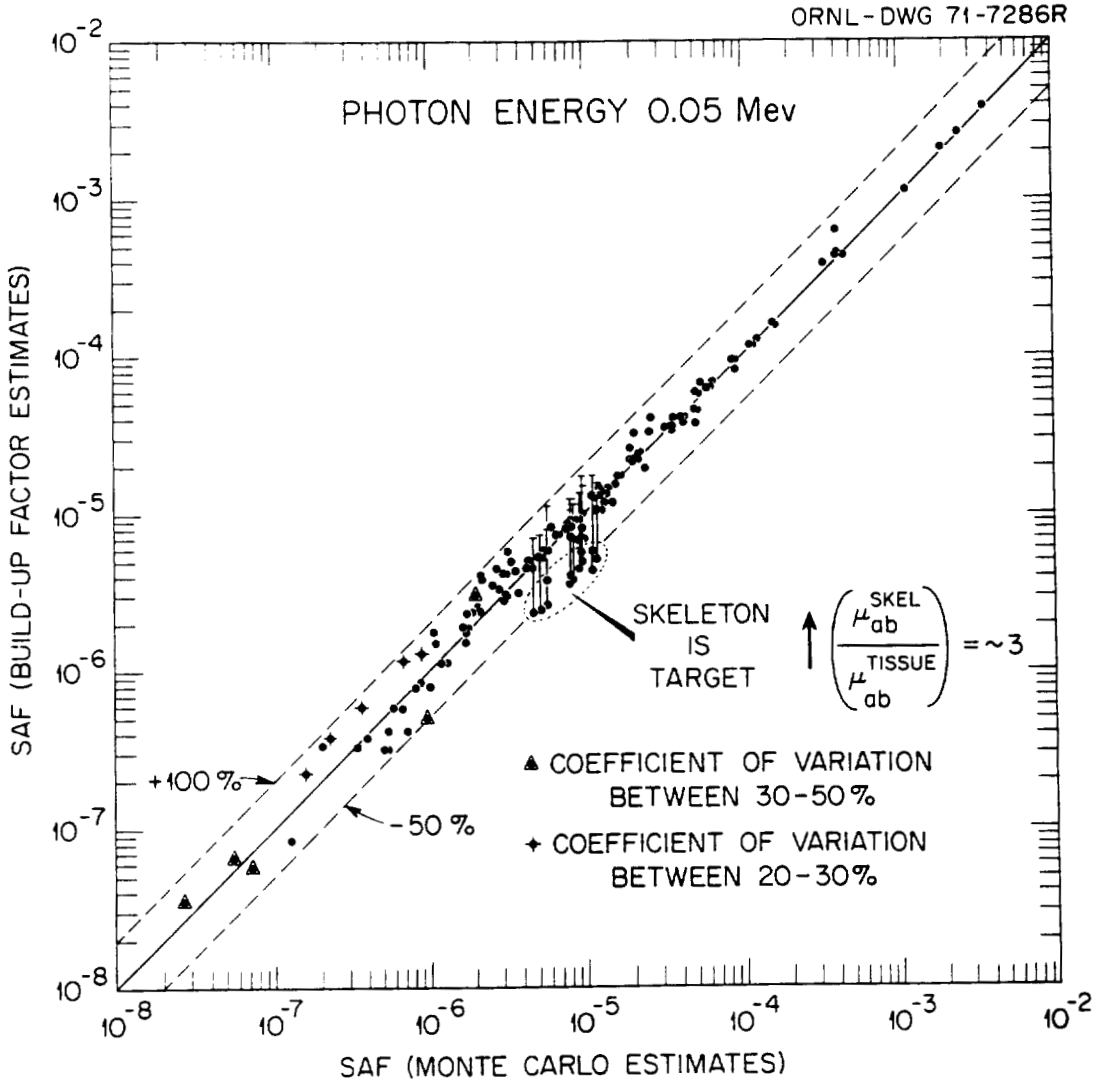

Monte Carlo Estimates of Specific Absorbed Fractions Compared with Build-up Factor Estimates.

FIG. 3.

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From these comparisons, it appears that the use of the methods which are reported by this author and colleagues in more detail in another paper at this symposium, will enable us to fill in most of the gaps left in the tables in MIRD Pamphlet No. 5 with errors of less than a factor of 2 and generally much less than this.

