RADIATION DOSIMETRY

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PREFACE

Radiation dosimetry is concerned with the determination of the energy absorbed in a medium exposed to ionizing alpha- and beta-rays, electrons, and protons, and to ionizing secondary radiation produced by x-rays, gamma-rays, and neutrons.

In recent years problems of radiation dosimetry have multiplied rapidly with the vast production of artificial radioactive materials by reactors and the increasing use of high-voltage accelerators of various kinds. The energy ranges have been expanded considerably and electron, proton, and neutron beams find an increasing variety of important applications.

The continuing growth of radiation dosimetry and its extensive and widespread literature have created the need for an up-to-date and unified presentation of the significant aspects of the field. This book, written for those working with the applications of radiation to medical, industrial, and research problems, is designed to fill this need. The rapid growth of industrial power programs and technical uses of isotopes may well cause these applications to overshadow the medical uses in the future. The basic techniques of radiation dosimetry are the same in all these areas of research, and dosimetric problems of all kinds, including questions of health physics and personnel protection, can be solved by using the information and data presented here. The extensive references to the original literature will help the reader to find more specialized information if necessary.

The book is divided into three main parts. The first part presents the fundamental principles of dosimetry. In the first two chapters the concepts of dosimetry and the physical properties of radiation and their interaction with matter are discussed. In the third chapter, some of the basic biological and medical effects of radiation are presented to help the nonmedical reader understand the important medical implications of the radiations he is dealing with.

In the second part of the book the various instruments available for dosage measurements are described together with their uses for different types of radiation. This part includes information on scintillation detectors, photographic film, chemical and colorimetric indicators, and calorimetric methods, none of which have been extensively discussed previously from the viewpoint of their dosimetric applications.

The third part of the book presents the problems of dosimetry of various radiation fields. The chapter on x-rays is a thorough, modern review of a widely discussed subject. The chapters dealing with electron and proton beams open subjects which have rarely been dealt with before. The treatment of beta-ray dosimetry is perhaps the first comprehensive approach to this difficult field. No attempt has been made to treat ultraviolet and other kinds of nonionizing radiations.

When, three years ago, Academic Press suggested the organization of a book on radiation dosimetry it became immediately apparent that an up-to-date presentation of the intricate aspects of the field could be written only with the help of a number of specialists. The editors' problem was then to produce a cohesive textbook dealing with all aspects of radiation dosimetry and not merely to present a collection of specialized papers on various subjects related to dosimetry. Towards that end numerous drafts have been written and rewritten and some sacrifices have been made in the subject matter of various chapters. The editors assume complete responsibility for deletions and alterations made necessary by the desire to achieve an integrated presentation.

We wish to acknowledge the assistance given by Professor R. D. Evans who has served as advisory editor for this book. We are grateful for the encouragement given by Professors Failla, Gray, and others. Numerous reviewers have carefully read the various chapters, and their help and criticism is greatly appreciated. The subject index has been prepared by Mr. Richard McCall, and the figures have been redrafted by Mrs. Grace Rowe.

We would like to thank Dr. Belton Burrows of the Boston Veterans Administration Hospital and Dr. Walter Bauer of the Massachusetts General Hospital for their encouragement and permission to allot the necessary time to this project.

Boston, Massachusetts
March, 1956

GERALD J. HINE
GORDON L. BROWNELL

Abbreviations of Names of Reports

AECU—Atomic Energy Commission Unclassified

AECD—Atomic Energy Commission Declassified

AERE T/R—Atomic Energy Research Establishment, Harwell, England

ALI—A. D. Little Company

ANL—Argonne National Laboratory

ARSC—Air Reduction Company

BNL—Brookhaven National Laboratory

BR—British Reports

CRM—Atomic Energy Project (Chalk River, Canada)

DP—E. I. du Pont de Nemours and Co.

HW—Hanford Works, General Electric Co.

IDO—Idaho Operations Office

JHUX—Johns Hopkins University

JHUL—Johns Hopkins University

KLX—Vitro Corporation of America

KAPL—Knolls Atomic Power Laboratory (General Electric Co.)

LA—Los Alamos Scientific Laboratory (University of California)

MDDC—Manhattan Engineer District and AEC declassified

NBS—National Bureau of Standards

NPL—National Physical Laboratory, England

NYO—New York Operations Office AEC

NP—Non project report

ONRL—Office of Naval Research (London)

ORNL—Oak Ridge National Laboratory

TOI—Technical Operations Inc.

