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Understanding the Response Characteristics of X-ray Verification Film

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Purpose : This study is intended to understand the sensitometric characteristics and the emulsion properties of the commercially available CEA TVS film in comparison with the Kodak X-Omat V film.

Materials and Methods : For this purpose, we have formulated an analytic expression of the characteristic curves for x-ray film exposed to mixed radiation of electrons, photons, and visible light. This mathematical expression was developed based on reaction-rate and target-hit theories. Unlike previous expressions, it relates optical density to emulsion properties such as grain size and silver bromide content. We have also developed a quantity which characterizes the film response to visible light relative to that to photons and electrons. This quantity could be expressed as a function of grain area. Thus, we have developed mathematical expressions and quantities with which the emulsion properties of the films can be revealed based on the sensitometric characteristics. Demonstrating the use of this analytical study, we exposed CEA and Kodak verification films to the mixed radiation of electrons, photons, and visible light, and interpreted the experimental results accordingly.

Results : We have demonstrated that: (1) the saturation density increases as the silver bromide content increases, (2) the time required to reach the threshold dose (to which the film begins to respond) when films are exposed to visible light decreases as the grain size increases, and (3) the CEA film contains more silver bromide, whereas the Kodak film contains larger grains. These findings were supported by the data provided by the manufacturers afterward.

Conclusion : This study presented an analytical and experimental basis for understanding the response of X-ray film with respect to the emulsion properties.

Key Words : X-ray film, Grain size, Silver bromide, Optical density (OD), Characteristic (H & D) curve

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INTRODUCTION

In this study, we investigate a mathematical expression which represent the sensitometric characteristics of x-ray film responding to a mixed radiation. Mixed radiation in this study implies electrons, photons, and visible light all together. Based on this investigation, we intend to identify the differences in the emulsion properties of CEA TVS (TVS film, CEA America Corp., 300 Garden Oaks Blvd., Houston, TX 77018-5502) and Kodak XV films (X-Omat RP/V, Eastman Kodak Company, 343 State Street, Rochester, NY 14650), which comparatively characterize the responses of the two films.

Since Nutting,[1] we can find several studies on the mathematical understanding of the H & D curve of x-ray film, which relates the film sensitivity (i.e. optical density) to dose.[2-4] Among these, not long ago Dixon and Ekstrand[4] has presented a simple model utilizing target-hit and reaction-rate theories. Their model was capable of representing the H & D curve for photon, electron, and light exposures separately. Also, James[3] described other studies that treat these forms of radiation separately. Shaw[5] was not an exception. We find no articles treating these forms of radiation at the same time. However, films, when they are used with intensifying screens, are exposed to not only visible light, but also primary radiation.

CEA film is relatively new, and thus its sensitometric characteristics needs to be understood. Furthermore, detailed information on the film emulsion is not normally available from the manufacturer. It is known that optical density (*OD*) is dependent on the emulsion properties such as the grain size and the silver bromide content of a specific film. In addition, it is also known that x-ray film responds in a different way to visible light than to photons and electrons. By investigating the previous facts analytically, we intend to compare the H & D characteristics of CEA V film with that of Kodak V film. For this purpose, we will develop a new model explaining the H & D characteristics of x-ray film responding to mixed radiation exposures by reformulating an analytic expression for H & D curve which has been available for photon and electron exposures. Consequently, this new model, like previous models, will relate OD to the emulsion properties, and will provide a intercomparison of the properties of the two film emulsion, based on the sensitometric properties of the films.

MATERIALS AND METHOD

1. Mathematical method

1) Derivation of the H & D curves for electron, photon, and light exposures, respectively

It is known that film's optical density (*OD*) can be mathematically expressed as:

$$OD = k\sigma_d \chi n, \qquad (1)$$

where $k = log(e) = 0.4343$, σ_d = developed grain area, χ = emulsion thickness, and n = grain number density in the emulsion. This type of formula has been modified since it was first derived by Nutting.[1] If n can be related to the amount of dose the film has received, OD will be expressed as a function of dose (*D*) representing the H & D curve (H & D curve is actully a relation between OD and logarithmic value of *D*).

