Radiobiological Dosimetry

Recommendations of the International Commission on Radiological Units and Measurements

Handbook 88

United States Department of Commerce
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*In preparation.

UNITED STATES DEPARTMENT OF COMMERCE • Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Radiobiological Dosimetry

Recommendations of the International Commission on Radiological Units and Measurements (ICRU) Report 10e 1962

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Foreword

The reports of The International Commission on Radiological Units and Measurements for a number of years have been published by the National Bureau of Standards in the Handbook series. In the past, each of the triennial reports of the ICRU represented a complete restatement of the recommendations of the Commission. Because of the increasing scope of its activities, however, the Commission in 1962 decided to modify the previous practice. It will issue a series of reports presenting the current recommendations of the Commission. Each report will cover a particular portion of the area of interest to the ICRU. This procedure will facilitate revision of ICRU recommendations and also spread out in time the workload of the Commission. This Handbook is one of the new series presenting the recommendations of the Commission on one aspect of the field with which the Commission is concerned. It presents recommendations agreed upon at the meeting of the Commission held in Montreux, Switzerland, in April 1962.

The National Bureau of Standards is pleased with its continuing opportunity of increasing the usefulness of these important reports by providing the publication outlet.

A. V. Astin, *Director.*

Contents

Preface

A. Scope

The International Commission on Radiological Units and Measurements (ICRU), since its inception in 1925, has had as its principal objective the development of internationally acceptable recommendations regarding:

(1) Quantities and units of radiation and radioactivity,

(2) Procedures suitable for the measurement and application of these quantities in clinical radiology and radiobiology,

(3) Physical data needed in the application of these procedures, the use of which tends to assure uniformity in reporting.

The Commission also considers and makes recommendations on radiation quantities, units and measurements in the field of radiation protection. In this connection, its work is carried out in close cooperation with the International Commission on Radiological Protection.

B. Policy

The ICRU endeavors to collect and evaluate the latest data and information pertinent to the problems of radiation measurement and dosimetry and to recommend the most acceptable values for current use.

Recognizing the confusion that exists in the evaluation of different radiological equipment and materials, the ICRU is studying standard methods of determination of characteristic data for the equipment and materials used in diagnostic and therapeutic radiology. This activity is confined to methods of measurement and does not include the standardization of radiological equipment or parts thereof.

The Commission's recommendations are kept under continual review in order to keep abreast of the rapidly expanding uses of radiation.

The ICRU feels it is the responsibility of national organizations to introduce their own detailed technical procedures for the development and maintenance of standards. However, it urges that all countries adhere as closely as possible to the internationally recommended basic concepts of radiation quantities and units.

The Commission feels its responsibility lies in developing a system of quantities and units having the widest possible range of applicability. Situations may arise from time to time when an expedient solution of a current problem may seem advisable. Generally speaking, however, the Commission feels that action based on expediency is inadvisable from a long-term viewpoint; it endeavors to base its decisions on the long-range advantages to be expected.

In 1955 the Commission entered into an official relationship with the World Health Organization (WHO). In this relationship, the ICRU will be looked to for primary guidance in matters of radiation units and measurements, and in turn WHO will undertake the worldwide dissemination of the Commission's recommendations. In 1960 the ICRU entered into consultative status with the International Atomic Energy Agency (IAEA).

The above relations with other international bodies do not affect the basic affiliation of the Commission with the International Society of Radiology.

The ICRU invites and welcomes constructive comments and suggestions regarding its recommendations and reports. These may be transmitted to the Chairman.

C. Current Program

A 2-week meeting of the ICRU was held in Montreux, Switzerland, April 2 to April 14, 1962. This meeting included the Main Commission and all of the Committees that had reports prepared for final approval. Some 70 persons attended. An additional meeting of the Commission and Committee Officers was held in Ottawa from August 21 to August 23, 1962, for the principal purposes of the preparation of the status report for the Xth International Congress of Radiology and the outlining of program objectives for the next several years.

Several meetings of committees or committee task groups have been held during the past three years. There were meetings of various task groups of the Committee on Standards and Measurement of Radiological Exposure—Paris in January 1961 and London in April and September 1961. The Committee on Radiobiological Dosimetry also held a meeting in April 1961. The ICRU was also represented at a meeting of the Consultative Committee on ionizing radiation of the International Committee of Weights and Measures at Sèvres in October 1961.

As noted in the last report, two joint committees had been established between the ICRU and the ICRP. The Joint Committee on RBE has met twice with ICRU participation. The Committee on Methods and Instruments for Radiation Protection has not met.

Upon the request from the United Nations Scientific Committee on the Effects of Atomic Radiations, the ICRU and the ICRP agreed to undertake a second study dealing with the Medical and Physical Parameters in Clinical Dosimetry. This committee met in New York for one week in September 1959 and for a week in Stockholm in June 1960. A report of this study entitled "Exposure of Man to Ionizing Radiation Arising from Medical Procedures with Special Reference

to Radiation Induced Diseases, An Inquiry into Methods of Evaluation," was published in Physics in Medicine and Biology, **6**, No. 2, 199 (Taylor & Francis, Ltd., London, England, Oct. 1961).

Reports and recommendations of the ICRU, originally designed for medical applications, have come into common use in other fields of science, particularly where "dosimetric" considerations are involved. For this reason the committees have included in their membership some scientists having competence outside of the medical radiology field. Material in the report is designed to meet physical, biological, and medical requirements wherever possible.

This has introduced a small problem in terminology. The name of the Commission includes the term "radiological". In many European countries the term "radiological" is taken as inclusive of both the physical and biological sciences. In other countries, the United States for example, "radiological" appears to carry the primary connotation of relationship to medicine. It therefore may be desirable to change the name of the Commission from "Radiological" to "Radiation." It is believed that this would be properly understood by all concerned. The question has been debated by the Commission, but final action is being delayed for future consideration.

D. The Current Series of Reports

Hitherto, the triennial reports of the ICRU have been published in single volumes. However the reports are now becoming too extensive, and in some cases too specialized, to make a single publication practicable. Beginning with this 1962 series, the ICRU reports will be issued in smaller entities, each dealing with a limited range of topics. The 1962 series supersedes the 1959 report. Revisions of the 1962 series will be undertaken individually as circumstances warrant. A full listing of ICRU recommendations, including the present series, is given on page iii of the cover of this report.

The current report series include revision of much of the material that appeared in the 1959 report in addition to a number of new topics. The following summary indicates some of the highlights of the current report series.

Radiation Quantities and Units (Report 10a)—One of the most important changes is the revision of the section on quantities and units. This revision resulted from the thorough study by an Ad Hoc Committee on Quantities and Units. It includes new names for certain quantities and clarified definitions for others. It presents a system of concepts and a set of definitions which is internally consistent and yet of sufficient generality to cover present requirements and such future requirements as can be foreseen.

Physical Aspects of Irradiation (Report 10b)—This report deals broadly with the physical aspects of irradiation with a considerable amount of new material added since the 1959 report. It includes an extensive discussion of the various techniques for the measurement of absorbed dose as well as exposure. Characteristics of radiation instrumentation are covered in some detail including the more sophisticated work on standards. The section on spectra has been up-dated and a new section added on neutron measurements and standards. Available data for stopping power ratios and the average energy (W) required to produce an ion pair in a gas have been reviewed. On the basis of this review it has been necessary to modify the previous ICRU tables for these factors. This modification amounts to about 1 or 2 percent change in stopping power ratios and up to 1 percent in W.

Radioactivity (Report 10c)—The portions of the report dealing with direct and relative measurements of radioactivity and the availability and requirements for radioactivity standards, and the parts dealing with the techniques and measurements of radioactivity in hospitals and biological laboratories are revisions of the 1959 report, embracing a review of the developments that have occurred since that report and bringing up to date the material included. In addition, a new section on low level radioactivity in materials as related to the problems of radiological measurements has been added. This topic is important because of the problems arising from the contamination, or possible contamination, in the last decade of a great many of the materials used in the construction of counting equipment, shields, and in the reagent chemicals employed in radioactivity measurements.

Clinical Dosimetry (Report 10d)—Much of the Commission's work on clinical dosimetry is brought together in this report. Included is an extensive discussion of practical calibration procedures and the determination of dose along the central ray. Depth dose data relative to stationary and moving-field therapy have been extended as have the conversion data necessary to relate ionization measurements to absorbed dose.

The principal effort has been toward the definition of nomenclature and the indication of methods. While some examples are given and data are provided for these, in general the reader is referred to other published data. The report considers ways of increasing the accuracy and comparability in clinical dosimetry. The discussion includes not only the physical aspects of dose measurement but also the wider subject of planning treatment in such a way as to deliver the prescribed absorbed dose to a defined "target volume." It also includes comments upon the common sources of error in clinical dosimetry and discusses the information which should be recorded during treatment and that which should be reported about any new treatment technique.

Appendices to this report include pertinent material taken from other reports in this series. Methods of Evaluating Radiological Equipment and Materials (Report 10f)—This is the first of a new group of ICRU reports dealing with methods of evaluating radiological equipment and materials. It includes a revised discussion on the measurement of focal spots and new sections on grids, image intensifiers, and body section equipment.

E. Operating Funds

Throughout most of its existence, the ICRU has operated essentially on a voluntary basis, with the travel and operating cost being borne by the parent organizations of the participants. (Only token assistance was available from the ISR.) Recognizing the impracticality of continuing this mode of operation on an indefinite basis, operating funds were sought from various sources in addition to those supplied by the International Society of Radiology.

Prior to 1959, the principal financial assistance to the ICRU had been provided by the Rockefeller Foundation which supplied some $11,000 to make possible various meetings. In 1959 the International Society of Radiology increased its contribution to the Commission to $3,000 to cover the period until the Xth Congress. In 1960 the Rockefeller Foundation supplied an additional sum of some $4,000 making possible a meeting of the Quantity and Units Committee in 1960.

In 1960 and 1961 the World Health Organization contributed the sum of $3,000 each year to the Commission for carrying forward its work. This was increased to $4,000 in 1962. It is expected that this sum will be allocated annually, at least for the next several years. In addition, the WHO has provided substantial assistance to the Commission in providing meeting space, secretarial services, etc., for the meetings held in Geneva and Montreux.

In connection with the Commission's Joint Study with the ICRP, the United Nations allocated the sum of $10,000 for the joint use of the two Commissions for the purpose of carrying out their second study. This fund has been administered by the ICRP.

The most substantial contribution to the work of the ICRU has come from the Ford Foundation through the particular efforts of Dr. Paul Pearson. Effective in December 1960, the Ford Foundation made available to the Commission the sum of $37,000 per year for a period of 5 years. This money is to be used for such things as travel expenses to meetings, for secretarial services, and other operating expenses. To a large extent, it is because of this grant that the Commission has been able to hold the several meetings considered to be necessary to move forward actively with its program.

The International Atomic Energy Agency has allocated the sum of $6,000 per year for use by the ICRU. It is expected that this sum will be allocated annually at least for the next several years.

A valuable indirect contribution has been made by the U.S. National Bureau of Standards where the Secretariat has resided. The Bureau has provided substantial secretarial services, reproduction services and traveling costs in the amount of several thousands of dollars.

The Commission wishes to express its deep appreciation to all of these and other organizations that have contributed so importantly to its work.

F. Composition of the ICRU

(a) It is of interest to note that the membership of the Commission and its committees for the period 1959–62 totals 139 persons drawn from 18 countries. This gives some indication of the extent to which the ICRU has achieved international breadth of membership within its basic selection requirement of high technical competence of individual members.

(b) The membership of the Main Commission during the preparation of this report was as follows:

Lauriston S. Taylor, Chairman	United States
L. H. Gray, Vice-chairman	United Kingdom
H. O. Wyckoff, Secretary	United States
K. K. Aglintsev	U.S.S.R.
A. Allisy	France
R. H. Chamberlain	United States
F. Ellis	United Kingdom
H. Fränz	Federal Republic of Germany
H. E. Johns	Canada
W. J. Oosterkamp	Netherlands
B. Rajewsky	Federal Republic of Germany
H. H. Rossi	United States
M. Tubiana	France

G. Composition of Committee Preparing Initial Draft of Present Report

J. W. Boag, Chairman, ICRU Committee III, "Measurement of Absorbed Dose and Clinical Dosimetry".
H. H. Rossi, Chairman, Committee III–C, "Radiobiological Dosimetry".
V. P. Bond
L. F. Lamerton
G. J. Neary
K. G. Zimmer
L. Ehrenberg, Consultant

H. The Present Report

This report deals primarily with radiobiological dosimetry, and considers methods of improving the accuracy and intercomparability of absorbed dose measurements in radiobiology. It is in effect a handbook for the experimental radiobiologists. It emphasizes the great importance of planning the experimental work in a way which makes the dosimetry easier and more accurate and it illustrates how this can be done.

Radiobiological Dosimetry*

International Commission on Radiological Units and Measurements (ICRU) Report 10e 1962

1. Introduction

The effects produced by ionizing radiations in biological systems depend on a large number of factors which may be physical, physiological, or chemical. Thus temperature, moisture content, oxygen tension, and other environmental factors can be of considerable consequence, and when they are, they should be specified numerically. However, the dose and factors related to it (such as dose rate, dose distribution, etc.) are usually the most important quantities, and often also the most difficult to evaluate.

The objective of this report is to recommend methods whereby ionizing radiation may be applied to biological systems with a minimum of ambiguity in dose specification. Radiobiological experimentation is carried out on a great variety of systems and the objectives of dosimetry range from incidental estimates of the magnitude of the traumatic agent to precise specifications of quantities required to test radiobiological theories. It is evident that experimental techniques and the desired dosimetric accuracy must vary greatly and that decisions on these matters must be left to the experimenter. However, the planning of the experiment and the choice of a method of measuring and reporting dose should follow certain general principles to ensure that an optimum amount of information is made available.

A systematic treatment of the problems of experimental design and dosimetric techniques was considered to be beyond the scope of this presentation. The approach chosen instead is one in which summary reviews of important concepts, technical considerations and possible sources of error are followed by examples of acceptable exposure arrangements utilizing sources of x and gamma radiation. If different conditions are required, these arrangements may often be suitably modified in the light of the preceding general information. While the primary emphasis is on problems connected with x and gamma radiations, many of the considerations presented apply also to corpuscular radiations; however, only one specific example of exposure arrangements will be given for these, since the great variability of sources and procedures makes it impractical to select standard conditions for exposure to high-speed electrons or beams of various nucleons (neutrons, protons, alpha particles, etc.). Some appropriate literature references will be given which deal with specific applications of these radiations.

*This report includes in Appendix I the definitions of general quantities and units are used in the 1962 reports of the ICRU.

2. Fundamental Principles

1. A complete specification of the dosimetric features of a radiobiological experiment would include the following information:

(a) The absorbed dose at all points of interest.[1]

(b) The time distribution of absorbed dose.

(c) The variation on a microscopic scale of local energy density. This is primarily related to the LET (linear energy transfer) of the charged particles that deliver the absorbed dose.

The absorbed dose is the macroscopic physical quantity which has been chosen as most suitable for correlation with the biological action of the radiation. However, equal absorbed doses of radiations of different type or energy delivered under similar conditions will usually produce different degrees of biological effect, and it must be concluded that microscopic nonuniformity of energy deposition is also a physical factor of fundamental importance.

It is often impossible or impractical to provide complete information on dose and on local energy density on the macroscopic scale. In such instances the partial data provided should be such that parameters of interest can be derived, or at least estimated with acceptable accuracy.

