Calculation of response of Chinese hamster cells to ions based on track structure theory*

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Abstract Considering biological cells as single target two-hit detectors, an analytic formula to calculate the response of cells to ions is developed based on track structure theory. In the calculation, the splitting deposition energy between ion kill mode and γ kill mode is not used. The results of calculation are in agreement with the experimental data for response of Chinese hamster cells, whose response to γ rays can be described by the response function of single target two hit detector to ions.

Keywords Chinese hamster cells, Track theory, Ions, Dose response

1 Introduction

A full physical description of all interactions which occur in an irradiated medium by ions is extremely complex. For interpreting the radiation effect of ions, the delta rays theory of track structure by Katz[1,2] attributes the radiation effects of ions to the secondary electrons (delta rays) ejected from the medium by the passing ion. Since γ rays always interact with a medium through secondary electrons, the difference in observed effects associated with γ rays and with ion irradiation arise from the partten of energy deposition by delta rays. Therefore, Katz theory connects the response of a detector to γ rays with action cross section and response functions for ions bombardment through the radial distribution of energy deposition of delta rays. The energy deposition in coaxial cylindrical shells around an ion's path is converted to the probability for target inactivation through the dose response for γ rays. For one-hit detector, such as dry enzymes and viruses, the inactivation cross section of an ion can be described by

$$\sigma = \int_0^{T_{\max}} 2\pi t P(D(t))\mathrm{d}t \qquad (1)$$

where $P(D) = 1-\exp(-D/D_{37})$ is the response function to γ rays, D_{37} the characteristic dose of γ rays, t the distance from the ion's path, $T_{\max}$ the maximum distance of delta rays from the ion's path, and $D(t)$ the radial distribution of energy deposition around the ion's path. With the equation, the inactivation cross section of ion can be calculated by using the numerical integral methods[1~3] or an analytical formula for point target and extended target mode.[4,5]

Unlike one-hit detectors, biological cells are more complex. Cells may be inactivated by a burst of delta rays accompanying the passage of a single energetic ion, it is a single particle effect, and suitably described by an inactivation cross section. In addition, cells may be damaged by the passage of a first ion, then inactivated by the passage of second ion, it is a multiparticle effect. These two kinds of mechanism are called ion kill mode and γ kill mode, respectively in the Katz theory.[2] By considering biological cells as multitarget single hit detectors, the response of cells to ions is successfully calculated by the track structure model via introducing four parameters. However, the splitting of energy between ion kill mode and γ kill mode is introduced in the calculation.

In this work, we develop an analytic formula to calculate the response of cells to ions based on the track structure theory. Instead of using a multi-target single-hit detector model, a single target two hit detector model is used in the calculation. The splitting energy between ion kill mode and γ kill mode is not used in our calculation. The calculated results are in agreement with the experimental results of response of Chinese hamster cells to ions.

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2 Theory

For single target two-hit detector model, cells are inactivated by two events of hitting. In track segment bombardment, the number of survival cells N is described by the equation

$$\mathrm{d}N = -\sigma_1 N_1 \mathrm{d}F - \sigma N \mathrm{d}F \tag{2}$$

where σ is the inactivation cross section of an ion, i.e, the cross section of more than two hits. F the fluence of ion beam, N_1 the number of cells which experience one hit still survival, and σ_1 the one hit cross section. The first term of righthand side in Eq.(2) is pure effect of two particles, and the second can be divided into two parts of $\sigma(N-N_1)\mathrm{d}F$ and $\sigma N_1 \mathrm{d}F$, the first part represents the effect of single particle, and the second represents the part of two particles. Assumption is that N_1 is proportional to the product of F, the number of survival cells N and the cross section of one hit σ_1, that is

$$N_1 = A\sigma_1 NF \tag{3}$$

where A is a fitting parameter. Substituting Eq.(3) into Eq.(2), one obtains

$$N = N_0 \exp(-\sigma F - A\sigma_1^2 F^2/2) \tag{4}$$

where N_0 is initial number of survival cells. From Eq.(4), parameter A can be considered as radiation sensitivity of two particles relative to single particle. The response function of single-target two hit detectors to γ rays, $P(D)$, is

$$P(D) = 1 - \sum_{i=1}^{2} (D/D_{37})^{i-1} \exp(-D/D_{37}) \tag{5}$$

and the one hit probability $p_1(D)$ is

$$p_1(D) = D/D_{37} \exp(-D/D_{37}) \tag{6}$$

According to the track structure theory, the inactivation cross section is calculated by substituting Eq.(5) into Eq.(1) and replacing D with radial energy deposition around an ion path $D(t)$. The one hit cross section σ_1 is found by replacing D by $D(t)$ and integrating it over all t, as

$$\sigma_1 = \int_0^{T_{max}} 2\pi t \frac{D(t)}{D_{37}} \exp[-D(t)/D_{37}] \mathrm{d}t \tag{7}$$

Because the absorbed dose in track segment irradiated by ions is $D = F \cdot L$, where L is the stopping power or its LET, the relation of survival fraction N/N_0 with dose D can be written as

$$N/N_0 = \exp(-\frac{\sigma D}{L} - \frac{A\sigma_1^2 D^2}{2L^2}) \tag{8}$$

3 Calculating the response of the Chinese hamster cells

The survival curves of the Chinese hamster cells irradiated by X-rays and ions have been measured experimentally[6] and calculated theoretically by Katz *et al.*[7] By using response of single target two hit detector to γ-rays, we fit the experimental survival data of the Chinese hamster cells irradiated by X-rays. From Fig.1 it can be seen that the survival data of the Chinese hamster cells irradiated by X-rays can be fitted by using the response function of single target two hit detector.

