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<Review>

Quantities and Units in Radiation Dosimetry

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Ⅰ. Introduction

"Radiation Dosimetry" in its broad sense is a term that is generally applied to the processes of calculating, predicting, measuring or otherwise quantitating radiation intensity of a source and energy deposition in the irradiated objects.

In order to do meaningful calculations in radiation protection problems, it is necessary to interpret a set of radiation quantities and units in terms of which radiation effects resulting from radiation fields can be expressed quantitatively.

In the field of radiation dosimetry the International Commission on Radiation Units and Measurements (ICRU) provides standardization and generally accepted definitions. According to the ICRU Report 19 there are many quantities of radiation, however only those that have a practical application in radiological health will be outlined in this paper.

Ⅱ. Fundamental Quantities and Units

A quantity may be defined as a description of a physical concept or principle. The magnitude or measure of a quantity is a unit. However, the quantity is more fundamental than the unit.

Radiation quantities can be described in terms of basic physical units like the other quantities, and they also have a "special unit". While a variety of systems of units have been employed, the ICRU has described all quantities and defined all special units in terms of the International System of Units, or SI Units.

1. Exposure (X)

Subsequent to the adoption of the roentgen which was the first unit of radiation, the ICRU defined a corresponding quantity, "exposure", and recommended units in the SI system.

Exposure is currently defined as the quotient of dQ by dm

$$X=\frac{dQ}{dm} \qquad (1)$$

where dQ 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 dm, are completely stopped in air. In addition it should be noted that the quantity, exposure, ap-

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* SI Units: "SI" is the acronym for the French "Systéme International d'Unités".

plies only to photon (X-and gamma-) radiation, that the effect is ionization in air, thus that the quantity is not meaningful for any other irradiated medium.

Units:

The SI units of exposure are coulombs per kilogram (C kg^{-1}). The special unit is the roentgen, R. This unit is named after Wilhelm Conrad Roentgen (1845~1923), who discovered X-rays in 1895. The roentgen was originally defined as "the quantity of X- or gamma-radiation such that the associated corpuscular emission per 0.001293g of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign". Accordingly, $1R=2.58\times10^{-4}$ C/kg. Units representing multiple of a roentgen are also used:

megaroentgen (MR), $1\text{MR}=10^6R$
kiloroentgen (KR) $1\text{KR}=10^3R$
*milliroentgen (mR) $1mR=10^{-3}R$
microroentgen (μR) $1\mu R=10^{-6}R$

It can be shown that one roengen of exposure 2.08×10^9 ion-pairs per cm^3 of air and correstonds to an energy deposit of 8.76×10^{-3} joules per kilogram or 87.6 ergs per gram of air.

That is,

$$1R=\frac{1\text{C.G.S. esu}}{0.001293\text{g of air}}\times\frac{1\text{ ion}}{4.8\times10^{-10}\text{C.G.S. esu}}$$
$$\times\ (34\ \text{eV/ion})^{**}\times1.6\times10^{-12}\ \text{ergs/g of air}$$

Limiations:

There are several important restrictions in the definition discussed above. The restrictions on exposure and its unit roentgen may be summarized as follows:

a. applies only to X- and gamma-radiation,
b. describes only ionization in air outside a body,
c. limited only up to photon energies of 3MeV or below.

Exposure rate ($\dot{X}$):

The rate at which dQ in Eg. (1) is liberated as the result of interactions in dm is called the exposure rate. Thus, is defined as $\dot{X}=dx/dt$ and has units of exposure per unit time (e.g., R/hr, mR/hr and R/min etc.).

2. Absorbed Dose (D)

Exposure discussed in the preceeding section does give information about energy absorbed by air in terms of ionization. However we are frequently more interested in the energy deposited in some other material, such as tissue. As a consequence, the absorbed dose, the quotient dE/dm, has been introduced as a measure of energy deposit in matter,

$$D=\frac{dE}{dm} \qquad (2)$$

where dE is the mean energy deposited by ionizion radiation in a volume element of the matter of mass dm. Occasionally dE can be called "integal dose" in the volume element, dm.