2. In all cases it is highly desirable that certain information be given regardless of the detail with which fundamental dosimetric data are provided. This includes the type (or types) of radiation emitted by the source, its energy, any filtration or moderation, the distance between the source and the surface or center of the irradiated object, physical data on the object (such as its dimensions and weight), and the characteristics of the container or apparatus used to hold the object during irradiation. A diagram which illustrates these geometrical features of the experiment is often very useful.

3. It is important that the problems of dosimetry be considered as an important part of experimental design *before* radiobiological experiments are begun. If an individual other than the one planning the experiment is to carry out the dosimetry, he should be consulted early. Often seemingly minor modifications may result in simplified and more accurate dosimetry.

4. Except for studies designed to explore their effects, arrangements yielding complex or unusual radiation patterns should be avoided. In the case of x rays this occurs when very high or very low

[1] This may include regions other than those of immediate concern; e.g., volumes that are outside the direct beam or under shields, or, if abscopal (i.e., effects appearing at a distance from the irradiated region) effects are possible, organs other than that under discussion.

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filtration is employed, or when micro-organisms are irradiated when in contact with material of medium or high atomic number (such as glass). In the case of neutrons, similar complications arise with excessive moderation of sources of known spectral emission or irradiation of large animals at neutron energies of a few Mev or less. Irradiation in mixed fields of neutrons and gamma rays or exposure of mammals to thermal neutrons also results in difficult dosimetric problems.

3. Absorbed Dose

3.1. Possible causes of nonuniform distribution

In all cases of practical interest, the absorbed dose distribution in irradiated organisms is not strictly uniform, although variations may often be reduced to acceptable levels. Factors that may result in nonuniformity include the following:

(a) *Geometry.* In either vacuum or matter, the radiation intensity decreases with distance from the source. In the case of a true point source, the reduction is inversely proportional to the square of the distance from the source (inverse square law). In the case of sources of finite size, the decrease of intensity is less rapid, particularly in the vicinity of the source.

(b) *Absorption.* Absorption is a process whereby the intensity of a radiation beam is reduced as a result of passage through matter because some of the particles (or photons) of the incident beam are eliminated or reduced in energy by interactions that often result in secondary radiation.

(c) *Secondary radiation.* The term "secondary radiation" is used either for primary radiation that has been deviated with or without change of energy, or for radiation that is produced by the primary radiation but differs in nature from it. Thus, the lower energy photon emerging from a Compton collision and the recoil electron are both referred to as secondary radiation.

One may classify scattered radiation with respect to the degree of deviation from the original beam direction (forward scatter, side scatter, back scatter).

If the primary radiation does not consist of charged particles, it usually produces charged particles in secondary or higher order radiations and these in turn contribute to the absorbed dose. If the range of these secondary charged particles is appreciable, the absorbed dose may vary greatly within a significant portion of the irradiated organism. For example, when supervoltage x rays impinge on an animal, the absorbed dose in the skin is usually quite low since the secondary particles will rarely be in equilibrium with the primary radiation before incidence.

(d) *Variation of atomic composition.* When a biological object is exposed to photons or uncharged particles, the local flux of charged secondaries depends on the atomic composition of the region surrounding the point of interest up to a distance that is equal to the maximum range of the charged secondaries. At this stage of the energy transfer process, the importance of any atomic species depends on the product of its relative abundance by its energy absorption coefficient for the incident radiation. Absorbed dose variations are particularly pronounced within bone and on either side of the bone-tissue interface if the irradiation is carried out with low energy electromagnetic radiation.

At the second stage of energy transfer—from the charged secondaries to the molecules of the medium—the atomic composition influences absorbed dose through mass stopping power. The energy deposited locally is proportional to mass stopping power, and the importance of any atomic species depends in this case on the product of relative abundance and mass stopping power for the secondary charged particles present.

A detailed discussion on the influence of atomic composition of tissues is given in 3.7.

3.2. Classification of Irradiation Conditions

In the great majority of radiobiological experiments it is desired that a well-defined volume be irradiated uniformly. Often this volume is the entire organism as is the case in whole-body exposure of mammals or in irradiation of micro-organisms. Sometimes only a portion of an organ is to be irradiated, but in such instances efforts are usually made to achieve uniform dosage in this volume with minimal irradiation of the remainder.

It is, therefore, useful to classify irradiation conditions according to the degree of uniformity of absorbed dose within the volume of interest and with respect to the main cause for nonuniformity. For purposes of convenience the following classification will be adopted although it is realized that the numerical values chosen to separate various classes are somewhat arbitrary. While the limits chosen here appear to be suitable in the majority of cases, different limits may, at times, be more appropriate.

A. *Uniform irradiation* obtains when the inevitable variations in absorbed dose throughout the volume of interest are not large enough to affect significantly the biological response considered. A ratio of less than 1.15 between maximum and minimum absorbed dose will be considered here as uniform irradiation.[2]

B. *Irradiation not uniform because of radiation absorption.* This condition obtains most commonly in comparatively large animals such as mammals when exposed to radiation having limited penetration. In such cases the most uniform practical conditions may involve a maximum to minimum dose ratio of up to 1.30. These limits will be taken to define *moderately uniform*

[2] It must be recognized that with x radiation of low quantum energies there may be dose variations of considerably more than 15 percent in soft tissue in the neighborhood of bone surfaces. For many types of experiments it may be justified to ignore this nonuniformity. However, when the response of soft tissues near bone surfaces is of special significance in the experiments, such an exposure cannot be considered to be uniform.

irradiation, and the term *nonuniform irradiation* will be used when variations exceed this limit.

C. *Irradiation not uniform because of incomplete secondary particle equilibrium.* This situation may occur under the conditions which are the reverse of those in class B, i.e., the biological objects are quite thin, and the radiation of high energy. A typical case is represented by the irradiation of bare plants in free air by cobalt 60 γ rays. Class C exposures may also be divided into moderately uniform and nonuniform conditions using the same limits as in class B.

It is evident that in the great majority of radiobiological experiments it is desirable to carry out class A irradiations. When this can be accomplished, the dose may be expressed by a single number. The recommended choice for this is the dose at the center or the midline of the irradiated object although this is unlikely to be the mean of the doses at the proximal and distal surfaces. It may often be desirable to furnish further information on the degree of nonuniformity. In some experiments having inherent high precision (as in microradiobiology), uniformity within a few percent is required, but this can usually be achieved without much difficulty. In the following the physical size of biological objects will be illustrated by reference to mammals, the biological objects most commonly irradiated. However, the remarks will apply equally to all biological objects of similar size. Small mammals are assumed to weigh less than about 250 g; medium mammals between 250 g and 2.5 kg; and large mammals more than 2.5 kg.

One may readily irradiate small- or medium-sized mammals under class A conditions if the radiation energy is sufficiently high. On the other hand, external irradiation of medium- or large-sized mammals under class A conditions is impossible even with bilateral exposure (see section 3.5), if the radiation energy is less than about 50 kev in the case of electromagnetic radiation or 1 Mev in the case of neutrons.

In class B or class C exposure one may quote a nominal dose which is again best chosen to be at the midline or the center of the volume of interest, but this should be supplemented by at least the entrance and the exit dose and preferably by a depth dose curve in a phantom that represents the experimental conditions.

Class B and class C irradiations are discussed below with a view to suggesting ways of improving uniformity. The adoption of some of these recommendations may enable experimenters to achieve class A conditions or at least moderately uniform rather than nonuniform conditions.

3.3. Limitations of Radiation Sources

The uniformity and reproducibility of an absorbed dose pattern can be limited by inherent characteristics of radiation sources. One of these is nonisotropic radiation emission. The beam of conventional x-ray therapy equipment usually has a high degree of uniformity when restricted to the apertures commonly used in radiotherapy. However, with the comparatively wide-angled beams frequently employed in radiobiology, an "anode shadow" may appear at the periphery of the field. With some tubes, the field may not be symmetrical around the beam "center" determined geometrically. (See fig. 1 and also ICRU 1962 report 10b for more complete physical discussion.) Other inhomogeneities may also arise particularly after long use of a tube. Such nonuniformities must be taken into account in a calibration of the equipment. If the objects are placed on a turntable during irradiation in order to average out such nonuniformities, the dosimetric device should be treated similarly during calibration. Supervoltage x-ray units are well known to exhibit a strongly directional emission, with intensity decreasing rapidly within a few degrees from the principal beam axis. Gamma-ray sources may exhibit anisotropic emission when the specific activity is so low that source absorption is of importance. Usually both the flux density and the energy of accelerator-produced neutrons depend on the direction with respect to the ion beam.

Change of radiation output with time is another factor which is of considerable importance in x-ray equipment. While modern machines are commonly well regulated with respect to tube current, voltage regulation is often insufficient.

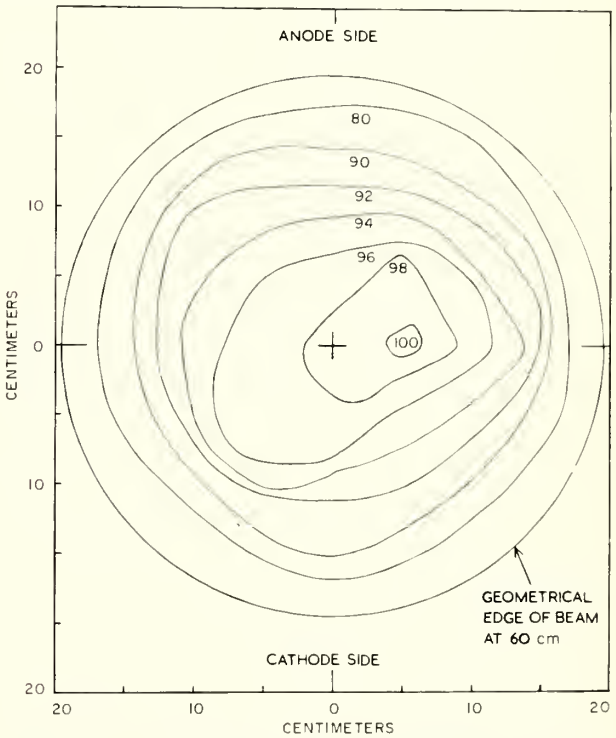

FIGURE 1. *Percentage exposure distribution in the cross section of a beam from an x-ray tube operating at 250 kv (constant potential), 15 ma, Filter 2 mm Al, HVL 0.5 mm Cu.*

To a first approximation the output varies only linearly with current but quadratically with voltage. Although the radiation output of gamma-ray sources may be expected to be very constant except for decay, errors may be introduced by the existence of short-lived impurities (such as Cs^{134} in Cs^{137}).

In order to obtain high dose rates it is necessary sometimes to place the object as near as possible to the x-ray tube. If the dimensions of the object are comparable with its distance from the x-ray target, significant nonuniformity can be introduced in two ways: because of the lateral extension of the object its ends are further removed from the x-ray target than is its center, and because of the thickness of the object its proximal surface may be appreciably closer than its distal surface. Figures 2 and 3 provide information on the percentage variation due to object thickness and length. In either instance the curves were derived assuming an inverse square relation between dose and distance. Deviations from an inverse square relation, absorption and scatter will require modifications of the values given in these graphs.

Because of radiation scatter and backscatter, the absorbed dose received by an object may rise rapidly as any material such as exposure apparatus, supports, other animals, etc., are brought near it. The influence of scattering on exposure rate for conventional x rays is indicated in table I. The increase is most marked for the first extra scattering material added and it is, therefore, easier to achieve reproducibility of dose if irradiations are carried out insofar as possible under conditions of maximum scatter. This procedure has the additional advantage that conventional depth dose data [7, 10]** (which are commonly determined with maximum scatter) may be utilized at least as first approximations. On the other hand, when it is desired that radiation quality be well defined, conditions giving minimum scatter may be preferable. But then dosimetry requires even greater care. For electromagnetic radiations, conditions of maximum scatter can be attained with substantial backing of Masonite or similar unit density material, approximately 7.5 cm thick and exceeding the width of the primary irradiation area by approximately 5 cm on all sides. For multiple irradiation it is necessary to have at each

**Figures in brackets indicate the literature references at the end of this paper.

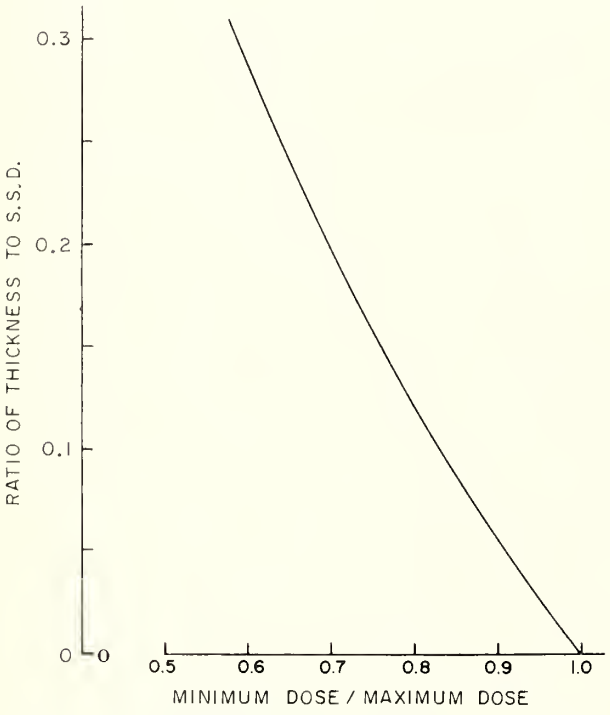

FIGURE 2. *Geometrical factor of variation of exposure introduced by object thickness.*

Example: If a 20-cm-thick animal is placed with its proximal surface at 1 m from a source, the ratio of thickness to source surface distance = 20/100 = 0.2. In this case the dose at the distal surface will be about 70 percent of that at the proximal surface. In the derivation of this curve only the inverse square law has been considered. Finite source size, anisotropy of radiation emission, absorption, scattering, etc., may require modifications.

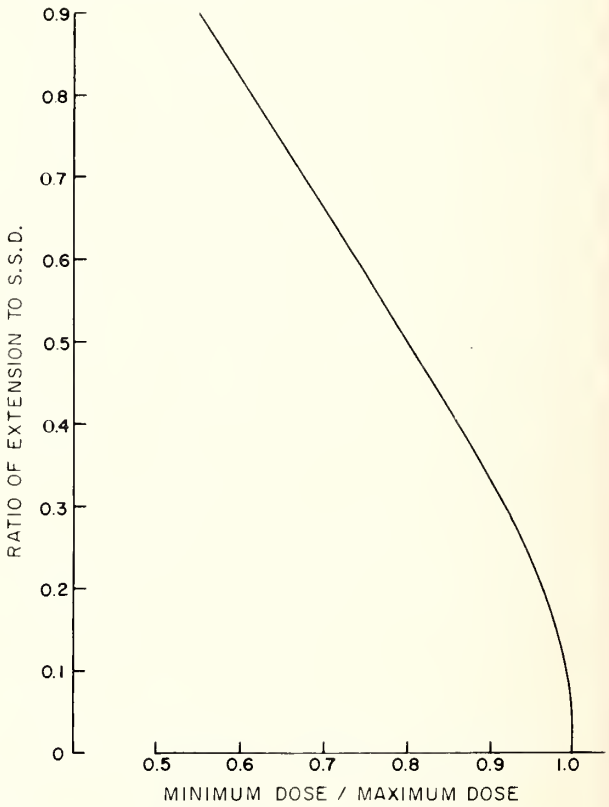

FIGURE 3. *Geometrical factor of variation of exposure introduced by the extension of the object.*

The term "extension" refers to the maximum extension of the object from the axis of the beam. In general, the object length may be twice the "extension" given above with the maximum exposure at the center and the minimum at either end. Example: a 100-cm-long object is to be placed at such a distance from a source that the exposure at either end is no less than 70 percent of that at the center. From the graph the required ratio of extension to source surface distance is less than 0.65. Hence the minimum distance is equal to the extension divided by 0.65, or 50/0.65=77 cm. In the derivation of this curve only the inverse square law has been considered. Finite source size anisotropy of radiation emission absorption, scattering, etc., may require modifications.