The use of these data would be quite burdensome for the health physicist or for the medical specialist. We have sought for methods which would spare him the necessity of making the hundreds and thousands of multiplications and additions that might be necessary in estimating dose from a gamma emitter. To do this, we define the specific effective energy from organ S to organ T, SEE ($T \leftarrow S$), to be the energy absorbed per gram in T per disintegration in S, weighted with quality factors that are appropriate. This weighted energy will be given separately for alphas, for beta-like particles, and for photons. The results will appear as a large matrix with the source organs listed along the top and the target organs on the side. This matrix will be produced for each radionuclide of interest. Then, when a metabolic model is available, one may compute the μCi-days (or disintegrations) occurring in each source organ, and a summation of the products of this, with the entries in each row, produces the total dose to the target organ designated for that row. (See Fig. 4.) These results will probably be issued as an ORNL report.

In summary, the physical methods now available suffice to determine an average dose to the major organs of the body. They are probably adequate for much finer determinations of dose if and whenever biological data are available in sufficient detail to warrant the effort to produce such microdoses. For example, if data on the deposition of alpha emitters on or near bone surfaces were available, the physical basis for dose to endosteal cells seems to be reasonably well in hand.

Problems for the Future

That is not to say there are no problems of physical dosimetry where research is needed. One of the more urgent needs is for an adequate basis for beta dosimetry in a nonhomogeneous medium. Berger's point kernel is correct only for a homogeneous medium and when applied at an interface, probably requires correction.[19] There are a few measurements, but they are mostly for high-Z materials, and one would like to know if the correction factor is correct for, say, an air-tissue boundary.

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TARGET ORGANS	SOURCE ORGANS		
	BLADDER CONTENTS	STOMACH CONTENTS	KIDNEYS ...
BLADDER WALL	GAMMA	GAMMA	GAMMA
	BETA	BETA	BETA
	ALPHA	ALPHA	ALPHA
	RECOIL	RECOIL	RECOIL
	TOTAL	TOTAL	TOTAL
STOMACH WALL	GAMMA	GAMMA	GAMMA
	BETA	BETA	BETA
	ALPHA	ALPHA	ALPHA
	RECOIL	RECOIL	RECOIL
	TOTAL	TOTAL	TOTAL
KIDNEYS	GAMMA	GAMMA	GAMMA
	BETA	BETA	BETA
	ALPHA	ALPHA	ALPHA
	RECOIL	RECOIL	RECOIL
⋮	TOTAL	TOTAL	TOTAL

Fig. 4. Specific Effective Energies, SEE

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The complexity of the body for dosimetry is another source of problems. Since the treatment of bone and bone marrow in MIRD Pamphlet No. 5 is not satisfactory, we have designed a more realistic model for red bone marrow, the percentages of red marrow present in various bones being taken from the literature.[20,21] (See Fig. 5.) But the complexity of marrow pockets and surrounding bony structure is not incorporated in the model. Although the gross distribution is perhaps reasonable, this finer detail is lacking, particularly the buildup of dose in bone due to the greater production of secondary electrons in bone. Moreover, we have not made extensive computations with the source in many organs, although results for the source in lungs[20] and in GI tract are available (Fig. 6).

It is well known that, generally, for the same source of photons in the organ of a child and an adult, the child will receive the greater dose rate. The inverse square law makes this a practical certainty. We have made some preliminary calculations on the magnitude of this excess dose. The adult phantom has been shrunk by a transformation which operates separately on the head, torso, and legs of the adult to produce the phantom for the child. Each of these transformations is a similitude so that non-intersecting loci (organs) remain non-intersecting. While this model is not entirely realistic, it avoids redesign of the phantom to match the characteristics of each age. In Fig. 7 we show the specific absorbed fraction as a function of age for lungs to liver and lungs to lungs. The specific absorbed fraction is directly proportional to dose rate, and thus the dose rate to the lungs or to the liver of the child is some two orders of magnitude greater than the corresponding dose rate received by the adult. Of course, the child may not breathe as much air, and so his lung burden may be smaller; but the warning is clear--the absorbed fractions published for the adult are not reasonable values for the child. Unfortunately, an inordinate amount of computing time is required if one attempts to duplicate the data in MIRD Pamphlet No. 5 for each age group!

It is clear that there is no lack of problems, but only of time and of imaginative research for attacking them. Perhaps in a few years new principles will emerge which will produce a simpler approach, but the present capability of our dosimetry seems as good as or better than the quality of the biological data we must use.

