Mathematical Model for Estimation of the UV Dose after Irradiation with Ionizing Radiation of Different Energy

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1. Introduction

It is a well-known fact that charged particles emit Čerenkov light when their velocity exceeds the phase velocity of light in a medium. This light includes wide spectra of visible and UV light. Its biological significance was demonstrated by the photoreactivation of UV-hypersensitive bacterial and yeast cells irradiated with ionizing radiation [1-5]. These data indicate that the biological effect of ionizing radiation was not totally due to ionization of molecules but their excitation may be important for some cases. It was found that the highest excitation contribution to cell inactivation could reach 50 % and even more [4]. In this study we propose a simple mathematical model for quantitative estimation of the UV dose after irradiation with ionizing radiation of different energy.

2. Mathematical Model

The mathematical model which will be analysed here has already been published [4] but it has never been used to estimate the UV dose. So, it is worth mentioning the main points of the model briefly. The survival curves of UV-hypersensitive bacterial and yeast cells exposed to ionizing radiation can be simply presented as:

$$S = e^{-kD}, \tag{1}$$

where S – the cell survival, D – the irradiation dose, k – the overall cell sensitivity, defined as the inverse of the mean lethal dose ($k = 1/D_o$). It is reasonable to assume that the excitation and ionization events act stochastically and independently of each other. Then equation (1) can be rewritten as follows

$$S = e^{-(k_1 + k_2)D}, \tag{2}$$

where k_1 and k_2 – are the cell sensitivities to the ionizations and excitations, respectively. We can normalize the overall radiosensitivity and consider that

$$k_1 + k_2 = 1 \tag{3}$$

Then k_1 and k_2 represent the relative contribution of ionization and excitation to cell inactivation. It is not difficult to choose some factors which can modify cell radiosensitivity through the selective influence on the consequences produced by ionization and excitation. For example, the oxygen effect is known to be exerted predominantly on cell inactivation produced by ionization. On the contrary, illumination by visible light during the postirradiation period is more effective in modifying the effects caused by excitation. Quantitatively, a change of the radiation effect is represented by the dose modifying factor (DMF) defined as the ratio of iso-survival radiation doses with and without modifying treatment.

Let us suppose that the initial survival curve (Eqn. 1) was obtained under oxic and dark conditions. Then the survival in hypoxia will be given by:

$$S = e^{-kD/F_1} = e^{-(k_1/f_1 + k_2)D}, \tag{4}$$

where F_1 is the DMF of the experimental survival curve obtained under hypoxic and dark conditions and f_1 is the DMF for the ionization component only.

If the initial survival curve (Eqn. 1) was obtained under an oxic condition during irradiation and the photoreactivating light was used after irradiation, the corresponding survival curve may be described by:

$$S = e^{-kD/F_2} = e^{-(k_1 + k_2/f_2)D}, \tag{5}$$

where F_2 is the DMF of the experimental survival curve obtained under oxic and light conditions and f_2 is the DMF for the excitation component only.

Taking into account equations (3-5), we obtain the following set of equations:

$$\begin{cases} k_1 + k_2 = 1 \\ k_1/f_1 + k_2 = 1/F_1 \\ k_1 + k_2/f_2 = 1/F_2 \end{cases}, \tag{6}$$

where k_1, k_2, f_1, and f_2 are unknown values, while F_1 and F_2 are known from the experiments. The DMF for the excitation component ($f_2 = 4.5$) was estimated from the experiments on photoreactivation of cells exposed to UV-light (254 nm) only. Then the solution of the set (6) yields:

$$k_1 = \frac{f_2 - F_2}{F_2(f_2 - 1)} \tag{7}$$

$$k_2 = \left(1 - 1/F_2\right)\left(1 + \frac{1}{f_2 - 1}\right). \tag{8}$$

3. Results and Discussions

Averaging survival curves of bacterial cells *Escherichia coli* (strain B_{S-1}) after irradiation with γ-rays of ^{60}Co (1,25 MeV) before and after exposure to photoreactivable light [2,3,5], we have that the value of F_2 = 1,29. Using equations (7) and (8) we obtain that values of k_1= 0,71 and k_2 = 0,29. It means that the contribution of the ionizations to the lethal effect induced by γ-rays of ^{60}Co, is 71%, while the contribution of the excitations is 29%. Dividing the initial survival curve into two components caused by the ionizations (71%) and the excitations, i.e. mainly by UV light (29%), we find that for the dose of 100 Gy the value of cell survival for the UV-component makes up 18%. This survival for the action 254 nm UV-light [2] only corresponds to UV dose of 0.4 J/m^2. Thus, the irradiation of bacterial cells (UV hypersensitive strain B_{S-1}) with γ-rays of ^{60}Co (100 Gy) is simultaneously accompanied by cell exposure to UV-dose of 0.4 J/m^2. It is of importance to note that for the sake of simplification we compared the whole spectra of Čerenkov light with the equivalent fluence of the most effectively lethal and genetic wave-length of UV light (254 nm).

Experimental data regarding the dependence of the extent of photoreactivation of bacterial cells of *Escherichia coli* (strain B_{S-1}) upon the energy of ionizing radiation have been published [3]. Using this data as well as the model presented here, and the above described example of calculations of the UV dose based on the relative contributions of the ionizations and the excitation to the lethal effect of ionizing radiation, we calculated the dependencies on the energy of ionizing radiation the following parameters: the extent of photereactivation (F_2), the relative contribution of excitation to the lethal effect (k_2) and the dose of the equivalent UV light accompanied 100 Gy of ionizing radiation. The results presented in Table 1. One can see that all these parameters are increased with the increase in the energy of ionizing radiation.

Table 1. The dependences of the extent of photoreactivation (F_2), the contribution of excitations to the lethal effects on bacterial cells (k_2) and the dose of the equivalent UV light accompanied by 100 Gy of ionizing radiation

Energy, MeV	F_2	k_2	UV dose, J/m^2
0.04	1.02	0.03	0.04
0.15	1.03	0.04	0.05
0.20	1.07	0.08	0.11
0.67	1.17	0.19	0.24
1.25	1.29	0.29	0.40
25.0	1.49	0.43	0.56

4. Conclusion

Mathematical model for the estimation of the UV dose after irradiation with ionizing radiation was suggested and applied to calculation of the UV dose regarding the dependence on the energy of sparsely ionizing radiation. The main conclusion of this study can be formulated as follows. The value of the UV dose for the same dose of ionizing radiation (100 Gy) is considerably increased with an increase in the energy of ionizing radiation. It is worth noting that the excitations produced by the UV light accompanied by the action of ionizing radiation may be important for cells hypersensitive to UV light. Since the UV light is more uniformly distributed on the irradiated volume than the ionizations, it is not excluded the low dose of ionizing radiation including the natural background can trigger reparation processes by the accompanied UV light thereby increasing the radioresistance of biological objects to the subsequent irradiation with higher doses.

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