A mathematical expression of n as a function of D was derived by Dixon using a simple target-hit model,[4] the target being the grains for the formation of latent image. This model made unnecessary the detailed treatment of the physics of radiation interaction with the silver-bromide grains; counting the number of hits scored in a grain will indicate quantitatively the image created in the emulsion. In this study, employing the target-hit model we intend to derive a formula relating OD to the number of radiation interactions (i.e. hits which will be defined later) in grains. The first step of this derivation is to define the meaning of 'hit' for the target-hit treatment. In order to define a hit, we need to understand what causes the formation of image in x-ray film.

When radiation is incident on the film, first, one absorption of incident radiation should lead to the production of one free electron in the crystalline structure of silver bromide grains, and second, if an electron is produced, it should be trapped by certain impurities (i.e. negatively charged specks in a grain structure). These steps will lead to the formation of latent image composed of neutral Ag atoms. A latent image can be transformed into a true image through a film developing process using chemicals. Thus, a hit can not be completely defined as an absorption of radiation (a visible light quantum, a photon, or an electron) nor the creation of one conductive electron in a crystalline structure of silver bromide grain. A true hit is the radiation interaction event with a grain which ultimately leads to the final neutralization of more than one Ag ion.

To mathematically derive an equation for *OD*, assume that m is the number of hits required for the generation of a latent image and denote that $N_i(t)$ is the number of grains/cm^3 which have received i hits at the exposure time t. If we assume that x-ray emulsion contains grains of a uniform size, the rate of change of N_i, then, is the production rate of N_i - the removal rate of N_i :

$$dN_i / dt = \lambda N_{i-1} - \lambda N_i, \quad (2)$$

where λ is the reaction rate between grains and incident particles for i greater than 0. With the initial conditions: $N_i(0) = 0$ for i greater than 0 and $N_0(0) = N$,

$$N_i(t) = N \frac{(\lambda t)^i}{i!} e^{-\lambda t} \quad (3)$$

where N is the initial number of grains.

Depending on the radiation field, λ can contain the terms which account for an interaction of a grain with either an electron (e^-), a photon (γ), or visible light (l). Namely, in general, for a mixed e^-, γ, and l field $\gamma = \sigma_e \phi_e + \sigma_\gamma \phi_\gamma + \sigma_l \phi_l$ where σ_e, σ_γ, & σ_l are cross-sections of interactions (i.e. hits) of a grain with an electron, a photon, and visible light, respectively and ϕ_e, ϕ_γ and ϕ_l are the respective fluence rates.

This number density can be used to calculate the number of developed grains per unit volume which is

n(t)=N- sum from i=0 to i=m-1 N_i
=&N left[1-e^-lambdat SUM fromi=0 to i=m-1 {(lambda t)^i} over i! right] (4)

where undeveloped grains has received the number of hits less than m. That is, per unit volume of emulsion the number of developed grains is equal to the total number of grains subtracted by the number of undeveloped grains.

Finally, *OD* can be related to λt by plugging eq. (4) to eq. (1):

OD(t)=k sigma_d chi N left[1-e^ -lambdat SUM fromi=0 to i=m-1 {(lambda t)^i} over i! right] (5)

This formula is not new; in principle it only replaces relative exposure term in the derivation by Dixon[6] with λt. Since λt is proportional to dose if the energy deposition is made by the radiation of constant fluence, *OD* is also a function of the total dose D. As a special case, if t is small in a low dose condition, expanding the exponential term into a series will cause *OD* to be dependent on $(\lambda t)^m$. This explains the trend of *OD* with dose as shown in Fig. 1: if $m = 1$ or if a single hit is required for electrons or photons, then a linear relation holds at low doses and if $m > 1$ or if multiple hits are required for visible light, then a parabolic relation holds at low doses. Examining eq. (5), we find that since *OD* saturates as $t \rightarrow \infty$, $OD_{sat} = OD\ (t \rightarrow \infty) = k\ \sigma_0 \chi N$, n being replaced by N. The term in the parenthesis of eq. (5) determines the shape of the curve; at an equal dose condition, the larger the grain area is, the earlier the curve saturates.

