Characteristics of sensitometric curves of radiographic films

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A new type of radiographic film, EDR (extended dose range) film, has been recently become available for film dosimetry. It is particularly attractive for composite isodose verification of intensity modulated radiation therapy because of its low sensitivity relative to the more common Kodak XV film. For XV film, the relationship between optical density and dose, commonly known as the sensitometric curve, depends linearly on the dose at low densities. Unlike XV film, the sensitometric curve of EDR film irradiated by megavoltage x rays is not linearly dependent on the dose at low densities. In this work, to understand the mechanisms governing the shape of the sensitometric curves, EDR film was studied with kilovoltage x rays, ^{60}Co γ rays, megavoltage x rays, and electron beams. As a comparison, XV film was also studied with the same beams mentioned above. The model originally developed by Silberstein [J. Opt. Soc. Am. **35**, 93–107, 1945)] is used to fit experimental data. It is found that the single hit model can be used to predict the sensitometric curve for XV films irradiated by all beams used in this work and for EDR films exposed to kilovoltage x rays. For EDR film irradiated by ^{60}Co γ rays, megavoltage x rays, and electron beams, the double hit model is used to fit the sensitometric curves. For doses less than 100 cGy, a systematic difference between measured densities and that predicted by the double hit model is observed. Possible causes of the observed differences are discussed. The results of this work provide a theoretical explanation of the sensitometric behavior of EDR film. [DOI: 10.1118/1.1568979]

Key words: radiographic film, EDR, XV, optical density

I. INTRODUCTION

Film dosimetry provides a convenient method to acquire high spatial resolution two-dimensional dose distributions.[1] Recently, there has been a renewed interest in film dosimetry in response to the need for verifying dose distributions resulting from intensity modulated therapy (IMRT).[2–4] However, there are several factors affecting the sensitivity of radiographic film [i.e., the relationship between optical density (OD) and delivered dose]. These factors include (a) photon beam energy, (b) film plane orientation with respect to beam direction, (c) emulsion difference amongst films of different batches, (d) processing conditions, and (e) type of densitometer.[5] The energy dependence of sensitometric curves is shown to be minimal if moderate field sizes at moderate depths are considered for Kodak XV films,[5] and extended dose range (EDR) films.[6] For XV films, it is reported that the dependence on beam orientation can also be minimized if the incident beam is angled by 2° with respect to the plane of the film.[7] The factors (c)–(e) can be minimized or eliminated entirely with appropriate calibration (e.g., specific to the film batch, processing conditions, and densitometer).[5] Therefore, the sensitometric curve for each experiment should be obtained. Determining the sensitometric curve for each experiment is a time-consuming process. It usually requires one to irradiate multiple films from the same batch with doses covering the range of interest and to process these films together with films irradiated for measuring the dose distributions. In addition, all films should be analyzed together with the same densitometer. If the characteristic of the sensitometric curve can be predicted based on physical principles, it might facilitate determination of the sensitometric curve.

XV film is the most common radiographic film used in radiation therapy clinics, including for verification of dose distributions of IMRT.[2–4] The sensitometric curve for XV film can be described by the single hit, single target theory,[1]

$$\mathrm{OD}=\mathrm{OD}_{\max}(1-e^{-\alpha D}), \tag{1}$$

where OD is the optical density, $\mathrm{OD}_{\max}$ is the maximum optical density (the optical density corresponds to the infinite dose), α is a measure of the film sensitivity (in units of reciprocal dose), and D is the dose. The main limitation of XV film for IMRT applications is its limited dose range. Recently, EDR film from Kodak has become available. The EDR film is a very slow speed, fine grain film. It uses very fine monodispersed grain cubic microcrystals. Double emulsion layers are coated on a 0.18 mm Estar base, which allows processing in a conventional rapid-process film processor.[8] In a recent study, it was found that the single hit model, Eq. (1), did not fit the sensitometric curves of EDR film irradiated by megavoltage x rays.[6] In this work, to understand the mechanisms governing the shape of the sensitometric curves, we have studied sensitometric curves of EDR film irradiated by kilovoltage x rays, Co-60 γ ray, megavoltage x rays, and electron beams. Sensitometric curves for XV film irradiated by the same ionizing radiation beams were also obtained for comparison.