Units:

The SI units of absorbed dose are joules per kilogram (J/kg). The special unit is the rad, which is an acronym for "radiation absorbed dose"

$$1\ \text{rad}=0.01\ J/\text{kg}=100\ \text{ergs/g}$$

In as much as absorbed dose is in a broad sense a general quantity, we can relate it to any other medium as to exposure in air.

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* milliroentgen (mR): when a unit smaller than the roentgen is desired, the milliroentgen is most commonly used.

** The average energy dissipated in the production of a single ion pair in air is 34 eV (electron volt).

In fact one roentgen is equivalent to 0.876 rad in air. Specifically, in human sofe tissues*, one rad is equal to one roenten for both X- and gamma-radiations. Multiples of this unit include:

megarad (Mrad)	$1\ \text{Mrad}=10^6$ rad
kilorad (krad)	$1\ \text{krad}=10^3$ rad
millirad (mrad)	$1\ \text{mrad}=10^{-3}$ rad
microrad (μrad)	$1\ \mu\text{rad}=10^{-6}$ rad

Very recently the ICRU has recommended the adoption of a new unit, the "gray", as the special unit of absorbed dose (named after Louis Harold Gray (1905~1967), who made fundamental contributions to radiation dosimetry). The gray, *Gy*, is defined as an absorbed dose of one joule per kilogram. Thus equivalences of absorbed dose units would be:

$$1\ Gy=100\ \text{rad}=1\ J/\text{kg}.$$

In addition, it should be noted that absorbed dose and its units are universally applicable to all types of radiation in all absorbing substances.

Absorbed dose rate ($\dot{D}$):

This is the rate at which the absorbed dose is received in matter. Thus, absorbed dose rate is defined as $D=\frac{dD}{dt}$ and is measured in rad/hr, mrad/hr, and rad/min, etc.

3. Dose Equivalent (H):

The dose equivalent concept was proposed following research work which showed that the effect of ionizing radiation on biological systems is not related exclusively to the energy deposition or absorbed dose. In fact the biological effects of ionizing radiatons are not only related to absorbed dose, but also several other factors as well.

These factors include:

a) the type of radiation (α, β, γ, X and n).

b) the spacial distrbution of the energy deposit in tissue (physical factors)

c) the species and strain of organism under observation (biological factors)

d) other modifying factors

Therefore, dose equivalent is defined by ICRUas the product of absorbed dose (D), quality factor (Q), and any other necessary modifying factors (N),

$$H=D\cdot Q\cdot N \qquad (3)$$

From this point of view, the dose equivalent is the modified absorbed dose equivalent.

Quality factor:

Quality factor, Q, is a modifying factor that is introduced to take into account the different degrees of biological effect that can result following exposure to the same absorbed doses of different types of radiation.

Table I. Quality factors for various ypes of radiations (Based on NCRP report No. 39)

Type of radiation	Q
X-rays and γ-rays	1
β-rays, $E_{max}>0.03$ MeV	1
β-rays, $E_{max}<0.03$ MeV	1.7
Naturally occuring α-particles	10
Heavy recoil nuclei	20
Neutrons:	
Thermal to 1 KeV	2
10 KeV	2.5
100 KeV	7.5
500 KeV	11
1 MeV	11
2.5 MeV	9
5 MeV	8
10 MeV	6.5
20 MeV	8
Energy not specified	10

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* Soft tissue: The principal elements are carbon, oxygen, hydrogen and nitrogen

The quality factor is dependent primarily upon the microscopic distribution of absorbed radiation energy. Q-values for various radiations are given as follows:

Units:

Dose equivalent has the same dimensions, Joules/kilogram, as absorbed dose in terms of SI units. The special unit of dose equivalent is the rem, which is the acronym for "roentgen equivalent man".

Hence, H(rem) $=D$(rad)$\cdot Q\cdot N$(rem/rad)

Dose equivalent rate ($\dot{H}$):

The rate at which dose equivalent is received, is by definition determined from the absorbed dose rate by $\dot{H}=\dot{D}\cdot O\cdot N$ and is expressed in rem/hr, mrem/hr, and rem/min etc.

III. Relationship between Radiation Quantities

Since an exposure of one roentgen results in an energy deposit of 87.6 ergs per g of air, this corresponds to:

87.6ergs/g÷100 ergs/g—rad=0.876 rad (in air).

