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Measurement of Short-Range Radiations

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MEASUREMENT OF SHORT-RANGE RADIATIONS

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CHAPTER 1

INTRODUCTION

The dosimetry, spectrometry and counting of nuclear radiations are now well established techniques with precisions of 0.1% attainable during standardization [1]. This generalization cannot be applied to the whole range of radiations because there are still many problems that arise in the routine measurement of low-energy X- and beta-radiations and in the determination of alpha-activity on surfaces and in the air. This manual seeks to present these problems, to show how they can be solved and then to indicate which type of instruments is most suitable for a given application. The need for such a manual arises because of the increasing use of radioisotopes (particularly ^{3}H and ^{14}C) in medicine, agriculture and industry, and in the rapid growth of systems using electron beams for welding, in power tubes and in the home (television).

1.1. SCOPE OF THE MANUAL

The definition of short-range radiation is necessarily arbitrary and the limits suggested here will not be taken as a rigid definition. The manual will include the measurement of all alpha-emitting isotopes, beta-emitting isotopes with a maximum energy of less than 200 keV and X-rays generated by machines and from isotopes with energies less than 50 keV. A brief mention of radiations of longer wavelength such as ultra-violet and microwave radiations will be included as they are sometimes associated with the larger machines encountered in modern nuclear physics and medicine.

When the radiation is external to the body then the thickness of the exposed skin is of major importance for these radiations. Recent work [2] suggests that even alpha contamination on the skin may be considered as a direct radiation hazard. Thus, in choosing a detector for a particular application it is necessary to consider possible reductions in maximum permissible levels and changes in accepted biological parameters such as skin thickness. The manual will therefore indicate where an instrument can be modified to accommodate such changes.

The necessary definitions will be set out in the latter half of Chapter 1. Chapter 2 is concerned with sources of radiation and the biological considerations in setting the maximum permissible levels, including those derived for surfaces and skin contamination. Chapter 3 is devoted to the methods of measurement and outlines the design of gas ionization devices, solid and liquid scintillators and solid state detectors such as semiconductors and thermoluminescent materials. The discussion in Chapter 3 is aimed at the types of detector that can be used for the external and internal measurement of short-range radiations in the environment or from body tissues. The actual choice of a particular technique is left to Chapter 4 which starts with a discussion of external measurements of dose from X-rays, beta rays and alpha particles. Special techniques are required for whole-body monitoring of such isotopes as ^{239}Pu and for the measurement of radon in the breath. This naturally leads to a discussion of the measurement of isotopes in the various biological tissues and the waste materials of the nuclear industry. Two isotopes are discussed separately because they are very widely used (^{3}H or tritium ($\beta_{max.}$: 18.6 keV)) or because of the extreme difficulties of monitoring (^{241}Pu ($\beta_{max.}$: 20.8 keV)). The calibration techniques for each type of problem will also be discussed in Chapter 4. Chapter 5 outlines the basis for a code of practice for the calibration of instruments. Chapter 6, finally, gives a tabulated summary of the techniques proposed for the measurement of the special isotopes emitting short-range radiations. Neither the discussion of techniques nor the final list of isotopes can hope to be exhaustive. An extensive bibliography is included at the end of the manual.

1.2. RADIATION QUANTITIES AND UNITS

The following definitions of fundamental quantities are taken from ICRU Report No. 20 [3] which summarizes the more detailed definitions in Report No. 19 [4]. SI units will be used as far as possible and the special units used in radiation monitoring will be referred to this system.

(a) Absorbed dose (D) is the energy absorbed per unit mass at a specific place in a material. The special unit of absorbed dose is the rad (10^{-2} J·kg^{-1} or 100 erg·g^{-1}).

(b) Dose equivalent (H). The biological effectiveness of a given absorbed dose depends on the type of radiation and on the irradiation conditions. In current radiation protection procedures, an indication of the effect upon a given organ is inferred by weighting the absorbed dose in that organ by certain modifying factors. The product of these modifying factors and the absorbed dose is called the dose equivalent, H. The special unit is the rem which has the same units as the rad.

