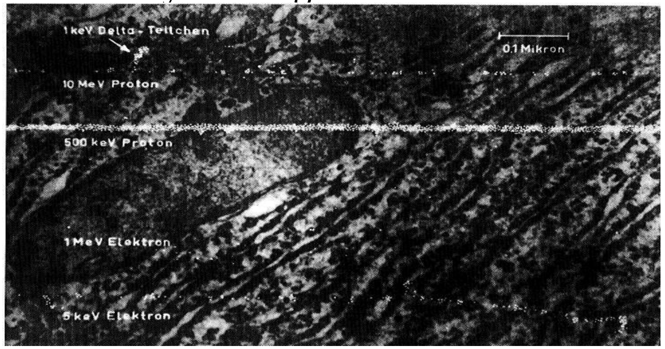
Linear Energy Transfer and Relative Biological Effectiveness

放射技術系王愛義

THE DEPOSITION OF RADIANT ENERGY

- sparsely ionizing
- densely ionizing



Outline

- THE DEPOSITION OF RADIANT ENERGY
- LINEAR ENERGY TRANSFER
- RELATIVE BIOLOGIC EFFECTIVENESS
- RELATIVE BIOLOGIC EFFECTIVENESS AND FRACTIONATED DOSES
- RELATIVE BIOLOGIC EFFECTIVENESS FOR DIFFERENT CELLS AND TISSUES
- RELATIVE BIOLOGIC EFFECTIVENESS AS A FUNCTION OF LET
- THE OPTIMAL LINEAR ENERGY TRANSFER
- FACTORS THAT DETERMINE RELATIVE BIOLOGIC EFFECTIVENESS
- THE OXYGEN EFFECT AND LINEAR ENERGY TRANSFER
- RADIATION WEIGHTING FACTOR
- SUMMARY

LINEAR ENERGY TRANSFER

- Linear energy transfer (LET) is the energy transferred per unit length of the track. The special unit usually used for this quantity is kiloelectron volt per micrometer (keV/μm) of unit density material. The International Commission on Radiological Units in 1962 defined this quantity as follows:

  The linear energy transfer (L) of charged particles in medium is the average energy locally imparted to the medium(dE) by a charged particle of specified energy in traversing a distance of dl.

  That is $L=dE/dl$

LINEAR ENERGY TRANSFER

- ✶ calculate the LET :
  1. track average is obtained by dividing the track into equal lengths, calculating the energy deposited in each length, and finding the mean.
  2. energy average is obtained by dividing the track into equal energy increments and averaging the lengths of track over which these energy increments are deposited.
- ✶ In the case of either x-rays or monoenergetic charged particles, the two methods of averaging yield similar results. In the case of 14-MeV neutrons, by contrast, the track average LET is about 12 keV/ μ m and the energy average LET is about 75 keV/ μ m.

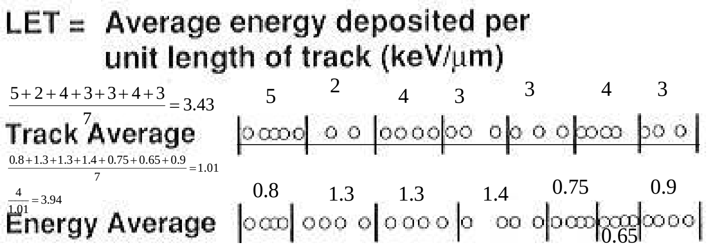


TABLE 7.1. *Typical Linear Energy Transfer Values*

Radiation	Linear Energy Transfer, KeV/µm		
Cobalt-60 γ-rays		0.2	
250-kV x-rays		2.0	
10-MeV protons		4.7	
150-MeV protons		0.5	
	Track Avg.		Energy Avg.
14-MeV neutrons	12		100
2.5-MeV α-particles		166	
2-GeV Fe ions		1,000	