Within the context of the derivation in this study, we can similarly define the film gamma and the film speed to the previous work.[4] Since the gamma is defined as the maximum slope of the H & D curve which lies at the inflection point of the curve, we need to first of all convert eq. (5) into a semilogarithmic curve by substituting $\exp(Z/k)$ for t ($Z = \log \lambda t$). The curve relating *OD* to Z, a logarithmic value of λt (or dose instead, traditionally by others[4]), is actually called the H & D curve. Then, we can use eq. (5) to obtain the slope called film gamma (γ). The inflection point can be obtained by setting $(dOD^2/d^2Z) = 0$, and it is calculated to be occurring when $\lambda t = m$. Next, by

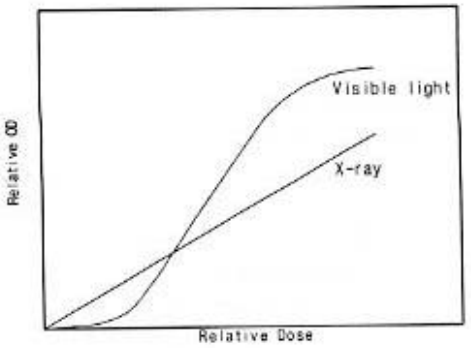

Fig. 1. Typical response of medical x-ray film to light and x-rays.[5] The for the light exposure is the typical trend for a multiole hit condition, where as that for x-ray exposure is for a single hit condition. The curve for x-ray is known to be linear in a low-dose region (up to 70 cGy for Kodak XV film). The H & D curve has the same trend as those above, but has the horizontal (i.e. relative dose) axis in log scale.

inserting the inflection point into the first derivative of OD,[4] which is the slope of the curve, we can obtain the gamma as follows:

gamma =left (dOD over dZ right)(U=m)=N sigma _d `rmchi itF (6)

where m is inserted into $U(U = \lambda i)$ andF={m^m e^-m} over (m-1)!

For example, based on the formula for F, F values can be calculated to be 0.3678, 0.5413, and 0.6721 for m=1, 2, and 3, respectively. Thus, the slope of the H & D curve is higher for visible light exposure than for electron or photon exposures, which is well represented by Fig. 1.

The physical significance of the inflection point lying at $U = m$ is in the fact that the highest slope of the curve is caused when the reaction number just reaches the minimum number of hits necessary for the formation of latent image. In a mixed radiation field where visible lights are included, m may not be just one.

Another parameter which characterizes dosimetric film is the film speed (S), which can be defined as the reciprocal of the reaction number (denoted as U_1) required to produce OD value of one. So, setting $OD(U = U_1) = 1$, for $m = 1$ we find

S= 1overU_1 = 1 over {left[kN sigma _d `chi /`(kN sigma _d chi -1) right]} (7)

For higher m's S cannot be analytically arranged. Thus, the speed can be interpreted as the optical density per unit reaction between the incident radiation and the grains for $U = U_1$. As a first order approximation, S can be equated to D_s.

The film gamma is proportional to $N\sigma_d\chi$ which is the number of interactions within a emulsion thickness χ. The speed is approximately proportional to $N\sigma_d\chi$. Note that the interaction of concern here is between the photons from the sensitometers and the developed grains. Also, as an another interpretation $N\sigma_d\chi$ = the fractional area occupied by grains, and this is proportional to silver bromide density (mg/cm^2).