(c) Quality factor (Q) is the main modifying factor which is used to account for the dependence of biological effect on the linear energy transfer (L) of charged particles within the irradiated medium. For X-rays, gamma-rays and electrons Q has a value of 1 and this includes beta-ray emmitters of less than 30 keV which formerly had a value of Q of 1.7 [5]. The value of Q for alpha particles from 4-10 MeV is 10. The factor Q is dimensionless.

(d) Particle fluence (Φ) is the number of particles which enter a small sphere divided by the cross-sectional area of the sphere. The units are m^{-2}.

(e) Exposure (X) is a measure of the ability of a particular field of electromagnetic radiation, i.e. X- or gamma rays, to ionize air. These radiations interact with the molecules in the air to produce electrons which in turn ionize the air. The special unit of exposure is the roentgen, R, which is equivalent to 2.58×10^{-4} C·kg^{-1} (1 e.s.u. per 0.001293 g) of air.

(f) The average energy required to produce an ion pair in a gas ($\overline{W}$) is a useful unit for gas ionization devices. $\overline{W}$ = 33.7 eV for air at s.t.p.

(g) Activity (A) is the time rate of disintegration of a radionuclide. The special unit of activity is the curie (Ci), equal to 3.7×10^{10} disintegrations per second. Successive factors of 10^{-3} are mCi, μCi, nCi, pCi, fCi, and aCi or 10^{-18} curies.

The following units do not appear as definitions in the ICRU reports but will be found throughout the literature and are required for this manual.

(h) kVp and kVcp are the peak potentials for an unstabilized X-ray set and of a fully stabilized or constant potential set, respectively.

(i) The half-value layer (HVL or HVL_X) is the thickness of specified material which attenuates a beam of radiation to an extent such that the exposure rate is reduced to one half of its original value.

(j) The quality of the radiation from an X-ray set is defined as either that monoenergetic radiation having the same HVL or more exactly by an integral of the complete exposure spectrum.

Finally there are two terms in radiological protection which are used in ICRP publications.

(k) Maximum permissible level (MPL) is a general term based upon ICRP recommendations [6]. In particular, MPC_a (maximum permissible concentration) is used for air activity with units of $\mu Ci \cdot m^{-3}$ ($pCi \cdot cm^{-3}$) and MPBB is the maximum permissible body burden (μCi).

(l) Derived working limit (DWL) is normally a local unit of control to ensure that the MPL is not exceeded. Such units as $\mu Ci \cdot cm^{-2}$ are used for surfaces, hands, clothing etc.

Other definitions will be developed as required.

CHAPTER 2

SOURCES OF RADIATION AND BIOLOGICAL CONSIDERATIONS

As indicated in the introduction, this manual is concerned with radiation that barely penetrates the epidermal layer of the skin. Thus in this chapter, following an initial introduction to the sources of radiation, it will be necessary to examine the nature of the skin surface. This will be followed by an assessment of external levels of radiation and contamination and finally a brief study of radioactivity in the body will be given.

2.1. SOURCES OF SHORT-RANGE RADIATION

2.1.1. Alpha-emitting nuclides

Alpha particles (^{4}He nuclei) are emitted mainly by nuclei of high atomic number ($Z > 80$). There are many isotopes which occur naturally that emit alpha particles and this means that there is always alpha activity in the air, in food and in people. In addition there is a range of isotopes that are produced artificially in nuclear reactors (Table I) [7]. Radiologically, the most important isotopes are those of plutonium which are produced by neutron capture and beta decay from uranium. Plutonium is chemically similar to calcium and if taken into the body it is deposited in bone where the radiation can damage the blood forming organs.

Alpha particles are emitted from radionuclides with discrete energies which range from 3 to 12 MeV. These particles lose energy very rapidly and only travel short distances through matter before being completely stopped. Even in air an alpha particle of energy 10 MeV will be stopped within about 11 cm and this corresponds to a range in tissue of about 70 μm or 7 mg$\cdot$cm^{-2}. Thus, alpha particles will only constitute an external radiation hazard when actually deposited on the skin's surface where the epidermal layer is less than 70 μm in thickness. This short range also makes detection difficult and the detector window must be very thin.