II. MATERIALS AND METHODS

A. Theory of the sensitometric curves

The emulsion of radiographic film consists of microscopic grains of silver halide, dispersed in a gelatin layer on a film. Incident charged particles such as secondary electrons from x-ray interactions in emulsion, which consist of grains, cellulose coating, and base, and in phantom produce ion pairs in or near the grains, and convert Ag^{+} ions to Ag atoms. A few such Ag atoms on a grain constitute a latent image, which renders the grain developable by a chemical process.[9] For x-ray photons, the formation of latent images in the grains is not caused directly by photons absorbed but indirectly by the electrons released.[10]

In this section, the model of sensitometric curve originally developed by Silberstein[11] is reviewed. The model is based on a general theory which assumes that each grain requires n hits ($n \geqslant 1$) of quanta or charged particles to render it developable. Here, a hit is defined as an effective radiation interaction event leading to the formation of neutralized silver atoms that constitute a latent image.[12] Let y be the average number of quanta or charged particles received by grains per unit area and N be the total number of grains per unit area of the emulsion. Assuming quanta or charged particles follow Poisson statistics, then the number of grains, K, per unit area developable, receiving at least n hits is[11]

$$K(y) = N \sum_{i=n}^{\infty} \frac{e^{-\epsilon\sigma y}(\epsilon\sigma y)^i}{i!}, \tag{2}$$

where ϵ represents the "intrinsic sensitivity" or the efficiency factor that an absorbed quantum or charged particle contributes to latent-image formation,[11,13] and σ is the effective area of each grain. Using the following identity for Poisson statistics,[14]

$$\sum_{i=0}^{\infty} \frac{e^{-x}x^i}{i!} = \sum_{i=0}^{n-1} \frac{e^{-x}x^i}{i!} + \sum_{i=n}^{\infty} \frac{e^{-x}x^i}{i!} = 1, \tag{3}$$

Eq. (2) becomes

$$K(y) = N\left(1 - \sum_{i=0}^{n-1} \frac{e^{-\epsilon\sigma y}(\epsilon\sigma y)^i}{i!}\right). \tag{4}$$

Assume that the least number of quanta or charged particles required for developability has the same value n for all grains. The average number of quanta or charged particles received per unit area, y, is proportional to dose, i.e., $y \propto D$, or $\epsilon\sigma y = \alpha D$, where α is a measure of the film sensitivity as introduced in Eq. (1), and it is proportional to the effective area of each grain and the efficiency factor ϵ of the grain. It is well known that the corresponding optical density is given by[15] $\mathrm{OD} = M\sigma K$, where $M = \log e = 0.4343$. For $y = \infty$, and $K = N$, the maximum optical density $\mathrm{OD}_{\max} = M\sigma N$. Therefore Eq. (4) can be expressed in terms of OD and dose, D, assuming all grains have the same sensitivity, α,[11,15]

$$\mathrm{OD}(D) = \mathrm{OD}_{\max}\left(1 - \sum_{i=0}^{n-1} \frac{e^{-\alpha D}(\alpha D)^i}{i!}\right). \tag{5}$$

When only the single hit is required to render grains developable, $n = 1$, Eq. (5) is reduced to Eq. (1). When there are only double hits, $n = 2$, Eq. (5) becomes

$$\mathrm{OD}(D) = \mathrm{OD}_{\max}[1 - e^{-\alpha D}(1 + \alpha D)]. \tag{6}$$

When the dose is low such that $\alpha D \ll 1$, Eq. (1) can be approximated as $\mathrm{OD}(D) = AD$, where $A = \mathrm{OD}_{\max}\alpha$, and Eq. (2) is reduced to $\mathrm{OD}(D) = BD^2$, where $B = \mathrm{OD}_{\max}\alpha^2/2$. Therefore, for low doses and low optical densities, the single hit model predicts a linear dependence on OD on dose, while the double hit model has a quadratic dependence on dose.

B. Measurements

The perpendicular geometry, i.e., the film oriented perpendicularly to the radiation beam, was used for all measurements. The parallel geometry was not chosen because there was a tendency of over-response due to the air-gap introduced by the film.[7] The objective of this work is to understand the characteristics of the sensitometric curves of EDR2 film and the perpendicular geometry serves the objective better.

Radiation beams used in this work included kilovoltage x-ray beams (Stabilipan, Siemens, Concord, CA) with nominal energies of 100 kVp (HVL 3 mm Al) and 200 kVp (HVL 1 mm Cu), a Co-60 beam (Eldorado 6, AECL Medical, Kanata, Canada), and high energy x-ray beams of 6 and 23 MV and electron beams of 6 and 21 MeV from a Primus accelerator (Siemens, Concord, CA). The output of each beam was calibrated according to AAPM TG-61[16] for kilovoltage x-ray beams and AAPM TG-51[17] for high energy photon and electron beams. All measurements were performed with the film embedded in a solid water phantom (Gammex RMI, Middleton, WI) at the nominal depth of maximum dose for each beam. The source to surface distances (SSDs) were 36 cm for kilovoltage x rays, and 100 cm for high-energy electron beams. For high energy photon beams, an isocentric setup was used. The source to detector distances were 80 cm for ^{60}Co and 100 cm for the x-ray beams. "Ready-pack" films in paper envelopes were used in this work. The field size used was either 5 cm diameter for circular fields (kilovoltage and electron beams) or 5×5 cm^2 for square fields (Co-60 and megavoltage x-ray beams) defined at the abovementioned SSDs. For EDR film irradiated with high-energy x rays and electrons, the dose range studied was approxi-

