RELATIONSHIP BETWEEN $\bar{Q}$ DEFINED IN TERMS OF y FOR 1 μm SITES AND INITIAL RADIATION DAMAGE*

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ABSTRACT

The recent suggestion that quality factor (Q) be defined in terms of lineal energy (y) rather than LET (IN 86) requires specification of the diameter of the site to be used. Since present knowledge of the mechanisms leading to effects of radiation is insufficient to specify the exact site size, an arbitrary choice of site size must be made. A site size of one or two micrometers has been recommended because it can be simulated by tissue equivalent proportional counters, making Q a measurable quantity. However, it is not immediately obvious that y measured in a 1 μm diameter site is relevant to the biological effectiveness of different radiations. Monte Carlo track structure calculations have been used to determine the distribution of energy deposition for protons and electrons at a variety of energies in 10 nm and 1000 nm diameter sites. The results indicate that measurements using large sites can be used to provide a satisfactory estimate of energy deposition in small sites and can thus be used to predict biological effectiveness, even if the effect depends on the concentration of damage in very small sites.

INTRODUCTION

Many years ago an experimental technique for measuring the energy deposited in microscopic volumes was introduced (Ro55). This technique was originally intended as a method for measuring LET, and thus a way to determine the mean quality factor of unknown radiation fields. Tissue equivalent proportional counters are still used in this way occasionally, but certain fundamental characteristics of radiation interactions place limitations on the relationship between LET and energy deposition in small sites. The study of these energy transfer processes and the resulting stochastics of dose in small regions has come to be known as microdosimetry. It has been proposed that the microdosimetric quantity lineal energy (y) be substituted for LET in a new definition of Q (IN 86). The advantages to such a system include the fact that y can be measured directly (while LET must be calculated from the mass, charge and velocity of the ionizing particle), that reasonably simple relationships between y and RBE have been found for many biological systems (Bo83, Ph87) and that y is more nearly related to the actual energy deposition in cell nuclei than is LET for those radiations where energy loss, straggling and delta ray escape may be important. These include most radiations of practical importance in protection from external sources. However, there are also disadvantages to a definition of Q based on y. Such a definition requires choosing the diameter of the site for which y will be specified. It is unlikely that a single site size is relevant to all biological systems and endpoints. Furthermore, data on the biological

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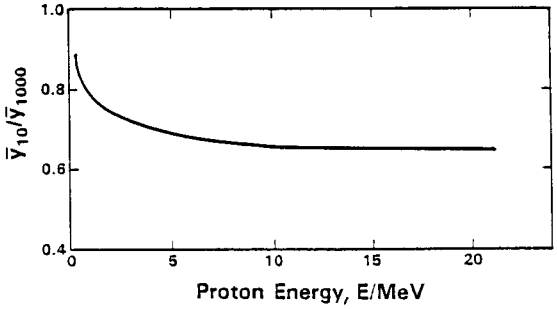

FIGURE 1. The ratio of lineal energy in 10 nanometer and 1000 nanometer diameter sites is nearly constant for protons above 5 MeV.

effectiveness of unusual radiations such as very soft x-rays (Go77) and molecular ions (Ro84) show that the initial damage responsible for common biological effects is governed by energy deposition in very small sites, on the order of 10 nm.

Current experimental techniques are limited to a minimum simulated site diameter of about 300 nm by the requirements of the gas gain mechanism. For low energy charged particles (range comparable to or less than the simulated site diameter), the energy deposited approaches the energy of the charged particle, and y depends directly on the site size. However, these short track radiations are relatively minor problems in radiation protection; x-rays below a few keV do not penetrate the body and neutrons below 100 keV are important primarily when the source is well shielded. This discussion will deal only with radiations which transfer energy via charged particles with range larger than the diameter simulated by the detector. For these long track radiations y is a slowly varying function of the site size.

ENERGY DEPOSITION IN SMALL SIGHTS

The primary tool for studying the energy deposition in small sites is track structure simulation by Monte Carlo techniques. Using suitable atomic cross section data the position of each ionization produced by a charged particle and its secondaries can be calculated (Wi80). The most noticeable characteristics of such tracks are the occurrence of occasional clumps of ionizations, and delta rays which often carry significant quantities of energy away from the path of the primary ion. The results of soft x-ray and molecular ion experiments suggest that the concentration of several ions in a small cluster may be responsible for the biochemical changes which initiate the biological effect. These clusters can be caused by the random occurrence of ionization along an ion or delta ray track, by the overlap of two or more elements of a track (for example,a delta ray track turning and crossing the primary ion track), or from the decreasing mean free path for ionization rear the end of an electron's range. Thus the question of the relationship between measurements in a relatively large site and effects in sites a few nanometers in diameter can be divided into two parts; the ionization produced by the primary ion and that produced by delta ray events.

Figure 1 shows the ratio of the mean lineal energy in a 10 nm site to the mean in a 1000 nm site as a function of proton energy.

It is evident that the lineal energy in the small site is less than in the large site. This is due primarily to transport of energy outside the small site by delta rays. Furthermore, the ratio is relatively constant down to a few MeV, indicating that energy deposited in μm diameter sites can be used as a reasonable indicator of mean energy deposited in much smaller sites. At the lower energies the range of delta rays is short and less energy is transported outside a small site. In this region the overlap of ionizations produced by the primary and those produced by the delta rays becomes more significant, but even in the extreme case the ratio of means changes by only about 50% while the stopping power changes by approximately a factor of ten.