2.1.2. Beta-emitting nuclides

Beta emitters occur throughout the whole periodic table and are widely used in various fields — research, medicine, agriculture and industry. The number of isotopes with a maximum beta energy of less than 200 keV is small but includes the widely used isotopes ^{3}H and ^{14}C and an important isotope of plutonium, ^{241}Pu. In addition, there is a wide range of nuclei which decay by electron capture with the emission of low-energy (Auger) electrons and characteristics X-rays.

Beta particles emitted by a radionuclide have a continuous distribution of energies from zero up to a definite maximum, characteristic of each nuclide ($\beta_{max.}$). The spectrum has a characteristic bell shape and the average energy is approximately one third of $\beta_{max.}$.

TABLE I. NUCLEAR DATA FOR ISOTOPES EMITTING ALPHA PARTICLES [7]*

Isotope	Half-life	α-energy (MeV)	Yield (%)	Source
^{210}Po	138.4 d	5.3	100	Natural (RaF); daughter of ^{210}Bi
^{230}Th	8.0×10^4 a	4.62	24	Natural daughter of ^{234}U
		4.68	76	
^{231}Pa	3.25×10^4 a	4.73	11	Natural descendant of ^{235}U
		4.95	22	
		5.02	24	
		5.03	23	
		5.06	11	
^{233}U	1.62×10^5 a	4.78	15	$^{232}Th(n,\gamma)\ ^{233}Th(\beta^-)$
^{234}U	2.47×10^5 a	4.72	28	Daughter of ^{238}Pu
		4.77	72	Natural descendant of ^{238}U
^{235}U	7.1×10^8 a	4.37	18	Natural
		4.4	57	
		4.42	4	
		4.56	4	
		4.6	5	
^{238}U	4.51×10^9 a	4.15	23	Natural
		4.2	77	
^{237}Np	2.14×10^6 a	4.77	36	$^{238}U(n,2n)\ ^{237}U(\beta^-)$
		4.79	51	
^{238}Pu	86 a	5.46	28	Daughter of ^{238}Np or ^{242}Cm
		5.5	72	
^{239}Pu	24400 a	5.1	12	$^{238}U(n,\gamma)\ ^{239}U(\beta^-)$
		5.14	15	
		5.16	73	
^{240}Pu	6580 a	5.12	24	Multiple n-capture from ^{238}U, ^{239}Pu
		5.17	76	
^{242}Pu	3.79×10^5 a	4.86	24	Multiple n-capture from ^{238}U, ^{239}Pu etc.,
		4.9	76	

* Excludes isotopes with significant gamma rays of energy > 50 keV or β or e^- > 200 keV or isotopes which have short-lived daughters with these energies.

The range of beta particles in matter is dependent upon their energy; for a 200-keV particle the range is 450 μm in tissue. The relevant data on the commonly encountered beta emitters is given in Table II. The external radiation hazard from this radiation is small and is limited mainly to the hands and wrists. Again the short range makes detection difficult.

2.1.3. X-ray machines and accelerated particle devices

Diagnostic X-ray machines are not normally operated at potentials much below 30 kVp although some mammography investigations require