If the size of target (extended target model) is taken into account, the radial energy deposition $D(t)$ must be replaced by the mean radial energy deposition $\overline{D}(t)$, and $\overline{D}(t)$ has a plateau with value proportional to $Z_{\rm eff}^2 \beta^{-2} a_0^{-2}$ when t is smaller than the radius of target a_0, and $\overline{D}(t)$ varies as $Z_{\rm eff}^2 \beta^{-2} t^{-2}$ when $t/a_0 > 3$, where β is the velocity relative to that of light in vaccum and $Z_{\rm eff}$ is the effective ion's charge.[2,7] In general, the size of cell a_0 is larger or comparable to the range of the delta rays, so we consider $\overline{D}(t)$ as

$$\overline{D}(t) = \begin{cases} C\frac{Z_{\rm eff}^2}{\beta^2 a_0^2} & \text{for } t \le a_0 \\ 0 & \text{for } t > a_0 \end{cases} \tag{9}$$

approximately in the present calculation, where C is coefficient which only depends on the absorbing medium. Substituting Eq.(9) into Eqs.(6,7), we can get σ and σ_1

$$\sigma = \sigma_0[1 - \exp(-\eta \frac{Z_{\rm eff}^2}{\beta^2}) - \eta \frac{Z_{\rm eff}^2}{\beta^2} \exp(-\eta \frac{Z_{\rm eff}^2}{\beta^2})] \tag{10}$$

$$\sigma_1 = \sigma_0 \eta \frac{Z_{\text{eff}}^2}{\beta^2} \exp(-\eta \frac{Z_{\text{eff}}^2}{\beta^2}) \tag{11}$$

where $\sigma_0 = \pi a_0^2$ is the size of a cell, and $\eta = C a_0^{-2} D_{37}^{-1}$. Using Eq.(8), we recalculate the response irradiated by ions, the results comparing with experimental data are shown in Fig.2. In the calculation, parameters σ_0, η and A are $5.6\times10^{-7}\text{cm}^2$, 8.0×10^{-4} and 0.01 respectively by fitting the experimental survival data. In Fig.2, survival curves are horizontally displaced by a factor s to avoid the overlap of curves. It can be seen that theoretical results are in good agreement with experimetal results. When $A = 0.01$, it can be seen that the radiation sensitivity of single particle is much larger than the radiation sensitivity of two particles. Biological cell is much more complex than a single target two hit detector. A cell may contain many sensitivity units and is inactivated only when a sensitivity unit contained in it is hitted two times. Two hitting events caused by single particle are in a sensitivity unit, but two hitting events caused by two particles in a cell may be in two sensitivity units and does not inactivated the cell. This means that the radiation sensitivity of two particles is smaller than that of single particle, and the parameter A is needed to fit the experimental response of cells to ions.

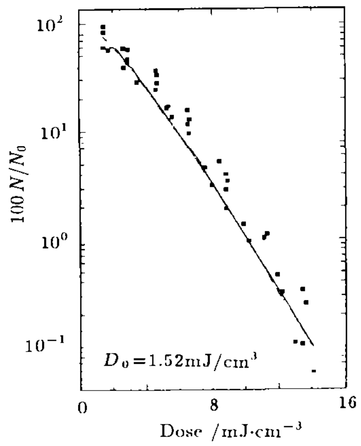

Fig.1 Survival data of the Chinese hamster cells irradiated by X-rays (solid square)[6] are superimposed on fitted survival curve

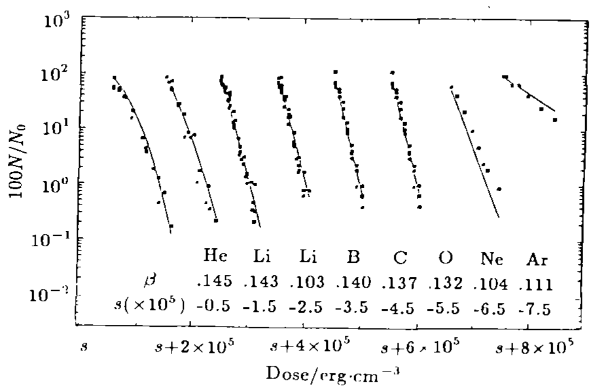

Fig.2 Survival data of the Chinese hamster cells (solid square)[6] are superimposed on fitted survival curves by using Eq.(8)

4 Conclusions

Based on the track structure theory, an analytic formula to calculate the response of cells, which are considered as one target two hit detector, to ions is developed. The calculated results show that Eq.(8) is an useful formula to the describe the survival data of the Chinese hamster cells, whose response to γ rays can be described by the response function of one target two hit detector.

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