NONLINEAR RESPONSES OF GAMMA–RAY DOSIMETERS

Luo Daling (罗达玲), E.C.M. Yong* (杨健明) and Zhang Chunxiang (张纯祥)

*(Department of Physics, Zhongshan University, Guangzhou 510275; * City Polytechnic of Hong Kong)*

ABSTRACT

Either sublinear or supralinear responses of dosimeters to γ-ray can be described by a response function derived from statistical Poisson distribution. The characteristic parameters of the function determine linearity, sublinearity and supralinearity in their responses. The experimental data of gamma dose-responses of alanine ESR dosimeters, film dosimeters, LiF(Mg, Cu, P) and LiF(Mg, Ti) thermoluminescence dosimeters are used to test the response function.

Keywords Dosimeters, Nonlinear responses, γ-ray

1 INTRODUCTION

The linearity of dose-response is the most important characteristic of radiation dosimeters among other radiation properties, such as tissue equivalent, stability, energy response *etc*. However, the linear range of dose-response in any dosimeter is always limited. The nonlinearity presented in the dose-response is either sublinearity or supralinearity. In dosimetric applications, both supralinearity and sublinearity of dose responses can cause the problems of under or over estimation, respectively. The nonlinearity is due to the influence of various factors. For example, the nonlinearity in LiF thermoluminescence dosimeters depends on the composition and the amount of activators in the LiF crystal. A lot of experimental results[1–4] have been observed to show the supralinearity in LiF(Mg, Ti) and the sublinear dose-responses to γ-rays in LiF (Mg, Cu, P). In order to explain the supralinearity of LiF(Mg, Ti), various models[5,9] have been proposed, which can not be used to explain the sublinearity in LiF(Mg, Cu, P), so that new model has to be proposed[4]. Luo Daling *et al*[10] obtained sublinear dose-responses by analyzing three individual TL glow peaks in LiF(Mg, Cu, P) experiments and proposed a dose-response function derived from statistical Poisson distribution on the basis of randomness of quantized events produced by γ-rays interacting with the medium theoretically. It not only can describe sublinear responses in LiF(Mg, Cu, P) but also supralinear responses in LiF(Mg, Ti). In this paper we have generalized the application of the response function given in Ref.[10] to various gamma radiation desimeters. And it is supported by experimental results of

Manuscript received date: 1993-02-20; Revised manuscript received date: 1993-10-05

several radiation dosimeters.

2 A DOSE RESPONSE FUNCTION

γ-rays interact with a medium through secondary electrons imparting energy and further resulting in various quantized events, such as, ionizing and exciting atoms or molecules, producing free radicals *etc.* Then observable endpoint macroscopic effects, which may be physical, chemical or biological effects, are formed. Basically, the spatial distribution of secondary electrons is rather homogeneous in the uniform irradiated with γ-rays, and the quantized events generated from secondary electrons are stochastic. Let us assume that a dosimeter consists of a set of identical sensitive elements, which may be atoms, molecules, or collective acting macroscopic aggregates. The probability of a sensitive element acted on n times, and average number A for acting on per sensitive element by secondary electrons is given by the statistical Poisson distribution as,

$$P(n) = A^{n} e^{-A} / n! \tag{1}$$

The probability $P(n)$ depends on the amount of γ radiation energy imparted in the medium. In other words, it is a function of gamma radiation absorbed dose D. Theoretically, there is a characteristic dose D_o, for which the average number $A = 1$, *i.e.*, averagely, secondary electrons act one time on per sensitive element. Then, for any values of absorbed dose D, $A = D/D_o$. Therefore, Eq (1) can be written as,

$$P(n) = (D/D_o)^{n} \exp(-D/D_o)/n! \tag{2}$$

On the other hand, the macroscopic effects resulting from γ-rays depened on the probability $P(n)$. Therefore, the dose-response function can be derived from Eq. (2). If just one time of action of secondary electron on a sensitive element can result in a endpoint effect, then it is named one-hit response. The probability which is proportional to the response is given by the difference between total action probability (equal to 1) and the probability that $n = 0$, as,