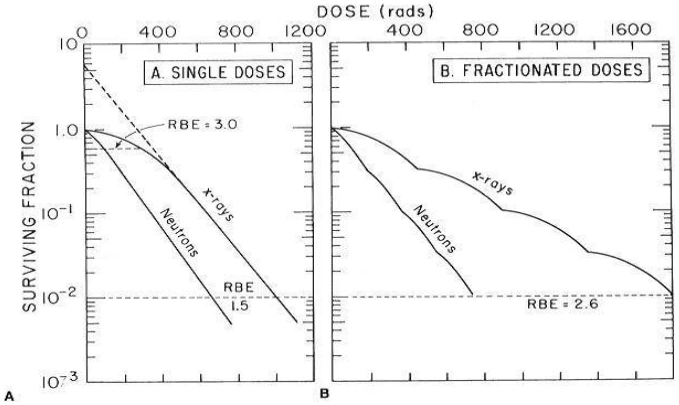
RELATIVE BIOLOGIC EFFECTIVENESS

- ✶ In comparing different radiations it is customary to use x-rays as the standard. The formal definition of relative biologic effectiveness (RBE) is as follows:

  The RBE of some test radiation (r) compared with x-rays is defined by the ratio D_{250}/D_r , where D_{250} and D_r are, respectively, the doses of x-rays and the test radiation required for equal biological effect.

RBE AND FRACTIONATED DOSES

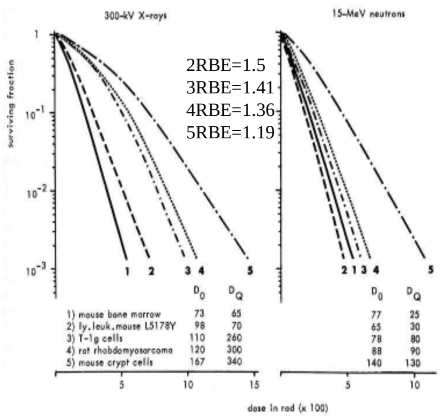
- ✶ The RBE for a fractionated regimen with neutrons is greater than for a single exposure, because a fractionated schedule consists of a number of small doses and the RBE is large for small doses.
- ✶ The width of the shoulder represents a part of the dose that is wasted; the larger the number of fractions, the greater the extent of the wastage. $RBE = \frac{D_{250}}{Dr}$
- ✶ The neutron RBE is larger at a low dose rate than for an acute exposure, because the effectiveness of neutrons decreases with dose rate to a much smaller extent than is the case for x- or γ -rays. Indeed, for low-energy neutrons there is no loss of effectiveness .



- ✶ Fractionated dose, the effect of giving doses of x-ray or fast neutron in four equal fractions to produce the same level of survival as in A. The shoulder of the survival curve is reexpressed after each dose fraction; since the shoulder is larger for x-ray than for neutron, this result in an enlarge RBE for fractionated treatments.

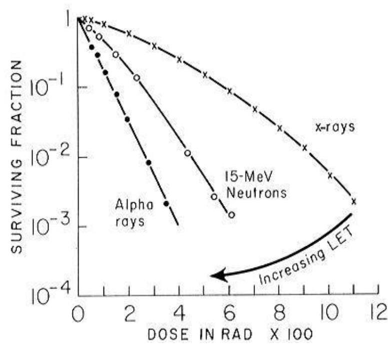
RBE FOR DIFFERENT CELLS AND TISSUES

- ✶ the RBE is different for each cell line, cells characterized by an x-ray survival curve with a large shoulder, indicating that they can accumulate and repair a large amount of sublethal radiation damage, show large RBEs for neutrons. Conversely, cells for which the x-ray survival curve has little if any shoulder exhibit small neutron RBE values



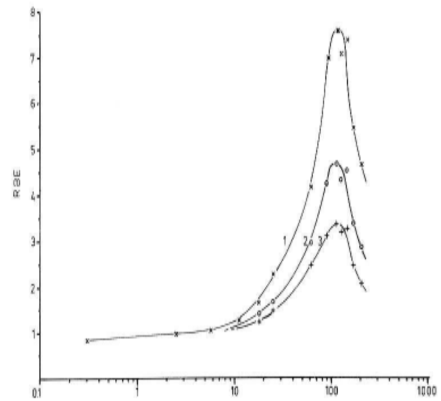
RBE AS A FUNCTION OF LINEAR ENERGY TRANSFER

- ✶ As the LET increases from about 2 keV/μm for x-rays up to 150 keV/μm for α-particles, the survival curve changes in two important respects. First, the survival curve becomes steeper. Second, the shoulder of the curve becomes progressively smaller as the LET increases.