TABLE II. NUCLEAR DATA FOR ISOTOPES DECAYING BY BETA EMISSION AND ELECTRON CAPTURE (< 200 keV) [7]*

Isotope	Half-life	Type of decay	Yield (%)	β-energy (max.) (keV)	Source
^{3}H	12.33 a	β^-	100	18.6	Natural and $^{6}Li(n,\alpha)$
^{14}C	5730 a	β^-	100	156	Natural and $^{14}N(n,p)$
^{35}S	87.4 d	β^-	100	167	$^{34}S(n,\gamma)$ $^{37}Cl(d,\alpha)$
^{37}Ar	35 d	EC	100		$^{37}Cl(p,n)$
		K_α		2.62	$^{37}Cl(d,2n)$ etc.
^{55}Fe	2.6 a	EC	100		$^{54}Fe(n,\gamma)$
		K_α		5.89	
^{59}Ni	8×10^4 a	EC	100		$^{58}Ni(n,\gamma)$
		K_α		6.93	
^{63}Ni	92 a	β^-	100	67	$^{62}Ni(n,\gamma)$
^{129}I	1.7×10^7 a	β^-	100	150	Fission
		e^-	96	5.0	
		K_α		29.6	
^{135}Cs	3.0×10^6 a	β^-	100	210	Fission; daughter ^{135}Xe
^{147}Pm	2.62 a	β^-	100	224	$^{146}Nd(p,n)$ $^{148}Nd(P,3n)$
^{151}Sm	87 a	β^-	98	76	Fission
		e^-	1.7	14.20	$^{150}Sm(n,\gamma)$
		L-X rays		22	
^{241}Pu	13.2 a	β^-	99 +	20.8	Multiple n-capture from ^{238}D, ^{239}Pu, etc.

* Excluding isotopes with gamma radiation of energy > 50 keV and daughters with high energy γ, β or e^-.

energies in this region. For some superficial therapy and for producing X-ray photographs of thin sections potentials down to a few kVp are used.

Low-energy X-rays are produced in all devices in which a particle beam is accelerated and strikes a target. Thus, the use of potentials up to 30 kVp in gas discharge tubes, rectifier tubes, home television sets, electron beam welders, etc., means that these are all potential hazards and must be investigated with a sensitive detector measuring the dose or exposure in the energy range from 5 to 50 keV. X-rays below 5 keV are rapidly attenuated by air and tissue and have little biological significance.

X-rays of these energies have relatively long ranges in air and tissue but are rapidly absorbed in materials with a higher atomic number (Z). This means that many detectors designed for use at above 50 keV are not suitable below this energy. This increased absorption with Z means a fourfold increase in bone dose compared with tissue dose at these energies (Table III) [8].

TABLE III. ATTENUATION AND ABSORPTION IN AIR, TISSUE AND BONE FOR X-RAYS FROM 1 - 50 keV [8]

Photon energy	Attenuation coefficient [b] μ/ρ ($cm^2 \cdot g^{-1}$)			Absorption coefficient [b] μ_{en}/ρ ($cm^2 \cdot g^{-1}$)			Dose in mrad for an exposure of 100 mR			
							Muscle		Bone	
	Air [a]	Muscle [a]	Bone [a]	Air [a]	Muscle [a]	Bone [a]	Surface	under 7 $mg \cdot cm^{-2}$ [c]	Surface	under 200 $mg \cdot cm^{-2}$ [c]
1	-	(4120) [d]	-	-	(4090) [d]	-	-	-	-	-
1.5	-	(1350) [d]	-	-	(1350) [d]	-	-	-	-	-
2	-	(601) [d]	-	-	(599) [d]	-	-	-	-	-
3	-	179	-	-	178	-	-	-	-	-
4	-	79	-	74.3	77.7	-	90.9	52.3	-	-
5	39.3	41.0	139	38.4	40.1	128	90.7	68.0	290	≪ 1
6	22.8	23.8	83.4	22.0	23.0	77.6	91.1	77.1	307	3
8	9.60	10.1	37.5	9.12	9.61	35.3	91.6	85.6	336	49
10	4.96	5.24	20.0	4.59	4.83	18.8	90.7	86.5	356	122
15	1.55	1.64	6.28	1.27	1.354	5.76	91.7	90.9	395	289
20	0.747	0.790	2.78	0.504	0.530	2.44	91.7	91.0	420	362
30	0.343	0.368	0.958	0.140	0.148	0.710	91.5	91.3	439	410
40	0.244	0.265	0.510	0.0620	0.0658	0.298	92.3	92.2	418	398
50	0.206	0.224	0.347	0.0378	0.0403	0.157	92.6	92.5	362	347