TABLE I. Physical properties of EDR and XV films.[a]

	EDR	XV
Grain crystal	AgBr	AgBr and AgI
Total silver density (g/m^2) (both sides of the film)	2.303	4.237
Effective dimension (μm)	0.2[b]	0.4[c]
Grain size distribution	Monodisperse	Variation in size and shape
Base thickness (μm)	0.18	0.18
Cellulose coating thickness (g/m^2) (per side)	5	3
Double sided	Yes	Yes

[a]Reference 18.
[b]Side of cubic.
[c]Effective edge length.

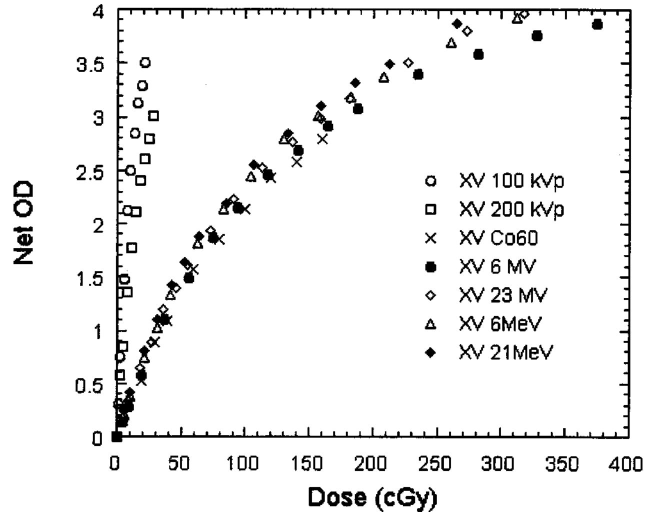

FIG. 2. Sensitometric curves of XV films irradiated by beams used in this work.

mately from 20 to 1000 cGy. For the ^{60}Co beam, the maximum dose used was limited approximately to 400 cGy because the dose rate of the beam available was low, approximately 19 cGy/min at 80 cm source to the detector distance.

The same measurements were also performed for Kodak X-OMAT V (XV) film with doses less than 400 cGy. All films from each experiment were processed at the same time after the processor (ALPHATEK, AX700LE) was warmed up with several scrap films. The OD was read by a manual densitometer (Macbeth, model TD932, Newburgh, NY) with an aperture of 2 mm. The densitometer is specified for the optical density range from 0.0 to 4.0. The densitometer was calibrated with a certified, step-wedge film with known ODs from Kodak. ODs read by the densitometer were within 0.01 OD of the values of the certificate for the range of ODs from 0.05 to 2.98.

C. Properties of radiographic films

Some of the physical properties of EDR and XV films are listed in Table I. EDR film uses very fine monodispersed, pure AgBr grain cubic microcrystals, with an effective dimension of 0.2 μm.[18] Grains for XV film are mixed AgBr and AgI crystals. The silver halide crystals of XV film are composed of different sizes and shapes, with the largest more than 10 times larger than the smallest.[19] The effective edge length of silver halide crystals of XV film is approximately 0.4 μm. The volume of an EDR grain is approximately 1/8 of the volume of an XV grain.[18]

D. Data analysis

Equations (1) and (6) were used to fit the measured sensitometric curves using a nonlinear least-squares method, the Marquardt method,[20] assuming proportional noises. For XV film in all beams and EDR film in kilovoltage beams, the single hit model, Eq. (1) was used. For EDR film in high energy photon and electron beams, the double hit model, Eq. (6) was used.

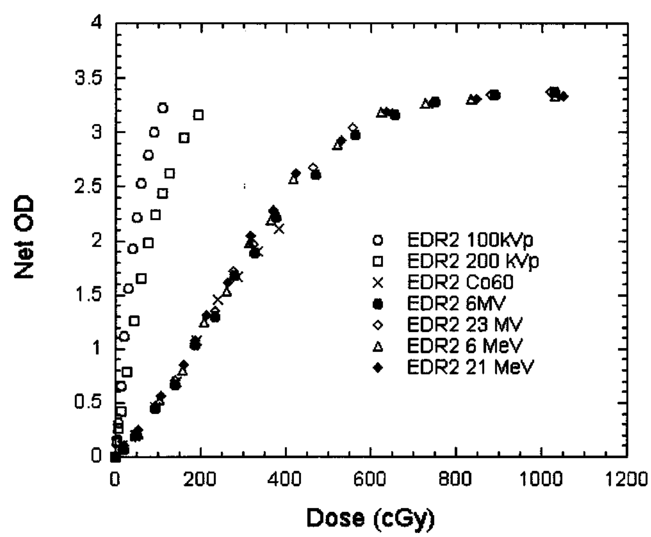

FIG. 1. Sensitometric curves of EDR films irradiated by beams used in this work.

