CONF-9507235--1

The Reference Individual of Radiation Protection

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1 INTRODUCTION

The 70-kg "standard man" representing a typical Western adult male has been used in physiological models since at least the 1920s. In 1949 at the Chalk River conference[1], health physicists from the U.S., U.K., and Canada agreed on the concept of a standard man to facilitate comparison of internal dose estimates. The 70-kg standard man included specifications of the masses of 25 organs and tissues, total body content of 15 elements, total water intake and output, water content of the body, and some anatomical and physiological data for the respiratory and gastrointestinal tracts. In 1959, in its Publication 2[2] on permissible doses for internal radiation the International Commission on Radiological Protection (ICRP) modified and vastly extended the biological data for standard man. In 1963 the ICRP established a task group to revise and extend the standard man concept. The name was changed later to Reference Man and the task group's work was published in 1975 as ICRP Publication 23[3]. Publication 23 contains data similar to that published in Publication 2, but the sources of the data were documented and the data were updated and extended. Data on women, children, and fetuses were also collected, where available, but these data were limited primarily to anatomical data and only a few reference values were established for these groups. Information assembled during the course of the effort on the Reference Man report was used at Oak Ridge National Laboratory (ORNL) to construct a mathematical representation of the body (a phantom) that was suitable for use with Monte Carlo methods in the calculation of organ doses[4-5]. That effort was undertaken to improve estimates of dose from photon-emitting radionuclides residing within organs, so-called internal emitters. The phantom, although updated throughout the years, remains today as the basis for organ dose estimates in nuclear medicine[5] and radiation protection[6] and underlies the radiation risk data derived from the epidemiologic studies of the atomic bomb survivors of Hiroshima and Nagasaki[7].

2 REFERENCE MAN

The purposes for Reference Man within radiation protection were spelled out in the introduction to ICRP Publication 23[3]. Estimation of the radiation dose to the human body, whether from external or internal sources, requires a certain amount of data about the exposed individual. It was appreciated that individuals vary considerably in these respects, but it was important to have a well-defined reference individual for estimation of radiation dose. Such a reference individual was considered convenient for routine exposures when the doses are sufficiently low that individual differences might be ignored. The well-defined reference individual enabled health physicists to compare and check their calculations without tedious enumeration of assumptions and without minor differences in these assumptions obscuring the basic agreement or disagreement of their estimated doses. It is, perhaps, more important that the basis of the reference values be known when adjusting the values to make a more precise estimate of dose for a given individual.

The Task Group on Reference Man limited "its attention to those characteristics of man which are known to be important or which are likely to be significant for estimation of doses from sources of radiation within or outside the body" (Ref. 3, p. 3). In spite of its limited purpose, Publication 23 has been widely used by scientists outside radiation protection.

Reference Man was defined as 20-30 years old, weighing 70 kg, 170 cm in height, and living in a climate with an average temperature of 10 - 20 °C. He is a Caucasian and is a Western European or North American in habitat and custom. Reference Woman is 58 kg in mass and 160 cm in height, but she was not defined in as much detail as Reference Man, especially in terms of chemical composition of the body, largely for lack of data.

In 1984, Committee 2 of the ICRP decided to update Publication 23 for two main reasons. First, much new information related to the biokinetics and dosimetry of radionuclides had been published since the compilation of the Reference Man data. Second, there was by that time a very strong emphasis on exposures to the public and, consequently, a need to develop reference characteristics for children and other subgroups of the population. A Task Group on Reference Man was formed, and this group was charged with updating the features of Reference Man, giving more emphasis to the normal variation among persons, and providing more information on young members of the population.

Initially, the intention was to revise all of ICRP Publication 23. It gradually became apparent, however, that funding for such a massive effort was not available. Consequently, Committee 2 decided that the task group should revise only certain parts of Publication 23 and that the revised parts should be published separately in order to expedite the publication of the information most needed for completion of other ICRP documents. In the discussion below we briefly point out some of the areas where the task group is making changes and the philosophy behind the changes. Some changes are being made because of new data published since 1970 or because of inevitable errors or shortcomings in the existing publication, and some changes result simply because the points of view among the new task group members are different from those of the original task group.