For electrons and photons (m = 1) and visible light ($m \geq 3$), respectively, the OD defined by eq. (5) can be expressed as

$$OD_e(t) = k\sigma_d\chi N(1-e^{-\sigma_e \phi_e t}) \quad (8)$$

$$OD_\gamma(t) = k\sigma_d\chi N(1-e^{-\sigma_\gamma \phi_\gamma t}) \quad (9)$$

$$OD_l(t) = k\sigma_d\chi N[1-(1+\sigma_l\phi_l t + \frac{1}{2!}(\sigma_l\phi_l t)^2)e^{-\sigma_l\phi_l t}] \quad (10)$$

Note that we have chosen $m \geq 3$ for the above derivation.[6] Here, σ_d is known to be approximately twice the developed grain area,[4] σ_e can simply be assumed to be σ_g, the geometrical cross-sectional area of a grain (every electron passage in a grain can be considered as a hit),[7] $\sigma_\gamma = p_l \mu_{AgBr} V$ where V is the volume of the grain, and $\sigma_l = p_1 p_2 \sigma_g$ where p_1 = the probability that an absorbed light quanta will register a hit and p_2 = the probability that a light quanta will be absorbed.[4] p_2 is proportional to the mean cord length of the spherical grain. Since the mean cord length is (2/3) times the grain diameter, we can assume that p_2 is proportional to grain radius.

If we only consider spherically shaped grains in an emulsion, $\sigma_g = \pi r^2$ with r the radius of a grain and V = (4π/3) r^3. At a low dose limit, optical densities can be related to g by $OD_e \propto \sigma_g^2$, $OD_\gamma \propto \sigma_g^{2.5}$, & $OD_l \propto \sigma_g^{5.5}$. Note that as m increases, the exponent jumps. If the effectiveness in rendering a grain developable increases or m decreases, then OD becomes less dependent on grain-area changes. Linearity between OD and exposure time can be readily shown by the equations for OD_e and OD_γ at low doses, but not for OD_l. These trends at low doses match the general trend shown by Fig. 1 for a x-ray exposure of a single hit particle (i.e. m =1).[3]

2) Derivation of the H & D curves for mixed radiation exposures consisting of electrons, photons and light quanta

If the film sandwiched by intensifying screens is placed in a mixed radiation field of electrons, photons, and visible light, the optical density in a mixed field or OD_m can take a somewhat different analytical form from the ones defined in eq.s (8) to (10). Namely, $OD_m \pm OD_e + OD + OD_l$: a simple linear combination of the constituents cannot make OD_m. The reason is that one grain can be exposed by electrons, photons, and visible light at the same time in a mixed field.

In order to find an analytic expression for OD_m as a function of exposure time or dose, we first need to explain the radiation field to which the film is open. When intensifying screens are not placed, in the mixed field of electrons and photons only, a grain can receive the following kinds of hits: (1) zero hit, (2) a hit by e$^-$, (3) a hit by γ, (4) multiple hits either by e$^-$'s only or γ's only, (5) multiple hits by some combination of e$^-$'s and γ's.

Then, using eq.s (3) and (4), [the number (no.) of developed grains (n)] = [the initial no. of total grains

(N)] - [the no. of grains received no hit (N_0)]:

$$n = N - No = N(1-e^{-\lambda' t}) \quad (11)$$

where $\lambda' = \lambda_e + \lambda_\gamma$ with $\lambda_e = \sigma_e \phi_e$ and $\lambda_\gamma = \sigma_\gamma \phi_\gamma$.

Consequently, the optical density in a film exposed without intensifying screens (ODn) is

$$OD_n = OD_s (1 - e^{-\lambda' t}) \quad (12)$$

where $OD_s = N \sigma_d \chi N$

When intensifying screens are placed, the film receive the following kinds of hits: (1) zero hit, (2) a hit by e^-, (3) a hit by γ, (4) a hit by a light quantum, (4) multiple hits either by e^-'s only, γ's only, or light quanta only, (5) multiple hits by some combination of e^-'s, γ's, and light quanta.

