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RADIATION PROTECTION QUANTITIES

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QUANTITIES AND UNITS

RADIOMETRIC

particle number
fluence ϕ
energy fluence Ψ

fluence rate $\dot{\phi}$
energy fluence rate $\dot{\Psi}$

DOSIMETRIC

stochastic

lineal energy
energy imparted
specific energy imparted

non-stochastic

interaction coefficients
linear energy transfer LET
absorbed dose D
kerma K K_c K_r
exposure X

absorbed dose rate $\dot{D}$
kerma rate $\dot{K}$
exposure rate $\dot{X}$

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equivalent dose H
effective equivalent dose E
committed equivalent dose
committed effective dose

ambient dose equivalent
directional dose equivalent

individual dose equivalent — penetrating / superficial

collective equivalent dose
collective effective dose

quantities	*stochastic*	*non-stochastic*
statistical fluctuations	yes	no
can be predicted	no	yes
can be measured directly	yes	no
differentiable	yes	no
defined in	finite volume	point

QUANTITIES BASED ON MEAN VALUES AND USED IN RADIATION PROTECTION

Radiological protection aims at avoiding deterministic effects by setting dose limits below their thresholds.
Stochastic effects are believed to occur, albeit with low frequency, even at the lowest doses and therefore have been taken into account at all doses.

The basic physical quantity used in radiation protection is the **absorbed dose, D_T,** averaged over an organ of defined tissue, T, where D_T is the energy deposited in the organ divided by the mass of the organ
The unit of absorbed dose is the called the **gray (Gy).**

Some radiations are more effective than others in causing stochastic effects.
To allow the quantity equivalent dose was introduced.

The **equivalent dose, H_T,** is the average dose in the organ or tissue T multiplied by the dimensionless
radiation weighting factor, w_R
The unit of equivalent dose is the called the **sievert (Sv).**

Note: For almost all the radiation used in medicine, the radiation-weighting factor is unity, so the absorbed dose and the equivalent dose are numerically equal

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The irradiation of the different organs and tissues in the body results in different probabilities of harm of different severities.
The combination of probability of induction and severity of harm is called detriment.
To reflect the combined detriment from stochastic effects in all the organs and tissues, the equivalent dose in each organ and tissue is multiplied by a
tissue weighting factor, w_T,
and the results are summed over the whole body to give the
effective dose, E
The unit of effective dose is the called the **sievert (Sv).**

SOURCE	emission	ORGANS	w_R	ORGANS	w_T	BODY
inside or outside the human body	⇒	absorbed dose, D_T (Gy)	⇒	equivalent dose, H_T (Sv)	⇒	effective dose, E (Sv)

BIOLOGICAL APSECTS OF RADIOLOGICAL PROTECTION

Ionizing radiation causes both deterministic and stochastic effects as a consequence of energy transfer from charged particles to molecules in living cells.

Deterministic effects result from the cell killing and inflammatory effects, which, if the dose is large enough, cause sufficient harm to impair integrity and the function of tissues or organs.
The probability of causing such harm will be zero at small doses, but above some level of dose, a threshold, the probability will increase steeply to 100%.
Above the threshold, the severity of harm will increase with dose
Thresholds of these effects are often at doses a few Gy or doses rates of a fraction of a Gy per year.

Radiological protection aims at avoiding deterministic effects by setting dose limits below their thresholds.

Stochastic effects may result when an irradiated cell is modified rather than killed.
Modified somatic cells, may after after prolonged delay, subsequently develop into a cancer.
There are repair and defence mechanisms that make this an improbable outcome.
The probability of cancer induction from irradiation increases with increase in dose, probably with no threshold.
The severity of harm is not affected by the dose.
If the damage occurs in a cell whose function is to transmit genetic information to later generations, any resulting effects are expressed in the progeny of the exposed person.
This type of stochastic effect is called "hereditary".

Stochastic effects are believed to occur, albeit with low frequency, even at the lowest doses therefore, the doses should be kept as low as reasonably achievable.

The Relative Biological Effectiveness, RBE, of radiation A to induce a specific biological effect in a biological system with respect to the effectiveness with respect to the reference radiation R, is defined as the ratio of absorbed dose D_R, in a tissue to the dose D_A that causes a quantitatively and qualitatively equal effect.

$$RBE = D_R / D_A$$

Therefore, the RBE derived from a set of observations for tissue cultures or for responses of tissues, in animals or in man, refers to a defined biological end-point, produced under specific set of exposure conditions.