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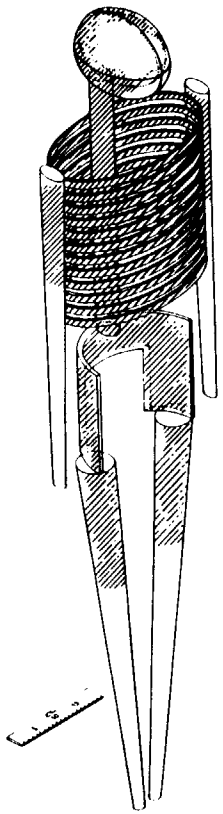
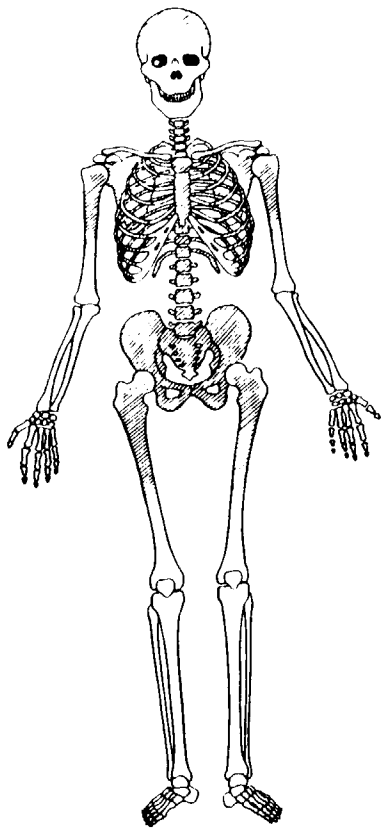


SKULL	13.1 %
VERTEBRAE	28.4 %
RIBS + STERNUM	10.2 %
SCAPULAE	4.8 %
HEAD AND NECK OF BOTH ARMS	1.9 %
BOTH CLAVICLES	1.6 %
HEAD AND NECK OF BOTH LEGS	3.8 %
PELVIS	36.2 %

TOTAL AMOUNT OF RED BONE MARROW: 1500 g

RED BONE MARROW



Idealized Model of the Skeleton for Computer Calculations (left) and a More Realistic Representation (right) with Percentages of Red Bone Marrow Found in the Shaded Portions of the Bones.

Fig. 5.

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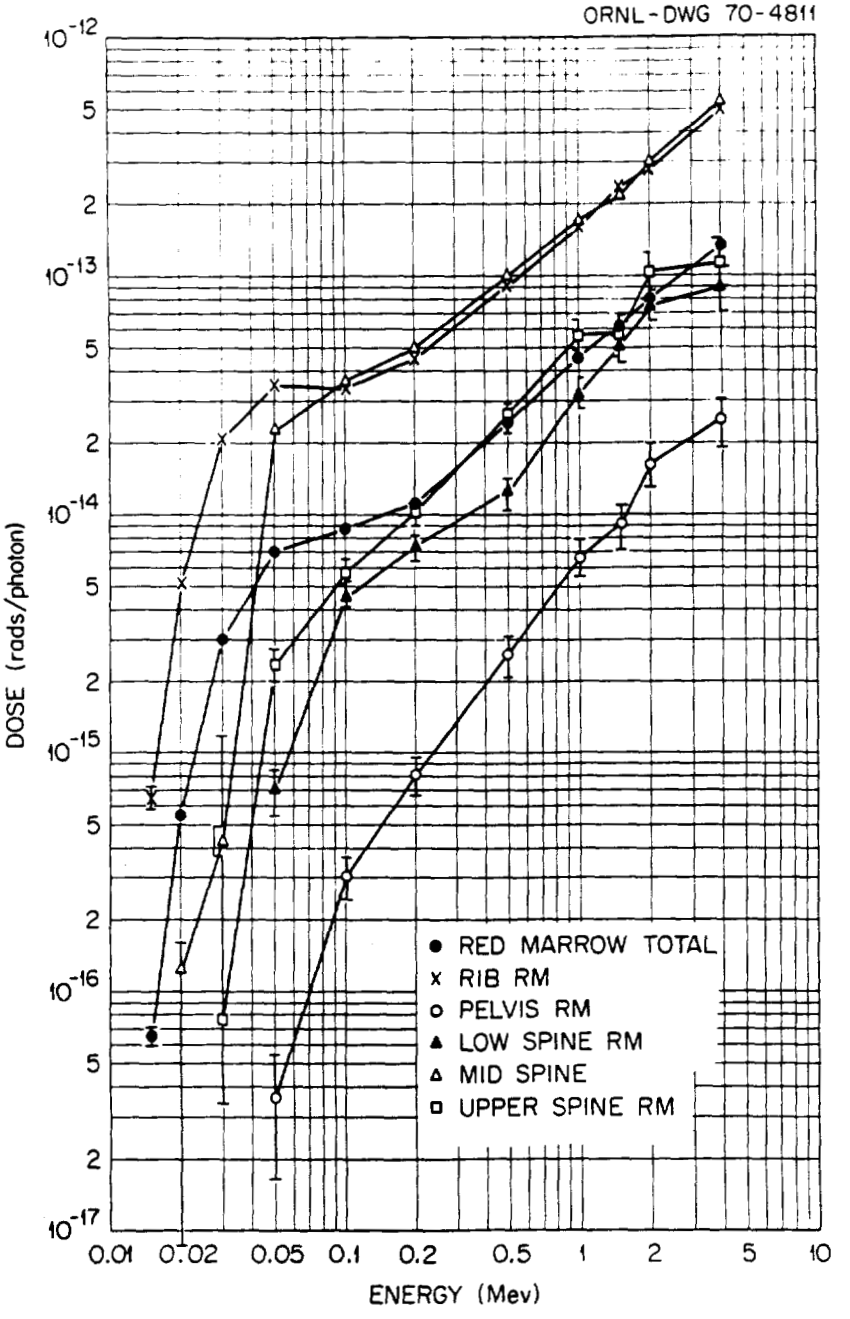

