CONCEPTS OF RADIATION DOSIMETRY

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PREFACE

This monograph is developed from a set of notes which accompanied a seminar series on the Concepts of Radiation Dosimetry given by the authors at Stanford University during the Spring Quarter 1970. The manuscript discusses the basic information required to understand the principles of photon and charged particle dose measurement from basic particle interactions to cavity chamber theory. As health physicists at the Stanford Linear Accelerator Center we were interested in the dosimetry of high energy photons and charged particles. Thus, throughout the text we have emphasized the extension of dosimetry principles to the high energy situation. We hope that the reader will gain some insight to the dosimetry of particles such as pions and muons as well as high energy electrons and photons. Because the audience during the seminars was composed primarily of experienced health physicists, radiological physicists, nuclear engineers, and medical doctors, the material is presented at a level requiring advanced understanding of mathematics and physics.

A detailed development of all the theories involved is not included because these have been adequately covered in several texts. We have attempted to discuss the pertinent theories and their relationship to dosimetry. What we have tried to do is gather together in one place the information necessary for charged particle and photon dosimetry, citing appropriate references the reader may consult for further background or a more complete theoretical treatment. We hope this monograph will be useful to the health physicist and radiological physicist.

The material in this monograph was drawn primarily from the following references:

1. F. H. Attix, W. C. Roesch, and E. Tochilin, Radiation Dosimetry, Second Edition, Volume I, Fundamentals (Academic Press, New York, 1968).
2. J. J. Fitzgerald, G. L. Brownell, and F. J. Mahoney, Mathematical Theory of Radiation Dosimetry (Gordon and Breach, New York, 1967).

3. K. Z. Morgan and J. E. Turner, Principles of Radiation Protection (Krieger Publishing Co., New York, 1973).

In the text, direct reference to these books will be made using the notation (ART), (FBM) and (MT). Additional references are cited at the end of each chapter and will be indicated in the text by number.

The authors gratefully acknowledge the encouragement and support of Dr. Richard McCall and Wade Patterson and in particular Professors C. J. Karzmark (Radiology) and T. J. Connolly (Nuclear Engineering) of Stanford University for sponsoring the seminar. We thank Dr. H. DeStaebler for reviewing Chapters 2 and 3 and Dr. Goran Svensson for reviewing Chapter 6. In general, their criticism has been very helpful to us. The bubble chamber pictures were provided by Dr. James Loos of Experimental Group B at SLAC, and were prepared by G. Fritzke. Finally, we thank the 40 or so people who attended the seminars and contributed to the discussion.

As this book reaches the final stages before publication, we wish to thank our many colleagues who have used the first set of notes and have provided us with useful criticism for updating the manuscript. In particular, the support from Ron Kathren, whose encouragement was instrumental in publishing this book, is truly appreciated.

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CHAPTER 1

BASIC CONCEPTS

1.1 Introduction

Before embarking on a study of radiation dosimetry it is necessary to understand the basic concepts and terminology involved. The history of radiation dosimetry is fraught with many, sometimes confusing, concepts and definitions. We will discuss dosimetry using the concepts, quantities and units defined by the International Commission on Radiological Units and Measurements (ICRU) in their 1971 Report 19, "Radiation Quantities and Units."[1] The definitions used in this monograph taken from ICRU Report 19 are presented in Section 1.2. Following the definitions we discuss some of the basic concepts involved in the quantities defined.

1.2 Dosimetry Terminology

1. Directly Ionizing Particles — charged particles having sufficient kinetic energy to produce ionization by collision.
2. Indirectly Ionizing Particles - uncharged particles which can liberate directly ionizing particles or can initiate nuclear transformations.
3. Exposure (X) - the quotient of dQ by dm where dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons liberated by photons in a volume element of air whose mass is dm are completely stopped in air.

   $$X = dQ/dm$$

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

   $$1\ R = 2.58 \times 10^{-4}\ C\text{-}kg^{-1}$$

4. Absorbed Dose (D) - the quotient of $d\bar{E}_D$ by dm where $d\bar{E}_D$ is the mean energy imparted by ionizing radiation to the mass dm of matter in a volume element.