One of most important philosophical differences is the use of the lean body mass (LBM) concept and the importance of body height in normalizing anatomical data being reviewed and in assigning reference values. Forbes[8] discusses both of these points at length. If LBM is not known, a combination of body height and body weight is often useful in assigning reference values. In Fig. 1 one can see that lean body mass among Caucasians and Asians of both sexes is largely a matter of stature. The utility of normalizing parameters by LBM is that many differences between males and females, between different population groups, and among individuals disappear or become smaller. For example, the body content of water on the basis of LBM is about 72-73% in animals and humans of both genders.

Another difference in philosophy is seen in the numerical rounding of reference values. The Task Group considers that the rounding in ICRP Publication 23 was unnecessary excessive — excessive because each number is rounded independently of the Reference Man model as a whole. In the body many parameters are interrelated and excessive rounding makes it difficult to preserve the correct interrelationships. For example, the body height was rounded to 170 from 174.5 cm; we would suggest rounding to the nearest cm in this case, especially in light of the information that other anatomical and functional parameters are strongly correlated with body height.

Potentially one of the more controversial changes is the body weight of the adult male. As mentioned above, the 70-kg adult male has been a standard since at least the 1920s. The new Reference Man will be 73 kg in mass and 176 cm in height; Reference Woman will be 60 kg in mass and 163 cm in height. The reason for the change is two-fold: (1) people are larger than they were in the 1920s, with 73 kg and 176 cm being closer to modern data for Europeans, the reference population; and (2) we rounded the modern data to the nearest kg rather than the nearest 5 or 10 kg. The new Reference Man is a little heavier, but 3 kg is a modest change.

The revised Reference Man will continue to be a Westerner, but world-wide anatomical data are being reviewed. The task group has changed the adult age from a young adult, range 20-30 years, to a young-to-middle-aged adult with a larger age range, 20-50 years. This change was made for two reasons: (1) the body is still maturing in many ways during the 20's, and many anatomical and physiological parameters reach a plateau in the 30's before declining after age 45 or so; or if there is a steady decline or increase from young adult to old, a middle value is more representative as a

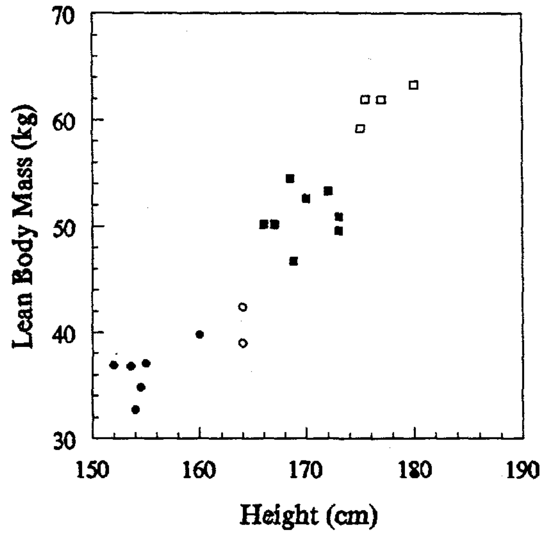

Fig. 1. Lean body mass as a function of stature. Circles are women; squares are men, filled symbols are Asians, open symbols are Caucasians. Adapted from Ref. 8.

reference value for adulthood than is a value for young adults; and (2) much of the data we are using comes from combining data from young and middle-aged adults, roughly from ages 18 or 20 to 50, for practical reasons of availability of data. We usually exclude older adults because changes in the body can be substantial after age 70. The data used to define the current Reference Man often included data on middle-aged adults, especially when data on the 20-30-year age group were sparse. Thus the current Reference Man is somewhat older than advertised.

The first report on the revised Reference Man, dealing with the skeleton, has appeared as ICRP Publication 70[9]. The next publication of the Task Group will provide the anatomical data for children and adults on total body height and weight, surface area, total body water, intracellular and extracellular water, blood volumes, body fat content, adipose tissue content, and organ masses. It will also include the elemental content of the organs, probably limited to about 12 elements necessary in defining the radiation interaction cross-sections. Some physiological data will also be included.