TABLE 1. *Influence of scattering material on the exposure rate*

Irradiation conditions: 250 kvp; 30 ma, 0.5mm Copper; 1.0 mm Al filter 70 cms SSD, 25 R condenser ionization chamber

Condition of exposure	Normalized reading [a]
	%
Chamber held by ring stand clamp, "free-in-air"	100
Chamber on ¼ in. thick plywood table	103
Chamber on ½ in. thick plywood table	106
Chamber on ¼ in. thick plywood table; ⅛ in. Pb sheet below	107
Chamber on ⅛ in. thick Pb sheet; ½ in. plywood below	108
Chamber on ¼ in. thick aluminum table	109
Chamber on ½ in. Masonite; plus Al table	115
Chamber on 1 in. Masonite; plus Al table	117
Chamber on 2 in. Masonite; plus Al table	125
Chamber on 3 in. Masonite; plus Al table	128
Chamber on 3 in. Masonite; plus Al table; inside of circular Lucite mouse cage (cage empty) shown in figure 4	135
Same as above; added 1 mouse phantom adjacent to chamber	136
Same as above; added 2 mouse phantoms; one on either side of chamber	138
Same as above; added a total of 9 mouse phantoms to cage	138
Same as above; added 3 in. side-scatter (fir wood)	146

[a] All data have been normalized to condition 1.

irradiation the same number of animals or the same total mass of irradiated material in the radiation apparatus. If animal groups to be irradiated are not of equal size, the smaller groups should be supplemented with unit density material or with dead or unwanted animals to bring the total number of animals or animal weight up to that of the largest group. Compressed laboratory food for rodents makes a suitable unit density material that can be added to supplement the lower number exposure groups.

If an x-ray machine producing a radial[3] beam is employed for small animal irradiations, the cages should be sections of a cylindrical annulus, with the center at the position of the target. Sufficient backing material should be placed behind the animals to allow conditions of maximum backscatter.

For maximum scatter, bolus materials should also be placed lateral to the primary exposure container. This can be accomplished by using cloth bags filled with rice or similar material which can easily be stacked. However, when the direct beam does not strike such materials, they add very little to the scatter (see table 1), and this procedure need only be considered where small differences in effect are being sought.

The physical characteristics of corpuscular radiations and of the accelerators that produce them are complex. Radiobiological experimentation in which such sources are utilized should be carried out in close cooperation with physicists who are familiar with their characteristics.

3.4. Class A Irradiations

When the experimental arrangement is designed to give uniform irradiation of a medium-sized or large object, it will usually be possible to measure dose by means of some dosimeter such as a condenser ionization chamber. In either case the measurement is best made at a point within the object, or within a phantom representing the object, so as to ensure that the dose measurement includes the full contribution from scattered radiation.

When very small objects or micro-organisms are exposed, it will usually be easy to irradiate under conditions satisfying the class A criterion on a macroscopic scale. Serious consideration must then be given to the dose distribution on the scale of the objects themselves, to insure that the variations on this scale do not exceed the stated limits. For instance, the x-ray dose to an insect wing irradiated free in air may be lower than to its body owing to differences in the secondary electron "buildup" unless the insect is closely surrounded by adequate buildup material. Or again, a cell attached to a glass surface may experience a nonuniform dose due to photoelectrons expelled from the higher atomic number elements in the glass. Such nonuniformities may extend over distances of only a small fraction of a millimeter. They are exceedingly difficult to calculate or measure, but they may seriously influence the biological effects studied. They should, whenever possible, be avoided by appropriate design of the experimental arrangement. These matters are illustrated in the examples given. Even when uniformity has been insured on the scale of the objects, the absolute measurements of the exposure by means of commercial instruments may present difficulties. These can often be overcome by placing the micro-organisms inside a sufficiently large block of scattering material to permit exposure measurements by conventional apparatus to be made within it.

Useful information on the attenuation of cobalt 60 gamma radiation in cylindrical and spherical tissue masses has recently become available [27].

3.5. Class B Irradiations

If the incident radiation is substantially attenuated in the irradiated volume, variations in exposure uniformity must exist. Apart from the obvious procedure of selecting a more penetrating radiation, uniformity may be increased substantially by multilateral exposure. The most significant improvement is obtained with bilateral exposure which may be performed by successive irradiation from each side or by simultaneous irradiation from both sides (cross-fire technique).

Rather than using bilateral irradiation with a single source, it is possible to deliver one-fourth of the total dose from each of four directions, one-eighth from eight directions, etc. The ultimate of this approach is either rotation of the animal in front of the source or its equivalent: rotation of the source around the stationary animal.[4] The most important step in achieving uniformity is carried out in the progression from unilateral to bilateral exposure. Further extension

[3] In radial beam machines a vertical electron beam strikes a target which emits x rays in a horizontal plane in a 360° aperture.

[4] Since stress can be important this latter procedure may often be preferable.

to multiport or rotational irradiation usually yields only a small additional improvement in uniformity. Thus, the complications incident to more complex configurations are seldom justified.

It is also possible to arrange multiple sources in an essentially spherical configuration around the animal to be irradiated. Although such a "4-pi" arrangement yields a very uniform dose pattern in free air, it can produce, in an elongated animal, a depth dose distribution which is significantly inferior to that obtained with bilateral irradiation. The reason for this becomes apparent when one considers that a large fraction of the incident radiation makes a small angle with the long axis of the animal and is therefore strongly attenuated by the animal. Thus, if multiple sources or multiple ports are not to be arranged in a common plane perpendicular to the long axis, the arrangement must be devised with great care.[5]

The kilovoltage required to achieve at least moderately uniform irradiation of mammals depends on animal size. Most x-ray machines designed for therapeutic irradiation are suitable for small animal irradiations and x rays having an HVL of 1.5 mm copper or greater are sufficiently penetrating to ensure at least moderately uniform whole-body exposure of large rats or medium-sized guinea pigs irradiated from one side only. However, for x rays generated by potentials below about 150 kv, bilateral exposure may be necessary for animals of this size unless excessive filtration is used.

Medium-sized animals, such as rabbits, large guinea pigs, or small monkeys, usually require for moderately uniform whole body bilateral irradiation, x rays generated by a potential of at least 200 kvp. For unilateral irradiation, x rays generated by potentials of at least 1000 kvp or with gamma rays of 300 kev are required. In the case of larger animals (dogs, goats, and small swine), bilateral exposure to 250 kvp x rays may be adequate for moderate uniformity. With still larger animals (large dogs or swine, burros, etc.) 250 kvp x rays are likely to be inadequate and bilateral exposure to supervoltage or hard gamma radiation may be necessary.

Appropriate apparatus for the constraint of animals can serve to increase uniformity of dose and ease of handling. In the case of small animals, groups of 10 or 12 are frequently exposed simultaneously. Satisfactory exposure apparatus can be made from Lucite and ideally, particularly in the case of x-ray exposures, the entire apparatus should be rotated during exposure to average out inhomogeneities in the beam as described in section 3.4. A suitable type of holder for mice is illustrated in figure 4. The circular container is divided into individual sector compartments. The peripheral end of these compartments can be elevated to compensate for intensity variations across the beam. A similar apparatus for the exposure of rats is shown in figure 5. Utilizing

[5] So-called "bilateral" irradiation is sometimes accomplished by applying one-half of the total dose to each side by means of multiple partial body exposures, i.e., 100 R total body irradiation is carried out by exposing the upper half of one side to 50 R, followed by 50 R to the lower half with the animal then being reversed and the proeedure repeated from tbe other side. Beeause of unavoidable overlap of fields near the eenter, the teehnique is inferior to bilateral irradiation with two exposures.

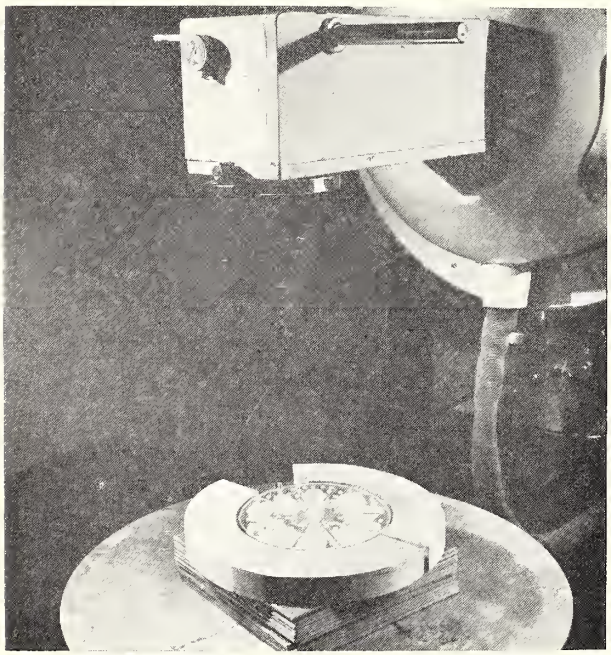

FIGURE 4. *Apparatus suitable for exposing mice under conditions of maximal scatter, using a conventional x-ray therapy machine.*

The entire apparatus is rotated during exposure.

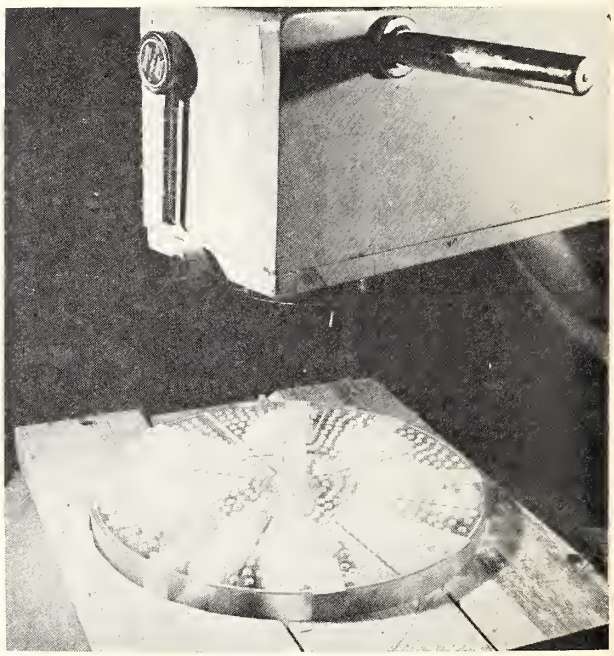

FIGURE 5. *Apparatus suitable for exposing rats under conditions of maximal scatter, using a conventional x-ray therapy machine.*

The entire apparatus is rotated during exposure.

containers of this type, uniformity to a few percent can be realized. A very high degree of dose uniformity may be achieved if animals are irradiated in cavities of tissue equivalent material [26]. A possible drawback of such measures is that the additional handling and constraint of the animals may produce physiological reactions and cause some modification of the response, thus introducing an additional source of individual variation.

Medium-sized animals are usually irradiated singly and may be restrained in snugly fitting boxes made of ¼ in. Lucite or similar material (fig. 6). It must be realized that animals in a group may vary in size and that equal exposure "free-in-air" will produce different absorbed dose patterns. In particular, the midline dose (which is perhaps the best single parameter that can be used to characterize the irradiation—see below) may be different for different animals.

Whole body irradiation of small dogs can be carried out with conventional therapy equipment at satisfactory uniformity and dose rate, provided the animal is "molded" so that its body presents an essentially circular configuration of minimum diameter. This is most easily accomplished by anesthetizing [6] the animal and placing it within an irradiation apparatus as shown in figure 7. Without anesthesia the animal usually must be permitted to stand up or lie down, necessitating irradiation at such large distances from the tube that the dose rate is considerably lower.

While still larger animals, such as swine and goats, can sometimes be irradiated with a similar technique, the use of radial beams is preferable. In this case (see fig. 8) animals are arranged tangentially to a circle around the target, and exposed in canvas slings or in simple cages or supports built of plywood or similar material. Anesthesia makes it much easier to handle the animals and tends to ensure more uniform irradiation conditions. In this manner several large animals can be exposed simultaneously. Bilateral irradiation is achieved by reversing the animals when half the dose has been delivered. The use of radial beams in the irradiation of small mammals is shown in figures 9 and 10.

3.6. Class C Irradiations

The degree to which incomplete radiation equilibrium contributes to dose inhomogeneity depends on the size of the object to be irradiated and the energy of the radiation in question. In micro-organisms or plants, appreciable nonuniformity of absorbed energy can occur with irradiation by x rays of conventional energies. The establishment of equilibrium for megavolt radiations requires an appreciable depth. A special case exists with irradiation by thermal neutrons, where an important secondary radiation (capture gamma rays from the H (n,γ) D reaction) has a penetration that exceeds that of the primary

[6] It must be realized that anesthesia may affect radiosensitivity and also result in important physiological changes such as change in blood count.

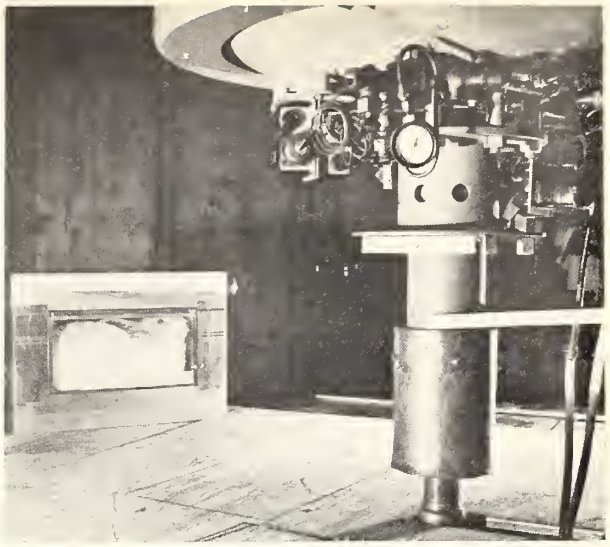

FIGURE 6. *Apparatus suitable for exposing rabbits or animals of similar size under conditions of maximal scatter.*

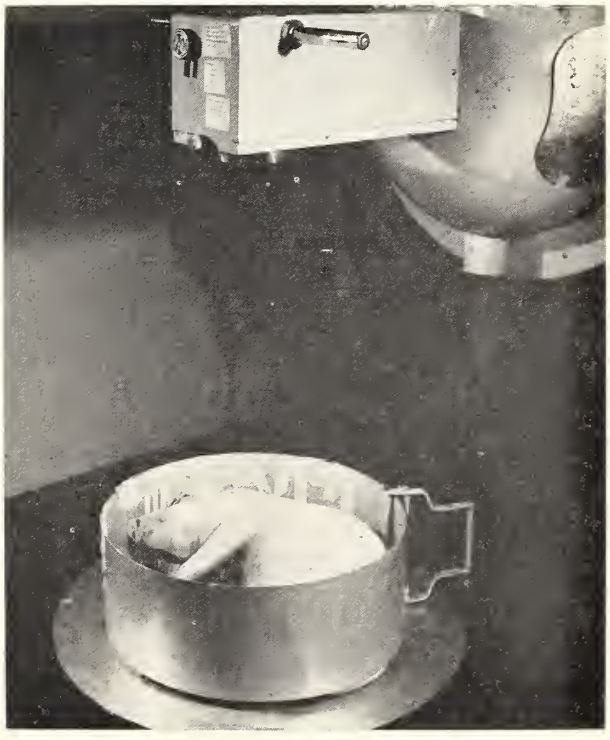

FIGURE 7. *Apparatus suitable for irradiating small to medium-sized swine or similar-sized animals, using a conventional head 250 kvp x-ray machine.*

The animal is anesthetized, and the entire apparatus is rotated during irradiation.