   $$D = d\bar{E}_D/dm$$

The special unit of absorbed dose is the Gray (Gy).

$$1 \text{ Gy} = 1 \text{ J-kg}^{-1} \quad (= 100 \text{ rad})$$

5. Energy Imparted (E_D) - a stochastic quantity which is the difference between the sum of the kinetic energies of all the directly and indirectly ionizing particles which have entered a volume ($\sum E_E$) and the sum of the kinetic energies of all those which have left it ($\sum E_L$) minus the energy equivalent of any increase in rest mass ($\sum E_R$) that took place in nuclear or elementary particle reactions within the volume.

$$E_D = \sum E_E - \sum E_L - \sum E_R$$

6. Mean Energy Imparted ($\bar{E}_D$) - the expectation value of the energy imparted, sometimes referred to as integral dose.

7. Mean energy expended in a gas per ion pair formed ($\overline{W}$) - the quotient of E by N, where N is the number of ion pairs formed when a directly ionizing particle of initial kinetic energy E is completely stopped by the gas.

$$\overline{W} = E/N$$

8. Particle Fluence (Φ) - the quotient of dN by da where dN is the number of particles which enter a sphere of cross sectional area da.

$$\Phi = dN/da$$

9. Particle Flux Density (ϕ) - the quotient of $d\Phi$ by dt where $d\Phi$ is the particle fluence in time dt.

$$\phi = d\Phi/dt$$

10. Energy Fluence (F) — the quotient of dE_f by da where dE_f is the sum of the energies, exclusive of rest energies, of all the particles which enter a sphere of cross sectional area da.

$$F = dE_f/da$$

11. Energy Flux Density (I) — the quotient of dF by dt where dF is the energy fluence in the time dt.

$$I = dF/dt$$

12. Kerma (K) — the quotient of dE_K by dm where dE_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. dm is the mass of the matter in that volume element.

$$K = dE_K/dm$$

13. Mass Attenuation Coefficient (μ/ρ) — for a given material, μ/ρ 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 interaction in this layer.

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

14. Mass Energy Transfer Coefficient (μ_K/ρ) — for a given material, μ_K/ρ 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, dE_K is the sum of the kinetic energies of all the charged particles liberated in this layer.

$$\mu_K/\rho = \frac{1}{E\rho}\frac{dE_K}{dl}$$

15. Mass Energy Absorption Coefficient (μ_{en}/ρ) — for a given material, μ_{en}/ρ for indirectly ionizing particles is (μ_K/ρ) (1 - G) where G is the proportion of the energy of secondary charged particles that is lost to bremsstrahlung in the material.

16. Mass Stopping Power (S/ρ)* — for a given material, S/ρ for charged particles is the quotient of dE_s by the product of ρ and dl 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.

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

17. Linear Energy Transfer (LET)* — for charged particles in medium, LET 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 traversing a distance dl.

18. Charged Particle Equilibrium (CPE) — CPE exists at a point P centered in a volume V if each charged particle carrying a certain energy out of V is replaced by another identical charged particle which carries the same energy into V. If CPE exists at a point then D = K at that point provided that bremsstrahlung production by secondary charged particles is negligible.

1.3 Stochastic and Macroscopic Quantities

Many of the quantities defined are macroscopic quantities such as absorbed dose, exposure, fluence, etc. On the other hand, stochastic quantities such as energy imparted, charge liberated, etc., may vary greatly from point to point since radiation fields are in general not uniform in space. Consequently, these quantities must be

*A discussion of these terms is given in Chapter 3.

determined for sufficiently small regions of space or time by some limiting procedure. We illustrate this procedure using the quantity "absorbed dose."

Absorbed dose is a measure of energy imparted to a medium divided by the mass of the medium. If we choose a large mass element and measure the energy imparted, we will obtain a value of $E/m)_1$ (see Fig. 1.1). Now, if we take a smaller mass element and measure the value $E/m)_2$, in general we find $E/m)_2$ will be larger than $E/m)_1$. When m is large enough to cause significant attenuation of the primary radiation (e.g., x rays), the fluence of charged particles in the mass element under consideration is not uniform. This causes the ratio E/m to increase as the size of the mass m is decreased.