RBE AS A FUNCTION OF LINEAR ENERGY TRANSFER

- ✶ As the LET increases, the RBE increases slowly at first, and then more rapidly as the LET increases beyond 10 keV/μm. Between 10 and 100 keV/μm, the RBE increases rapidly with increasing LET and in fact reaches a maximum at about 100 keV/μm. Beyond this value for the LET, the RBE again falls to lower values.

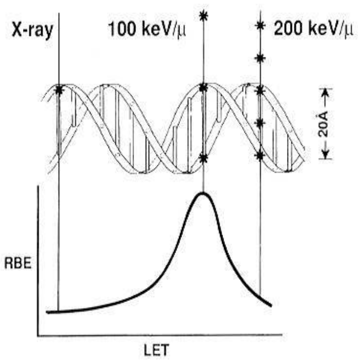


THE OPTIMAL LINEAR ENERGY TRANSFER

- It is of interest to ask why radiation with an LET of about 100 keV/µm is optimal in terms of producing a biologic effect.
- At this density of ionization, the average separation between ionizing events just about coincides with the diameter of the DNA double helix (20 Å or 2 nm). Radiation with this density of ionization has the highest probability of causing a double-strand break by the passage of a single charged particle, and double-strand breaks are the basis of most biologic effects.

THE OPTIMAL LINEAR ENERGY TRANSFER

- In the case of x-rays, which are more sparsely ionizing, the probability of a single track causing a double-strand break is low, and in general more than one track is required. As a consequence, x-rays have a low biologic effectiveness. At the other extreme, much more densely ionizing radiations (with an



LET of 200 keV/um, for example) "wasted" because the ionizing events are too close together.

THE OPTIMAL LINEAR ENERGY TRANSFER

- Because RBE is the ratio of doses producing equal biologic effect, this more densely ionizing radiation has a lower RBE than the optimal LET radiation. The more densely ionizing radiation is just as effective per track, but less effective per unit dose. It is possible, therefore, to understand why RBE reaches a maximum value in terms of the production of double-strand breaks, because the interaction of two double-strand breaks to form an exchange-type aberration is the basis of most biologic effects. In short, the most biologically effective LET is that at which there is a coincidence between the diameter of the DNA helix and the average separation of ionizing events. Radiations having this optimal LET include neutrons of a few hundred kiloelectron volts, as well as low-energy protons and α -particles.

FACTORS THAT DETERMINE RBE

- RBE depends on the following

Radiation quality (LET) : the type of radiation and its energy, whether electromagnetic or particulate and whether charged or uncharged.

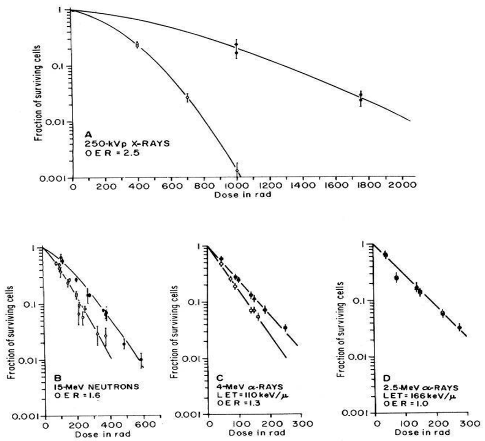
Radiation dose :RBE depends on the dose level and the number of dose fractions (the dose per fraction) because the shape of the dose-response relationship varies for radiations that differ substantially in their LET.