$$P_1(D, D_o) = 1 - \exp(-D/D_o) \tag{3}$$

which is named one-hit response equation. If two times of action on a sensitive element can just result in a endpoint effect, then, it is named two-hit response. The probability of zero and that of one are no contribution to this response. Therefore, the probability related to two-hit response is equal to the difference between $P_1(D, D_o)$ given in Eq.(3) and the probability that $n = 1$, then

$$P_2(D, D_o) = 1 - (1 + D/D_o) \exp(-D/D_o) \tag{4}$$

which is named two-hit response equation. There are perhaps three, four, $\cdots$ i-hit response. These are called multi-hit responses which are represented as,

$$P_i(D, D_0) = 1 - \sum_{n=0}^{i-1} (D/D_0)^n \exp(-D/D_0)/n! \tag{5}$$

Here, the contribution to the dose-response from more than two-hit responses is ignored. The dose-response function can be represented by one-hit response overlaid with two-hit response, as,

$$F(D) = R(1-\exp(-D/D_0)) + (1-R)[1-(1+D/D_0)\exp(-D/D_0)] \tag{6}$$

where R is a fraction of one-hit response and termed one-hit factor. In order to describe how dose-response of γ-ray dosimeters depend on the two parameters D_0 and R, $\exp(-D/D_0)$ in Eq (6) is expanded to a series and ignored the terms in which power is higher than two. Eq.(6) can be rewritten as

$$F(D) = RD/D_0 + (1/2-R)(D/D_0)^2 \tag{7}$$

From Eq. (7), one can observe the following:

a. When R is not equal to zero and $D << D_0$, the response can be regarded as linear. When $R=0$, the response is not linear absolutely.

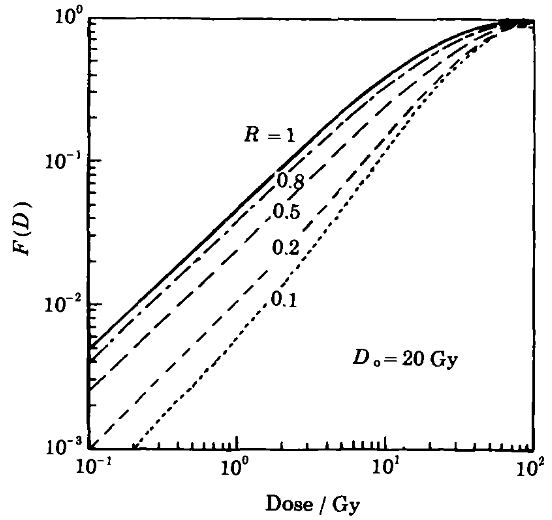

Fig.1 The dose–response curves with various values of one–hit factor R for given the value of characteristic dose D_0 in γ radiation dosimeters

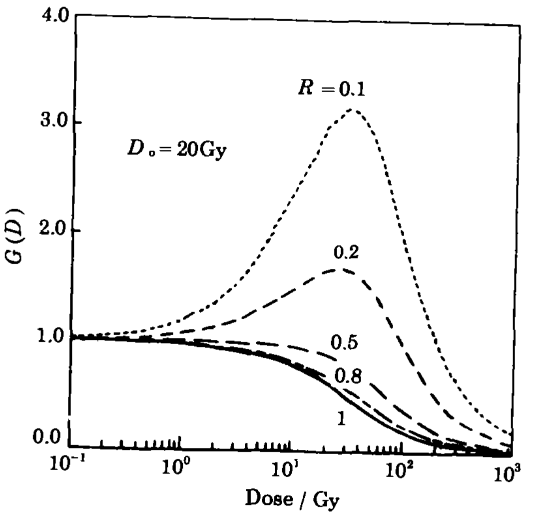

Fig.2 The dose–response curves with various values of one–hit factor R for given the value of characteristic dose D_0 in γ radiation dosimeters

$G(D)$ is the nonlinearity factor

b. When $1/2 < R < 1$, the response is linear as $D << D_0$. Then, it will become sublinear following an increase in dose D. Because the first term, expressing linear relation, has to add a negative value.

c. When $0 < R < 1/2$, first, the response is linear as $D << D_0$. Then, it will become supralinear following an increase in dose D. It is due to a positive valve added to a linear term in Eq.(7).

d. Given the value of D_0, as $R=1/2$, it implies that the component of one-hit response is equal to that of two-hit response. This is the widest linear region in the response.

e. Given the value $0<R<1$, as the value of D_0 becomes smaller, the linear region will get shorter.