Then, using eq.s (3) and (4) and assuming $m = 3$ for visible light exposure,[6] [the no. of developed grains (n)] = [the initial no. of total grains (N)] - [the no. of grains received no hit (N_0)] - [the no. of grains received one hit by visible light ($N_1 \sigma_l \phi_l / \lambda$)] - [the no. of grains received two hits by visible light ($N_2 (\sigma_l \phi_l / \lambda)^2$)] :

n＝N-N_0 -N_l {sigma _l ø_l} over lambda -N_2 left({sigma _l ø_l} over lambda right)^2

＝&N left[1-left(1＋ sigma _l ø_l ``t＋{(sigma _l ø_l)^2} over 2!} right)e^-lambdat right] (13)

where $\lambda = \lambda' + \lambda_l$ with $\lambda_l = \sigma_l \phi_l$.

Consequently, the optical density in a film sandwiched by scintillator screens OD_m is

OD_m ＝OD_S left [1-left(1+ sigma _l ø_l ~t+ {left(sigma _l ø_l ~t)^2} over 2! right)e^ -lambdat right] (14)

It can be observed that if $\lambda >> \lambda'$ or $\lambda_l >> \lambda_e + \lambda_\gamma$, OD_m is reduced to OD_l given by eq. (10) with λ being replaced by λ_l. Otherwise, if $\lambda_l << \lambda'$ or no intensification-limit, OD_m should approach OD_n with λ being replaced by λ' and ϕ_l by zero.

In general, for arbitrary hit size of m,

OD_m = OD_s left[1- SUM fromi=1 to m-1 {(sigma _l ø_l `t)^i} over i! e^-lambdat right] . (15)

We can investigate the increase in film response via intensifying screens using eq.s (12) and (14). The ratio of OD_m to OD_n is:

OD_m over OD_n ＝{1- left(1＋ lambda _l t＋{(lambda _l t)^2} over 2! right)e^-lambdat} over 1-e^-lambda't} (16)

This ratio can be analyzed with two extreme conditions:

1) At low doses (i.e. $\lambda t \rightarrow 0$, and $\lambda' t \rightarrow 0$),
   $OD_m / OD_n = 1$
2) At high doses (i.e. $\lambda t \rightarrow \infty$, and $\lambda' t \rightarrow \infty$),
   $OD_m / OD_n = 1$

For an intermediate exposure, OD_m / OD_n is greater than 1 because OD_m is always greater than OD_n. This ratio contains no information concerning OD_s or silver bromide content, and it is characterized only by its cross-section dependence for a constant radiation fluence. Cross-sections are functions of geometrical grain area of films and energy of interacting radiation. Eq. (16) will help understand the differences in the grain sizes of the two different films.

2. Calculations

In order to quantitatively understand the trend of OD_m / OD_n given by eq. (16) with total dose or t, we have approximately calculated the parameters (mainly cross-sections) in the equation based on the discussions on the cross-sections covered in section I.D.

Farnell, Chanter, and Marriage have found through an experiment that the minimum latent image size is about 4 to 10 silver atoms.[8, 9] Their work provides different hit number from the one used previously, but it provides the difference between the minimum and average numbers of hit. According to their work, the average image size will be about 7 silver atoms. Since we haven't used an average number as the threshold hit number in the mathematical derivation of the H & D curve (we could have used $m \geq 7$), it will be necessary to multiply the factor 4/7 to the cross section σ_l (in eq.s (10), (13)-(16)). The absorption probability for a grain is given, based on Mie's formula for cross-sections,[10] as $p_2 = 0.02$ for the light with the wavelength of 423 nm emitted by BC400 (It will be introduced later in chapter 3. Also, let's assume that $p_1 = 1$ whose value is not known.