Mean Dose per Photon to Red Bone Marrow and Portions of Red Bone Marrow from a Monoenergetic Source Uniformly Distributed in Lungs.

Fig. 6.

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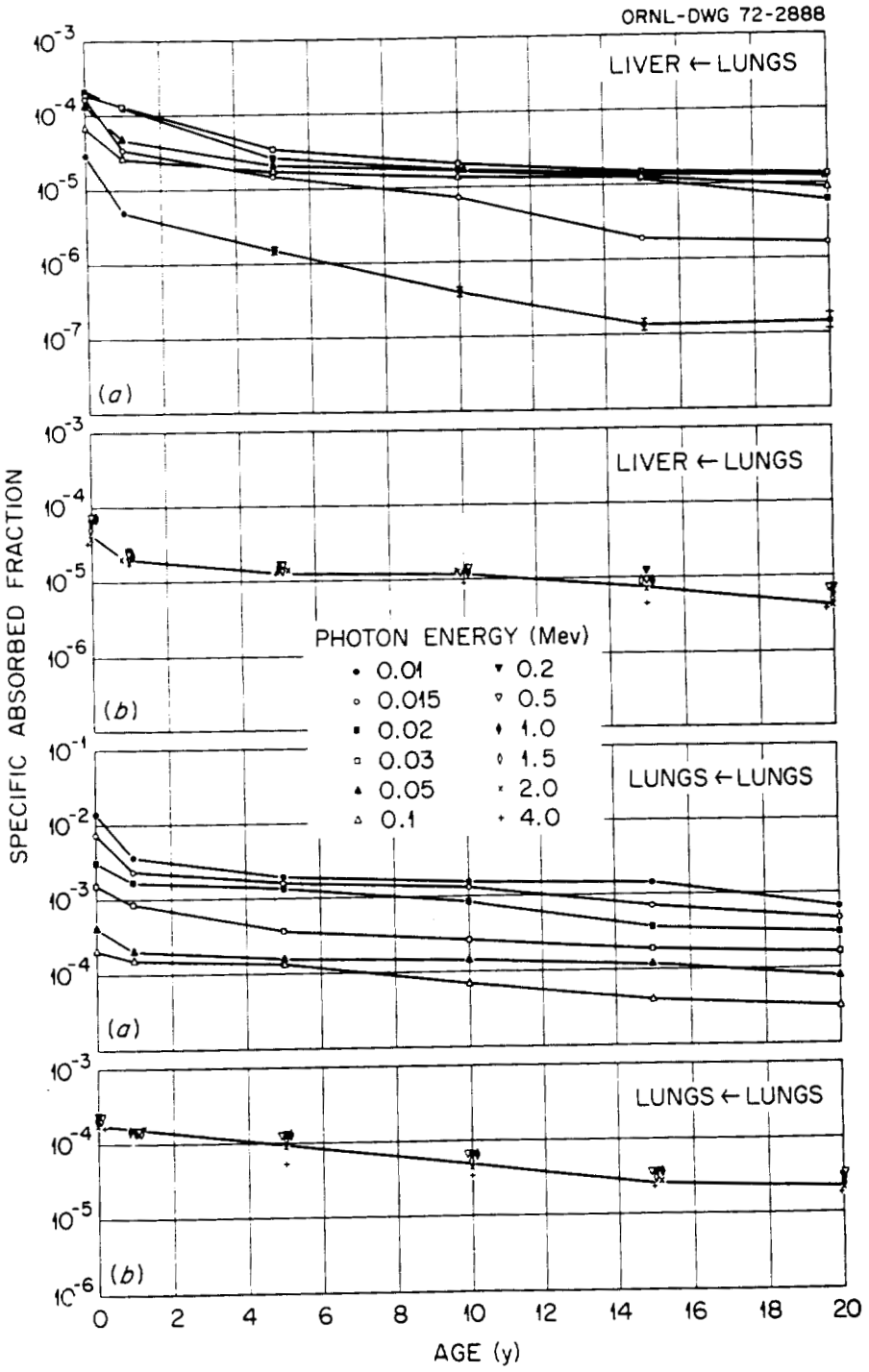