TID—Technical Information Service, AEC

UCRL—University of California Radiation Laboratory

UR—University of Rochester Atomic Energy Project

UCLA—University of California at Los Angeles Atomic Energy Project

WASH—Atomic Energy Commission, Washington

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Tables of Data Directly Applicable to Dose Determinations

CHAPTER 1

RADIATION UNITS AND THEORY OF IONIZATION DOSIMETRY

F. W. Spiers

I. INTRODUCTION

The subject of radiation dosimetry has its origins in the last years of the nineteenth century when x-rays, then newly discovered, were put to almost immediate medical use. Both the successes, like that of the first recorded tumor treatment in 1899, and the failures of those early attempts underlined the necessity for some quantitative measurement of the radiations emanating from an x-ray tube. Most of the early workers used photographic or fluorescence methods for measuring x-ray intensities; but it is of interest that chemical methods were tried and also that as early as 1897 a measurement was made of the heat produced by the complete absorption of an x-ray beam in a metal. For reasons of lack of sensitivity, of unreliability, or of unwanted quality dependence, these early physical techniques were eventually displaced by ionization methods; but three decades passed before an internationally acceptable method of defining and measuring an x-ray dose was achieved. The introduction of the roentgen in 1928 likewise turned attention away from use of biological indicators, which by their nature inevitably lacked the precision of physical measurements.

The problem today is no longer solely that of standardizing dose in the medical use of x-rays and radium γ-rays. The advance of nuclear science and the now-abundant production of radioactive materials pose the problems of dosimetry in new and complicated forms. More than ever it is necessary to determine the *physical energy deposition* in a variety of media when irradiated by any one of a wide energy range of quanta or by any type of ionizing particle. Modern versions of some of the earlier methods, notably chemical (Chapter 8) and calorimetric (Chapter 9) methods, are gaining an important place in radiation dosimetry. At first, however, the fundamental concept of radiation dose and the extent to which it has been satisfactorily measured by ionization methods has to be considered.

A. Types of Ionizing Radiation

Some indication of the extent and nature of the problem of radiation dosimetry is apparent from the great variety of the ionizing radiations which are now available. Table I gives a list of commonly used radiations, their energies, and the approximate average range, in low atomic number material, of the associated ionizing particle. Electromagnetic radiations, having energies above a few kev, ionize by virtue of the secondary electrons released when they are absorbed. Corpuscular radiations ionize either directly, because they are charged, or indirectly through charged particles set in motion by collision processes.

The ionizing particles have complex energy spectra, and hence only the order of the mean range is given in Table I. In biological materials which have nearly unit density the range can vary from about 1 micron to a few centimeters, or even to as much as 1 meter in the case of very-high-energy protons. The magnitude of the range in relation to the size of the biological entity is fundamental to the problem of determining the energy deposition

TABLE I

TYPES OF IONIZING RADIATION

Radiation	Energy range, Mev	Ionizing particle in tissue	Average range of ionizing particle in low atomic number material: gm/cm²	Average range of ionizing particle in low atomic number material: cm of air at NTP
1. β-rays	0.015–5	Electron	10^{-4}–1.0	0.1–800
2. Electron beams	2–20	Electron	1–10	800–8000
3. γ-rays	0.05–2.9	Electron	5×10^{-4}–0.6	0.4–450
4. X-rays	0.01–0.4	Electron	10^{-4}–5×10^{-3}	0.1–4
5. X-rays	1–10	Electron	5×10^{-2}–1.2	30–230
6. X-rays	10–30	Electron	1.2–3.5	1500–2700
7. Fast neutrons	0.1–10	Proton	10^{-4}–6×10^{-2}	0.1–45
8. Slow neutrons	0.1 ev	0.6-Mev protons (+2.2-Mev γ-rays)	10^{-3} (protons) 0.5 (electrons)	0.8 (protons) 400 (electrons)
9. Proton beams	5–400	Proton	3×10^{-2}–10^{2}	23–8×10^{4}
10. α-rays	5–10	α-particle	3×10^{-3}–10^{-2}	2–8

in irradiated organisms. Likewise the particle range in air or other gases is a major consideration in the practical realization of the theory of ionization dosimetry. Although detailed consideration will follow later in this and other chapters, it may be noted that air-ionization methods are applicable where the same type of ionizing particle is released in the ionization chamber and in tissue. Where this is not so, as in the case of neutrons and high-energy protons, both the walls of the ionization chamber and the gas filling must simulate tissue in atomic composition, especially in respect to the hydrogen content (see Chapter 15). Further considerations are necessary when more than one type of radiation is present and where nuclear reactions occur.

B. Physical Quality and Intensity

For many purposes an exact specification of radiation *quality* is not necessary. In therapeutic x-ray work, for example, a sufficient indication of the quality of the radiation is given by a simple function of the penetration of the beam. The function frequently employed is the *half-value layer* (HVL), defined as the amount of some standard material which transmits 50% of of the incident radiation. The half-value layer can be used further to specify an *effective wavelength* or *effective energy* as that wavelength or energy of a monoenergetic radiation which exhibits the same half-value layer as the heterogeneous beam in question. The only complete specification of the physical quality of a radiation, however, is the spectral distribution of wavelengths or energies present (Chapter 2). In its most useful form, the dis-