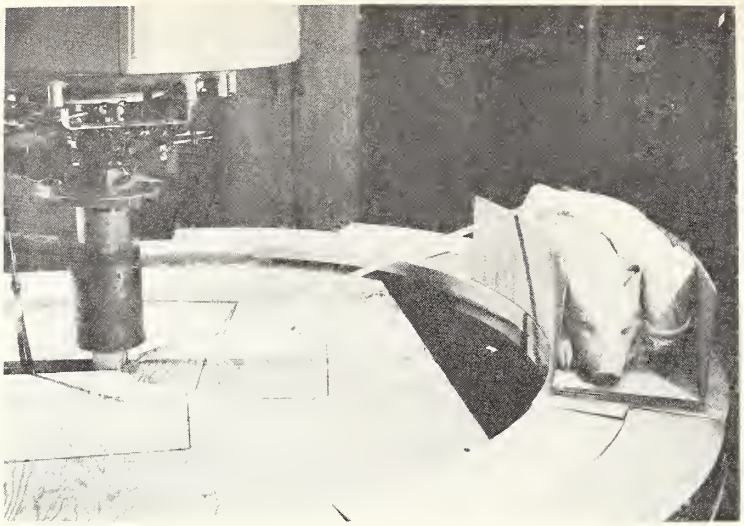

FIGURE 8. *A simple apparatus suitable for exposing swine or similar-sized animals, using the radial beam from a 250 kvp x-ray generator.*

The animal is anesthetized during exposure. Several animals can be exposed at one time using this method.

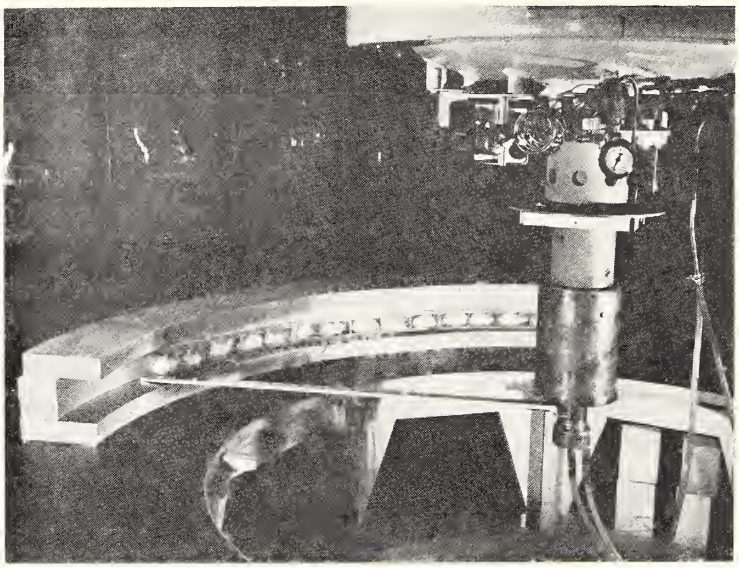

FIGURE 9. *Apparatus for exposing mice under conditions of maximal scatter, using the radial beam from a 250 kvp x-ray generator.*

radiation. In this case equilibrium is never established and uniform irradiation is particularly difficult to achieve.

Figure 11 shows the approximate thickness of unit density material required to establish electronic equilibrium in the case of irradiation by x and gamma rays. Figure 12 shows the thickness of water required to establish proton equilibrium for fast neutrons. Because a buildup curve has in either case a typical "saturation shape," substantially thinner layers furnish a high degree of equilibrium. Thus in layers having half the thicknessess given in figures 11 and 12, the dose might be within a few percent of its equilibrium value.

Obviously the simplest way of overcoming the difficulty is to irradiate material behind a bolus of inert material having an appropriate composition and a sufficient thickness. With x and gamma rays such buildup layers are usually required only at quantum energies where the photoelectric effect is unimportant. Hence identical atomic composition is not essential and various unit density materials are suitable, provided their hydrogen content is that of most commonly available plastics (7 to 14 percent). Plastics containing higher atomic number constituents (polytetrafluoroethylene, vinylchloride, etc.) should be avoided.[7] In the case of

[7] When plastics are irradiated, volatile compounds can be produced which may, on occasion, be dangerous to the living material irradiated. Thus the results of gamma irradiation of dried T_1 coli bacteriophage between plastic foils have been shown to depend on the nature of the plastic to a degree which was much beyond the expected small influence of variation in hydrogen content. The presence of Teflon was found to result in higher survival than that of Plexiglass which, in turn, was less deleterious than polyethylene [19].

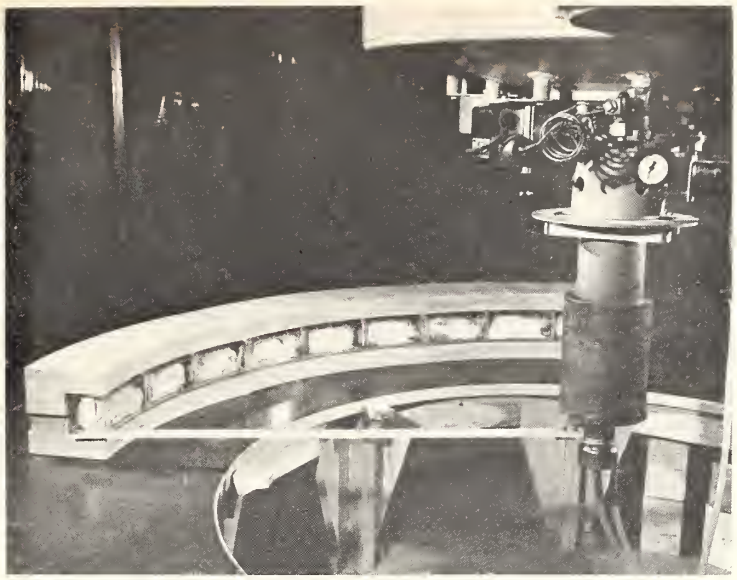

FIGURE 10. *Apparatus for exposing rats under conditions of maximal scatter, using the radial beam from a 250 kvp x-ray generator.*

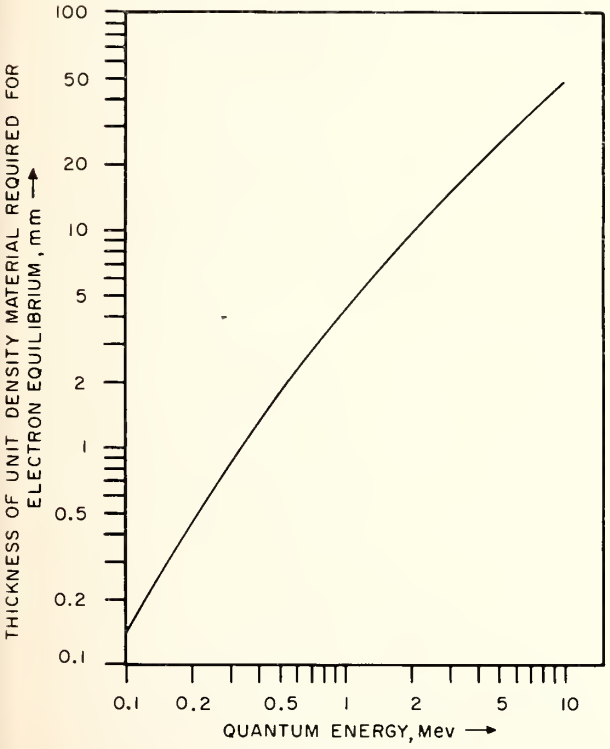

FIGURE 11. *Approximate thickness of unit density material required to establish complete electron equilibrium for monochromatic x-radiation.*

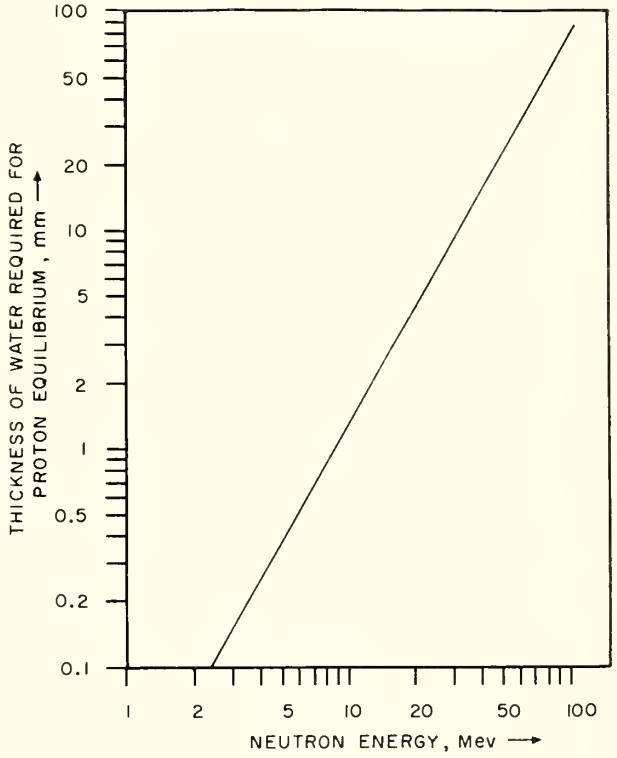

FIGURE 12. *Thickness of hydrogenous material required to establish complete proton equilibrium for neutrons of various energies.*

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fast neutrons the hydrogen content is more critical, and at low neutron energies certain trace elements, such as boron and lithium, may also become important. Hence the bolus material must be carefully selected in such a way as to have the same atomic composition as the irradiated tissues (see section 3.7). In the case of growing plants, it is often found convenient to surround the plant to be irradiated with a plastic cylinder.

When a broad beam of intrinsically neutral radiation traverses a medium of uniform atomic composition but varying density and if the kerma is constant throughout the medium, the absorbed dose is constant regardless of density variations [5, 6]. It might, therefore, be supposed that apart from minor differences in Compton scattering, a plant which is at a distance from a gamma-ray source greater than the maximum electron range in air does not require application of bolus material, since buildup should occur in the intervening air space. However, this is not the case because (1) the radiation field is divergent at such a distance from the source and equilibrium is not approached until the object is several electron ranges removed from the source [4], and (2) even at distances sufficiently large, for the establishment of equilibrium (a condition rarely attained in practice) constant beam intensity must exist in any direction from the plant up to a distance that is equal to the maximum electron range in air unless solid objects within electron range are tissue or air equivalent. This requirement is usually vitiated by the presence of soil. For these reasons there appears to be no satisfactory method of avoiding the use of bolus.

3.7. Effect of Atomic Composition

(a) *X rays and gamma rays.* The relation between the absorbed dose D, measured in rads, and the exposure X, measured in roentgens, at any point in an irradiated medium is given [13] by

$$D=f\times X \text{ where } f=0.869\times\frac{\left(\frac{\mu_{en}}{\rho}\right)_{\text{medium}}}{\left(\frac{\mu_{en}}{\rho}\right)_{\text{air}}}$$

and $\frac{\mu_{en}}{\rho}$ represents the total mass energy absorption coefficient for the medium irradiated and for air, respectively.

The problem of determining the effect of atomic composition on the absorbed dose for different qualities of x or gamma radiation is therefore equivalent to determining how the factor f varies with atomic composition and radiation quality.

The relevant theoretical and experimental data have been collected together in tables IA1 and IA2 of ICRU Report 10b. For air at all radiation qualities, f, by definition, must have the value 0.869 rad per roentgen. For water the value of f varies between 0.87 and 0.97 over a range of the photon energy from 10 kev to 3 Mev. Over the same energy range f for muscle (assuming the chemical composition given in footnote 3 of Report 10b) varies between 0.91 and 0.96.

Bone, by virtue of its high content of calcium and phosphorus, gives high values for f at the lower photon energies. Over photon energies from 10 kev to 40 kev, f for bone has a value of about 4 (table IA1 of ICRU Report 10b). At higher photon energy the value falls, reaching values slightly below those for muscle at photon energies above 300 kev. Various aspects of the dosage problem in and near bone, including the problem of absorbed dose in a small volume of soft tissue enclosed within bone, are discussed in detail in ICRU Report 10d. However, because of different trabecular distances, some of the numerical results are not necessarily applicable to smaller mammals.

The effect on the absorbed dose to exposure dose ratio of the presence in soft tissue of elements of higher atomic number can conveniently be illustrated by curves showing the concentration by weight of various elements necessary to produce a given percentage change in f, over a range of photon energies.

Calculations have been made of the concentration by weight (in $\mu g/g$) of various elements necessary to produce a 1-percent change in $\frac{\mu_{en}}{\rho}$ for muscle, at photon energies between 20 kev and 10 Mev, the chemical composition of muscle being that given in ICRU Report 10b.

If $\left(\frac{\mu_{en}}{\rho}\right)_{mus}$ is the value of the mass energy absorption coefficient for muscle and $\left(\frac{\mu_{en}}{\rho}\right)_{n}$ that for an element "n," the concentration (in micrograms per gram) of the added element that is required to produce a 1-percent change in the overall mass energy absorption coefficient is given by the formula.

$$x=\frac{10^4}{\left[\left(\frac{\mu_{en}}{\rho}\right)_n\Big/\left(\frac{\mu_{en}}{\rho}\right)_{mus}\right]-1}$$

In the calculations that have been made, table IA1 of ICRU Report 10b was used for values of $\left(\frac{\mu_{en}}{\rho}\right)$ for muscle and for all elements up to atomic number 20. For elements of higher atomic number the values of $\left(\frac{\mu_{en}}{\rho}\right)$ were obtained by summing the values for photoelectric absorption coefficients given by Grodstein [8] and values for Compton real absorption for free electrons from the Klein-Nishina formula. The values for the pair production real absorption coefficients have been derived from the total pair production absorption coefficients given by Grodstein.

Figure 13 shows the change with atomic number of the concentration of the element (in micrograms per gram) required to produce a 1-percent change in the value of f. Curves are shown for photon energies of 20, 50, 80, and 100 kev. The discontinuities in the curves for 20, 50, and 80 kev relate to the K absorption edge at these atomic numbers. No values are given for photon energies greater than 100 kev, since for higher energies the values of x for a 1-percent change in f are much greater than those which would normally be encountered.

Data on the concentration of many elements in the various tissues of the body are given in table 7 ("Elements in the body organs of standard man") of the Report of ICRP Committee II, 1959 [9]. From these data it can be seen that the reported concentrations of the heavier elements in the great majority of the soft tissues of the body are insufficient to cause a variation of more than ± 5 percent in the total absorption coefficient at 20–50 kev photon energy as compared with that for muscle. For most tissues the variation is much less than ± 5 percent. The elements responsible for a greater variation in the energy range 20–50 kev are iodine in the thyroid (increasing the absorption coefficient by about 10 percent) and tellurium in liver and spleen. If the quoted tellurium levels in these two tissues are correct, the value of the total absorption coefficient in liver could be increased by as much as 30 percent and in the spleen by about 10 percent.