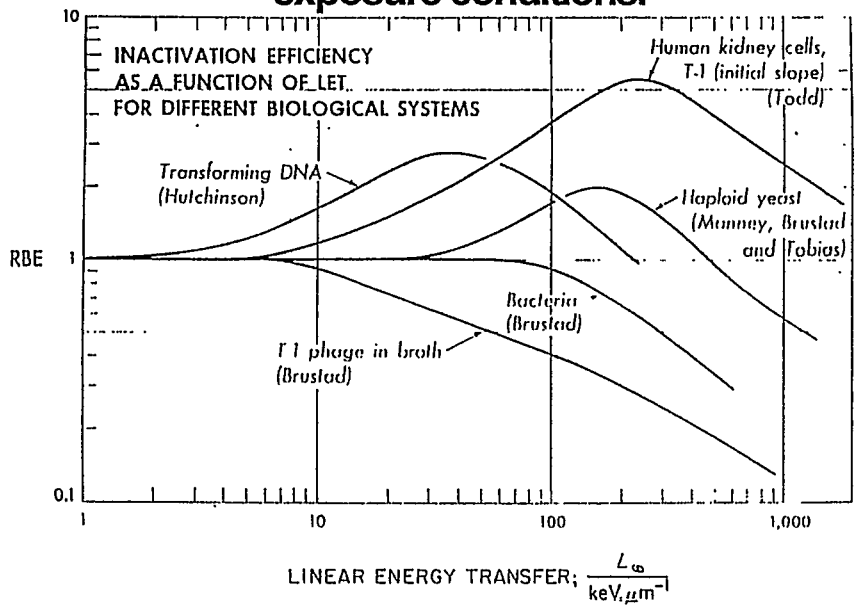


Fig. RBE vs linear energy transfer.

(ICRU: Linear Energy Transfer ICRU report 16, 1970, Washington DC, USA

Since the probability of induction of stochastic effects is found to be depedent on the quality of the radiation, a weighting factor has been traditionally introduced to modify the absorbed dose.

This dimensional factor, Q, is given as a function of the unrestricted linear energy transfer, L_{oo}

Table Specified Q-L_{oo} relationships proposed by ICRP (1990)

L_{oo} in water (keV/μm)	$Q(L_{oo})$
<10	1
10-100	$0.32\ L_{oo}-2.2$
>100	$300 / L_{oo}^{1/2}$

High LET radiation differs from low LET radiation in affecting both the shoulder and the slope of the radiation survival curves of cells , survival being determined by the ability to form a macroscopic colony.

