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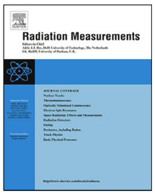

The microdosimetric one-hit detector model to calculate the energy response of radiographic films

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HIGHLIGHTS

- The microdosimetric one-hit detector model is used to calculate the energy response.
- The cubical AgBr grains of 1 μm in dimensions are selected as the sensitive targets.
- The model predicts the energy response of radiographic films within 20% difference.

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ABSTRACT

In the present work, the microdosimetric one-hit detector model is evaluated by calculating the relative energy response of radiographic films. A small sample of typical radiographic films including the covering paper and the polyester base coated on by one emulsion layer is simulated by Geant4 toolkit. Silver bromide grains with the same cubical shape and dimensions of 1 μm randomly positioned in the emulsion are considered as the targets of the model. The relative energy response for eleven photon energies between 20 keV and 1.25 MeV is determined using the microdosimetric distributions of single energy deposition events in the grains. Calculations are performed for a few weight fractions of the silver bromide in the emulsion. The results show that for the weight fraction 13.3% of the silver bromide in the emulsion, calculated values of the relative energy response are in agreement with the experimental data within 20% difference. It can be concluded that the microdosimetric one-hit detector model satisfactorily predicts the energy response of radiographic films.

1. Introduction

Hit theory of radiation action aims to describe the response of an object under study such as living cell, detector, etc., to the ionizing radiation concentrating on the energy deposition events or *hits* occurred in the object. This theory generally considers the multi-hit, multi-target schemes (Katz, 1978; Roesch, 1968; Zaider, 1990) which assume that the object contains a large number of sensitive sites or *targets* having a certain probability to receive hits and generate the desired effect (or response) (Katz, 1978; Roesch, 1968).

The *one-hit* model represents a system with a single-hit, single-target response (Zaider, 1990). It means that a one-hit detector contains only one type of targets and passage of a single charged particle through a target is sufficient to produce an effect. Consequently, for low absorbed doses a one-hit detector has a linear response which saturates exponentially (Katz, 1978). The microdosimetric description of these detectors is presented by Zaider (1990). He has shown that the one-hit detector response can be expressed by the distributions of single-hits occurred in the targets. The response of some solid state detectors, e.g. TLDs has been studied by this model (Olko, 2002, 2006).

Radiographic films are known as the personal dosimeters for a long time (Jones and Marshall, 1964). They have been used for various applications such as obtaining the relative dose distributions of clinical electron beams in phantoms (Van Battum and Huizenga, 1990), dosimetry of high energy photon and electron beams in the intensity modulated radiotherapy (IMRT) systems

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(Ahmad et al., 2006; Martens et al., 2002; Palm et al., 2004), imaging requirements (Bontempi et al., 2012), etc. Track structure investigations performed on the radiographic emulsions (Katz, 1978; Katz and Kobetich, 1969) which explore the structure of particle tracks in the emulsion and study distribution of the affected silver bromide grains, show a linear response approaching an exponential saturation for low doses of uniform exposures. In addition, in our previous publication (Moslehi et al., 2010), the photon energy response of radiographic films has been calculated by proposing a model based on counting the number of affected silver halide grains experiencing only one-hit of the secondary electrons.

Various applications and one-hit behavior of the radiographic films are motivating in the present work to examine the microdosimetric one-hit detector model with calculating the relative energy response of these films. This study includes Monte Carlo simulations to calculate the required microdosimetric distributions.

2. The microdosimetric one-hit detector model

Microdosimetry deals with the distribution of energy deposition events occurred in the microscopic volumes (Rossi and Zaider, 1996). For this purpose *stochastic* quantities are defined which are subject to random fluctuation (ICRU, 1983). By definition, an energy deposition event is the production of statistically correlated points where energy is transferred, for instance track of a charged particle and/or its secondary electrons. The quotient of the energy imparted corresponding to an event, ε, by the mass of microscopic volume, m, is called the *specific energy*, as:

$$z = \frac{\varepsilon}{m} \tag{1}$$

that is in the unit of Gray. The probability density of z is $f(z) = dF(z)/dz$ in which $F(z)$ is the distribution function of z. Specific energy may be due to one or more events. For the single-event distribution, the probability density is:

$$f_1(z) = \frac{dF_1(z)}{dz} \tag{2}$$

which is called the single-event distribution of z.