Figs. 1 and 2 show that the nonlinearity of the dose-response depends on one-hit factor R in a given the value of D_0. The nonlinearity factor $G(D)$ is defined as,

$$G(D) = [F(D)/D]/F(D)_L/D_L] \tag{8}$$

where $F(D)_L$ is response at dose D_L which is within linear region of the response. Figs. 3 and 4 show dependence of the supralinearity and sublinearity on characteristic dose D_0 in a given the value of R.

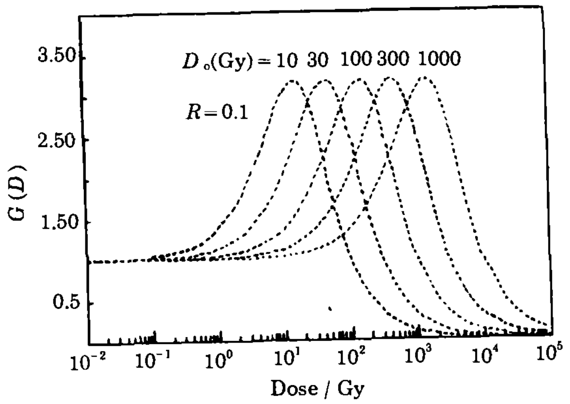

Fig.3 The dose—response curves with various values of characteristic dose D_0 for given the value of one—hit factor in the supralinear γ radiation dosimeters

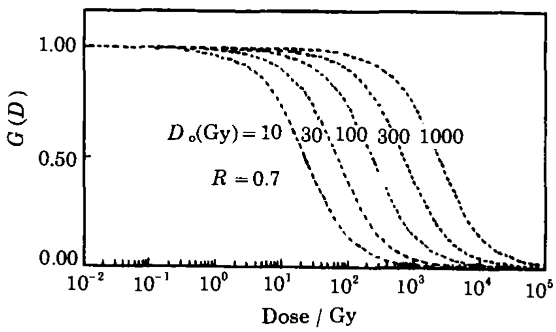

Fig.4 The dose—response curves with various values of characteristic dose D_0 for given the one—hit factor in the sublinear γ radiation dosimeters

3 RESULTS AND DISCUSSION

3.1 Sublinear responses of alanine ESR dosimeters

Luo Daling *et al*[11] made alanine dosimeters in the form of a pellet and measured their dose-response to γ-rays, in which the linear response has an intermediate dose range around 10^0—10^4Gy and saturation behavior dominates over 10^4Gy. The response is expressed by an increment in ESR signal measured in millimeter per unit mass (gram) of samples irradiated (f(mm · g^{-1})). In this paper, we use the response function given in Eq.(6) to fit the experimental data from Ref.[11]. The relative response $F(D)$ is given as,

$$F(D) = f(\mathrm{mm}\cdot \mathrm{g}^{-1})/f_0(\mathrm{mm}\cdot \mathrm{g}^{-1})_{max} \tag{9}$$

where f_0(mm · g^{-1}))$_{max}$ is the maximum increment in ESR signal per gram of samples.

The fitting results are shown in Fig.5. It is obtained that the characteristic dose D_o = 6.39×10^4Gy and one-hit factor R = 0.92 with $f_o(\mathrm{mm}\cdot \mathrm{g}^{-1})_{max} = 5.29\times 10^3$. In conclusion, the γ radiation dose response of alanine ESR dosimeter is sublinearity. However, it is not just one-hit response, but it involves a little component of two-hit response.