Then, given the grain size and energy of the incident radiation, the cross sections in eq. (16) can be calculated. For $\gamma = 0.3 \times 10^{-4}$ cm the average grain radius[11] for Kodak film and overline E_ gamma =1.45 rm`MeV the average photon energy of a 4MV LINAC beam,[12]

$\sigma_l = (4/3)\ \pi r^3 \cdot \mu_{AgBr} (E\gamma = 1.45\ MeV)$

$= 1.013 \times 10^{-14}$ cm^2 (17)

where $\mu_{AgBr}(E = 1.45$ MeV$) = 8.923$ cm^{-1}, the linear attenuation coefficient of the photons in silver-bromide emulsion,

$\sigma_l = (4/7)p_1p_2\,\pi r^2 = 3.232 \times 10^{-11}$ cm^2 (18)

$\sigma_e = \pi r^2 = 2.827 \times 10^{-9}$ cm^2 (19)

Table 1. Cross-sections and Fluence Ratio ϕ/ϕ_e (for the Approximate Calculations of OD_m/OD_n for Various Radii of Grains for E_γ =1.45MeV.p=(4/7)p_1p_2

r(μ)	σ_e(cm^2)	σ_γ(cm^2)	σ_l(cm^2)	ϕ/ϕ_e	p
0.2	1.257e-9	3.0e-15	p 1,257e-9	2374	0.0057
0.3	2.827e-9	1.013e-14	p 2,827e-9	2374	1
0.4	5.027e-9	2.4e-14	p 5.027e-9	2374	0.0114
					0.02

In order to find the ratio between ϕ_e and ϕ_γ, assume that there is a charged particle equilibrium so that electrons liberated by 1.45 MeV photons are uniformly incident on the scintillator-film set. Then, the light fluence liberated by these electrons can be calculated in the following way. Let's first assume that all electrons were liberated by the photon of the average energy: overline E_ gamma =1.45 rm`MeV . Then, the average energy of an electron (overline E_e) can be calculated as:

overline E_ e = overline E_ gamma over 2 mu _tr over mu (E_gamma = 1.45MeV)=0.3581MeV (20)

where μ_{tr} ($E_\gamma = 1.45$ MeV) = 0.00284 cm^2/g, the transfer mass absorption coefficient in water, and μ ($E_\gamma = 1.45$ MeV) = 0.0575 cm^2/g, the total mass absorption coefficients in water. Based on this, the visible light fluence ϕ can be calculated as follows. The average electron energy loss is

TRIANGLE overline E_e = dE over dx (E_e =0.3581 MeV)T=0.2318MeV (21)

where the linear energy transfer dE/dx ($E_e = 0.3581$ MeV) = 2.187 MeV cm^2/g and the thickness of the scintillator T = 0.1 cm.

Given the electron fluence ϕ_e,

ø_l =ø_e {TRIANGLE overlineE_e} over overline E_l epsilon CONG ø_e (2,374) (22)