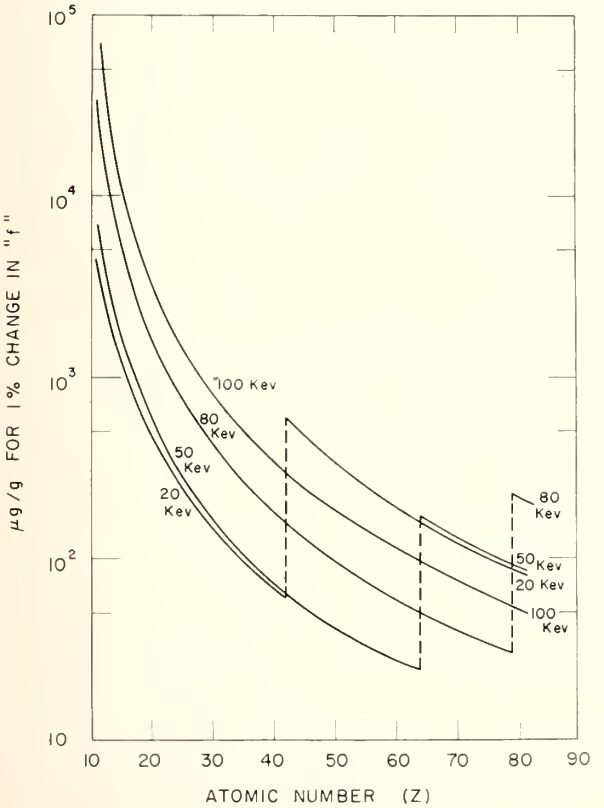

FIGURE 13. *Concentration in μc/g of additional element to produce 1 percent change in value of* f *(relative to value for muscle).*

At higher photon energies the effect of the presence of the heavier elements becomes less important. Under most experimental conditions it can be assumed that the value of f for all the soft tissues of the body will have the same value within a few percent, but if soft radiations of photon energies less than 100 kev are being used it may be necessary to take into account the heavier elements present in thyroid, liver, and spleen.

For plants and other types of biological material the concentrations of the heavier elements will sometimes greatly exceed those found in the soft tissues of man. The diagram may then be useful in giving a guide to the order of change to be expected in the value of f.

(b) *Neutrons.* The effect of atomic composition on dose in irradiation by neutrons involves quite different considerations from those above relating to x or gamma radiation.

(b.1) *Fast Neutrons.* For fast neutrons (neutrons of energies between 10 kev and 10 Mev) the important process of energy transfer is elastic scattering; the recoil nuclei resulting from this process constitute the charged secondary particle radiation which directly imparts energy to the tissue; the range is about 1 mm or less for neutron energies up to 10 Mev. The cross section for elastic scattering and the mean energy transfer per collision depend on the nature and the mass of the struck nucleus. Hence the atomic composition of the tissue is important.

The mean energy, ϵ_i, transferred in an elastic collision between a neutron of energy ϵ (Mev) and an atom of type i is given by

$$\epsilon_i = \frac{2A_i \epsilon \sigma_i(\epsilon) K_i(\epsilon)}{(1+A_i)^2}$$

where

$$K_i(\epsilon) = \int_0^{\pi} [\sigma_i(\theta, \epsilon)/\sigma_i(\epsilon)](1-\cos\theta) 2\pi \sin\theta d\theta$$

$\sigma_i(\epsilon)$ = Total elastic scattering cross section for neutrons (barns)

$\sigma_i(\theta, \epsilon)$ = Differential elastic scattering cross section for neutrons scattered at angle θ (barns/steradian)

A_i = Atomic weight of atom of type i

The absorbed dose in rads in a pure material of type i, for a fluence 10^9 neutrons/cm^2, assuming scattered neutrons can be neglected, is

$$\frac{2A_i \epsilon \sigma_i(\epsilon) K_i(\epsilon) 10^{-24}}{(1+A_i)^2} \times \frac{6.026 \times 10^{23}}{A_i} \times 1.602 \times 10^{-8} \times 10^9$$

i.e.

$$\text{Dose (rads) for } 10^9 \text{ } n/\text{cm}^2 = 19.31 \times \frac{\epsilon K_i(\epsilon) \sigma_i(\epsilon)}{(1+A_i)^2}$$

Owing to the presence of the term $(1+A_i)^2$ in the denominator of this expression, the dose falls off rapidly as the atomic weight of the irradiated substance increases. For this reason, the hydrogen content in a mixture of atoms has a great effect on the dose; for example, with 1 Mev neutrons about 85 percent of the dose in tissue containing 10 percent of hydrogen by weight (c.f. ICRP Standard Man) is due to neutron interactions with hydrogen.

Values of the dose at various neutron energies have been calculated from the expression above, using the following reference sources:

Values $\sigma_i(\epsilon)$, are given in BNL–325[2]

$K_H=1$ (Because the scattering is isotropic for hydrogen in the center of mass system.)

K_C and K_N Are given in BNL–400[3] except that beyond $\epsilon=7.0$ Mev, a fixed value of $K_C=0.74$ is used; beyond $\epsilon=2.4$ Mev, a fixed value of $K_N=0.9$ is used.

K_O Are available from the theoretical data in Okazaki [11] at $\epsilon=0.41$, 0.438, 0.465, 0.49 Mev and in Baldinger et al. [1] at $\epsilon=2.0$, 2.2, 2.4, 2.5, 2.9, 3.1, 3.2, 3.33, 3.44, 3.57, 3.7, 3.83, 3.96, 4.08 Mev; interpolation is used where necessary and beyond $\epsilon=4.4$ Mev, a fixed value of $K_O=0.7$ is used.

Figure 14 gives neutron doses in pure hydrogen, carbon, nitrogen, and oxygen. In order to calculate the neutron dose for tissuelike materials, it is only necessary to multiply the value for each constituent by the percentage composition by weight and add the contributions. For example, the dose in a sample of tissue corresponding to the ICRP Standard Man ($H=10$ percent, $C=18$ percent, $N=3.0$ percent, $O=65$ percent, remainder=4 percent) is:

(0.1)(Rads for pure H)+(0.18)(Rads for pure C)+(0.03)(Rads for pure N)+(0.65)(Rads for pure O)

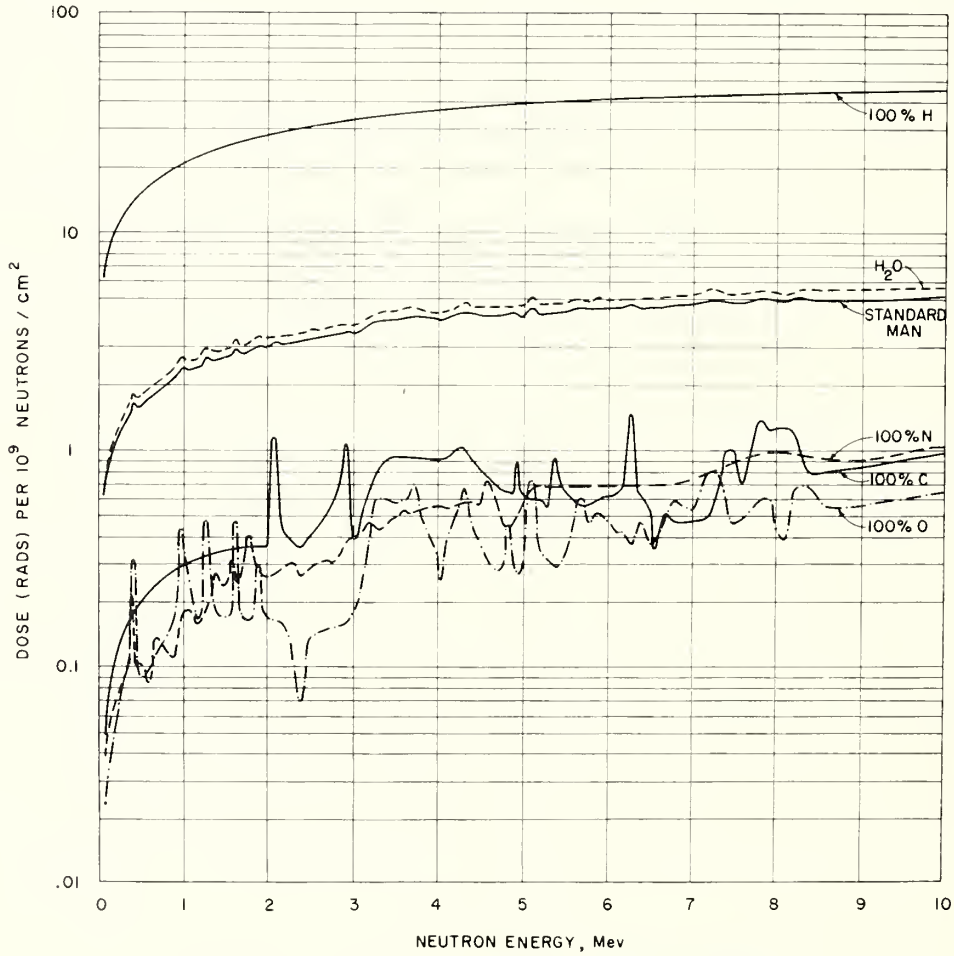

FIGURE 14. *Absorbed dose delivered under equilibrium conditions by a time-integrated flux of 10^9 neutrons/cm² as a function of neutron energy.*

The remainder of 4 percent heavier atoms make negligible contribution to the energy transfer processes. The figure gives neutron doses in the "Standard Man" and in water (*H*, 11.19 percent; *O*, 88.81 percent).

Under most practical conditions of irradiation, there is an appreciable spread of neutron energies and in such cases the irregularities in the curves would be effectively smoothed out.

It may be seen that for a given neutron exposure the absorbed dose in water is about 10 percent greater than in "Standard Man", mainly due to the difference in hydrogen content. The factor of atomic composition can become even more important in the irradiation of seeds with fast neutrons since the water content can be varied over a considerable range. For the highest accuracy of dose estimation, the atomic composition of any tissue should be measured. For example, the composition of the terminal 5 mm segment of growing root tips of the bean, *Vicia faba*, was found to be: *H*, 10.4 percent; *C*, 7.5 percent; *N*, 1.5 percent; *O*, 80.2 percent [25] (Neary, Tonkinson and Williamson). This composition is significantly different from either the "Standard Man" or water.

The data given refer only to elastic scattering of fast neutrons. Near the upper end of the fast neutron range and for relativistic neutrons (i.e., neutrons having energies in excess of 10 Mev), the possibility of inelastic neutron interactions with nuclei has to be taken into account, and few generalizations are possible. The particular case of 14.1 Mev neutrons has been discussed by Randolph [12].

(b.2) *Slow Neutrons.* The dosimetry of thermal ($E_N < 0.5$ *ev*) and intermediate (0.5 *ev* $< E_N <$ 10 kev) neutrons is considerably more complicated than that of fast neutrons. The most important contribution to the dose normally is due to nuclear disintegration of nitrogen, N^{14} (n,p) C^{14}, the proton and the recoil carbon-14 nucleus contributing directly to the absorbed dose. Thus the nitrogen composition of tissue is most important, and this quantity can vary considerably from one type of tissue to another. Under special circumstances other elements can assume importance if the neutron capture cross sections are large; e.g., boron, for which the cross section per nucleus for thermal neutrons is 741 barns. One of the boron isotopes undergoes disintegration on capturing a neutron, B^{10} (n,a) Li^7 and the alpha particle and Li^7 recoil contribute to the absorbed overall tissue dose. For example, Conger and Giles [31] have estimated that when inflorescences of *Tradescantia* are irradiated with thermal neutrons, about one-third of the dose in the nuclei of the pollen cells is due to the disintegration of the boron in this tissue.

A further complication arises with slow neutrons, that the capture of a neutron by a nucleus of hydrogen leads to the emission of a hard gamma ray, $H(n,\gamma)D$. This gamma ray contributes little to the local absorbed dose. If, however, the size of the tissue sample is not extremely small, the contribution of the gamma rays from the whole mass to the absorbed dose at any one point becomes appreciable. The precise assessment of the relative contributions of the various processes of interaction of slow neutrons with tissue is thus difficult; further, the different components of absorbed dose have markedly different LET characteristics. For these reasons the use of slow neutrons for biological irradiations requires great care.

3.8. Internal Irradiation

Internal irradiation is not generally used nor recommended for "routine" irradiation, since measurement or calculation of the absorbed dose with any reasonable accuracy is generally difficult and frequently impossible, and in addition there is the problem of a varying dose rate. Even with an energetic gamma emitter such as Na^{24}, which has a comparatively uniform distribution in the body, the dose falls off markedly at the periphery because of geometrical considerations, and there is a "pooling" of sodium in the bony structures. Thus, the administration of internal emitters, in most cases, will usually be for the purpose of studying the effects of that isotope, or of the particular absorbed dose distribution attained with the isotope in a particular chemical form.

With internal emitters it is necessary to distinguish the following concepts:

Isotope dose [8]—the amount of administered radionuclide which should be expressed in terms of millicuries or microcuries administered per gram body weight.

Absorbed dose—the measured or calculated radiation dose at a given point which should be expressed in rads.

Nonuniformity of distribution of a radionuclide in a tissue can lead to very great problems in the calculation of the absorbed dose distribution, particularly for alpha-emitters and the lower-energy beta-emitters. For such calculations very full information is required on the distribution of the radionuclide within the tissue considered, but even when this is available there may still remain severe physical and mathematical problems.

However, thick section autoradiographic techniques provide a means of measurement of the distribution of absorbed dose from a specimen of the material. With alpha-emitters, dose data can be computed from the distribution of track counts in the photographic emulsion. With beta-emitters, either counts of photographic grains or measurements of photographic blackening are made and compared with that produced by a source of known dose rate of the same radionuclide.

[8] Isotope dose is the commonly used name for this quantity. "Radionuclide" would be a better choice than "isotope," and "dose" as used here has a different meaning from the word "dose" as used in "absorbed dose." However, the ICRU has not yet suggested a more appropriate name for this quantity.

In all cases, whether calculations or measurements of the absorbed dose are quoted or not, adequate information should be given about the administration of the radionuclide, including:

1. Radionuclide involved and its chemical form.
2. Specific activity; i.e., concentration of active radionuclide in terms of total element present.
3. Vehicle in which administered, pH and activity concentration of administered solution.
4. Isotope dose; i.e., millicuries or microcuries administered per gram body weight.
5. Route of administration.
6. Any special remarks; e.g., particulars of preparation of the solution which might be relevant.
7. Details of recipients. In the case of animals this must include species, strain, sex, age, weight, and other relevant particulars.

3.9. Determination of Absorbed Dose

The dosimetry of radiobiological experiments commonly involves two types of radiation measurements, and it is important that the different nature of these measurements be clearly realized.

In order to establish an accurate basis of comparison between the irradiations carried out at various times at the same installation, the rate of radiation emission by the source should be determined frequently. The determination of the exposure rate or kerma rate at a convenient distance from the source is usually used as a measure of this rate of emission. Such an exposure rate or kerma rate is often loosely called the output of the source. The usefulness of such a measurement is often apparent when a source operating under seemingly identical conditions is found to vary in output. In the ensuing irradiation of a biological object, it is assumed that the absorbed dose in it is proportional to the output. Such a measurement of output is commonly carried out with a minimum of scattering material present and utilizing a dosimetric device having minimal mass and supported with a minimum of surrounding material (i.e., with a lightweight clamp), in order to avoid potentially variable scattering contributions. Sometimes a monitoring device (usually an ionization chamber) is employed to determine the output or a proportional quantity during an irradiation.

The absorbed dose is frequently determined on the basis of exposure rate within the irradiated biological object, and the same physical device may be employed which is utilized in the measurement of output. However, in this case the measurement is carried out with all the scatter material normally present, including suitable phantom material to simulate the object to be irradiated. Because of the various effects discussed in 3.1, such an assessment of absorbed dose is essential in accurate work. General methods for the determination of absorbed dose are discussed in ICRU Report 10b and the factors relating exposure and absorbed dose are also discussed there. Whatever method is employed to derive the absorbed dose, the procedure as well as the numerical factors employed should be stated explicitly. The derivation should be carried out by the experimenter whenever possible; a mere statement of the magnitude of exposure or kerma is usually insufficient.