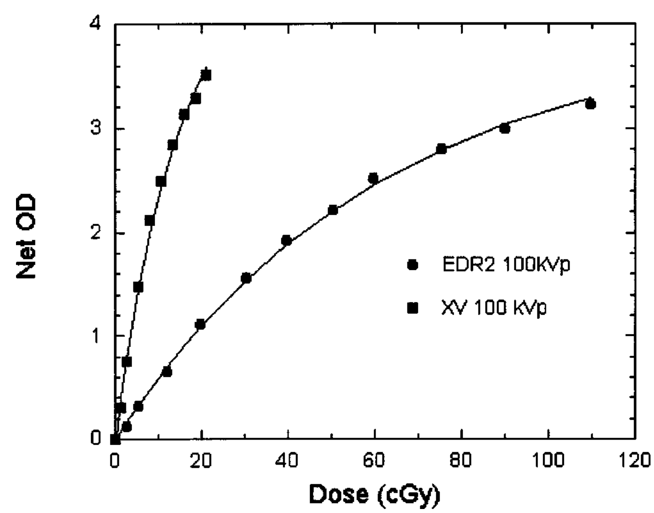

FIG. 3. Sensitometric curves of EDR and XV films irradiated by 100 kVp x rays. Solid lines are calculated by the single hit model [Eq. (1)].

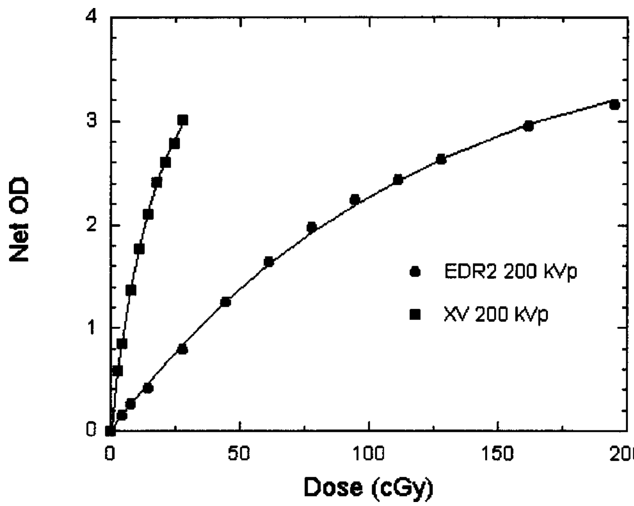

FIG. 4. Same as Fig. 3, for films irradiated by 200 kVp x rays.

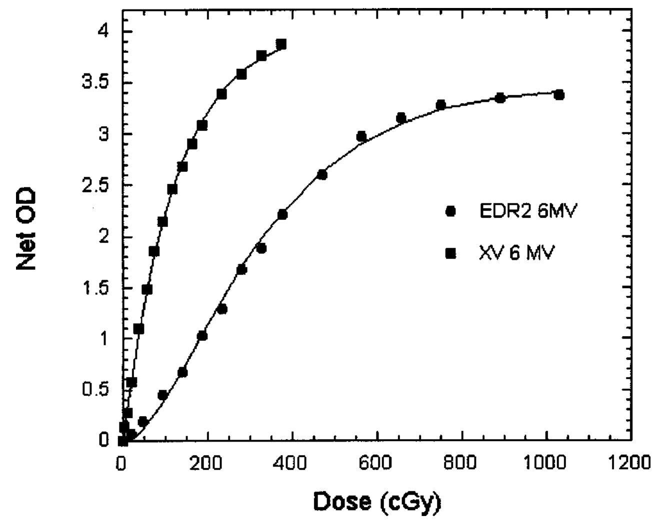

FIG. 6. Same as Fig. 5, for films irradiated by 6 MV x rays.

III. RESULTS AND DISCUSSION

Shown in Figs. 1 and 2 are sensitometric curves for EDR and XV films, respectively, for all the beams studied in this work. It is obvious from Figs. 1 and 2 that for both types of film, the film exposed to the lower kilovoltage x ray is more sensitive and that for the same beam quality, EDR film is less sensitive than XV film for all the beams. On the other hand, the film responses are nearly the same for all the megavoltage beams, although the XV film displays somewhat larger differences among the megavoltage beams. It should be pointed out that some of the differences in the film response could be attributed to different processor conditions, because each experiment was carried out at different times. To understand the characteristics of sensitometric curves of both types of film, we will carefully exam the quality of fit each set of experimental data to the single or double hit model in the following paragraphs.