Thus the dose in air is:

$$D_{air}(\text{rad})=0.876(\text{rad}/R)\cdot X(R) \qquad (4)$$

For a given exposure, the ratio of the ab-

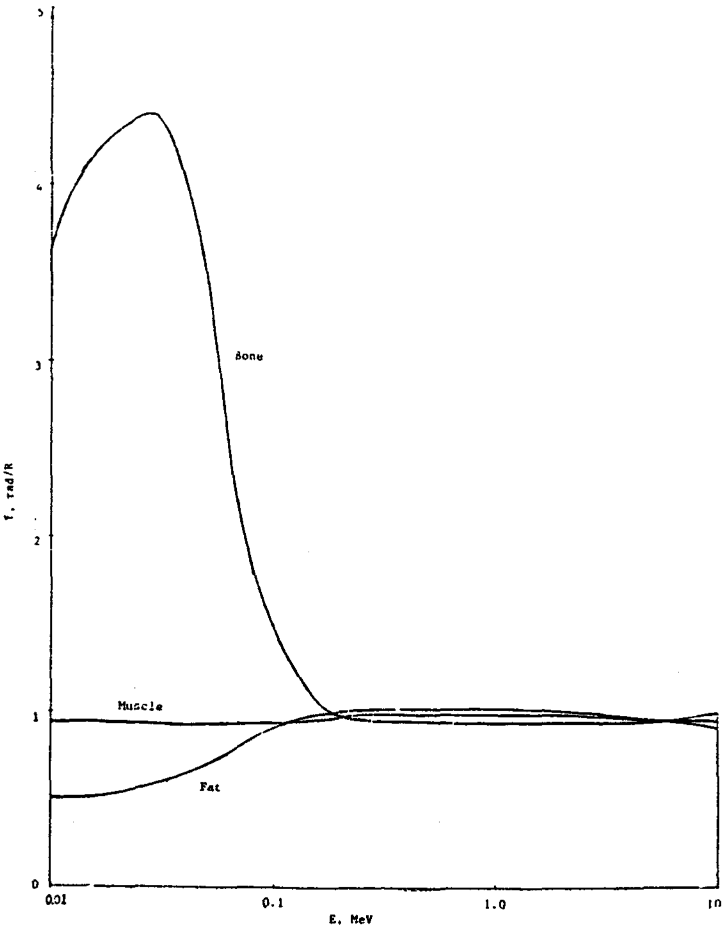

Fig. 1. Values of "f" as a function of γ-ray energy (From Morgan and Turner, Principles of Radiation Protection)

sorbed dose in any medium to the absorbed dose in air is equal to the ratio of the mass-energy absorption coefficients (μ_{en}/ρ) of the medium and of air:

$$\frac{D_{\text{medium}}}{D_{\text{air}}}=\frac{(\mu_{en}/\rho)\ \text{medium}}{(\mu_{en}/\rho)\ \text{air}}$$

Thus, $D_{\text{medium}}(\text{rad})=\frac{(\mu_{en}/\rho)\,\text{medium}}{(\mu_{en}/\rho)\,\text{air}}\cdot D_{\text{air}}(\text{rad})$

and considering Eq (4):

$$D_{\text{medium}}(\text{rad})=0.876\frac{(\mu_{en}/\rho)\,\text{medium}}{(\mu_{en}/\rho)\,\text{air}}\cdot X(R)$$

Sometimes this is expressed as:

$$E_{\text{medium}}\ (\text{rad})=f\ (\text{rad}/R)\cdot X(R) \qquad (5)$$

where $f=0.876\frac{(\mu_{en}/\rho)\,\text{medium}}{(\mu_{en}/\rho)\,\text{air}}$

Accordingly, $D_{\text{medium}}=f\cdot X_{\text{air}}$

For f-values for various photon energies, Radiological Health Handbook published by U. S. DHEW (Department of Health, Education, and Walfare) can be recommended.

For soft tissue (muscle and solid organs), the average atomic number is not greatly dfferent from air; thus for the photon energy range 0.1 to 10 MeV,

$$\frac{(\mu_{en}/\rho)\ \text{tissue}}{(\mu_{en}/\rho)\ \text{air}}\cong 1.09$$

therefore, $f=1.09\times 0.876=0.95$. (Fig. 1)

Hence for soft tissue and photon energies in the 0.1 to 10 MeV range, one roentgen delivers about 0.95 rad. Since $Q=1$, for X- and gamma-radiation, however, $1R=1$ rad $=1$ rem (for soft tissue). This result does not hold for other tissues or outside this energy range (0.1~10 MeV).