In case of uniform (class A) irradiation, the absorbed dose may be expressed as a single number. In other cases some information on dose distribution should be given, but in referring to "the dose" received by the animal, the absorbed dose at the center of the animal should be used. This choice does not reflect any particular biological significance of the organs at the midpoint of the animal, but only the fact that it is relatively easy to measure or calculate the central dose using central axis depth dose curves, and that the center is usually a region of soft tissue relatively distant from bony structures. As nearly as can be deduced from the relatively scanty data available, the biological effects of interest when whole body irradiation is administered are, in a given animal species, sensibly the same for individuals of different size if the basis of comparison is the midline absorbed dose in bilateral exposure.

It is usually desirable to supplement information on the dose near the center of the animal with the dose distribution along two axes intersecting at this point, one being in the direction of the beam and one at right angles to it (preferably along a body axis). From these data it is possible to estimate the entire dose distribution reasonably well. It is, of course, preferable if more detailed measurements performed with either animal cadavers or phantoms of appropriate material are available.

4. Time Factors

The temporal distribution of absorbed dose may usually be expressed with little difficulty. Nevertheless the information given is often incomplete. The factors which are of importance are not only the time over which the dose was delivered or, alternatively, the mean absorbed dose rate, but also any intensity variations that may occur in the case of pulsed radiation sources. In moderately uniform or nonuniform irradiations it is evident that of necessity the dose rate given must be an average. However, the existence of a range of variation about this average is usually of little significance.

If any fractionation scheme is employed, the relative timing of successive exposures as well as the doses and dose rates delivered must be specified. Most of this information may be displayed conveniently in the form of a graph showing either dose per treatment or accumulated dose versus time.

5. Numerical Specification of Local Energy Density in Irradiated Tissues

The biological effect of a given absorbed dose depends on the type of radiation used. Hence a

statement of the latter is always essential. Since the differences in biological effectiveness of radiations are attributed to variations in the microscopic pattern of energy deposition, a more explicit specification of such variations is desirable in RBE studies and in certain other radiobiological experiments, particularly those that are concerned with the mechanism of radiation effects.

There are several levels of increasing detail which may be employed in the specification of radiation quality.

The simplest and minimal characterization consists of a statement of the type and energy of the radiation to which the biological object was exposed. In the case of a mixture of several radiations, the absorbed dose delivered by each must be given. Frequently radiation energy is distributed over a spectrum with the precise mode of distribution being difficult to determine. In such cases partial information may be furnished by appropriate parameters. In the case of x rays these are tube potential and half-value layer (sometimes both first and second half-value layer and homogeneity factor—see Report 10b). In the case of neutrons, appropriate parameters have not been established but corresponding specifications can be given.[9]

Somewhat more detailed information is the distribution of absorbed dose with respect to type and energy of charged particles. This is particularly desirable if the external radiation may liberate a variety of charged secondaries as is the case with neutrons.

A still more explicit description is in terms of the "distribution of dose in LET" of the charged particles that deliver the dose. For certain radiobiological studies the distribution of track length with respect to LET is also employed. There are, however, a number of uncertainties in such a representation which arise from the fact that the track of an ionizing particle has finite lateral extension, curvature and finite length. As a result, it is impossible to provide a clear definition of what part of the energy is deposited "locally," and whatever choice is made, the actual amount of energy deposited in some small volume in the irradiated tissue cannot be derived from the LET distribution.

In order that ambiguity in the meaning of the term "LET distribution of dose" be avoided, it is recommended that the LET distribution considered be that of the charged particles produced in tissue by uncharged primaries or, in the case of external irradiation with charged particles, the LET distribution of the latter. Energy communicated to delta rays should be considered as part of the LET of the charged particle that produces them unless there is an explicit statement to the contrary.

Some of the limitations of the LET concept may be overcome by use of the parameter "Y" which has been defined [14] as the energy delivered in individual events to small spherical regions in irradiated tissue divided by the sphere diameter. The distribution of dose in Y depends on the sphere diameter and, consequently, complete specification in terms of this parameter consists of a set of curves, each of which corresponds to a different diameter.

The local energy density ΔZ produced in a microscopic sphere of irradiated tissue as a result of an event of magnitude Y is equal to $(30.6\ Y/d^2)\times 10^2$ ergs/g. If the absorbed dose is large, the LET low, or the sphere large, several events may occur in the sphere during the delivery of the entire dose. The total energy Z [15], will then depend on the Y spectrum of dose in a rather complex manner. Z is then not only a function of sphere diameter, but also of dose. Such a representation while very complete is evidently also very complex, and it should be reserved for instances where there is need for considerable detail.

6. Examples

In the following, examples of recommended exposure arrangements will be given in a form in which they might be reported for publication.

6.1. Class A Exposure of Mice

A constant potential x-ray machine was used to irradiate the mice, using the following exposure factors: 250 kv; added filtration of 0.5 mm copper, 1 mm aluminum; HVL, 1.2 mm copper; 30 ma; source distance (to center of animal): 100 cm. The mice were exposed, 10 at one time in a circular container measuring 20 cm in diameter, divided into sectors, and placed on top of a block of wood measuring 25x25x7 cm. The exposure with scatter was measured by placing a _____(give make) dosimeter in the center of a phantom placed at a point corresponding to that of a representative animal, and the exposure rate thus determined, with the apparatus rotating at approximately 3 revolutions per minute, was found to be 24 R per minute. The absorbed doses reported were derived from the exposure dose with scatter by applying the factor of 0.95. A diagram of the exposure arrangement used is shown in figure _____.

6.2. Class A Exposure of Micro-Organisms to Electrons. Irradiation of Dried Spores of B. Megatherium

The electron beam was produced in a microwave linear accelerator operating at 10 cm wavelength and delivering current in 2 μsec pulses. The mean electron energy used in these experiments was 2 Mev with about 10 percent energy spread and the peak current was about 0.1 amp. Pulse repetition frequencies of 50, 100, 150, and 200 pulses per second were used. The electron beam emerged through a .001 in. thick Al window and with the shutter open it encountered no other scattering material except air, until it struck the spore holder, at 20 cm distance from the window.

[9] E.g., "Neutrons emerging at 0° with respect to an 8-Mev deuteron beam bombarding a 1-cm-thick beryllium target and filtered by 1.5 cm of brass."

The mean dose per pulse at the spore holder was generally about 20 kilorads, varying a little in the different experiments. The beam intensity was set, prior to each irradiation, by closing a thick Al shutter immediately in front of the window and adjusting the electron current to the appropriate value, known from previous measurements of dose.

The spores were deposited on millipore filter material which was dried and cut into discs 6.5 mm in diameter. The spore concentration was 10^2, 10^3, 10^4, 10^5, or 10^6 per disc, depending upon the dose to be delivered. At each dose level five discs of the appropriate titer were taken and placed between monitor discs of Lucite 3 mm thick, in a special holder. The beam of 2-Mev electrons passed through the complete assembly and the spore discs lay close to the peak of the depth dose curve, which had been plotted out previously, using a stack of 1-mm thick Lucite discs in the same holder.

After each irradiation, the optical density induced in the two Lucite monitor discs was measured and the corresponding mean dose in each deduced from a calibration curve. Knowing the depth dose curve, the dose at the spore discs could be calculated with a standard error of some 2 percent. The depth dose curve was flat near its peak and the five spore discs showed no significant differences in the dose received.

6.3. Class A Exposure of Plants to X Rays

The root tips of broad beans, *Vicia faba*, were irradiated with x rays. The tube voltage was 250 kv constant potential, the added filter was ¾ mm of aluminum plus a thickness of copper which varied over the beam cross section to ensure uniformity to ±2 percent. The thickness of the copper filter at the beam center was ¼ mm and the HVL of the beam on the axis was 1.2 mm of copper. The tube current was adjusted so that different groups of bean roots received the same dose, of 161 rads at different dose rates.

The bean roots, about 10 per group, were immersed in water in a vertical flat cell, whose internal dimension in the direction of the horizontal x-ray beam was 5 mm; the walls of the cell were of Perspex (Lucite), each 1/16 inch thick. The region of a root in which the dose was required to be uniform and accurately known was about 3 mm long and all the tips in the cell were contained within an area (normal to x-ray beam) of less than 1 cm^2. The distance of the center of the cell to the x-ray focal spot was 34.8 cm; the x-ray beam was defined by a 9x9 cm square lead diaphragm in the tube port at 20.0 cm from the focal spot. The bean cell was supported in a light stand so that the root tips were at a height of 37 cm above a table.

There was little scattered radiation, but in any case the exposure was measured by a small graphite ionization chamber specially arranged in a dummy cell; the chamber, which had a guard ring, was connected to a D.C. amplifier. The difference between the amount of absorbing material between x-ray source and chamber and x-ray source and bean root axes was negligible (0.05 g/cm^2). The chamber had been calibrated free-in-air in the same x-ray beam by exposing a 250 R chamber alongside it. The chamber correction factor at this radiation quality was 1.19 at 22 °C and 760 mm as indicated by comparison with the free air chamber at the national standardizing laboratory. The absorbed dose to the bean roots, in rads, was obtained from the exposure in roentgens by multiplying by the factor 0.94 (see ICRU, 1962 Report 10b).

6.4. Class B. Moderately Uniform Exposure to X Rays of Medium-Sized Mammals

Rats were irradiated unilaterally by x rays. The rats were contained in a Perspex (Lucite) cage of overall dimensions 18x18x6 cm high which was divided into three compartments to take three rats side by side at a time. The thickness of the lid, base, side, and partition walls was 6.4 mm.

The cage was placed on top of a Mix D back-scattering mass of square section 30x30 cm and thickness 16 cm. The cage was also surrounded on all sides by scattering material whose thickness and width were 5 cm. Irradiation was from above and the beam irradiated the whole of the phantom.

The x-ray factors were:
250 kv constant potential; 1.0 mm copper filter; HVL 1.95 mm copper; 14 ma; source distance, 70 cm to top of the cage.

For dose measurements the rats were represented by phantoms constructed of Mix D wax; the length was 17 cm and the cross section corresponded to a square of side 4.5 cm with four corners at one end cut off at 45° at points on each side 1 cm from a corner. The mass of a phantom was 300 g.

Air-wall condenser chambers of Type _____ were used to measure the exposures at points in the phantoms. The exposure rate at the center point of a phantom in the central compartment of the cage was 48.3 R/min. and so the absorbed dose rate in soft tissue would be, according to ICRU 1962 Report 10b, table I–2, $48.3 \times 0.95 = 46.4$ rads/min.

The exposure rate at the entry surface in a vertical cross section through the midpoint of the long axis of the phantom was 52.6 R/min., and at the exit surface in this plane was 42.7 R/min. In a cross section through a point 3 cm from the end of a phantom, the entry and exit exposure rates were 51.8 and 40.6 R/min. respectively. The ratio of maximum to minimum was therefore about $52.6/40.6 = 1.29$. Exposure rates in the phantoms in the two outer compartments of the cage were about 1 percent less than in the center compartment.

6.5. Class B Moderately Uniform Exposure of Large-Sized Animals to X Rays

The dogs were exposed, four at one time, using the radial beam from a pulsed x-ray machine and bilateral technique. Radiation factors were: 250 kvp; no added filtration; HVL, 0.6 mm copper; 30 ma; source distance (to proximal skin surface of animal), 100 cm. One-half of the treatment was given from one side of the animals, following which the animals were reversed and the other half of the treatment was given. Barbiturate anesthesia was used during exposure, and the animals were placed in plywood containers as illustrated in figure _____. These containers were shaped to conform to an arc of a circle of 1-meter radius, and the animals were molded by placing bolus material on the distal side such that the proximal skin surface at all points was at 1-meter radius. Output measurements were taken before and after each exposure with an instrument, and these readings were related by a separate measurement of the exposure with scatter at the proximal side of the animals. A central-axis depth dose curve was determined (fig. _____) by placing an instrument at various depths in a cadaver. The resulting curve, with the known thickness of each animal measured at the time of exposure, allowed construction of bilateral depth-dose curves[10] and allowed output readings to be related to the midline depth dose. All exposures reported are in terms of the midline exposure thus determined and are converted to absorbed dose by means of the factor 0.94.

6.6. Internal Exposure

The isotope, Ca^{45}, of specific activity 50 μc per mg of calcium, was administered in the form of a solution of $CaCl_2$ in isotonic saline at pH=6, in a concentration of 10 μc per ml. 0.1 μc per gm body weight was administered by tail vein, under light ether anesthesia, to 10 male rats of the "August" strain weighing 105 to 115 gms and aged 6 to 7 weeks.

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[10] "Depth dose curves" is a commonly used term which perhaps more properly should be "depth-exposure curves" but may continue to be used.

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Appendix I.

Radiation Quantities and Units*

1. Introduction

There has recently been much discussion of the fundamental concepts and quantities employed in radiation dosimetry. This has arisen partly from the rapid increase in the number of individuals using these concepts in the expanding field of nuclear science and technology, partly because of the need for extending the concepts so that they would be of use at higher photon energies and for particulate as well as for photon radiation, but chiefly because of certain obscurities in the existing formulation of the quantities and units themselves.

The roentgen, for example, was originally defined to provide the best quantitative measure of exposure to medium energy x radiation which the measuring techniques of that day (1928) permitted. The choice of air as a standard substance was not only convenient, but also appropriate for a physical quantity which was to be correlated with the biological effect of x rays, since the effective atomic number of air is not very different from that of tissue. Thus a given biological response could be reproduced approximately by an equal exposure in roentgens for x-ray energies available at that time. Since 1928 the definition of the roentgen has been changed several times, and this has reflected some feeling of dissatisfaction with the clarity of the concept.

The most serious source of confusion was the failure to define adequately the radiation quantity of which the roentgen was said to be the unit.[1] As a consequence of this omission, the roentgen had gradually acquired a double role. The use of this name for the unit had become recognized as a way of specifying not only the magnitude but also the nature of the quantity measured. This practice conflicts with the general usage in physics, which permits, within the same field, the use of a particular unit for all quantities having the same dimensions.

Even before this, the need for accurate dosimetry of neutrons and of charged particles from accelerators or from radionuclides had compelled the International Commission on Radiological Units and Measurements (ICRU) to extend the number of concepts. It was also desired to introduce a new quantity which could be more directly correlated with the local biological and chemical effects of radiation. This quantity, *absorbed dose*, has a generality and simplicity which greatly facilitated its acceptance, and in a very few years it has become widely used in every branch of radiation dosimetry.

The introduction of absorbed dose into the medical and biological field was further assisted by defining a special unit—the *rad*. One rad is approximately equal to the absorbed dose delivered when soft tissue is exposed to 1 roentgen of medium voltage x radiation. Thus in many situations of interest to medical radiology, but not in all, the numbers of roentgens and rads associated with a particular medical or biological effect are approximately equal and experience with the earlier unit could be readily transferred to the new one. Although the *rad* is merely a convenient multiple of the fundamental unit, erg/g, it has already acquired, at least in some circles, the additional connotation that the only quantity which can be measured in rads is absorbed dose. On the other hand, the rad has been used by some authors as a unit for a quantity called by them *first collision dose;* this practice is deprecated by the Commission.

Being aware of the need for preventing the emergence of different interpretations of the same quantity, or the introduction of undesirable, unrelated quantities or units in this or similar fields of measurement, the ICRU set up, during its meeting in Geneva in September 1958, an *Ad Hoc* Committee. The task of this committee was to review the fundamental concepts, quantities, and units which are required in radiation dosimetry and to recommend a system of concepts and a set of definitions which would be, as far as possible, internally consistent and of sufficient generality to cover present requirements and such future requirements as can be foreseen. The committee was instructed to pay more attention to consistency and rigor than to the historical development of the subject, and was authorized to reject any existing quantities or units which seemed to hinder a consistent and unified formulation of the concepts.