Fig. 7. Specific Absorbed Fraction as a Function of Age and Photon Energy. (Source in Lungs. SD <10% unless Shown)

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Acknowledgment

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References

1. A Review of the Radiosensitivity of the Tissues in Bone, ICRP Publication 11 (Pergamon Press, Great Britain, 1968).

2. Report of Task Group on Local Retention Functions of Bone Seekers (in draft).

3. F. W. Spiers, ed., Radioisotopes in the Human Body, Physical and Biological Aspects (Academic Press, New York, 1968), p. 326.

4. Task Group on Lung Dynamics, "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract," Health Phys. 12, 173 (1966).

5. I. S. Eve, "A Review of the Physiology of the Gastrointestinal Tract in Relation to Radiation Doses from Radioactive Materials," Health Phys. 12, 131 (1966).

6. R. L. Hayes, J. E. Carlton, and W. R. Butler, Jr., "Radiation Dose to the Human Intestinal Tract from Internal Emitters," Health Phys. 9, 915 (1963).

7. T. G. Clark, Jr., J. L. Thompson, and B. R. Fish, "Retention of Small Particles in the Gastrointestinal Tract and Their Proximity to the Wall during Transit," Health Phys. Div. Annual Progress Report for Period Ending July 31, 1965, ORNL-3849, p. 223.

8. Leo Wade, Jr., et al., "Radiation Dose to the Gastrointestinal Tract of Sheep Fed an Insoluble β-Emitter," Health Phys. 19, 57 (1970).

9. L. T. Dillman, "Radionuclide Decay Schemes and Nuclear Parameters for Use in Radiation-Dose Estimation," MIRD Pamphlet No. 4, J. Nucl. Med. Suppl. No. 2, 10, 5 (1969).

10. L. T. Dillman, "Radionuclide Decay Schemes and Nuclear Parameters for Use in Radiation-Dose Estimation, Part 2," MIRD Pamphlet No. 6, J. Nucl. Med. Suppl. No. 4, 11, 5 (1970).

1169645

11. L. T. Dillman, MIRD Pamphlet (in press, J. Nucl. Med.)

12. M. J. Martin and P. H. Blichert-Toft, "Radioactive Atoms – Auger-Electron, α-, β-, γ-, and X-Ray Data," Nuclear Data, Tables A8, 1-198 (1970).

13. W. Whaling, Ency. Phys. 34(2), 193 (1958).

14. Martin J. Berger, "Distribution of Absorbed Dose around Point Sources of Electrons and Beta Particles in Water and Other Media," MIRD Pamphlet No. 7. J. Nucl. Med. Suppl. No. 5, 12, 5 (1971).

15. G. L. Brownell, W. H. Ellett, and A. R. Reddy, "Absorbed Fractions for Photon Dosimetry," MIRD Pamphlet No. 3, J. Nucl. Med. Suppl. No. 1, 27 (1968).

16. W. H. Ellett and R. M. Humes, "Absorbed Fractions for Small Volumes Containing Photon-Emitting Radioactivity," MIRD Pamphlet No. 8, J. Nucl. Med. Suppl. No. 5, 12, 25 (1971).

17. W. S. Snyder et al., "Estimates of Absorbed Fractions for Monoenergetic Photon Sources Uniformly Distributed in Various Organs of a Heterogeneous Phantom," MIRD Pamphlet No. 5, J. Nucl. Med. Suppl. No. 3, 10, 5 (1969).

18. Martin J. Berger, "Energy Deposition in Water by Photons from Point Isotropic Sources," MIRD Pamphlet No. 2, J. Nucl. Med. Suppl. No. 1, 15 (1968).

19. F. T. Cross, "Beta Ray Dose Distributions Near an Interface" (in press).

20. R. E. Ellis, "The Distribution of Active Bone Marrow in the Adult," Phys. Med. Biol. 5, 255 (1961).

21. M. J. Cook, W. S. Snyder, and G. G. Warner, "Estimates of Dose to Red Bone Marrow from Monoenergetic Sources of Photons in Lungs and Other Organs," Health Phys. Div. Annual Progress Report for Period Ending July 31, 1970, ORNL-4584, p. 200.

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