Fig. 1 shows, for a unit roentgen exposure, the energy absorbed per one gram of bone, muscle, and fat as a function of photon energy. The differences between the various tissues at low energies of photons (0.01 to 0.1 MeV) is quite evident

IV. Radioactivity (A)

The rate at which a radioactive isotope undergoes nuclear disintegration is called the radioactivity. Radioactivity is the quotient dN/dt, where dN is the number of spontaneous nuclear transformations occurring during a time interval dt.

$$A=\frac{dN}{dt} \qquad (6)$$

Radioactivity (or activity in brief) applies only to the number of nuclear transformations taking place per unit time in a radioactive isotope (in brief, radioisotope). This is not directly related to exposure rate $(\dot{X})$, absorbed dose rate $(\dot{D})$, and dose equivalent rate$(\dot{H})$.

Units:

This SI units of radioactivity are disintegrations per second (dps). The "special" unit is the curie (symbolized by Ci). The curie was originally defined as the number of disintegrations occurring in 1 gm of pure radium per second. To be meaningful, the unit for quantity of radioactivity must be based upon activity.

1 Ci $=3.70\times10^{10}$ disintegrations/sec,
$=2.22\times10^{12}$ disintegrations/min.

The curie is a rather large unit, thus in practice the millicurie(mCi) and microcurie (μCi) are more commonly used units. Multiples of the unit, curie:

millicurie(mCi),	$1m\text{Ci}=10^{-3}$ Ci
microcurie (μCi),	$1\mu\text{Ci}=10^{-6}$ Ci
picocurie (pCi),	$1p\text{Ci}=10^{-12}$ Ci

In 1975, the ICRU proposed new unit, becquerel (symbolized by Bq).

1 $Bq=1$ disintegration/sec$\cong 2.703\times10^{-11}$Ci

V. Radiation Dose Calculations

1. External exposure rate

As previously emphasized, the concept of exposure and exposure rate applies only to gamma rays (or X-rays) in air at a point outside a body. The radiation intensity from any given gamma-ray source is used as a measure of the source strength (S photons/sec). In particular the gamma ray exposure rate from a point source of one millicurie (mCi) at the distance, 1cm is termed the "specific gamma-ray constant". It is symbolized by "Γ" and is frequently given in units of roentgens per hour at 1cm from a point source of the activity, 1mCi. (R/hr·mCi at 1cm or R·cm²/hr·mCi).

The gamma ray exposure rate is calculated by considering the energy absorbed per unit mass of air at the specified distance from the one curie point source dut to the photon flux at that distance. Thus:

$$\dot{X}=\phi E\left(\frac{\mu_{en}}{\rho}\right)_{air}\ R/\text{hr}=\frac{S}{4\pi r^2}E\left(\frac{\mu_{en}}{\rho}\right)_{air}$$

$$R/\text{hr}=\frac{AB}{4\pi r^2}E\left(\frac{\mu_{en}}{\rho}\right)_{air}\ R/\text{hr} \qquad (7)$$

where ϕ=gamma ray flux (photons/cm²·sec)

$\phi=\frac{S}{4\pi r^2}$

S=source strength (photons/sec), $S=AB$

r=distance from the source to the irradiated object (cm)

A=source activity (mCi)

B=branching factor of disintegrations that result in a gamma ray of energy under consideration (photons/disintegration)

E=gamma ray energy (MeV)

$\left(\frac{\mu_{en}}{\rho}\right)_{air}$=mass energy absorption coefficient for air (cm²/g)

μ_{en}=linear energy absorption coefficient for air (cm⁻¹)

ρ=density of air (g/cm³)