Shown in Figs. 3 and 4 are sensitometric curves for EDR and XV films irradiated by kilovoltage x rays of 100 and 200 kVp, respectively. Sensitometric curves for both films at both kilovoltage energies have the same characteristics that can be described by the single hit model, Eq. (1) (solid lines in Figs. 3 and 4). Sensitometric curves for EDR and XV films irradiated by ^{60}Co γ ray, 6 and 23 MV x rays, and 6 and 21 MeV electron beams are plotted in Figs. 5–9, respectively. While the solid lines for XV film in Figs. 5–9 are results fitted by Eq. (1) for the single hit model, the solid lines for EDR films are results fitted by Eq. (6) for the double hit model. As pointed out earlier, both EDR and XV films are nearly independent of the beam quality of megavoltage beams. In fact, α values for all megavoltage beams are nearly constant, as shown in Tables II and III. The most interesting result is that the sensitometric curves of EDR film changes characteristics from single hit in kilovoltage beams to double hit in the megavoltage beams. While it provides reasonably good overall fits to the data of EDR film in megavoltage beams, the double hit model predicts significantly lower values of opti-

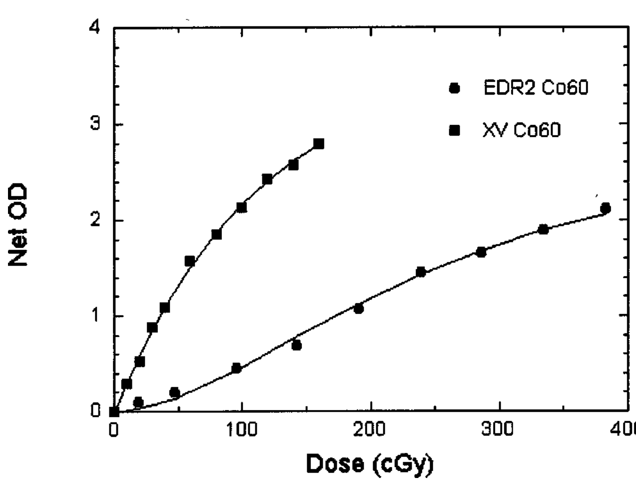

FIG. 5. Sensitometric curves of EDR and XV films irradiated by ^{60}Co γ rays. The solid line for EDR film is fitted result of the double hit model [Eq. (6)]; the solid line for XV film is calculated by the single hit model [Eq. (1)].

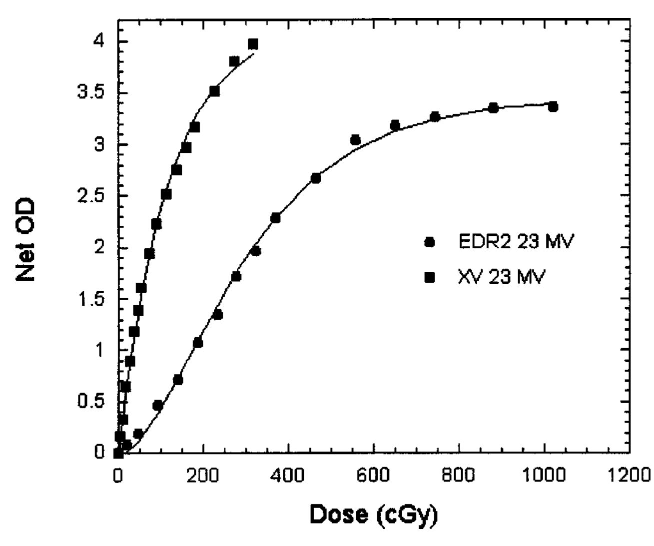

FIG. 7. Same as Fig. 5, for films irradiated by 23 MV x rays.

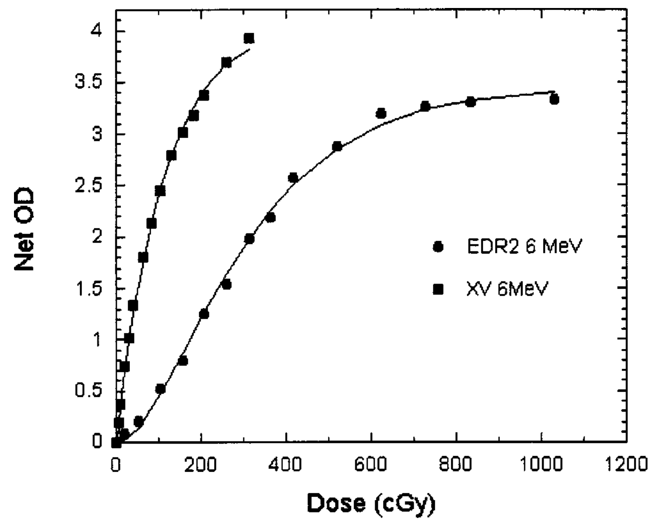

FIG. 8. Same as Fig. 5, for films irradiated by 6 MeV electrons.

cal density than the measured values for doses less than 100 cGy (more discussion on this point later).