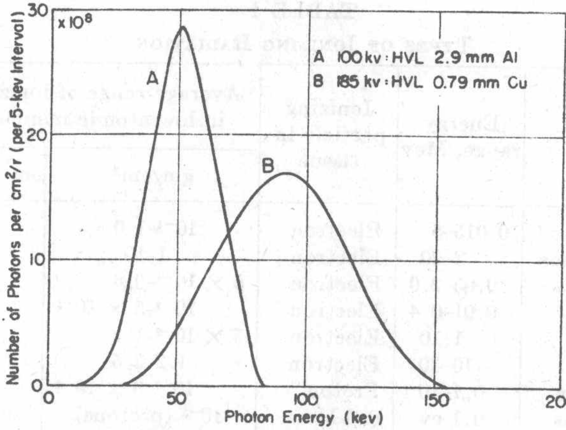

FIG. 1. Photon spectra deduced from absorption data. The mean energies of radiations A and B are, respectively, 52 kev and 90 kev. The effective energies derived from the stated half-value layers are 34 kev and 71 kev, respectively.

tribution, showing the number of photons in each energy interval, enables calculation to be made of the numbers and energies of the secondary ionizing particles released in tissues or other media, when these are needed for purposes of dosimetry or for the interpretation of chemical and biological effects. The effective energy of the beam derived simply from the half-value layer does not necessarily coincide with the mean energy more correctly deduced from the photon spectrum. Methods of specifying the effective energies of heterogeneous radiations should be carefully scrutinized if they are being used to correlate possible energy-dependent phenomena. The photon spectra in Fig. 1, which have been deduced from absorption data by a method described in Chapter 2, illustrate the points discussed. The effective energies derived from the half-value layers are 34 kev and 71 kev for radiations which have mean energies of 52 kev and 90 kev, respectively. Deductions from the single absorption measurement of the half-value layer underestimate the mean energy of the radiation.

The methods of radiation spectroscopy are dealt with in Chapter 2; here it should be noted that where quality dependence is being investigated the complete energy spectrum of the radiation has to be determined.

The *intensity* of electromagnetic radiation at any point is defined in its precise sense as the radiation energy in ergs flowing per second through 1 cm^2 of area perpendicular to the direction of propagation (40). The radiation at a given point is completely specified, therefore, if the photon energy spectrum and the energy flux are known.

An equivalent and sometimes useful specification is the statement of the photon energy spectrum and the photon flux, i.e., the number and energy of photons flowing per second through 1 cm^2 perpendicular to the incident direction. The relationship of the energy flux to the rate of energy absorption in any particular physical or biological system depends primarily on the photon energy. Because the detection and measurement of any radiation necessarily involves energy absorption by the measuring system, intensity measurements and dose or dose-rate measurements will be seen to present very similar problems. The ease or difficulty with which they can be solved depends in a like manner on the radiation quality.

C. Concept of Radiation Dose

It may be regarded as axiomatic that radiation can bring about a change in a system only by virtue of the *energy* actually *absorbed*. A biological effect, however, may also depend on the spatial distribution of the energy released along the track of the ionizing particle. It will depend, therefore, on the type and quality of the radiation, and equal energy absorptions of different radiations may not produce equal biological effects. These features of the action of ionizing radiations on living cells are illustrated in Fig. 2, where the relative biological effect of a given energy absorption is shown to vary markedly with the density of ion formation along the track of the ionizing particle (33, 59). Generally, the effect of radiation on cell structures increases with increase in linear ion density, but certain "all or none" actions, like the inactivation of bacteria and viruses, become less efficient

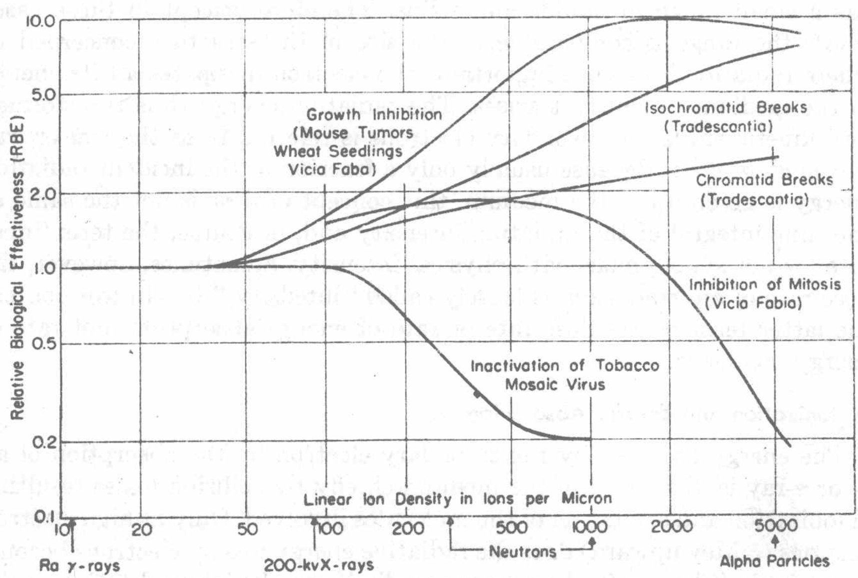

FIG. 2. Variation of relative biological effectiveness (RBE) with linear ion density for a number of radiobiological actions (33, 59).