Composition

Element	Muscle	Compact bone	Air
H	10.2	6.4	-
C	12.3	27.8	-
N	3.5	2.7	75.5
O	72.9	41.0	23.2
Na	0.08	-	-
Mg	0.02	0.2	-
P	0.2	7.0	-
S	0.5	0.2	-
Ar	-	-	1.3
K	0.3	-	-
Ca	0.007	14.7	-

a Compositions (% w/w) are given in the lower table.
b Divide by 10 to obtain $m^2\ kg^{-1}$.
c $mg \cdot cm^{-2}$ of muscle.
d Figures in brackets indicate water.
- No data below K edge.

2.1.4. Ultrasoft radiations

Below the X-ray energies of a few hundred electron volts there are ultra-violet, infra-red and radio radiations which have some biological effect without causing ionization of the atoms. It may be an over-simplification but essentially the damaging effect is due to the heating of the tissues and depends upon the power input per unit area. In particular, microwaves in the frequency range from 10^7 to 10^{11} hertz (3 mm to 30 m) are often encountered in radar, television, and more recently in microwave ovens. There is some penetration into the body dependent upon the frequency. In the United Kingdom and the United States of America maximum permissible levels of 10 $mW\cdot cm^{-2}$ have been proposed [9].

2.2. BIOLOGICAL AND RELATED PARAMETERS

2.2.1. Skin thickness and permeability

The skin consists of the epidermis or outermost layer, and the dermis. The epidermis contains several to many layers of cells (Fig. 1). The cells in the deeper layer proliferate actively, and the daughter cells are passed gradually towards the surface, undergoing cornification as they approach it, and finally they are lost by desquamation. The outermost layer of the cornified surface is called the dead stratum corneum. Skin has normally

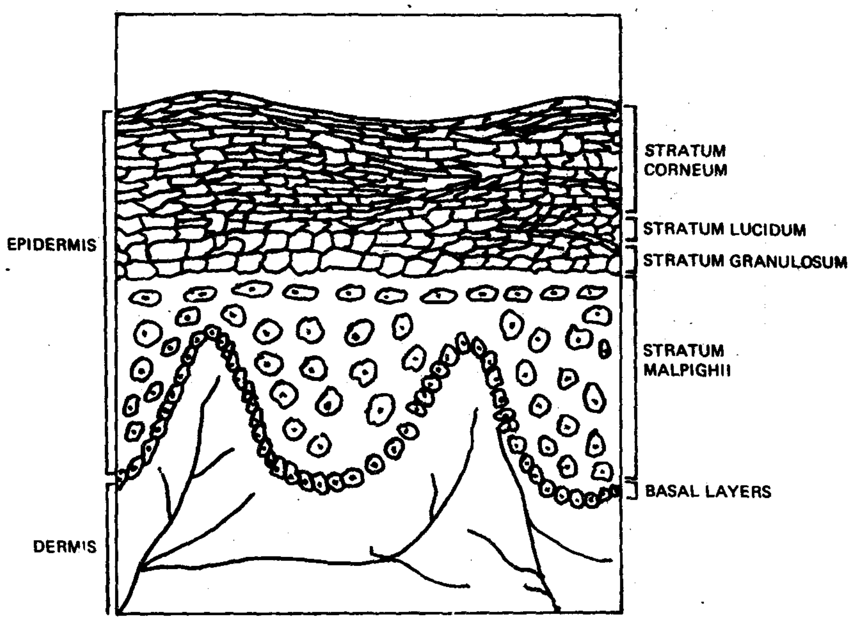

FIG. 1. A section through the skin showing the principal layers of the epidermis. The stratum corneum is of variable thickness over the body [2].

been taken as being uniform over the whole body with the dead layer of thickness 7 $mg \cdot cm^{-2}$ in which radiation has no effect. Similarly it is assumed that skin is impervious to radioactive isotopes although tritium as ^3H_2O has long been recognized as an exception.