3 MATHEMATICAL PHANTOMS

The estimation of absorbed dose in organs of the body from radiation sources outside or inside the body is complicated by the complex geometry of the organs and tissues. Information assembled during the course of the effort on the Reference Man report was used to construct a mathematical representation of the body that was suitable for use with Monte Carlo methods in the calculation of organ doses[4]. The results for photon transport calculations in the phantom were published in Pamphlet 5 issued by the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine and the phantom became known as the MIRD or MIRD-5 phantom[5,10]. The major features of the body and its organs with regard to shape and dimensions were approximated by the union and intersection of simple conic sections. Each "organ" in the model was considered to be homogeneous in composition and density, although different compositions and densities were used for the skeleton, lungs, and the rest of the body.

The original MIRD phantom[5] consisted of three principal sections: (1) an elliptical cylinder representing the arms, torso, and hips; (2) a truncated elliptical cone representing both the legs and feet; and (3) an elliptical cylinder representing the head and neck. In the 1978 version[10] the legs were separated and geometries of additional internal organs were specified. The phantom contained both the male and female sex organs (an hermaphrodite phantom), but the female breast was not included in the earlier designs. The mathematical descriptions of the organs were formulated after consideration of the descriptive and schematic materials from general anatomy references. The representation of the organs by mathematical equations are only approximate. The goal was to approximate the major features of size, shape and location of the organ using a few mathematical equations which could be readily evaluated, thus minimizing computation time.

The adult phantom evolved somewhat and in 1980 Cristy[11] designed a pediatric phantom series that form a developmentally consistent family with the adult phantom. The exterior of each phantom has approximately the form of the human body; but, as in the adult phantom, there was no attempt to include minor features. Similarly, the description of the interior organs, while approximately correct as to size, shape, position, composition and density, are simplified to provide formulas which are readily evaluated on a computer. The Cristy phantom series as described by Cristy and Eckerman[12] is the basis for the photon absorbed fraction data currently being used by the ICRP in its publications on age-dependent dose coefficients[13].

The current version of the adult hermaphrodite phantom used at ORNL is shown in Fig. 2. Note that the legs are separate, female breasts are included, and the head region consists of a neck and head with a rounded skull. Additional versions of the phantom exist representing males and females, and the female at the end of each trimester of pregnancy[14].

The mathematical phantom was developed to estimate the fraction of the energy of photons emitted within an organ that is absorbed in the organ and other organs of the body. An excessive amount of computer time was associated with tracing the ray representing the flight of a photon through the complex geometry. This difficulty was avoided by adding a cross section for a fictitious scattering event in each media present in the problem such that all media have the same total interaction cross-section. A potential site of interaction is determined from the total interaction cross-section and then, with knowledge of which medium contains the site, a game of chance is played to determine if the interaction was real or fictitious. For the latter, no deposition of energy nor change is direction of the photon takes place. This technique is referred to as fictitious scattering and is attributed to Coleman[15] (see also the paper by Jones in these proceedings). Radiation transport codes employing ray-tracing may encounter numerical difficulties (loss of significance) when solving the 4th-order polynomial equation for the intersection of a line with the elliptical torus representing the clavicles, the "terrible tori" problem discussed in Ref. 16. As noted above, other mathematical representations of the organs might be considered to avoid the computational problem associated with quartic equations.