$\rho=0.001293\text{g/cm}^3$

Meanwhile, substituting the appropriate numerical values into Eq. (7),

we have: $\dot{X}=\left(\frac{ABE}{4\pi r^2}\times3.7\times10^7\text{dps}\right)\left(\frac{\mu_{en}}{\rho}\right)_{air}\times\left(\frac{1.6\times10^{-6}\text{ergs/MeV}}{87.6\text{ergs/g}\cdot R}\times3.6\times10^3\text{sec/hr}=\right.$

$$\frac{A}{r^2}\left[BE\left(\frac{\mu_{en}}{\rho}\right)_{air}\times\frac{3.7\times1.6\times3.6\times10^4}{4\pi r\times87.6}\right]$$

$$=\frac{A}{r^2}\left[1.935\times10^2BE\left(\frac{\mu_{en}}{\rho}\right)_{air}\right],$$

letting $\Gamma=1.935\times10^2\ BE\left(\frac{\mu_{en}}{\rho}\right)_{air}$ R·cm²/hr·mCi,

Consequently: $\dot{X}=\frac{A}{r^2}\Gamma$ (8)

Values of "Γ" can be found tabulated in Radiological Health Handbook by U. S. DHEW (p. 131).

2. Internal dose rate

From the biological point of view, by internal dose is meant absorbed dost from internally deposited radionuclides. Hence a practical calculation of absorbed dose and absorbed dose rate follows directly from the definition of the rad.

The general approach to internal dose rate calculation entails:

1) Specification of determination of the activity, A, in the source region,
2) Computation of the corresponding energy emission, and
3) Application of an absorbed fraction to determine the energy deposited in the target volume.

Meanwhile, two geometric extremes are usually considered:

a) self-irradiation (source region=target volume)
b) cross-irradiation (source region≒target volume)

A general expression for the calculation of internal absorbed dose rate is:

$$\dot{D}=\frac{A\Delta F}{M_v}\ \text{rad/hr} \qquad (9)$$

where A: activity in source region (μCi)

Δ: equilibrium absorbed dose constant (ergs/hr·μCi)

F: absorbed fraction

M_v: mass of a target volume (g)

For a radionuclide with n types and energies of radiation, Δ and F must be specified for each type and energy of radiation. Therefore, the general equation becomes:

$$\dot{D}=\frac{A}{M_v}\sum_{i=1}^{n}\Delta_i\cdot F_i \text{ rad/hr} \qquad (10)$$

Note that A/M_v can also be expressed as activity concentration, C. Thus the general equation is sometimes seen in the form:

$$\dot{D}=C\sum_{i=1}^{n}\Delta_i\ F_i \qquad \text{rad/hr} \qquad (11)$$

Now, it is necessary to describe Δ_i and F_i in detail.

(A) Equilibrium absorbed Dose Constant (Δ_i)

The equilibrium absorbed dose constant represents the energy emission rate per unit activity expressed as potential for delivering dose. It is simply:

$$\Delta_i=\eta_i\cdot\overline{E}_i(\text{MeV})\cdot 1.6\times10^{-6}(\text{erg/MeV})\cdot\frac{1}{100}(\text{g}\cdot\text{rad/erg})\cdot 3.7\times10^{4}(\text{sec}^{-1}/\mu\text{Ci})\cdot 3.6\times10^{3}(\text{sec/hr}),\ \text{thus,}\ \Delta_i=2.13\eta_i\overline{E}_i\ \text{g}\cdot\text{rad}/\mu\text{Ci}\cdot\text{hr} \qquad (12)$$

Where η_i: fractional abundance of i-th radiation per disintegration,

$\overline{E}_i$: average energy, MeV of i-th type of radiation.

For alpha and gamma radiation, $\overline{E}$ is the energyof the radiation. $\overline{E}$ for beta radiation depends upon the shape of the beta particle energy spectrum. For beta radiation, however, a commonly used approximation is: $\overline{E}_\beta=\frac{1}{3}E_{max}$ where E_{max} means the maximum beta radiation energy.

The value of the equilibrium ablorbed does constant can be calcusated for each case by using Eq. (12) or it may be found tabulated in the pamphlets No. 4 and No. 5 of the Medical Internal Radiation Does (MIRD)* Committee of the Society for Nuclear Medicine.

