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# Irradiation Equivalence

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Recent analyses of track structure show that the parameters describing a radiation field are not separable from those describing a detecting system;[1] that is, it is impossible to write an expression describing the effect of irradiation as a product of 2 factors, one of which contains only parameters describing the detecting system, while the other contains parameters describing only the radiation field. From this perspective it is difficult to understand the use of a "quality factor," applicable to all biological substances and given as a function of the "effective LET," for the conversion of rads to rems. One cannot define, nor can a single instrument measure, a universal "radiation quality."

Nevertheless, it is possible to generate a useful, simplified description of the interaction of a radiation field with a particular detector in a particular ambient environment, by specifying the "equivalent track-segment bombardment." For cells, this is the bombardment yielding equal sur-

**Table 1.** Equivalent monoenergetic lithium bombardments to 14 MeV neutron and stopped negative pion irradiation of cells whose cellular parameters are given in Reference 2.

| Cells | | 14 MeV neutrons | | | Stopped negative pions | | |
|---|---|---|---|---|---|---|---|
| | | Energy | | | Energy | | |
| | | Nucleon (MeV/amu) | Speed ($\beta$) | LET (MeV g$^{-1}$ cm$^2$) | Nucleon (MeV/amu) | Speed ($\beta$) | LET (MeV g$^{-1}$ cm$^2$) |
| Bacterial Spores | $N_2$ | 6.0 | 0.113 | 620 | 7.0 | 0.122 | 550 |
| | $O_2$ | 7.4 | 0.125 | 530 | 8.0 | 0.130 | 490 |
| Haploid Yeast | | 11.8 | 0.158 | 360 | 12.0 | 0.160 | 360 |
| T.1 Kidney (Todd) | $N_2$ | 7.5 | 0.126 | 520 | 9.0 | 0.138 | 450 |
| | $O_2$ | 10.0 | 0.145 | 420 | 11.0 | 0.152 | 380 |
| T.1 Kidney (Barendsen) | $N_2$ | 4.9 | 0.102 | 730 | 7.0 | 0.122 | 550 |
| | $O_2$ | 7.6 | 0.127 | 520 | 9.0 | 0.138 | 450 |
| Chinese Hamster | | 8.5 | 0.134 | 470 | 9.0 | 0.138 | 450 |
| HeLa | | 11.4 | 0.155 | 370 | 11.0 | 0.152 | 380 |

vival for equal dose, under the specified conditions.

For those cellular systems which have been described by the delta-ray theory of track structure,[2] we can readily demonstrate the existence of an equivalent track-segment bombardment [3] for a mixed radiation field, for a particular cellular system, in a particular environment. We consider the total particulate irradiation to be made up of components homogeneous in charge $Z$ and velocity $\beta$. The ion-kill survival probability of each component is calculated separately. The total ion-kill survival probability, $\Pi_i$, is the product of these separate, independent ion-kill survival probabilities. The total gamma-kill survival probability, $\Pi_\gamma$, arises from the total gamma-kill dose obtained from the separate components of the radiation field.[4] It is necessary that the probability $\Pi_i$ for surviving ion-kill, and the probability $\Pi_\gamma$ for surviving gamma-kill are equal for the two irradiations at the same dose $D$. These conditions lead to the specification of a fluence $F$, an LET $L$, and an ion-kill probability $P$ for the equivalent bombardment, from which we can extract $Z$ and $\beta$, subject to the condition that only integral values $Z$ are observable. Calculations show that Li bombardments of different energies as listed in Table 1 give survival curves which fit closely those calculated for irradiation with 14 MeV neutrons and with stopped negative pions.

We emphasize that the equivalent bombardment is different for different cells and for the same cells exposed under different ambient conditions to the same mixed radiation field. Just as an arbitrary radiation field cannot be represented by a single "biologically effective LET," so also it cannot be represented by a single effective bombardment.

It appears that the value of the ion-kill survival probability of the equivalent bombardment, $P$, may prove to be a simple and particularly useful specification of the effects of radiation, incorporating both the
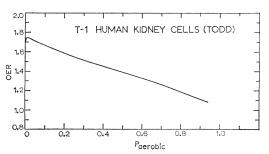


**Figure 1.** Calculated values of the OER (from the extrapolated radiosensitivity) are plotted against $P_{aerobic}$ for T.1 human kidney cells (Todd), for bombarding ions for which $Z = 1, 2, 5, 10, 20, 50$, of different speeds such that $P < 0.95$. For these cells OER is a single valued function of $P$, and does not depend on $Z$ or $\beta$.
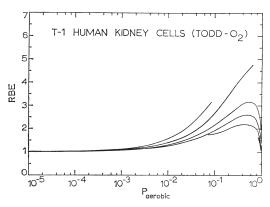


**Figure 2.** Calculated values of the RBE are plotted against $P$ for aerobically irradiated kidney cells, shown, from top to bottom for ions for which $Z = 1, 2, 5, 10, 20, 50$, in a series of track segment bombardments at different values of $\beta$, decreasing along each curve from left to right. The RBE passes through a maximum near $P = 0.5$.

properties of the radiation field and properties of the cellular system.

In Figure 1, we plot calculated values of the OER for T.1 human kidney cells (Todd) against $P_{aerobic}$ for aerobically irradiated cells. For these cells, the OER is a single valued function of $P_{aerobic}$, and does not depend on the value of $Z$ of the bombarding particle or its energy. This graph implies that we can estimate the value of the OER for an arbitrary irradiation of these

cells, by measurement of the initial slope of the survival curve after aerobic irradiation (from which we obtain the ion-kill cross-section $\sigma$) and knowledge of the "saturation cross-section $\sigma_0$" (size of the cell nucleus, approx.), for $P = \sigma/\sigma_0$.

In Figure 2, we plot the calculated value of the RBE for aerobically irradiated kidney cells against $P_{aerobic}$. While the RBE is not a single-valued function of $P$ (since $L$ is not a single valued function of $z^2/\beta^2$), the RBE passes through a broad maximum near $P = 0.5$. At maximum, the RBE decreases with increasing values of the atomic number $Z$ of the bombarding ion.

## References

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