4 VOXEL PHANTOMS

Detailed anatomical information is present in the computed tomographic images derived from nuclear magnetic resonance (MRI) or x-ray scans. Both modalities share some common features; the former is generally preferred in visualization of the soft tissues while the latter has considerable advantages in visualization of the skeleton. Information from either modality can be used to represent the geometry of the body as an array of volume elements (voxels) to associated parameters which identify the voxel with a particular organ or tissue and ascribe the necessary attributes required in the transport calculations. Transport calculations for photons incident upon the body have been carried out in voxel phantoms by researchers at the Gesellschaft fur Strahlen- und Umweltforschung (GSF), the National Radiological Protection Board (NRPB), and ORNL (see papers by Zankel, Dimbylow, and Jones in these proceedings). Voxel phantoms were first used for external radiation sources in part because of the rather obvious shortcomings of a mathematical phantom with respect

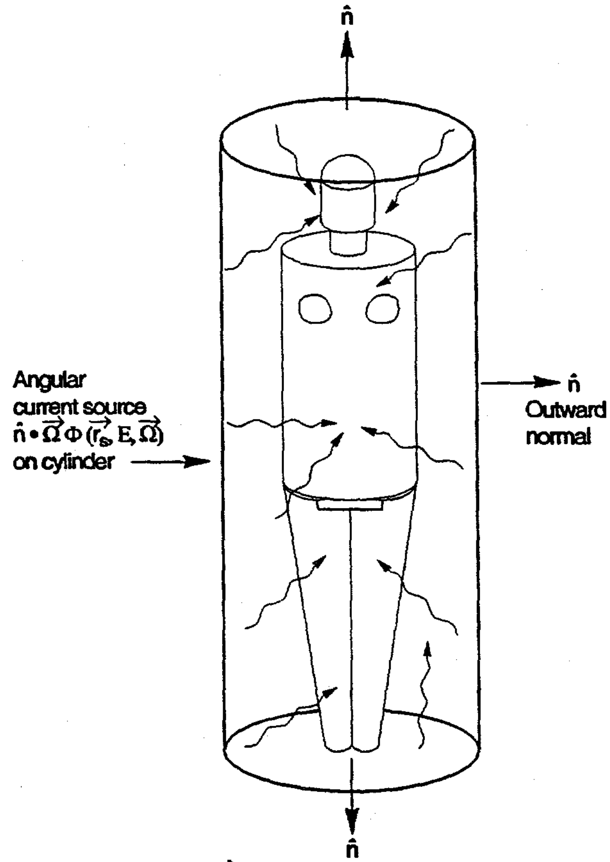

Fig. 2. The adult hermaphrodite phantom as used in calculation of organ dose from an angular current source on a surrounding cylinder.

to its exterior shape. Application of voxel phantoms to radiation sources within the body requires the development of schemes for random selection of the ordinates of the emitted particle. Such schemes are in principle rather simple, but a substantial amount of data can be involved for distributed source regions; e.g., consider sampling a source in the red marrow which is heterogenous in its distribution among the bones of the skeleton.

As noted above, the limitations of the mathematical phantom with respect to external shape are readily apparent. To investigate this aspect of the phantom design we examined the distribution of chord lengths in the mathematical phantom and the voxel phantom NORMAN (see papers of Dimbylow and Jones in these proceedings). The phantoms were exposed to uniform parallel beams of lines incident on the anterior body surface in a direction orthogonal to the long axis of the body, i.e., an anterior to posterior (AP) beam. The length of the chords formed by the intersection of the lines and the surface of the phantom were determined for 100,000 lines. (A line may reenter the phantom and thus the chord length is the total length of the line within the phantom). The mean chord-lengths in the phantom were 13.6 and 12.0 cm in the mathematical and voxel phantom, respectively. Fig. 3 shows the distribution of the chord-lengths in the two phantoms. The distribution in the mathematical phantom is dominated by chords of length greater that 19 cm arising in both the trunk and head. For NORMAN the distribution is considerably more uniform with some chords exceeding 20 cm in length. The mathematical phantom is, on average, too thick.

