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Microdosimetry and Detector Responses

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When a charged particle passes through a defined volume of material, a radiation detector, component in an electronic circuit, or a cell in your body, it will lose some energy and cause a number of ionizations and excitations in the material. Since the ionizations and excitations occur randomly along the path of the particle, the number that occurs within the defined volume is also random. For a given type of radiation (charge and velocity) the number of ionizations increases with the length of the particle path in the volume. For large volumes, such as organs in the human body, the number of ionizations produced along the charged particle path is large and the variation in the number is a small fraction of the total. In this situation the average number of ionizations, or the average energy loss per track length, LET_{∞} (also known as dE/dx), is a useful way to characterize the radiation. However, for small volumes, such as transistors and capacitors in integrated circuit electronics, mammalian cell nuclei, or other sub-cellular volumes, only a small number of ions will be formed and the variation from one track to another will be a large fraction of the average. In this situation, the amount of damage done by a charged particle passing through the target can vary from one track to the next, and LET does not provide a good description of what is likely to happen in the target. When the target is small, it is important to know not only the average amount of energy the radiation would deposit if the track was repeated a large number of times, but also the range of energy depositions that occur when individual tracks interact with targets. These individual interactions are referred to as "events," and the most convenient way to describe these events is the probability density function $f(\varepsilon)$, where ε is the energy imparted in a single event. This probability density function gives the probability that the energy deposited in the specified target will be between ε and $\varepsilon + \Delta\varepsilon$. That is, it gives the probability that the energy deposited will be ε (plus or minus a small amount) for each value of ε from zero to the maximum possible amount.

In addition to the random variation in the amount of energy lost by a charged particle per length of its track, other properties of the charged particle track contribute to the variation in ε in a specified volume. For example, if the charged particle track is short it may stop in the volume and ε will be less than if it had completely crossed the volume. If the charged particle is traveling fast enough, the electrons that it dislodges when it ionizes an atom may receive enough energy to travel a significant distance (they are then called delta rays) and these delta rays may deposit part of their energy outside the volume being considered. Similarly, delta rays, produced by charged particles that do not traverse the volume, may enter it and produce energy deposition. Energy deposited by delta rays may be responsible for the difference in biological effectiveness of different cosmic rays that lose energy at the same rate (i.e., have the same LET_{∞}).

The field of study involving the evaluation of the energy imparted, ε, in microscopic volumes, typically a fraction of a micrometer to several micrometers across, is referred to as microdosimetry, and an understanding of the probability density distribution of ε for different radiations may be helpful in understanding the biological consequences of those radiations. Fortunately, it is also possible to measure ε and $f(\varepsilon)$ in microscopic sites using any of several types of instruments. The most commonly used instrument for this purpose is the tissue equivalent proportional counter (TEPC) which uses a relatively large volume of gas at low pressure to measure the energy that would be deposited by an ion track in a very small volume of tissue. The energy, ε_l, deposited in a distance l in a volume of density ρ, assuming that LET is an adequate description of the energy deposited by the ion in the volume, is

$$\varepsilon_l = l\rho \cdot dE/\rho dx \qquad (1)$$

where l is the track length through the volume and $l\rho$ is the track length expressed in mass/unit area. $dE/\rho dx$ is the energy loss per unit length expressed in mass/unit area, a value which is independent of the phase of the material. A spherical *gas* volume 2 cm in diameter with a density $\rho=10^{-4}$g/cm^3 will experience the same energy deposition from a particle track as a *tissue* volume (ρ=1g/cm^3) 2 micrometers in diameter since 2 centimeters/2 micrometers is 10^4, exactly cancelling the ratio of the volume densities. However, a low pressure proportional counter receives many more events than does the tissue volume that it is simulating. This is because the number of events detected is proportional to the area of the detector and a 5 cm diameter detector simulating a 1 micrometer diameter tissue volume will receive 25 x 10^8 times as many events as the 1 micrometer diameter site would. This large number of events, combined with the gas gain of a proportional counter, makes it a convenient instrument for measuring the total energy imparted per mass, the absorbed dose, over a wide range of dose rates. In addition, since it measures each individual event in the detector, the data can be used to estimate roughly the LET, based on equation 1. As a result, the data can be used to estimate roughly the radiation quality and evaluate H, the absorbed dose times the quality factor, for the incident radiation field. Thus, a TEPC is probably the first choice for evaluating the dose equivalent in radiation environments, such as in space, where a wide range of radiation types contribute to making the dose equivalent larger than the absorbed dose.