Number of dose fractions :

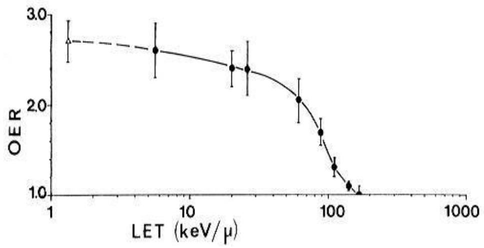
Dose rate :RBE can vary with the dose rate because the slope of the dose-response curve for sparsely ionizing radiations

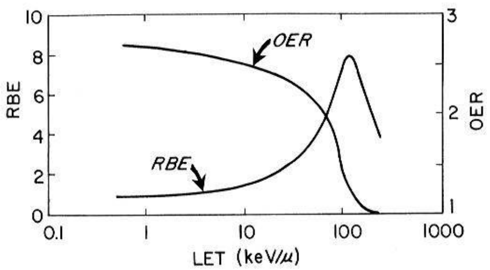
Biologic system or endpoint: RBE values are high for tissues that accumulate and repair a great deal of sublethal damage and low for those that do not.

THE OXYGEN EFFECT AND LINEAR ENERGY TRANSFER



* At low LET, corresponding to x- or γ -rays, the OER is between 2.5 and 3; as the LET increases, the OER falls slowly at first, until the LET exceeds about 60 keV/μm, after which the OER falls rapidly and reaches unity by the time the LET has reached about 200 keV/μm(160 keV/μm).





RADIATION WEIGHTING FACTOR

* The quantity produced by multiplying the absorbed dose by the weighting factor is called the equivalent dose. $H=D\times Q$
* When dose is expressed in grays, the equivalent dose is in sieverts(Sv); if dose is in rads, the equivalent dose is in rad equivalent man (rem). Radiation weighting factors are chosen by the International Commission on Radiological Protection (ICRP) based on a consideration of experimental RBE values, biased for biologic endpoints relevant to radiation protection such as cancer at low dose and low dose rate.

SUMMARY

* X- and γ -rays are called sparsely ionizing because along the tracks of the electrons set in motion, primary ionizing events are well separated in space.
* α -Particles and neutrons are densely ionizing because the tracks consist of dense columns of ionization.
* Linear energy transfer (LET) is the energy transferred per unit length of track. Typical values are 0.3 keV/μm for cobalt-60 γ -rays, 2 keV/μm for 250-kV x-rays, and 100 to 2,000 keV/μm for heavy charged particles.

SUMMARY

- ✶ Relative biologic effectiveness (RBE) of some test radiation (r) is the ratio D_x/D_r, in which D_x and D_r are the doses of 250-kV x-rays and the test radiation, respectively, required to produce equal biologic effect.
- ✶ RBE increases with LET to a maximum at about 100 keV/µm, thereafter decreasing with higher LET.
- ✶ For radiation with the optimal LET of 100 keV/µm, the average separation between ionizing events is similar to the diameter of the DNA double helix (2 nm). It can most efficiently produce double-strand breaks by a single track.

SUMMARY

- ✶ The RBE of high-LET radiations compared with that of low-LET radiations increases as the dose per fraction decreases. This is a direct consequence of the fact that the dose-response curve for low-LET radiations has a broader shoulder than for high-LET radiations.
- ✶ RBE varies according to the tissue or endpoint studied. In general, RBE values are high for cells or tissues that accumulate and repair a great deal of sublethal damage, so that their dose-response curves for x-rays have a broad initial shoulder.
- ✶ RBE depends on the following: Radiation quality (LET)、Radiation dose、Number of fractions、Dose rate、Biologic system or endpoint

SUMMARY

- ✶ The oxygen enhancement ratio has a value of about 3 for low-LET radiations, falls when the LET rises above about 30 keV/µm, and reaches unity by an LET of about 160 keV/µm .
- ✶ The radiation weighting factor depends on LET and is specified by the International Commission on Radiological Protection as a representative RBE at low dose and low dose rate for biologic effects relevant to radiation protection such as cancer induction and heritable effects. It is used in radiologic protection to reduce radiations of different biologic effectiveness to a common scale.
- ✶ Equivalent dose is the product of absorbed dose and the radiation weighting factor. If absorbed dose is expressed in grays, equivalent dose is in sieverts. If absorbed dose is in rads, equivalent dose is in rem.