The design of the mathematical phantom results in an overestimate of the tissue shielding some organs and hence may lead to underestimates of organ dose particularly for low-energy photons and neutrons. The situation with respect to photons emitted within the body is less clear. Limited comparison of calculational results at GSF and ORNL for photon sources within a voxel phantom

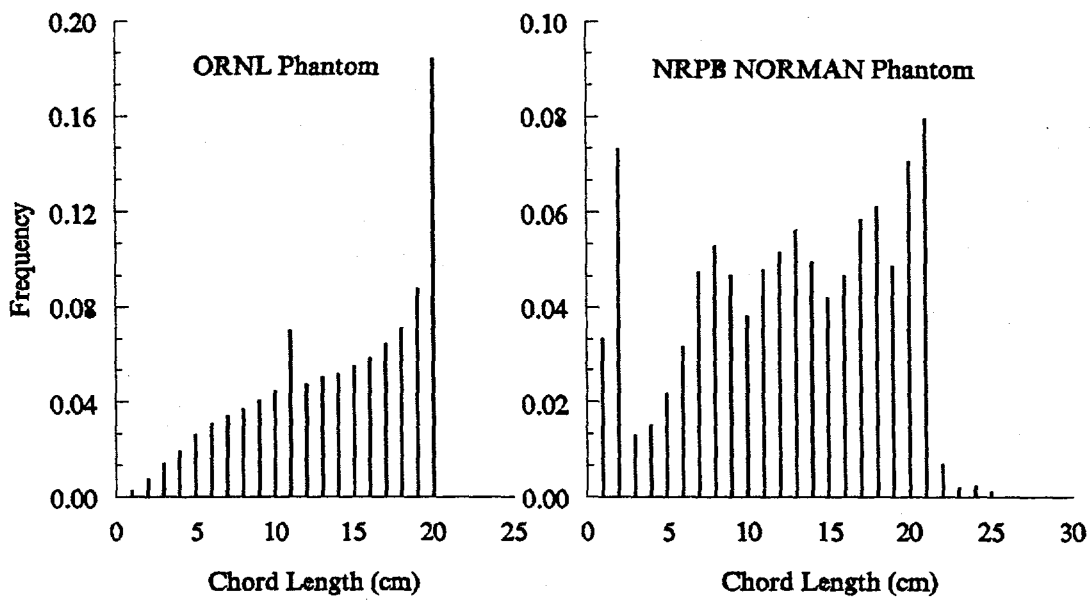

Fig. 3. Chord length distribution in the ORNL mathematical phantom and the NRPB voxel phantom NORMAN. The phantoms were exposed to a parallel beam of lines incident on the anterior of the body in a direction orthogonal to the long axis of the body.

have indicated substantial agreement with values obtained using the mathematical phantom.

Medical images provide a means to establish a complete, anatomically detailed, three-dimensional representation of the body. However, development of a reference phantom involves more than just geometry, particularly when one seeks to evaluate the absorbed dose to the cells at carcinogenic risk. The design must consider information derived from diverse studies. For example, an appropriate representation of the skeleton[17] would utilize data derived from biokinetic studies of iron uptake (defining the distribution of the active marrow) and scans of microstructure of cortical and trabecular bone. A particularly rich source of additional anatomical data is being assembled in the Visible Human Project of the U.S. National Library of Medicine. That project has released a data set for an adult male which consists of MRI, CT, and cross-sectional photographic images. The photo (2048 x 1216 pixels, 24 bit color) and CT (512 x 512) images are at 1-mm intervals while the MRI (256 x 256 pixel) data are at 4-mm intervals. There are 1871 cross-sections for each image mode; the complete male data set is about 15 gigabytes in size. A data set from a female cadaver is expected to be released in 1995 and will include photographic cross-sections at 0.33 mm. The female data set is expected to be about 40 gigabytes in size. Additional information regarding this project can be found on the World Wide Web (http://www.nlm.nih.gov).

5 CONCLUSIONS

The geometric limitations of the current mathematical phantoms can best be addressed using information from medical images. The geometric data from these sources must be processed and merged with nongeometric data from more traditional studies. For example, data on the elemental composition and other physical properties of the tissues are derived from studies of tissue samples obtained at autopsy. These data are being reviewed as part of the updating of ICRP Publication 23, and the completion of that work will provide the basis to define a consensus phantom or phantoms approximating Reference Man. Based on our experience we suggest that the consensus phantom will be a composite derived by processing (e.g., removing image artifacts) and scaling image data from a number of individuals. The phantom will be a hybrid in presentation; i.e., include both discrete (voxels) and continuous (conic sections) mathematical descriptions of the organs with tissue attributes assigned as in current practice. Such a phantom could be used directly or with suitable software translated into a voxel representation for particular applications. Methods will be established for merging individual-specific cross-sectional data into the reference phantom and for articulation of the phantom. The voxel geometry is the solution to the geometric aspects of the phantom, but we should not lose sight of the other aspects of the design and implementation of computational phantoms.