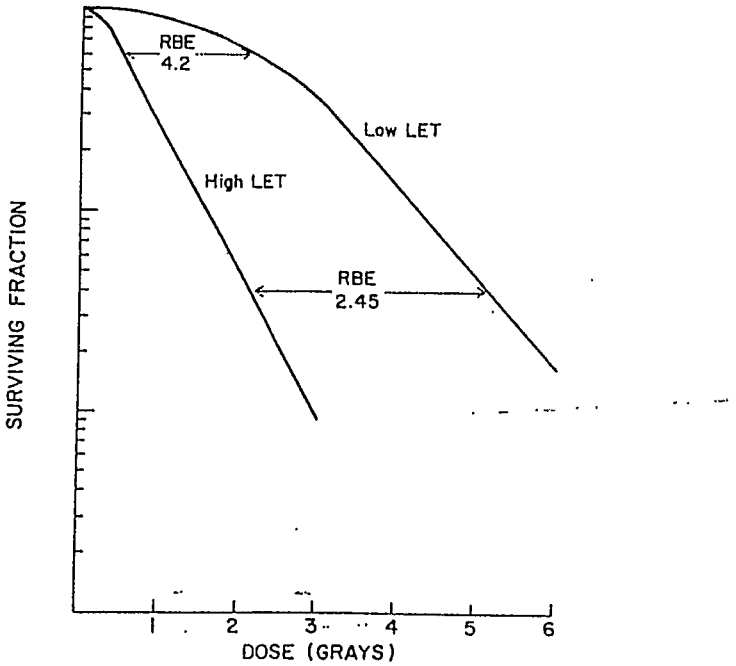
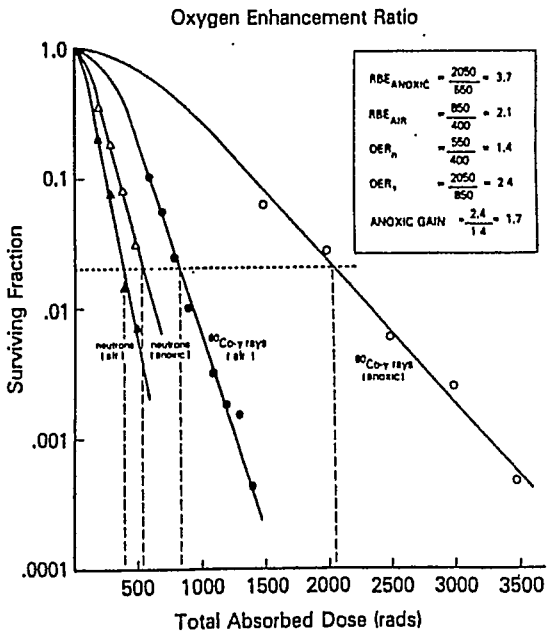
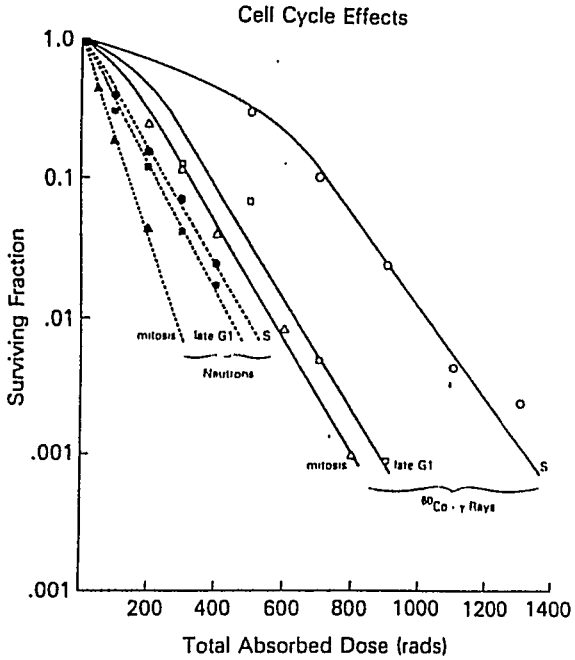


Fig. Survival fraction for high and low LET radiation



Survival curves of Chineses hamster ovary (CHO) cells irradiated with ^{60}C0 γ-rays ans 50 MeV d-Be fast neutrons under aerated and anoxic condtions.

Ref: DeVita,Hellman, Rosenberg: Cancer: Principles and Practice of Oncolgy, 1989, Lippincot Com. New York, USA



Survival curves of Chineses hamster ovary (CHO) cells irradiated with ^{60}C0 γ-rays ans 50 MeV d-Be illustrating the variation in radiosensetivity with position in the cell cycle.

Ref: DeVita, Hellman, Rosenberg: Cancer: Principles and Practice of Oncolgy, 1989 Lippincot Com. New York, USA

Table: RBE values for deterministic effects induced by neutrons of 1-20 MeV mean energy

tissue/ organ	type of effect	species	energy (MeV)	RBE for photons 2-3Gy	10-20Gy
Skin	early response	mouse	2.5	5.6	2.8
		mouse	7.5	3.5	1.9
		mouse	20	3.6	2
		pig	16	2.8	2
		human	7.5	3.5	2.0
	late effects	mouse	7.5	4.0	
		rat	14	2.2	1.5
		pig	16	3.1	1.8
		human	14	2.9	
		human	20	3.0	
Eyes	late effects	mouse	2.0		4.5
		human	7.5		3
G.I. track	early response	mouse	1.0	5	3.0
		mouse	2.5	5	2
		mouse	7.5	5	2.6
		mouse	14	2.8	1.4
		mouse	22	2.6	1.8
		pig	16		2.5
		human	15		3.2
	late effects	mouse	2.5	6	3
		rat	2.0	4.0	2
		pig	16		3
		human	15		3.2
Testis	early effects	mouse	1	5.7	5.7
		mouse	2.5	4.6	4.6
		mouse	7.5	4.1	1.7
		mouse	20	5.8	2.8
		pig	16	6.3	3.0

Data compiled from: ICRP RBE for deterministic effects, ICRP Publication 58 1990, Pergamon Press, Oxford, UK

Conclusions

- RBE values of high LET radiations depend on many factors.
- The type of radiation and the type of the effect are of importance.
- RBE values generally increase with decreasing dose, dose per fraction and dose rate

EFFECTIVE DOSE

The relationship between the probability of stochastic effects and dose is found also to vary with the organ or tissue irradiated.