In order to accurately measure the energy deposition by high energy charged particles and their delta rays, however, it is essential that the boundary of the detector not block the delta rays or disturb the rate of delta-ray production. A detector which has essentially no wall, but records only the ionization produced in a defined volume, is required. One example of measurement of high energy heavy ions was reported by Metting et al (1988). Energy deposited in a volume defined by a 6.4mm-diameter wire grid simulating a 1.3 micrometer diameter tissue volume was measured for 600 MeV/n iron ions at the LBNL Bevelac. These ions are typical of the high energy heavy ions in the galactic cosmic ray spectrum. In order for the detector to see all of the delta ray events that occur in tissue, the radius of the charged particle beam must be larger than the range of the most energetic delta ray in the detector gas. For 600 MeV/n particles this is 8000 micrometers in tissue or 3900 cm in the low pressure gas. Since the machines used to produce these high energy heavy ions in the laboratory cannot produce such a large beam, an alternative approach was used. The distance between the center of the TEPC and the path of each iron ion was measured using a special solid state detector, and the $f(\varepsilon)$ distribution and probability of a delta ray event was determined for each distance between the site and the path of the charged particle. These measurements clearly showed that for each small object hit by the iron ion there are many more objects hit only by the delta rays. These delta ray events can occur at large distances from the path of the primary ion, but within the region where delta ray events occur, only a small fraction of the objects are actually hit by a delta ray. The energy deposited in an object, when it is hit by a delta ray, is much larger than the energy per mass deposited in the region within the delta ray range, and is similar to the energy deposited by 170 kV x-rays, independent of the distance from the primary ion path. Adding up all of the events in 8 micrometer diameter cell nuclei, there are about 4500 cell nuclei within range of the delta rays for each one hit by the iron ion, Figure 1. Of these 4500 cell nuclei, only about 32 are actually hit by a delta ray (Brooks et al., 2001).

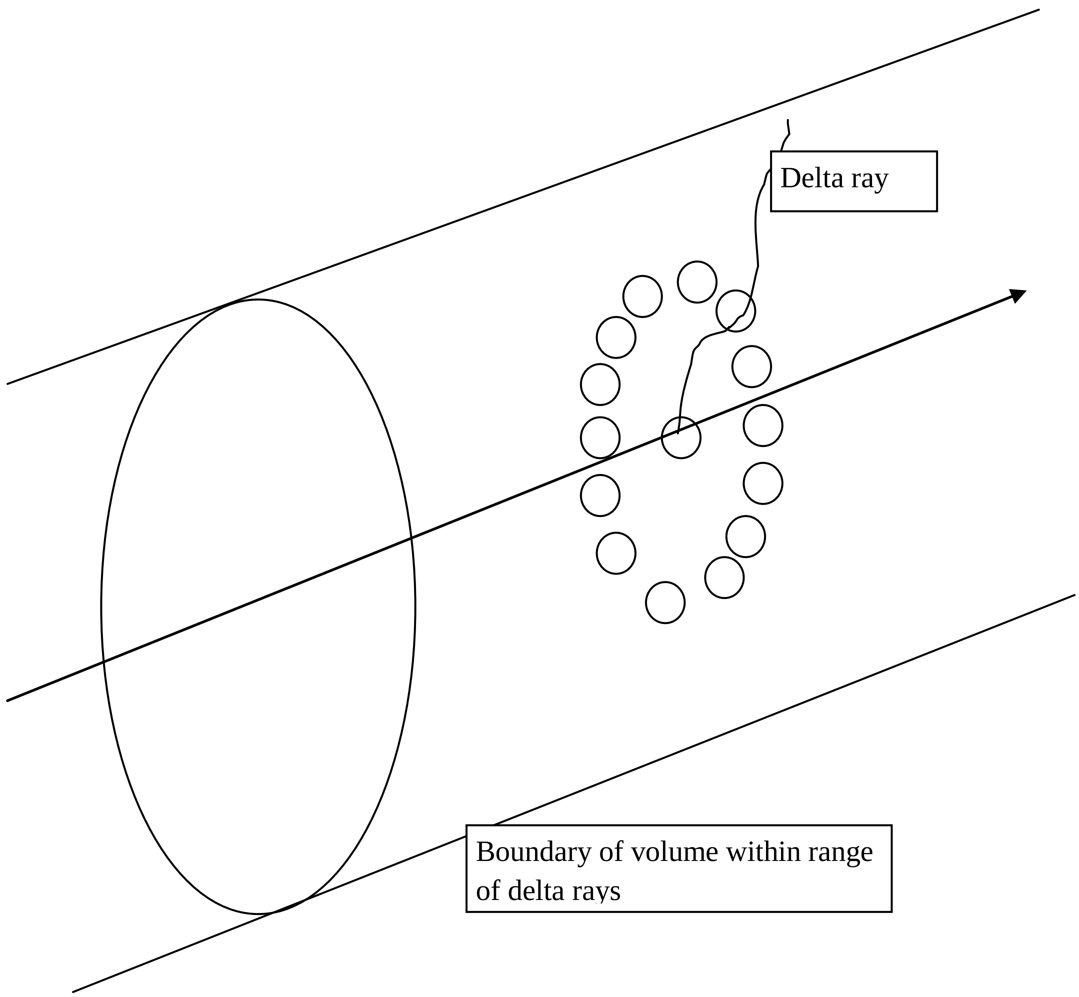

Figure 1. Schematic representation of a 600 MeV/n iron ion (cosmic ray) track in tissue. The entire volume is filled with cells. On average, for each cell nucleus hit by the iron ion, there are 4500 cells within range of the delta rays and about 32 of those cells are hit by a delta ray.

References

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