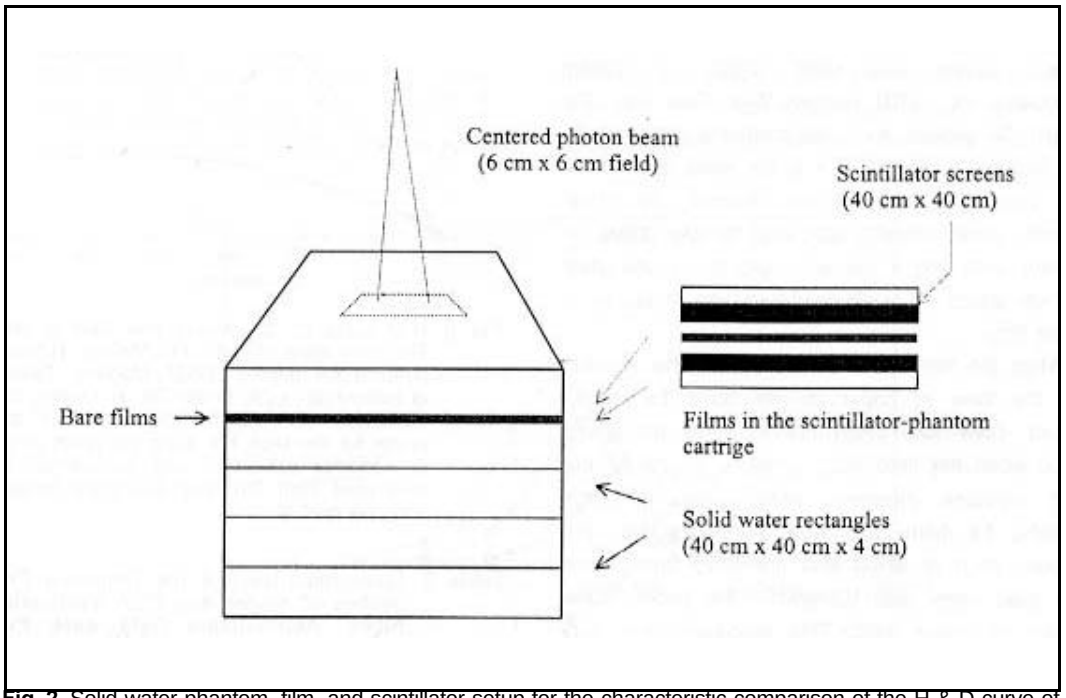

Fig. 2. Solid water phantom, film, and scintillator setup for the characteristic comparison of the H & D curve of CEA and kodak V film. For the film exposure to photons and electrons, films in paper jackets were placed. However, when the film is sandwched by the scinitillor screens (model no. BC400), films taken out from the jackets were first sandwiched by the scibntillator screens and by thin phantom slabs. This cartridge is inserted into and sandwiched by the stack of solid rectangles. Compression is provided by the gravity only.

where overline E_l = 2.93 eV, the average energy of the visible light quantum from BC400, and ε = 0.03, the approximate scintillation efficiency of the BC400. Similarly, one can calculate cross-sections and relative light fluence for different electron energies and grain sizes. The results of this calculation is listed in Table 1.

3. Experimental method

The CEA and Kodak films are different in their grain sizes and silver bromide content, which should affect their sensitometric characteristics. In order to understand the sensitometric characteristics of the Kodak and CEA films based on the mathematical study performed in chapters 1 and 2, experiments were performed to generate their H & D curves. Through this process, we have studied the characteristics of the films for both electron/photon and mixed radiation exposures, respectively.

Since the V films are blue-light sensitive, we chose the BC400 organic scintillator (BC400, BICRON, 12345 Kinsman Road, Newbury, Ohio 44065-9677) as an intensifier which is mainly a blue light emitter (Its spectra is peaked at the wavelength of 423 nm). The BC400 is very tissue equivalent, compared with regular phosphor screens. It is composed of H, C, and O with the H/C ratio of 1.103, and its density (1.032 g/cm^3) is very close to that of muscle (1.04 g/cm^3). Thus, the plastic scintillator screen is very compatible with the phantom material which will be used in this experiment. In addition, this low-Z material is sensitive to electrons mainly.

When the films are placed at a substantial depth of a phantom exposed to a photon beam (see Fig. 2 as an example) where the charged particle equilibrium can be established, they can be exposed to the stable secondary electrons as well as the primary and scattered photons. When the film is sandwiched by the scintillator screens at the same depth, the film becomes exposed to the mixed radiation part of which was generated from the screens. The BC400 converts 3%, as an average, of the incident electron energy-lost into the energy carried by visible light it emits. Therefore, even an electron with a small amount of energy can be transformed into the large number of visible light quanta, each of which has only 3.5 eV approximately. At this stable depth, thus, the equilibrium concentration of electrons effectively liberates many visible light quanta from the scintillator screens (Note that the sensitivity of the silver-bromide film increases dramatically as the photon energy decreases, rendering the x-ray film very sensitive to visible lights). The electrons which experienced collisions in the screens are still incident on the film. Thus, the film is exposed to the radiation field consisting of the primary and scattered photons, the secondary electrons penetrated and liberated by the screens, and the tertiary visible light.

In this study, the films were placed at 5 cm depth and at 80 SAD of the solid water phantom, and were placed perpendicular to the beam direction (see Fig. 2). The LINAC of 4MV as a low energy source was used (Clinac 4, Varian Associates Inc., 3120 Hansen Way, Palo Alto, Ca 94304). To provide an equal scattering environment, the small field size of 6 x 6 cm were shot about the center of the phantom surface. To show linearity, small intervals are used at low doses or monitor units and a few saturating points are used at high doses. A single exposure was made to a single film.