The quantity effective dose is defined, to indicate the combination of different equivalent doses to several different tissues in a way which is likely to correlate well with the total of the stochastic effects.

The factor by which the equivalent dose in tissue or organ T is weighted is called the tissue weighting factor, w_T.
The sum of the 22 tissue weighting factors is unity by definition.

The values of w_T are chosen so that a uniform equivalent dose over the whole body gives an effective dose numerically equal to that uniform equivalent dose.

The effective dose, E, is the sum of the weighted equivalent doses in all the tissues and organs of the body and is given by the expression:

$$E = \sum_T w_T H_T$$

where H_T is the equivalent dose in tissue or organ T and w_T is the weighting factor for tissue T. Evidently:

$$E = \sum_T w_T \sum_R w_R D_{T,R} \qquad H_T = \sum_R w_R D_{T,R}$$

where $D_{T,R}$ is the mean absorbed dose in tissue or organ T delivered by radiation R.

In both expressions the radiation is that incident on the body or emitted by a source within the body.

Note: The w_T values have been developed from a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose they apply to workers, to the whole population, and to either sex.

Tissue weighting factors

Tissue or organ	Tissue weighting factor, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

The remainder is composed of the following 10 additional tissues and organs:

- adrenals,
- brain,
- upper large intestine,
- small intestine,
- kidney,
- muscle,
- pancreas,
- spleen,
- thymus and
- uterus.

A value of 0.005 is assigned to each of them

Notes: The list includes organs which are likely to be selectively irradiated. Some organs in the list are known to be susceptible to cancer induction. If other tissues and organs subsequently become identified as having a significant risk of induced cancer they will then be included either with a specific w_T or in this additional list constituting the remainder. The latter may also include other tissues or organs selectively irradiated.

In those exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the twelve organs for which a weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and a weighting factor of 0.025 to the average dose in the rest of the remainder as defined above.

Table 1. Nominal risks[a] at low doses and low dose rates for low-LET[b] radiation expressed as severe hereditary disorders and fatal cancers (lifetime)

Effect	Nominal risk per milligray	Nominal ratio: total cancers to fatal cancers
Hereditary (gonads)[c]	10×10^{-6} (all generations)	—
Cancers	*Fatality probability*	
Leukaemia (active bone marrow)	5×10^{-6}	1.01
Bone surface	0.5×10^{-6}	1.4
Breast (females only)	4×10^{-6}	2.0
Lung	8.5×10^{-6}	1.05
Thyroid	0.8×10^{-6}	10
Colon	8.5×10^{-6}	1.8
Oesophagus	3×10^{-6}	1.05
Skin	0.2×10^{-6}	500
Stomach	11×10^{-6}	1.1
Liver	1.5×10^{-6}	1.05
Bladder	3×10^{-6}	2.0
Ovary (females only)	2×10^{-6}	1.4
Other (combined remaining tissues and organs)	5×10^{-6}	1.8
Sum of fatal cancers for whole-body irradiation (average for male and female)[d]	50×10^{-6} (1 in 20,000) per milligray	
Baseline cancer mortality	0.15 (1 in 6.7) to 0.25 (1 in 4)	

[a]The nominal risks are average values for a population comprised of equal numbers of males and females of all ages (except for the breast and ovary, which are for females only).

[b]LET means linear energy transfer; low-LET radiation refers to sparsely ionising radiations such as gamma rays, x rays and beta particles.

[c]For infants and children with a full expectation of reproductive potential, the nominal risk per milligray for severe hereditary disorders is a few times larger than the value given. For older age groups, the nominal risk per milligray would decrease towards zero as the expectation of reproductive potential decreases.

[d]For infants and children who are irradiated, the nominal risk is very likely 2 to 3 times higher than the value of 50×10^{-6} per milligray given for whole-body irradiation and the risk appears after a long latency (except for some types of leukaemia). For adults aged over 50 years at the time of irradiation, the nominal risk is 5 to 10 times lower than the value of 50×10^{-6} per milligray given for whole-body irradiation. This lower risk reflects the latency associated with radiation-induced cancers other than some types of leukaemia.

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