For XV film, the single hit model can fit all sensitometric data studied in this work from kilovoltage x rays to megavoltage x rays and electrons. On the other hand, for EDR film, the single hit model can only fit the data obtained with the kilovoltage x rays, but not appropriate for ^{60}Co γ rays, and megavoltage x rays and electrons. In general, the response of a radiographic film to x rays or electrons depends on the number of and energy of the quanta or charged particles absorbed per unit area of an emulsion, and on the efficiency of the conversion of the absorbed radiation energy into developable silver halide.[10] As pointed out earlier, the radiographic effect of x rays on film is not caused directly by x-ray photons but indirectly by secondary electrons released through the interaction processes.[10,21] Thus the response of the radiographic film to x ray and electron obeys the same laws governed by the rate of energy transfer of these electrons to the grains [i.e., linear energy transfer (LET)].[10,21]

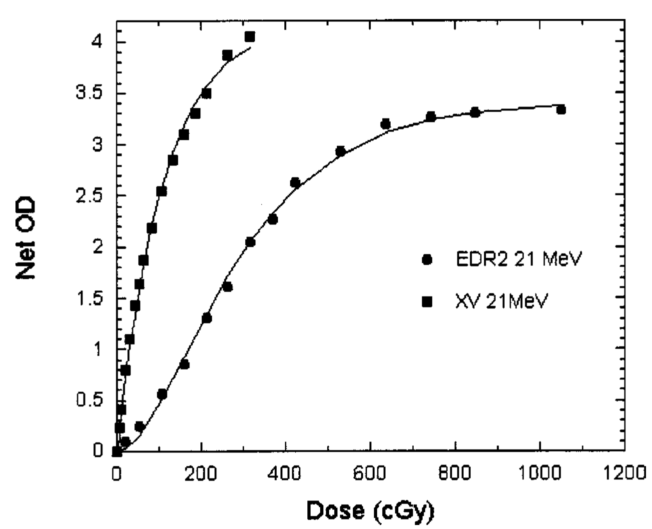

FIG. 9. Same as Fig. 5, for films irradiated by 21 MeV electrons.

TABLE II. Fitting parameters for XV film—the single hit model, Eq. (1).

Beam quality	OD_{max}	α (cGy^{-1})
X-ray 100 kVp	4.65±0.38	0.070±0.009
X-ray 200 kVp	3.70±0.05	0.059±0.001
γ-ray Co-60	3.67±0.14	0.0089±0.0005
X-ray 6 MV	4.02±0.03	0.0080±0.0001
X-ray 23 MV	4.14±0.07	0.0085±0.0003
Electron 6 MeV	4.07±0.06	0.0090±0.0003
Electron 21 MeV	4.18±0.07	0.0090±0.0003

For silver halide grains, as the radiation beam quality varies from kilovoltage to megavoltage x rays, there are two important physical parameters that change significantly: (1) the mass energy transfer coefficient of the photons and (2) LET coefficient of the secondary electrons. The mass energy transfer coefficient of silver bromide decreases rapidly with increasing photon energy from keV to MeV, reaches the minimum near 3 MeV, and then slowly increases for energies greater than 3 MeV.[22] This explains why both films are much more sensitive to kilovoltage x rays than to megavoltage x rays. Similarly, the LET decreases first rapidly with increasing energy of electrons, then the curve flattens and reaches a minimum energy loss.[10,22] For silver bromide, the minimum energy loss occurs between 1 and 2 MeV. In the energy range between 1 and 10 MeV, the LET is nearly constant, only increasing slightly with the energy of electrons.[22] This discussion explains why the film sensitivity, measured by α values, is nearly independent of the beam quality of megavoltage beams, as shown in Tables II and III.

For all beams studied in this work, the grains on XV film are sensitive enough to be developable by a single effective x-ray photon or electron. For kilovoltage photons, the physical properties, including the grain size and the efficiency factor, of EDR film still allow it to have the single hit behavior because of the larger LET of the electrons produced by the low energy x rays. For higher energy beams, the electrons produced by absorption of high energy photons or direct electrons have a very small LET at the beginning of their paths. Thus, it is possible that such an electron, in traversing a grain, could transfer insufficient energy to render the grain developable. Whether or not this occurred would depend on the size, the sensitivity of the individual grains, and perhaps upon the development.[21] For EDR film in megavoltage beams, the double hit is the dominant process.

TABLE III. Fitting parameters for EDR film.