*Taken from Radiation Quantities and Units, International Commission on Radiological Units and Measurements, Report 10a, National Bureau of Standards Handbook 84 (numbers refer to paragraphs in the original report).

[1] Fränz, H., and Hübner, W. Concepts and Measurement of Dose, Proceedings of Second International Conference on the Peaceful Uses of Atomic Energy, Geneva 1958, P/971 **21**, 101, United Nations, Geneva (1958).

Bertrand Russell,[2] in commenting on the use and abuse of the concept of infinitesimals by mathematicians, remarks: "But mathematicians did not at first pay heed to (these) warnings. They went ahead and developed their science, and it is well that they should have done so. It is a peculiar fact about the genesis and growth of new disciplines that too much rigor too early imposed stifles the imagination and stultifies invention. A certain freedom from the strictures of sustained formality tends to promote the development of a subject in its early stages, even if this means the risk of a certain amount of error. Nonetheless, there comes a time in the development of any field when standards of rigor have to be tightened."

The purpose of the present reexamination of the concepts to be employed in radiation dosimetry was primarily "to tighten standards of rigor." If, in the process, some increased formality is required in the definitions in order to eliminate any foreseeable ambiguities, this must be accepted.

2. General Considerations

The development of the more unified presentations of quantities and units which is here proposed was stimulated and greatly assisted by mathematical models of the dosimetric field which had been proposed by some members of the committee in an effort to clarify the concepts. It appeared, however, that the essential features of the mathematical models had been incorporated into the definitions and hence the need for their exposition in this report largely disappeared. The mathematical approach is published elsewhere.[3]

As far as possible, the definitions of the various fundamental quantities given here conform to a common pattern. Complex quantities are defined in terms of the simpler quantities of which they are comprised.

The passage to a "macroscopic limit" which has to be used in defining point quantities in other fields of physics can be adapted to radiation quantities and a special discussion of this is included in the section headed "limiting procedures".

The general pattern adopted is to give a short definition and to indicate the precise meaning of any special phrase or term used by means of an explanatory note following the definition. There has been no attempt to make the list of quantities which are defined here comprehensive. Rather, the Commission has striven to clarify the fundamental dosimetric quantities and a few others (such as activity) which were specifically referred to it for discussion.

It is recognized that certain terms for which definitions are proposed here are of interest in other fields of science and that they are already variously defined elsewhere. The precise wording of the definition and even the name and symbol given to any such quantity, may at some future date require alteration if discussions with representatives of the other interested groups of scientists should lead to agreement on a common definition or symbol. Although the definitions presented here represent some degree of compromise, they are believed to meet the requirements in the field of radiation dosimetry.

3. Quantities, Units, and Their Names

The Commission is of the opinion that the definition of concepts and quantities is a fundamental matter and that the choice of units is of less importance. Ambiguity can best be avoided if the defined quantity which is being measured is specified. Nevertheless, the special units do exist in this as in many other fields. For example, the hertz is restricted, by established convention, to the measurement of vibrational frequency, and the curie, in the present recommendations, to the measurement of the activity of a quantity of a nuclide. One does not measure activity in hertz nor frequency in curies, although these quantities have the same dimensions.

It was necessary to decide whether or not to extend the use of the special dosimetric units to other more recently defined quantities having the same dimensions, to retain the existing restriction on their use to one quantity each, or to abandon the special units altogether. The Commission considers that the addition of further special units in the field of radiation dosimetry is undesirable, but continues to recognize the existing special units. It sees no objection, however, to the expression of any defined quantity in the appropriate units of a coherent physical system. Thus, to express absorbed dose in ergs per gram or joules per kilogram, exposure in coulombs per kilogram or activity in reciprocal seconds, are entirely acceptable alternatives to the use of the special units which, for historical reasons, are usually associated with these quantities.

The ICRU recommends that the use of each special unit be restricted to one quantity as follows:

The rad—solely for absorbed dose
The roentgen—solely for exposure
The curie—solely for activity.

It recommends further that those who prefer to express quantities such as absorbed dose and kerma (see below) in the same units should use units of an internationally agreed coherent system.

Several new names are proposed in the present report. When the absorbed dose concept was adopted in 1953, the Commission recognized the need for a term to distinguish it from the quantity of which the roentgen is the unit. In 1956 the Commission proposed the term *exposure* for this latter quantity. To meet objections by the ICRP, a compromise term, "exposure dose," was agreed upon.[4] While this term has come into

[2] Russell, B., Wisdom of the West, p. 280, (Doubleday & Co., Inc., New York, 1959).
[3] Rossi, H. H., and Roesch, W. C., Field Equations in Dosimetry, Radiation Res. **16**, 783 (1962).
[4] For details, see ICRU, 1956 Report, NBS Handb. 62, p. 2 (1957

some use since then, it has never been considered as completely satisfactory. In the meantime, the basic cause of the ICRP objection has largely disappeared since most legal codes use either the units rad or rem.

Since in this report the whole system of radiological quantities and units has come under critical review, it seemed appropriate to reconsider the 1956 decision. Numerous names were examined as a replacement for exposure dose, but there were serious objections to any which included the word dose. There appeared to be a minimum of objection to the name *exposure* and hence this term has been adopted by the Commission with the hope that the question has been permanently settled. It involves a minimum change from the older name exposure dose. Furthermore, the elimination of the term "dose" accomplishes the long-felt desire of the Commission to retain the term dose for one quantity only—the absorbed dose.

The term "RBE dose" has in past publications of the Commission not been included in the list of definitions but was merely presented as a "recognized symbol." In its 1959 report the Commission also expressed misgivings over the utilization of the same term, "*RBE*," in both radiobiology and radiation protection. It now recommends that the term *RBE* be used in radiobiology only and that another name be used for the linear-energy-transfer-dependent factor by which absorbed doses are to be multiplied to obtain for purposes of radiation protection a quantity that expresses on a common scale for all ionizing radiations the irradiation incurred by exposed persons. The name recommended for this factor is the *quality factor* (*QF*). Provisions for other factors are also made. Thus a *distribution factor* (*DF*) may be used to express the modification of biological effect due to non-uniform distribution of internally deposited isotopes. The product of absorbed dose and modifying factors is termed the *dose equivalent* (*DE*). As a result of discussions between ICRU and ICRP, the following formulation has been agreed upon:

The Dose Equivalent

1. For protection purposes it is useful to define a quantity which will be termed the "dose equivalent" (*DE*).
2. (*DE*) is defined as the product of absorbed dose, *D*, quality factor, (*QF*); dose distribution factor (*DF*); and other necessary modifying factors.

$$(DE)=\mathrm{D}\ (QF)\ (DF)\ \ldots\ .$$

3. The unit of dose equivalent is the "rem". The dose equivalent is numerically equal to the dose in rads multiplied by the appropriate modifying factors.

Although this statement does not cover a number of theoretical aspects (in particular the physical dimensions of some of the quantities), it fulfills the immediate requirement for an unequivocal specification of a scale that may be used for numerical expression in radiation protection.

Another new name is that for the quantity which represents the kinetic energy transferred to charged particles by the uncharged particles per unit mass of the irradiated medium. This is the same as one of the common interpretations of a concept "first collision dose," that has proved to be of great value in the dosimetry of fast neutrons. The concept is also closely related to the energy equivalent of exposure in an x-ray beam. The name proposed, *kerma*, is based on the initials of *k*inetic *e*nergy *r*eleased in *m*aterial.

Still another new name is the *energy fluence* which is here attached to the quantity in the 1953 ICRU report called *quantity of radiation*. The latter term was dropped in the 1956 ICRU report, but the concept—time integral of intensity—remains a useful one and the proposed term appears to be acceptable in other languages as well as English. A related quantity, *particle fluence*, which is equivalent to the quantity *nvt* used in neutron physics, is included to round out the system of radiation quantities.

The quantity for which the curie is the unit was referred to the committee for a name and definition. Hitherto the curie has been defined as a *quantity of the radioactive nuclide* such that 3.7×10^{10} disintegrations per second occur in it. However, it has never been specified what was meant by quantity of a nuclide, whether it be a number, mass, volume, etc. Meanwhile the custom has grown of identifying the number of curies of radionuclide with its transformation rate. Because of the vagueness of the original concept, because of the custom of identifying curies with transformation rate and because it appeared not to interfere with any other use of the curie, the Commission recommends that the term *activity* be used for the transformation rate, and that the curie be made its unit. It is recognized that the definition of the curie is of interest to other bodies in addition to the ICRU, but by this report we recommend that steps be taken to redefine it as $3.7\times10^{10}s^{-1}$; i.e., as a unit of activity and not of quantity of a nuclide.

It is also recommended that the term *specific gamma ray constant* be used instead of *specific gamma ray emission* for the quotient of the exposure rate at a given distance by the activity. The former term focuses attention on the *constancy* of this quotient for a given nuclide rather than the *emission* of the source.

4. Detailed Considerations

A. Limiting Procedures

Except in the case of a uniform distribution of sources throughout a large region, radiation fields are in general nonuniform in space. They may also be variable in time. Many of the quantities defined in this report have to be specified as functions of space or time, and in principle they must therefore be determined for sufficiently small

regions of space or intervals of time by some limiting procedure. There are conceptual difficulties in taking such limits for quantities which depend upon the discrete interactions between radiations and atoms. Similar difficulties arise with other macroscopic physical quantities such as density or temperature and they must be overcome by means of an appropriate averaging procedure.

To illustrate this procedure, we may consider the measurement of the macroscopic quantity "absorbed dose" in a nonuniform radiation field. In measuring this dose the quotient of energy by mass must be taken in an elementary volume in the medium which, on the one hand, is so small that a further reduction in its size would not appreciably change the measured value of the quotient energy by mass and, on the other hand, is still large enough to contain many interactions and be traversed by many particles.[5] If it is impossible to find a mass such that both these conditions are met, the dose cannot be established directly in a single measurment. It can only be deduced from multiple measurements that involve extrapolation or averaging procedures. Similar considerations apply to some of the other concepts defined below. The symbol Δ precedes the symbols for quantities that may be concerned in such averaging procedures.

In the measurement of certain material constants such as stopping power, absorption coefficient, etc., the limiting procedure can be specified more rigorously. Such constants can be determined for a given material with any desired accuracy without difficulties from statistical fluctuations. In these cases the formulae quoted in the definitions are presented as differential quotients.

B. Spectral Distributions and Mean Values

In practice many of the quantities defined below to characterize a radiation field and its interaction with matter are used for radiations having a complex energy spectrum. An important general concept in this connection is the *spectral concentration* of one quantity with respect to another. The spectral concentration is the ordinate of the distribution function of the first quantity with respect to the second. The independent quantity need not always be energy or frequency; one can speak of the spectral concentration of flux density with respect to quantum energy or of the absorbed dose with respect to linear energy transfer. The interaction constants (such as μ, S and W) referred to in this report are often mean values taken over the appropriate spectral distributions of the corresponding quantities.

C. Units

For any of the quantities defined below the appropriate unit of an internationally agreed coherent system can be used. In addition, certain special units are reserved for special quantities:

the rad for absorbed dose
the roentgen for exposure
the curie for activity.

D. Definitions

(1) *Directly ionizing particles* are charged particles (electrons, protons, α-particles, etc.) having sufficient kinetic energy to produce ionization by collision.

(2) *Indirectly ionizing particles* are uncharged particles (neutrons, photons, etc.) which can liberate directly ionizing particles or can initiate a nuclear transformation.

(3) *Ionizing radiation* is any radiation consisting of directly or indirectly ionizing particles or a mixture of both.

(4) *The energy imparted* by ionizing radiation to the matter in a volume is the difference between the sum of the energies of all the directly and indirectly ionizing particles which have entered the volume and the sum of the energies of all those which have left it, minus the energy equivalent of any increase in rest mass that took place in nuclear or elementary particle reactions within the volume.

Notes: (a) The above definition is intended to be exactly equivalent to the previous meanings given by the ICRU to "energy retained by matter and made locally available" or "energy which appears as ionization, excitation, or changes of chemical bond energies". The present formulation specifies what energy is to be included without requiring a lengthy, and possibly incomplete, catalog of the different types of energy transfer.

(b) Ultimately, most of the energy imparted will be degraded and appear as heat. Some of it, however, may appear as a change in interatomic bond energies. Moreover, during the degradation process the energy will diffuse and the distribution of heat produced may be different from the distribution of imparted energy. For these reasons the energy imparted cannot always be equated with the heat produced.

(c) The quantity *energy imparted to matter* in a given volume is identical with the quantity often called *integral absorbed dose* in that volume.

(5) The *absorbed dose* (D) is the quotient of ΔE_D by Δm, where ΔE_D is the energy imparted by ionizing radiation to the matter in a volume element, Δm is the mass of the matter in that volume element and Δ has the meaning indicated in section 4.A.

$$D=\frac{\Delta E_D}{\Delta m}$$

The special unit of absorbed dose is the *rad*.

$$1 \text{ rad}=100 \text{ erg/}g=\frac{1}{100} \text{ J/}kg$$

Note: J is the abbreviation for Joule.

[5] In interpreting radiation effects the macroscopic concept of absorbed dose may not be sufficient. Whenever the statistical fluctuations around the mean value are important, additional parameters describing the distribution of absorbed energy on a microscopic scale are necessary.

(6) The *absorbed dose rate* is the quotient of ΔD by Δt, where ΔD is the increment in absorbed dose in time Δt and Δ has the meaning indicated in section 4.A.

$$\text{Absorbed dose rate}=\frac{\Delta D}{\Delta t}$$

A special unit of absorbed dose rate is any quotient of the rad by a suitable unit of time (rad/*d*, rad/min, rad/*h*, etc.).

(7) The *particle fluence*[6] or *fluence* (Φ) of particles is the quotient of ΔN by Δa, where ΔN is the number of particles which enter a sphere[7] of cross-sectional area Δa and Δ has the meaning indicated in section 4.A.

$$\Phi=\frac{\Delta N}{\Delta a}$$

(8) The *particle flux density* or *flux density* (φ) of particles is the quotient of $\Delta\Phi$ by Δt where $\Delta\Phi$ is the particle fluence in time Δt and Δ has the meaning indicated in section 4.A.

$$\varphi=\frac{\Delta\Phi}{\Delta t}$$

NOTE: This quantity may also be referred to as particle fluence rate.

(9) The *energy fluence* (F) of particles is the quotient of ΔE_F by Δa, where ΔE_F is the sum of the energies, exclusive of rest energies, of all the particles which enter a sphere[8] of cross-sectional area Δa and Δ has the meaning indicated in section 4.A.

$$F=\frac{\Delta E_F}{\Delta a}$$

(10) The *energy flux density* or *intensity* (I) is the quotient of ΔF by Δt, where ΔF is the energy fluence in the time Δt and Δ has the meaning indicated in section 4.A.

$$I=\frac{\Delta F}{\Delta t}$$

NOTE: This quantity may also be referred to as energy fluence rate.

(11) The *kerma*[9] (K) is the quotient of ΔE_K by Δm, where ΔE_K is the sum of the initial kinetic energies of all the charged particles liberated by indirectly ionizing particles in a volume element of the specified material, Δm is the mass of the matter in that volume element and Δ has the meaning indicated in section 4.A.

$$K=\frac{\Delta E_K}{\Delta m}$$

NOTES: (a) Since ΔE_K is the sum of the initial kinetic energies of the charged particles liberated by the indirectly ionizing particles, it includes not only the kinetic energy these charged particles expend in collisions but also the energy they radiate in bremsstrahlung. The energy of any charged particles is also included when these are produced in secondary processes occurring within the volume element. Thus the energy of Auger electrons is part of ΔE_K.