Consequently if the internal does rate equation is written in terms of energy rather than Δi, it becomes:

$$D=\frac{A}{M_V}\sum_{i-1}^{n}2.13\eta_i\overline{E}_iF_i=\frac{2.13A}{M_V}\sum_{i-1}^{n}\eta_i\overline{E}_iF_i \text{ rad/hr}$$

Some prefer to express the internal dose rate on a per day basis. Then it becomes:

$$D=\frac{2.13A}{M_V}\sum_{i-}^{n}\eta_i\overline{E}_iF_i\times 24\text{hrs/day}$$

$$=51.2\frac{A}{M_V}\sum_{i-1}^{n}\eta_i\overline{E}_iF_i \text{ rad/day}$$

$$=51.2\,C\sum_{i-1}^{n}\eta_i\overline{E}_iF_i\text{rad/day}$$

(B) Absorbed Fraction (F_i)

(a) Alpha particles: for self irradiation (in source organ), F = 1.0 and for cross irradiation, F = 0.

(b) Bata particles: also, for self irradiation, F =1.0 and for cross irradiation, F =0.

(c) Gamma rays: valuse of F can be found tabulated in the pamphlet No. 5.

VI. Conclusion

Wheresoever just by living on the earth, the average individual is always exposed to a certain amount of unavoidable environmental or "background" radiation from the natural and man-made radioactive sources. Furthermore, it has been documented that radiation exposure can induce malignant diseases in the human body such as cancer and leukemia. From this point of view, it is absolutely necessary to make the units of radiation does that is suitable for both gen-

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* MIRD: MIRD Committee, 404 Church Avenue, Suite 15, Maryville, Tn. 37801 U. S. A.

Table 11. Radiation Quantities and Units

Quantity (symbol)	Exposure (X)	Absorbed Dose (D)	Dose Equivalent (H)
Unit	roentgen (R)	rad	rem
Radiation Type	X-rays and gamma-rays	All ionizingradiations	All ionizing radiations
Media in which mesaured	air	any medium	biological system
Effect measured	ionizatiion	deposited energy	biological effect

eral radiation protection and medical radiation therapy.

Radiation quantities and units which could be biologically meaningful and physically general, in quantitative study of the effects of radiation, have been discussed so far. However, it should be noted that since the fraction of radiation field depends upon its initial incident energy, it is important to distinguish between radiation exposure and radiation dose. For this reason, the radiation exposure and the radiation absorbed dose were introduced separately as the radiation quantity in the previout section.

In particular, it should be emphasized that it is impractical to measure the amount of exposure to photon energies greater than 3MeV, because it becomes very difficult to stop them in air. For such high energies of photon, therefore, exposure is in units of watt-seconds per cm^2. On the other hand, the quantity termed KERMA (Kinetic Energy Released to Matter) is introduced as a measure of imparted initial energy to matter in the ICRU Report 19. Its SI units are joule per kilogram (*J*/kg). The special unit is the rad or the Gray (*G,*).

Finally for the convenient understanding of the core part in this paper, Table II summarizes and makes distinctions between the principal three radiation quantities and their units.

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—抄 錄—

放射線量 및 單位

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概 要

오늘날 에너지 供給을 위한 새로운 解決策의 하나로서 登場한 原子力發電所, 在來의 X線 診療 以外에 醫學界에 導入된 放射線源, 그리고 各種 電子生產品 等의 增加現象은 放射線 防禦 問題와 關聯하여 保健醫學分野에서 從事하는 사람들에게 至大한 關心거리가 되고있다 그래서, 于先 放射線에 關한 事項중에서 가장 基礎가되는 放射線量計測에 있어서 그 量과 單位 問題가 體系的으로 敍述되었다. 即 放射線이 人體에 끼칠 수 있는 害로운 影響에 그 主眼點을 두어 照射線量, 吸收線量, 線量當量, 그리고 그들의 關係 및 放射能等에 關하여 討論되었다. 特히 照射線量率, $\dot{X}$는 比감마線常數, (Γ)를 包含하는 函數로 表現되었고, 끝으로 人體 內部에 蓄積된 放射能으로부터의 影響에 依한 이른바 生物學的効果 (Somatic or Genetic Effects)와 關聯되는 內部吸收線量率은 平衡吸收線量常數(Δ_i)와 吸收率(F_i)를 包含하는 數學的 모델로 紹介되었다.

한편 放射能은 放射線源 物質의 自然崩壞率이므로 다른 放射線量들 即 照射線量, 吸收線量, 그리고 線量當量과는 別途로 取扱하였음을 附言한다.