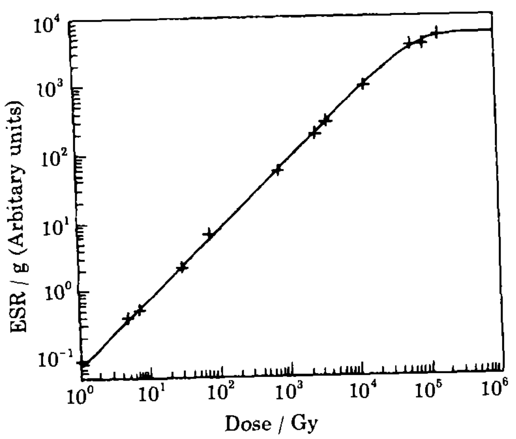

Fig.5 The dose-response of alanine ESR dosimeters to γ-rays

The calculated curves fits with the experimental data (points). (△ESR/g) expressed response is an increase in ESR signal per unit mass

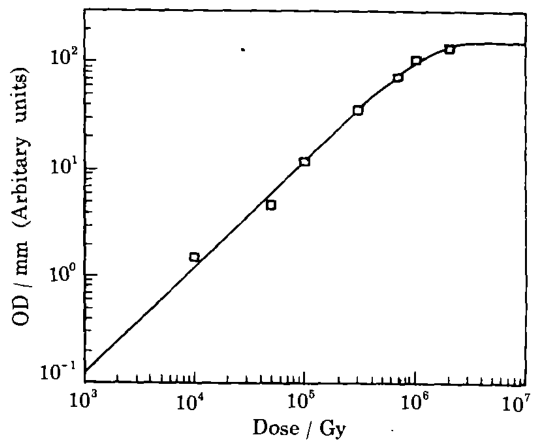

Fig.6 The dose-response of DPA/CB4 film dosimeters to γ-rays

The calculated curves fits with the experimental data (points). (△OD/mm) is an increase of optical density per unit film thickness

3.2 Supralinear responses of DPA/CBr4 film dosimeters

The DPA/CBr_4 film is a kind of photosensitive material. and sensitive to γ-rays and high energy electrons[12]. The response is expressed by an increment of optical density per unit film thickness, (△OD/mm). The dose responses to γ rays were measured in dose range from 10^4 to 10^6Gy, with wavelength of 460nm which is on the edge of absorption peak in our experiment. Here the dose response function given in Eq.(6) are used to fit the experimental data of the response curve from Ref.[12]. The relative response of the film dosimeter is given as,

$$F(D) = (\triangle \mathrm{OD/mm}) / (\triangle \mathrm{OD/mm})_{max} \tag{10}$$

where $(\triangle \mathrm{OD/mm})_{max}$ is the maximum increment in optical density per unit film thickness. The fitting results are shown in Fig.(6). It is obtained that one hit factor R = 0.456 and the characteristic dose $D_o = 6.0\times 10^5$Gy with $(\triangle \mathrm{OD/mm})_{max}$ = 157. Therefore, the dose response of DPA/CBr_4 film dosimeter is supralinearity.

3.3 Sublinear responses of LiF(Mg,Cu,P) and supralinear responses of LiF(Mg,Ti)

In order to study the nonlinearity of responses of LiF thermoluminescence dosimeters, LiF(Mg,Ti) and LiF(Mg,Cu,P) samples in powder were used simultaneously to carry out γ irradiation experiment in ^{60}Co facility. The TL glow curves of these samples were measured by a computerized TLD reader detailed in Ref.[10]. The glow curves have been analyzed by the method of curve fitting with Gaussion function to get areas of individual glow peaks. We regard the peak area per milligram weight of sample as the relative TL intensity and select fifth glow peak for LiF(Mg, Ti) and third glow peak for LiF(Mg, Cu, P) as the dosimetric peaks to obtain their dose-response curves. The experimental data are fitted by Eq.(6). It is assumed that $F(D) = (TL)/(TL)_{max}$. The results are shown in Fig.(7). The characteristic parameters have been gotten by fitting. For LiF(Mg, Ti), $D_o = 3.97\times 10^2$Gy and $R = 0.137$ with $(TL)_{max} = 1.51\times 10^5$. From the results, we can get the conclusion that LiF(Mg, Ti) is supralinear. For LiF(Mg, Cu, P), $D_o = 8.9\times 10^1$Gy and $R = 0.940$ with $(TL)_{max} = 1.35\times 10^5$. That shows the sublinearity of dose response to γ-rays in LiF(Mg, Cu, P). It is in agreement with the conclusion having been gotten from results of three individual TL glow peaks in LiF(Mg, Cu, P)[10].