(b) In actual measurements Δm should be so small that its introduction does not appreciably disturb the radiation field. This is particularly necessary if the medium for which kerma is determined is different from the ambient medium; if the disturbance is appreciable an appropriate correction must be applied.

(c) It may often be convenient to refer to a value of kerma or of kerma rate for a specified material in free space or at a point inside a different material. In such a case the value will be that which would be obtained if a small quantity of the specified material were placed at the point of interest. It is, however, permissible to make a statement such as: "The kerma for air at the point P inside a water phantom is . . .," recognizing that this is a shorthand version of the fuller description given above.

(d) A fundamental physical description of a radiation field is the intensity (energy flux density) at all relevant points. For the purpose of dosimetry, however, it may be convenient to describe the field of indirectly ionizing particles in terms of the kerma rate for a specified material. A suitable material would be air for electromagnetic radiation of moderate energies, tissue for all radiations in medicine or biology, or any relevant material for studies of radiation effects.

Kerma can also be a useful quantity in dosimetry when charged particle equilibrium exists at the position and in the material of interest, and bremsstrahlung losses are negligible. It is then equal to the absorbed dose at that point. In beams of x or gamma rays or neutrons, whose energies are moderately high, transient charged-particle equilibrium can occur; in this condition the kerma is just slightly less than the absorbed dose. At very high energies the difference becomes appreciable. In general, if the range of directly ionizing particles becomes comparable with the mean free path of the indirectly ionizing particles, no equilibrium will exist.

(12) The *kerma rate* is the quotient of ΔK by Δt, where ΔK is the increment in kerma in time Δt and Δ has the meaning indicated in section 4.A.

[6] This quantity is the same as the quantity, *nvt*, commonly used in neutron physics.

[7] This quantity is sometimes defined with reference to a plane of area Δa, instead of a sphere of cross-sectional area Δa. The plane quantity is less useful for the present purposes and it will not be defined. The two quantities are equal for a unidirectional beam of particles perpendicularly incident upon the plane area.

[8] See footnote 7.

[9] Various other methods of specifying a radiation field have been used; e.g., for a neutron source the "first collision dose" in a standard material at a specified point (see Introduction).

(13) The *exposure* (X) is the quotient of ΔQ by Δm, where ΔQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons (negatrons and positrons), liberated by photons in a volume element of air whose mass is Δm, are completely stopped in air and Δ has the meaning indicated in section 4.A.

$$X=\frac{\Delta Q}{\Delta m}$$

The special unit of exposure is the roentgen (R).

$$1R=2.58\times10^{-4}\ C/kg\ ^{10}$$

NOTES: (a) The words "charges on all the ions of one sign" should be interpreted in the mathematically absolute sense.

(b) The ionization arising from the absorption of bremsstrahlung emitted by the secondary electrons is not to be included in ΔQ. Except for this small difference, significant only at high energies, the exposure as defined above is the ionization equivalent of the kerma in air.

(c) With present techniques it is difficult to measure exposure when the photon energies involved lie above a few Mev or below a few kev.

(d) As in the case of kerma (4D(11), note (c)), it may often be convenient to refer to a value of exposure or of exposure rate in free space or at a point inside a material different from air. In such a case the value will be that which would be determined for a small quantity of air placed at the point of interest. It is, however, permissible to make a statement such as: "The exposure at the point P inside a water phantom is . . . ."

(14) The *exposure rate* is the quotient of ΔX by Δt, where ΔX is the increment in exposure in time Δt and Δ has the meaning indicated in section 4.A.

$$\text{Exposure rate}=\frac{\Delta X}{\Delta t}$$

A special unit of exposure rate is any quotient of the roentgen by a suitable unit of time (R/s, R/min, R/h, etc.).

(15) The *mass attenuation coefficient* $\left(\frac{\mu}{\rho}\right)$ of a material for indirectly ionizing particles is the quotient of dN by the product of ρ, N, and dl, where N is the number of particles incident normally upon a layer of thickness dl and density ρ, and dN is the number of particles that experience interactions in this layer.

$$\frac{\mu}{\rho}=\frac{1}{\rho N}\frac{dN}{dl}$$

NOTES: (a) The term "interactions" refers to processes whereby the energy or direction of the indirectly ionizing particles is altered.

[10] This unit is numerically identical with the old one defined as 1 e.s.u. of charge per .001293 gram of air. C is the abbreviation for coulomb.

(b) For x or gamma radiations

$$\frac{\mu}{\rho}=\frac{\tau}{\rho}+\frac{\sigma}{\rho}+\frac{\sigma_{\text{coh}}}{\rho}+\frac{\kappa}{\rho}$$

where $\frac{\tau}{\rho}$ is the mass photoelectric attenuation coefficient, $\frac{\sigma}{\rho}$ is the total Compton mass attenuation coefficient, $\frac{\sigma_{\text{coh}}}{\rho}$ is the mass attenuation coefficient for coherent scattering, and $\frac{\kappa}{\rho}$ is the pair-production mass attenuation coefficient.

(16) The *mass energy transfer coefficient* $\left(\frac{\mu^K}{\rho}\right)$ of a material for indirectly ionizing particles is the quotient of dE_K by the product of E, ρ, and dl, where E is the sum of the energies (excluding rest energies) of the indirectly ionizing particles incident normally upon a layer of thickness dl and density ρ, and dE_K is the sum of the kinetic energies of all the charged particles liberated in this layer.

$$\frac{\mu^K}{\rho}=\frac{1}{E\rho}\frac{dE_K}{dl}$$

NOTES: (a) The relation between fluence and kerma may be written as

$$K=F\frac{\mu_K}{\rho}$$

(b) For x or gamma rays of energy $h\nu$

$$\frac{\mu_K}{\rho}=\frac{\tau_a}{\rho}+\frac{\sigma_a}{\rho}+\frac{\kappa}{\rho}$$

where

$$\frac{\tau_a}{\rho}=\frac{\tau}{\rho}\left(1-\frac{\delta}{h\nu}\right)$$

$\left(\frac{\tau}{\rho}\right.$=the photoelectric mass attenuation coefficient, δ=average energy emitted as fluorescent radiation per photon absorbed.$\left.\right)$ and

$$\frac{\sigma_e}{\rho}=\frac{\sigma}{\rho}\frac{E_e}{h\nu}$$

$\left(\frac{\sigma}{\rho}\right.$=total Compton mass attenuation coefficient, E_e=average energy of the Compton electrons per scattered photon.$\left.\right)$ and

$$\frac{\kappa_a}{\rho}=\frac{\kappa}{\rho}\left(1-\frac{2mc^2}{h\nu}\right)$$

$\left(\frac{\kappa}{\rho}\right.$=mass attenuation coefficient for pair production, mc^2=rest energy of the electron.$\left.\right)$

(17) The *mass energy-absorption coefficient* $\left(\frac{\mu_{en}}{\rho}\right)$ of a material for indirectly ionizing particles is $\frac{\mu_K}{\rho}(1-G)$, where G is the proportion of the energy of secondary charged particles that is lost to bremsstrahlung in the material.

NOTES: (a) When the material is air, $\frac{\mu_{en}}{\rho}$ is proportional to the quotient of exposure by fluence.

(b) $\frac{\mu_K}{\rho}$ and $\frac{\mu_{en}}{\rho}$ do not differ appreciably unless the kinetic energies of the secondary particles are comparable with or larger than their rest energy.

(18) The *mass stopping power* $\left(\frac{S}{\rho}\right)$ of a material for charged particles is the quotient of dE_s by the product of dl and ρ, where dE_s is the average energy lost by a charged particle of specified energy in traversing a path length dl, and ρ is the density of the medium.

$$\frac{S}{\rho}=\frac{1}{\rho}\frac{dE_s}{dl}$$

NOTE: dE_s denotes energy lost due to ionization, electronic excitation and radiation. For some purposes it is desirable to consider stopping power with the exclusion of bremsstrahlung losses. In this case $\frac{S}{\rho}$ must be multiplied by an appropriate factor that is less than unity.

(19) The *linear energy transfer* (L) of charged particles in a medium is the quotient of dE_L by dl where dE_L is the average energy locally imparted to the medium by a charged particle of specified energy in traversing a distance of dl.

$$L=\frac{dE_L}{dl}$$

NOTES: (a) The term "locally imparted" may refer either to a maximum distance from the track or to a maximum value of discrete energy loss by the particle beyond which losses are no longer considered as local. In either case the limits chosen should be specified.

(b) The concept of linear energy transfer is different from that of stopping power. The former refers to energy imparted within a limited volume, the latter to loss of energy regardless of where this energy is absorbed.

(20) The *average energy* (W) *expended in a gas per ion pair formed* is the quotient of E by N_W, where N_W is the average number of ion pairs formed when a charged particle of initial energy E is completely stopped by the gas.

$$W=\frac{E}{N_W}$$

NOTES: (a) The ions arising from the absorption of bremsstrahlung emitted by the charged particles are not to be counted in N_W.

(b) In certain cases it may be necessary to consider the variation in W along the path of the particle, and a differential concept is then required, but is not specifically defined here.

(21) A *nuclide* is a species of atom having specified numbers of neutrons and protons in its nucleus.

(22) The *activity* (A) of a quantity of a radioactive nuclide is the quotient of ΔN by Δt, where ΔN is the number of nuclear transformations which occur in this quantity in time Δt and Δ has the meaning indicated in section 4.A.

$$A=\frac{\Delta N}{\Delta t}$$

The special unit of activity is the curie (c).

$$1\text{c}=3.7\times10^{10}\text{s}^{-1}\text{ (exactly)}$$

NOTE: In accordance with the former definition of the curie as a unit of quantity of a radioactive nuclide, it was customary and correct to say: "Y curies of P–32 were administered . . . ." It is still permissible to make such statements rather than use the longer form which is now correct: "A quantity of P–32 was administered whose activity was Y curies."

(23) The *specific gamma ray constant* (Γ) of a gamma-emitting nuclide is the quotient of $l^2\frac{\Delta X}{\Delta t}$ by A, where $\frac{\Delta X}{\Delta t}$ is the exposure rate at a distance l from a point source of this nuclide having an activity A and Δ has the meaning indicated in section 4.A.

$$\Gamma=\frac{l^2\Delta X}{A\,\Delta t}$$

Special units of specific gamma ray constant are $Rm^2h^{-1}c^{-1}$ or any convenient multiple of this.

NOTE: It is assumed that the attenuation in the source and along l is negligible. However, in the case of radium the value of Γ is determined for a filter thickness of 0.5 mm of platinum and in this case the special units are $Rm^2h^{-1}g^{-1}$ or any convenient multiple of this.

TABLE 4.1. *Table of Quantities and Units*

No.	Name	Symbol	Dimensions [a]	Units		
				MKSA	cgs	Special
4	Energy imparted (integral absorbed dose)		E	J	erg	g. rad.
5	Absorbed dose	D	EM^{-1}	J kg^{-1}	erg g^{-1}	rad.
6	Absorbed dose rate		$EM^{-1}T^{-1}$	J $kg^{-1}s^{-1}$	erg $g^{-1}s^{-1}$	rad s^{-1}, etc.
7	Particle fluence or fluence	Φ	L^{-2}	m^{-2}	cm^{-2}	
8	Particle flux density	φ	$L^{-2}T^{-1}$	$m^{-2}s^{-1}$	$cm^{-2}s^{-1}$	
9	Energy fluence	F	EL^{-2}	J m^{-2}	erg cm^{-2}	
10	Energy flux density or intensity	I	$EL^{-2}T^{-1}$	J $m^{-2}s^{-1}$	erg $cm^{-2}s^{-1}$	
11	Kerma	K	EM^{-1}	J kg^{-1}	erg g^{-1}	
12	Kerma rate		$EM^{-1}T^{-1}$	J $kg^{-1}s^{-1}$	erg $g^{-1}s^{-1}$	
13	Exposure	X	QM^{-1}	C kg^{-1}	esu g^{-1}	R (roentgen).
14	Exposure rate		$QM^{-1}T^{-1}$	C $kg^{-1}s^{-1}$	esu $g^{-1}s^{-1}$	Rs^{-1}, etc.
15	Mass attenuation coefficient	$\frac{\mu}{\rho}$	L^2M^{-1}	m^2kg^{-1}	cm^2g^{-1}	
16	Mass energy transfer coefficient	$\frac{\mu_K}{\rho}$	L^2M^{-1}	m^2kg^{-1}	cm^2g^{-1}	
17	Mass energy absorption coefficient	$\frac{\mu_{en}}{\rho}$	L^2M^{-1}	m^2kg^{-1}	cm^2g^{-1}	
18	Mass stopping power	$\frac{S}{\rho}$	EL^2M^{-1}	J m^2kg^{-1}	erg cm^2g^{-1}	
19	Linear energy transfer	L	EL^{-1}	J m^{-1}	erg cm^{-1}	kev $(\mu m)^{-1}$.
20	Average energy per ion pair	W	E	J	erg	ev.
22	Activity	A	T^{-1}	s^{-1}	s^{-1}	c (curie).
23	Specific gamma-ray constant	Γ	QL^2M^{-1}	Cm^2kg^{-1}	esu cm^2g^{-1}	$Rm^2h^{-1}c^{-1}$, etc.
	Dose equivalent	DE				rem.

[a] It was desired to present only 1 set of dimensions for each quantity, a set that would be suitable in both the MKSA and electrostatic-cgs systems. To do this it was necessary to use a dimension Q, for the electrical charge, that is not a fundamental dimension in either system. In the MKSA system (fundamental dimensions M, L, T, I) Q represents the product IT; in the electrostatic-cgs system (M, L, T) it represents $M^{1/2}L^{3/2}T^{-1}$.

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Recommendations [a] of International Commission on Radiological Units and Measurements (ICRU)

ICRU Report Number	Reference [b]
1	Discussion on International Units and Standards for X-ray work Brit. J. Radiol. **23,** 64 (1927)
2	International X-ray Unit of Intensity Brit. J. Radiol. (new series) **1,** 363 (1928)
3	Report of Committee on Standardization of X-ray Measurements Radiology **22,** 289 (1934)
4	Recommendations of the International Committee for Radiological Units Radiology **23,** 580 (1934)
5	Recommendations of the International Committee for Radiological Units Radiology **29,** 634 (1937)
6	Report of International Commission on Radiological Protection and International Commission on Radiological Units National Bureau of Standards Handbook 47, Washington, D.C. (1951)
7	Recommendations of the International Commission for Radiological Units Radiology **62,** 106 (1954)
8	Report of International Commission on Radiological Units and Measurements (ICRU) 1956 National Bureau of Standards Handbook 62, Washington, D.C. (1957)
9	Report of International Commission on Radiological Units and Measurements (ICRU) 1959 National Bureau of Standards Handbook 78, Washington, D.C. (1961)
10a	Radiation Quantities and Units National Bureau of Standards Handbook 84, Washington, D.C. (1962)
10b	Physical Aspects of Irradiation National Bureau of Standards Handbook 85, Washington, D.C. [c]
10c	Radioactivity National Bureau of Standards Handbook 86, Washington, D.C. [c]
10d	Clinical Dosimetry National Bureau of Standards Handbook 87, Washington, D.C. [c]
10e	Radiobiological Dosimetry National Bureau of Standards Handbook 88, Washington, D.C. (1963)
10f	Methods of Evaluating Radiological Equipment and Materials National Bureau of Standards Handbook 89, Washington, D.C. [c]

[a] Current recommendations are included.
[b] References given are in English. Many of them were also published in other languages.
[c] In preparation.