	Beam quality	OD_{max}	α (cGy^{-1})
Single hit model Eq. (1)	X-ray 100 kVp	3.96±0.15	0.016±0.001
	X-ray 200 kVp	3.97±0.12	0.0080±0.0004
Double hit model Eq. (6)	γ-ray Co-60	2.59±0.32	0.0077±0.0010
	X-ray 6 MV	3.46±0.10	0.00587±0.00024
	X-ray 23 MV	3.44±0.09	0.00616±0.00024
	Electron 6 MeV	3.44±0.09	0.00617±0.00024
	Electron 21 MeV	3.40±0.10	0.00640±0.00029

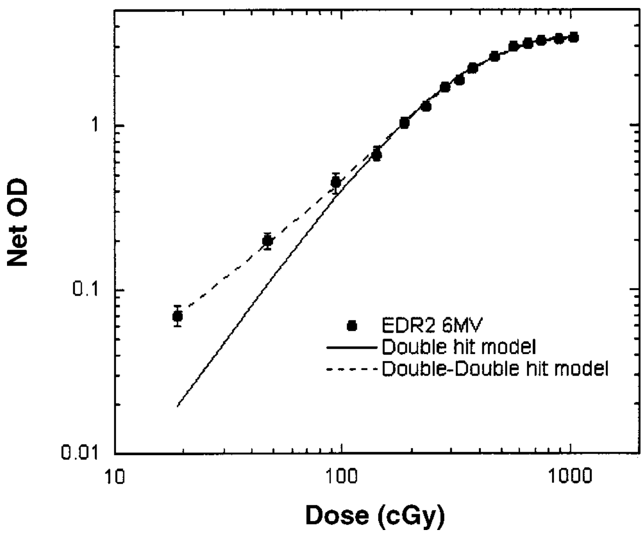

FIG. 10. Sensitometric curves of EDR irradiated by 6 MV x rays plotted on log–log scale. The solid line is fitted result of the double hit model [Eq. (6)] and the dashed line is fitted result of the double-double hit model [Eq. (7)]. Error bars represents errors with 95% confidence level based on the student t-distribution.

As pointed out earlier, significant differences are observed between the double hit model and measured optical densities of EDR films for all megavoltage beams for doses less than 100 cGy. To illustrate this point, Fig. 10 is a log–log plot of data displayed in Fig. 6 for EDR film irradiated by the 6 MV x-ray beam. Error bars represent errors of the measured data with 95% confidence level based on the student t-distribution. Figure 10 clearly demonstrates the failure of the double hit model at the low dose and low density region. This failure could be attributed to variability of the efficiency factor ϵ within observationally distinct grain classes.[13] Silberstein demonstrated that when the simple double hit model failed to fit the experimental data, a superposition of two terms of the double hit model could often lead to better results.[11] Following this approach, Eq. (6) can be expanded to have two double hit terms,

$$\mathrm{OD}=\mathrm{OD}_{1,\max}[1-e^{-\alpha_1 D}(1+\alpha_1 D)] + \mathrm{OD}_{2,\max}[1-e^{-\alpha_2 D}(1+\alpha_2 D)]. \tag{7}$$

The dashed line in Fig. 10 is calculated by Eq. (7) with the fitting parameters listed in Table IV. The maximum, mean, and minimum relative difference between the measured and the calculated, by Eq. (7), optical densities shown in Fig. 10 are 7.2%, 2.5%, and 0.4%, respectively. As a comparison, the maximum, mean, and minimum relative difference between the measured and the calculated, by Eq. (6), optical densities shown in Fig. 10 are 72%, 10.7%, and 0.3%, respectively. This demonstrates that Eq. (7) indeed provides better fit for EDR films irradiated with megavoltage beams. Also included in Table IV are the fitting parameters using Eq. (7) for EDR film irradiated by other megavoltage beams. It is obvious that these parameters are approximately the same within experimental uncertainties for each megavoltage beam.

Equation (7) essentially assumes that there are two group grains with two different values of α.[11,23] From the parameters listed in Table IV, the second double hit term only accounts for approximately 3% of the maximum optical density, but the film sensitivity, α, is about a factor of 16 larger than the first term. This is not unreasonable when compared with previously published values ranging from a factor of 4 to 32 for different films.[11] Since the EDR film has a nearly monodispersed distribution of grain size, it would be only possible that the larger sensitivity in the second term of double hit is due to a larger efficiency factor ϵ. Alternative to Eq. (7) is a superposition of the single and double hit model. This mixed model was previously used to fit the EDR film irradiated by a 6 MV x-ray beam.[6] Models similar to the mixed single and double hit model were also used by Silberstein to analyze some of the 600–700 emulsions.[11]

Equations (1), (6), and (7) assume the grains have identical size. This is a reasonable assumption for EDR film, but not for XV film (Table I). It is somewhat surprising that Eq. (1) provides very good fits to all data of XV film. If the distribution of grain size were known, it would be possible to incorporate the size distribution into the equations of sensitometric curves. Assuming that the grain size distribution could be described by an exponential function and all grains were developable by a single hit, Silberstein[11] derived the following equation for the single hit model:

$$\mathrm{OD}(D)=\mathrm{OD}_{\max}\frac{\alpha D(2+\alpha D)}{(1+\alpha D)^2}. \tag{8}$$

We have tested Eq. (8) in place of Eq. (1) and found that Eq. (8) is equally good or better for XV film. This result suggests that fitting experimental data of XV film to the single hit model is not sensitive to the grain size distribution.