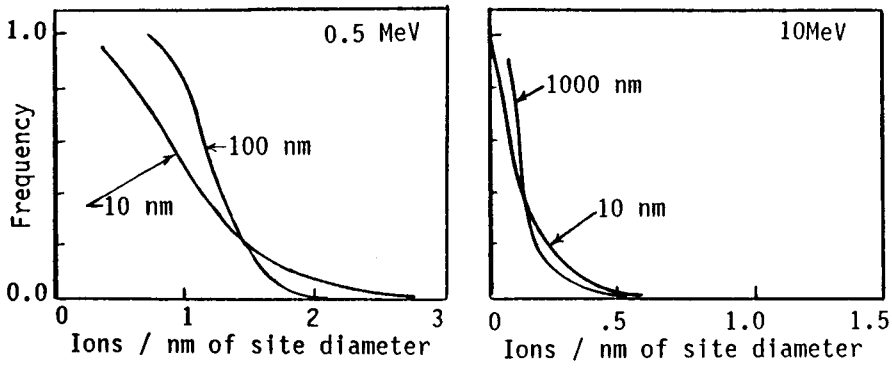

FIGURE 2. The distribution functions for protons crossing through the centers of 10 nm and 1000 nm sites.

If it is the relatively large energy deposition events which are relevant biologically, then one must consider the shape of the distribution of events in addition to their means. Distribution functions shown in figure 2, give the probability that an event will deposit more energy per unit path length than $\bar{y}$. For large site sizes this distribution is a steep curve. For small sites the curve is less steep and crosses the large site curve at about 0.7. Thus for protons from 0.5 to 20 MeV crossing 10 nm sites, the effect of increasing the site size is simply to narrow the distribution of energy deposition events, and increase the mean lineal energy by including some delta ray ionizations which would occur outside a smaller site. The difference between those curves is less for event sizes greater than the median than it is for the smaller events. Thus, for the portion of the energy deposition distribution assumed to be most relevant to the production of biological damage, the large events in small volumes, the energy deposition measured in larger sites would provide a better indication of biological effectiveness than would be suggested by a simple comparison of mean values.

Approximately one third of the energy deposited in matter by protons with initial energy greater than 3 MeV is carried beyond a 5 nm radius around its track by secondary electrons (delta rays). Experimental work using relatively large simulated site sizes (G172) suggest that if only delta rays interact with a site the energy deposition is nearly independent of the primary ion energy as well as the distance from the site to the track. This can be

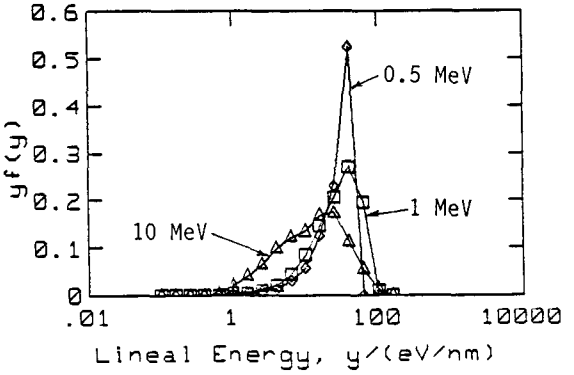

FIGURE 3. Calculated lineal energy distributions in small sites are similar for a wide range of initial electron energies.

understood based on the characteristics of electron tracks. An electron can transfer any fraction of its energy to another electron in a collision so a characteristic distribution of electron energies develops after monoenergetic electrons have undergone only a few collisions. Thus electron spectra differ only with respect to the frequency of the highest energy electrons, and since these have low stopping power they contribute very little to the energy deposition distribution. To illustrate this for very small sites the lineal energy in random 10 nm diameter sites irradiated by electrons of different initial energies is illustrated in figure 3. It is evident that the distribution of delta ray events is essentially independent of the initial particle energy. Thus the energy deposition in large sites, which is a good indication of the total amount of energy transferred by delta rays, can be used to estimate the amount of biological damage caused through this mechanism as well as that caused by the primary ionizations.

REFERENCES

Bo83 Bond, V.P., and Varma, M.N. 1983 "A Stochastic, Weighted Hit Size Theory of Cellular Radiobiological Action" Radiation Protection ed by J. Booz and H.G. Ebert Commission of the European Communities.

Gi72 Glass, W.A. and Roesch W.C., 1972 "Measurement of Ionization Distribution in Tissue - Equivalent Gas" Rad. Res. 49, 477-494.

Go77 Goodhead, D.T., 1977 "Inactivation and Mutation of Cultured Mammalian Cells by Aluminum Characteristic Ultrasoft X-rays" Int. J. Radiat. Biol. 32,43-70

IN86 International Commission on Radiation Units and Measurements, 1986 "The Quality Factor in Radiation Protection" Report 40 ICRU Bethesda.

Ro55 Rossi, H.H. and Rosenzweig, W., 1955 "A Device for the Measurement of Dose as a Function of Specific Ionization" Radiology 64, 404-410.

Wi80 Wilson, W.E. and Paretzke, H.G., 1980 "Calculation of Ionization Frequency Distributions in Small Sites" Rad. Res. 81, 326-335.