According to the one-hit detector model, the response of a one-hit detector to the ionizing radiations is characterized by two assumptions: (a) the detector contains a large number of one-typed targets and (b) the hits contribute equally and independently to generate the response (Zaider, 1990). Once a hit occurs in a target, it is potentially able to provide the response and more hits will not produce additional effect.

By definition, the probability of survival (experiencing no hit) of each target after irradiation of the detector with absorbed dose D is purely exponential:

$$S(D) = \exp(-\alpha D) \tag{3}$$

in which α is a saturation parameter. If geometry and size of the targets are known, the microdosimetric one-hit detector model expresses the survival function in terms of the statistical distribution of hits in the target (Zaider, 1990):

$$S(D) = \int_0^\infty e^{-\alpha z} f(z;D)dz \tag{4}$$

where z is the specific energy and α is the probability that a unit increment of the specific energy results in a hit. Also, $f(z;D)$ is the distribution of z after irradiation with absorbed dose D (ICRU, 1983) which is defined as follows:

$$f(z;D) = \sum_{k=0}^{\infty} e^{-n}\frac{n^k}{k!} f_k(z) \tag{5}$$

with n as the mean number of events and $f_k(z)$ as the distribution of z corresponding to exactly k events:

$$f_k(z) = \int_0^z f_1(z') f_{k-1}(z-z')dz' \tag{6}$$

Considering $n = D/\overline{z_F}$ and substituting equations (5) and (6) in equation (4), $f(z;D)$ can be written in terms of single-event distribution of z, i.e. $f_1(z)$ (Zaider, 1990; Rossi and Zaider, 1996). Therefore, the survival function will change to:

$$S(D) = exp\left[-\frac{D}{\overline{z_F}}\int_0^\infty \left(1-e^{-\alpha z}\right) f_1(z)dz\right] \tag{7}$$

where $\overline{z_F} = \int_0^\infty z f_1(z)dz$ is the first moment of $f_1(z)$ and is called the frequency-mean specific energy.

The probability of receiving a hit (i.e. *detector dose response*) is defined as the inverse probability of survival:

$$r(D) = 1 - exp\left[-\frac{D}{\overline{z_F}}\int_0^\infty \left(1-e^{-\alpha z}\right) f_1(z)dz\right] \tag{8}$$

This is the basic expression of the microdosimetric one-hit detector model. For low absorbed doses, $D << \overline{z_F}$ and equation (8) can be written as the following form:

$$r(D) \cong \frac{D}{\overline{z_F}}\int_0^\infty \left(1-e^{-\alpha z}\right) f_1(z)dz \tag{9}$$

The term $(1-e^{-\alpha z})$ is the probability of effect after occurrence a hit possessing the specific energy of z. Subsequently, the expression under the integral gives the probability of hit per event. Since the average number of events is $D/\overline{z_F}$, equation (9) gives the number of those events (effective events) causing the effect after irradiation with dose D (Olko, 2002). From the fact that the events are supposed to be Poisson-distributed, the detector response gives the fraction of targets (affected targets) in which effective events occurred (Zaider, 1990). In general the saturation parameter and the target size are free parameters of the model which can be adjusted leading to the agreement with the experimental data. The both parameters influence on the hits distribution in the targets.

3. The energy response of radiographic films

The sensitive volume of a radiographic film is an emulsion layer which contains a large number of silver bromide grains suspended in gelatin. After exposing to ionizing radiation, *latent image* is formed in some grains due to radiolysis process occurring in the silver bromide crystals (Herz and James, 1977). During the exposure, latent images grow and change to silver nucleation in the affected grains. After irradiation, by using a chemical etching process and resolving the gelatin, the nucleation surrounds the grains. Finally, an optical density forms on the film as the overall effect of the radiation.

By definition, the photon *energy response* of a radiographic film