3.4 Characteristic parameters of dose—responses

The characteristic parameters in the response function given in Eq.(6) can be used to describe the nonlinear response to γ rays in various dosimeters quantitatively. The one-hit factor R can be used to indicate whether there is a linear region in the dose-response, and that the responses are sublinear or supralinear and furthermore to determine degree of the nonlinearity. The characteristic dose D_o can be used to compare the range of the linear region in responses for the same value of R, and sensitivity of response to γ-rays for various dosimeters. The characteristic parameters of dose-responses for several dosimeters are listed in Table 1.

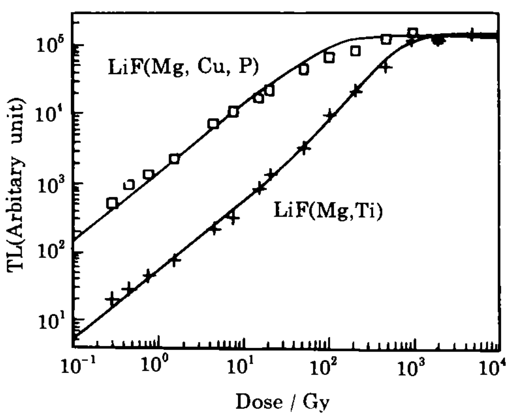

Fig.7 The dose—responses of both LiF (Mg, Ti) and LiF (Mg, Cu, P) TLD to γ—rays

The calculated curves fit with the experimental data (points). TL expresses relative thermoluminescence

In summary, we can regard the response function expression given in Eq.(6) as a fundamental equation to describe the dose-responses for various γ radiation dosimeters. That is based on the stochastic property of quantized events produced by γ rays interacting with the medium. Two characteristic parameters, D_o and R in this function can be used to indicate different characters of various responses. They are influenced by various factors, such as physical and chemical properties of dosimeters, experimental conditions and equipment *etc*, we have applied the function given in

Table 1

The characteristic parameters of dose—responses for several dosimeters

	LiF(Mg, Cu, P)	LiF (Mg, Ti)	Alanine / ESR	DPA / CBr_4 film
R	0.940	0.137	0.920	0.456
D_0/Gy	8.90×10^1	3.97×10^2	6.39×10^4	6.00×10^5

Eq.(6) to γ dosimetry in this paper. It can be predicted that this function also is suitable for X-rays, high energy electrons, and, perhaps, neutrons. However, whether Eq.(6) can be used in the case of energetic heavy ions must be studied theoretically and experimentally in the future.

REFERENCES

1 Montret-Brugerolle M. Distribution Spaitiale de L'Energie, Depose par des ions Energetigues dans les Milieux Condenses Etude Par Thermoluminescence. Audiere [France]: Universite de clermont-Ferrand II, 1980

2 Zimmerean J. J Phys, C: Sol St Phys, 1971; 4:3277

3 Wu Dake, Shun Fuyin, Dai Hongchen. Chinese J Radiat Med Prot, 1981; 5:13

4 Cai Gangang. J Phys, D: Appl Phys, 1989; 22:812

5 Larsson L, Katz R. Nucl Instr Meth, 1976; 138:631

6 Kos H J, Nink R. Nucl Instr Meth, 1980; 175:24

7 Lakshmanan A R, Chanda B, Bhatt R C. J Phys, D:Appl Phys, 1982; 15:1501

8 Horowitz Y S. Radiat Prot Dosim, 1990; 83:33(1—4)

9 Mckeever S W S. Radiat Prot Dosim, 1990; 83:33(1—4)

10 Luo Daling, Huang Naiming, Zhang Chunxiang. Nucl Tech (in Chinese), 1992; 15:51

11 Luo Daling, Li Mianfeng, Zhang Chunxiang *et al.* Acta Scientiarum Naturalium Universitis Sunyatceni (in Chinese), 1988; (4):50

12 Luo Daling, Li Mianfeng, Zhang Chunxiang *et al.* Acta Scientiarum Naturalium Universitis Sunyatseni (in Chinese), 1987; (3):70