6 REFERENCES

1 McMurtrie, G E, 1950, Permissible Doses Conference held at Chalk River, Ontario, September 1949 (minutes taken by secretary of UK delegation).

2 ICRP, 1959, Report of Committee II on Permissible Dose for Internal Radiation. ICRP Publication 2.

3 ICRP, 1975, Report of the Task Group on Reference Man. ICRP Publication 23.

4 Fisher Jr, H L and Snyder, W S, 1967, Distribution of dose in the body from a source of gamma rays distributed uniformly in an organ in Health Phys. Div. Ann. Progr. Rept., July 1967, Oak Ridge National Laboratory Report ORNL-4168.

5 Snyder, W S, Fisher Jr, H L, Ford, M R and Warner, G G, 1969, Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom. J. Nucl. Med. 10 (Suppl. 3), Pamphlet No. 5.

6 ICRP, 1979, Limits for Intakes of Radionuclides by Workers. ICRP Publication 30, Part 1, Annals of the ICRP 2(3/4).

7 Kerr, G D, Eckerman, K F, Tang, J S, Ryman, J C and Cristy, M, 1984, Organ dosimetry in Proceedings of a U.S.-Japan Joint Workshop on Reassessment of Atomic Bomb Radiation Dosimetry with Special Reference to Shielding and Organ Doses, held at Hiroshima, Japan, November 8-9, 1983 (Hiroshima: Radiation Effects Research Foundation), pp. 79-82.

8 Forbes, G B, 1987, Human Body Composition. Growth, Aging, Nutrition, and Activity, Springer Verlag, New York.

9 ICRP, 1995, Basic Anatomical and Physiological Data for Use in Radiological Protection: The Skeleton. ICRP Publication 70, Annals of the ICRP 25(2).

10 Snyder, W S, Ford, M R and Warner, G G, 1978, Estimates of Specific Absorbed Fractions for Monoenergetic Photon Sources Uniformly Distributed in Various Organs of a Heterogeneous Phantom. MIRD Pamphlet 5, Revised, Society of Nuclear Medicine, New York.

11 Cristy, M, 1980, Mathematical Phantoms Representing Children of Various Ages for Use in Estimates of Internal Dose. Oak Ridge National Laboratory Report ORNL/NUREG/TM-367.

12 Cristy, M and Eckerman, K F, 1987, Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources. Oak Ridge National Laboratory Report ORNL/TM-8381, Volumes 1-7.

13 Stabin, M G, Watson, E E, Cristy, M, Ryman, J C, Eckerman, K F, Davis, J C, Marshall, D and Gehlen, M K, 1995, Mathematical Models and Specific Absorbed Fractions of Photon Energy in the Nonpregnant Adult Female and at the End of Each Trimester of Pregnancy. Oak Ridge National Laboratory Report ORNL/TM-12907.

14 ICRP, 1989, Age-dependent Doses to Members of the Public from Intake of Radionuclides. ICRP Publication 56, Part 1, Annals of the ICRP 20(2).

15 Coleman, W A, 1968, Mathematical verification of a certain Monte Carlo sampling technique and applications of the technique to radiation transport problems. Nucl. Sci. Eng. 32(76).

16 Van Riper, K A, 1993, SABRINA User's Guide. Los Alamos National Laboratory Report LS-UR-93-3696.

17 Eckerman, K F, 1986, Aspects of the dosimetry of radionuclides within the skeleton with particular emphasis on the active marrow in Fourth International Radiopharmaceutical Dosimetry Symposium, Proc. Conf. held at Oak Ridge, Tennessee, November 5-8, 1985, ed. A T Schlafke-Stelson and E E Watson, CONF-851113--(DE86010102), pp 514-534.