We have analyzed our data based on the modified Silberstein model.[11] The original Silberstein model does not include the efficiency factor.[15] It is clear that such a simple model has its limitations and the parameters of the model are also subject to interpretation. Ames[13] contended that the n value defined in Eq. (2), determined from fitting experimental data to model equation (1), (6), or (7), does not necessar-

TABLE IV. Fitting parameters for EDR film—Double-double hit model, Eq. (7).

Beam quality	$\mathrm{OD}_{1,\max}$	α_1 (cGy^{-1})	$\mathrm{OD}_{2,\max}$	α_2 (cGy^{-1})
γ-ray Co-60	3.00±0.21	0.006 11±0.000 47	0.10±0.02	0.18±0.11
X-ray 6 MV	3.45±0.05	0.005 40±0.000 14	0.11±0.02	0.09±0.03
X-ray 23 MV	3.42±0.04	0.005 74±0.000 13	0.09±0.02	0.12±0.04
Electron 6 MeV	3.43±0.06	0.005 83±0.000 17	0.07±0.03	0.13±0.09
Electron 21 MeV	3.37±0.06	0.005 93±0.000 18	0.11±0.03	0.12±0.06

ily represent the number of quanta or charged particles needed to produce a developable latent image. For our discussion, we have considered $n=1$ as an effective single hit and $n=2$ as an effective double hit. Ames[13] also pointed out that a fit of Eq. (1), (6), or (7) with experimental data does not necessarily mean that the efficiency factor ϵ is constant, but only that any variation in ϵ within a grain class has a small effect compared to the statistical fluctuations in the number of effective quanta or charged particles, though it was shown[23] that, if the efficiency factors are Poisson distributed, their only effect is a lateral shift of the sensitometric curve. Hamilton[23] pointed out that the fact that the measured optical density data have slopes too low to be fitted by a single theoretical curve, such as Eq. (1) or Eq. (6), may be interpreted as indicating that the inefficiencies cannot be represented by a succession of independent random losses, and that overall efficiency factors have a variance greater than the Poisson Value. This may be the case for EDR film irradiated by megavoltage beams. The factors determining the quantum sensitivity (efficiency factor) include quantum yield of silver formation, efficiency of concentration of silver, surface versus internal location of silver, and threshold size of catalytic silver aggregate.[23] Bird *et al.*[24] suggested that the most important single factor in the inefficiency is the low quantum yield of silver production, owing to recombination of photoelectron–hole pairs. But Hamilton[25] indicated that it is the variance of the inefficiency, and not the inefficiency itself, which lowers the detective quantum efficiency. Hamilton[23] also showed, using Monte Carlo simulation of emulsion response, that when inefficiencies are present, the random variations of the sequence events among grains are sufficient to account for a broader-than-Poisson spread, matching experimental data, even when all grains are identical before exposure. Techniques such as Monte Carlo simulation would provide a thorough understanding of the radiographic processes of EDR and XV film.[26] This is beyond the scope of this work.

The practical implication of this study is that one cannot simply assume the sensitometric curve of EDR film is linear in the dose range commonly used for megavoltage beam film dosimetry, e.g., 0–300 cGy. If the linear relationship is assumed, the low doses derived from optical density will have large errors. Since low doses are present in every beam near penumbra, one should be cautious about the nonlinearity of sensitometric curve of EDR film in the low density region.

IV. CONCLUSIONS

There is great interest in using the newly available EDR film for dose verification of IMRT, because it has lower sensitivity than XV film and dose distributions of actual clinical fraction doses can be verified.[6] Sensitometric curves of the EDR film have characteristics that are different from XV film in high-energy beams. It is found that in the megavoltage beams the double hit process is dominant for EDR film, while the single hit process is appropriate for XV film irradiated by all beams studied in this work. It is also found that in the kilovoltage region the sensitometric curves of EDR film can be interpreted by the single hit process just as for the XV film. The models used in this work are the ones originally developed by Silberstein.[11,15] For EDR film, the reduction of LET from kilovoltage to megavoltage beams causes a transition from a single hit to a double hit process, probably due to its smaller grain size and/or lower efficiency factor. On the other hand, for XV film, the single hit mechanism of creating latent image is appropriate for all beams studied here. The results of this work provide a theoretical explanation, within the framework of the model, of the sensitometric behavior of EDR film.

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