As m is further reduced we will find a region in which the charged particle fluence is sufficiently uniform that the ratio E/m will be constant. It is in this region that the ratio E/m represents absorbed dose. Thus, the expectation value $\overline{E}$ of the energy imparted over an appropriate size mass element must be used to determine absorbed dose.

At the other extreme, m must not be so small that the energy deposition is caused by a few interactions. If m is further decreased from the region of constant E/m, we will find that the ratio will diverge. That is, as m gets very small the energy deposition is determined by whether or not a charged particle interacts within m. Consequently, E will be zero for many mass elements and very large for others. These fluctuations occur because charged particles lose energy in discrete steps. Hence, the determination of absorbed dose also requires that the mass element m be large enough so that the energy deposition is caused by many particles and many interactions.

Similar discussions may be made for other quantities and it must be realized that the macroscopic quantities defined using the differential notation imply that a limiting process as described above has occurred.

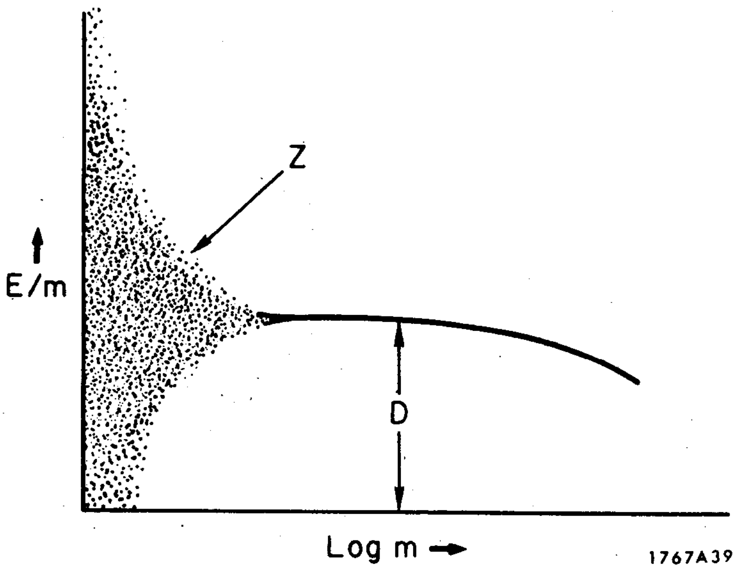

FIG. 1.1

Energy density as a function of the mass for which energy density is determined. The horizontal line covers the region in which the absorbed dose can be established in a single measurement. The shaded portion represents the range where statistical fluctuations are important. (From (ART), Chapter 2.)

1.4 Exposure

The quantity, exposure, as currently defined requires that all the electrons liberated by photons in a mass element of air be completely stopped in air. It also requires that all the ions (of one sign) produced by these electrons be collected. To make any absolute measurement of exposure, therefore, requires use of a free air ionization chamber. This in turn puts an upper limit on the photon energy for which absolute exposure measurements are practicable. This energy limit (a few hundred KeV) is determined by the range of the electrons and the ion chamber size.

In principle there is no energy limit on the quantity dQ/dm. There is simply a practical limit on the accuracy with which exposure can be measured as the photon energy increases. Relative measurement of exposure can be made at any photon energy using air-equivalent cavity chambers (see Chapter 6). The accuracy of these measurements depends on the photon energy and the chamber construction. Accuracies of 1-2% can be achieved for photons up to a few MeV. As the photon energy increases, the uncertainty in the measurement increases because of failure to collect all the ions produced by electrons liberated in the mass element. Further uncertainty is introduced when there is significant attenuation of the photon field within the range of the electrons liberated by those photons. Consequently, the quantity exposure as presently defined is practical only for photon fields below a few MeV in energy.

1.5 Energy Imparted and Energy Transferred (Absorbed Dose and Kerma)

To better understand absorbed dose, kerma and charged particle equilibrium, one must understand how the energy balance is made for a mass element exposed to radiation. Figure 1.2 is a schematic drawing showing 10 photons incident on a mass element. Each in some way involves the movement of energy into and out of the mass. Table 1.1 gives an arbitrary breakdown of the energy entering and leaving the mass on charged and uncharged particles.