Whitton [2a, b, c] has studied the depth of the basal layer in a wide range and recommends that the minimum epidermal depth should be reduced from 7 to 4 $mg \cdot cm^{-2}$. This represents the thickness on the back of the hand, wrist, forearms, face and neck which are the most likely sites for exposure to low-energy radiation or to splashes of contamination. The finger tips and palms have an epidermal layer thickness of about 40 $mg \cdot cm^{-2}$ and hence would be much less sensitive to low-energy radiation. The ranges of thickness of the epidermis at various sites of skin for adult males and females are given in Table IV [10].

TABLE IV. SKIN THICKNESS FOR VARIOUS PARTS OF THE BODY OF ADULT MALES AND FEMALES [10]

Location	Male		Female	
	Average thickness (μm)[a]	Range of thickness (μm)[a]	Average thickness (μm)[a]	Range of thickness (μm)[a]
Finger	547	420-673	462	384-539
Forearm, back	57	49-65	54	53-55
front	50	34-65	50	39-61
Arm, medial	45	37-52	39	34-43
lat.	56	41-71	47	40-54
Face	52	52	-	-
Thigh, medial	61	50-71	37	18-55
lat.	58	39-78	54	45-63
post.	64	37-91	48	35-60
Leg, medial	46	38-55	-	35-113
lat.	67	55-78	47	39-56
post.	64	47-80	49	39-59
Abdomen, ant.	42	34-49	40	34-46
Thorax, ant.	51	39-62	36	25-47
Axilla	44	43-45	51	51
Back	71	49-92	53	45-61
Pubis	45	42-48	43	43
Sole	1159	940-1377	972	850-1094
Forehead[b]	82	61-102		
Cheek[b]	104	85-123		
Neck[b]	83	46-120		
Eyelid[b]	40	30-50		

[a] 10 μm ≃ 1 $mg \cdot cm^{-2}$.

[b] Adult, sex not specified.

TABLE V. MAXIMUM PERMISSIBLE ANNUAL DOSE LIMITS FOR OCCUPATIONAL EXPOSURE OF INDIVIDUALS [6]

Organ or tissue	MPAD (rems)
Gonads, red bone-marrow	5
Skin, bone, thyroid	30
Hands and forearms, feet and ankles	75
Other single organs	15

Skin is permeable to tritium (^3H) which can penetrate the epidermis and be absorbed directly into the body. Early work by Pinson and Langham [11] showed that for tritiated water (^3H_2O) in air, 0.8 times as much tritium entered the body through the skin as through the lungs and this factor must be taken into account in calculating the maximum permissible levels. Eakins [12] has also shown that $^3H_2$ gas can be absorbed from metal surfaces.

2.2.2. Maximum permissible levels for external radiation

As mentioned earlier, low-energy radiations rarely present any external radiation hazard and only photon radiations need to be considered in most cases. This includes bremsstrahlung radiations from beta-ray sources of high activity, e.g. 1 Ci of ^3H adsorbed on to titanium will give a dose rate of about 2 $mR\cdot h^{-1}$ at 10 cm from the source. The maximum permissible annual doses (MPAD) for various parts of the body of occupationally exposed persons are given in Table V. The ICRP recommends that in any one year the MPAD should not be exceeded and that in a period of a quarter of a year up to one-half the MPAD may be accumulated. The MPAD shall be the sum of the doses of exposures from both external and internal sources resulting from the circumstances imposed by the occupation. For the radiations considered in this manual, parts of the body that might be at risk to external radiation hazard are mostly the hands and wrists. For these parts the MPAD as shown in Table V is 75 rems.

2.2.3. Derived working levels for surface and skin contamination

Contamination of the working environment as well as parts of the body, especially hands, wrists, fingers, etc. may result from the handling of loose radioactive materials. The measurement of surface contamination is a common radiation protection problem. It is difficult to establish an accurate correlation between the level of surface contamination and consequent radiation dose to man. However, a derived working limit (DWL) based on the approximate upper limit of the dose to man may by worked out for the purpose of making decisions concerning decontamination and control of operations.