When the films were placed without the scintillator,

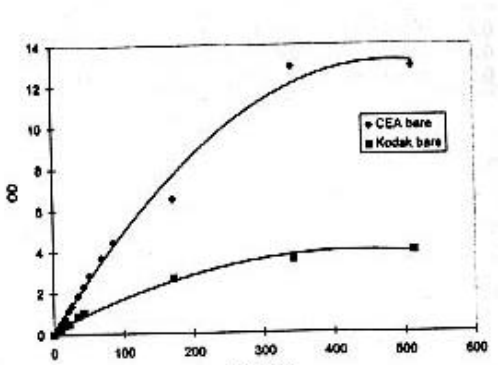

Fig. 3. H-D curve for the Kodak and CEA V films. The films were read by the McBeth TD502LB densitometer (Model TD502, Macbeth, Division of Kollmorgen, Little Britain Rd. P. O. Box 230, Newburgh, NY 12550). The final two data points for the CEA film were the result of the densitometer saturation, and, accordingly, the third point from the final data point deviates from the best fit curve.

Table 2. Intercomparison of the Emulsion Properties of Kodak and CEA Verification Films. Approximate Data were Provided by Manufactures[11, 13]

Film/Properties	Emulsion density	Grain size
Kodak	0.7 mg/cm^2	0.6 μm
CEA	0.93 mg/cm^2	0.33 μm

the films in paper jackets could be simply placed. Care was taken not to move the entire setup when the films were simply changed for the next exposure. However, when using scintillator screens, the bare films were sandwiched by the screens each of which was previously taped to a thin solid water slab (Otherwise, the paper jacket blocks all visible light). This procedure was performed in a dark room for every single exposure. Then, the four sides of this slab were taped to be light-proof, and then placed within the solid water blocks. The films were compressed only by gravity.

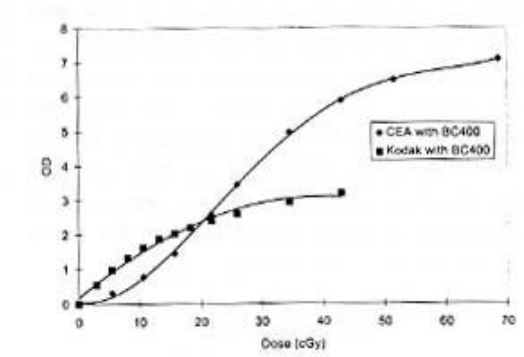

Fig. 4. H & D curve for the Kodak and CEA V films sandwiched by the BC400 scintillator screens. The exposure through scintillator screens is due to the mixed radiation consisting of x-rays, eletrons, and visible light. The films were read by McBeth TD502LB densitometer.

RESULTS AND DISCUSSION

Fig. 3 to 5 show a comparative information on the emulsion properties such as the grain size and silver bromide content of the CEA and the Kodak V films. Fig. 3 contains two H-D curves which show the dose-characteristics of CEA and Kodak V films, respectively. For x-ray and electron exposures, the figure shows linearity at low doses and saturation at high doses for both films. CEA film has a wider dose range in which linearity holds. Relatively large saturation OD of the CEA film implies relatively large silver bromide content, i.e. the density in mg/cm2 as shown in eq. (12). We can estimate, based on Fig. 3, that more silver bromide density would be present in the CEA film than the Kodak film. This was supported by the manufacturers data which was later available to us (Table 2). Both the film gamma and the speed are proportional to the saturation density of the film (see eq.s (6) & (7)). Therefore, the CEA film should show larger values of film gamma and speed than does the Kodak film as indicated by Fig. 3.

The CEA film does not begin to saturate until 300 cGy, whereas the Kodak film begins to saturate at relatively low doses well below 100 cGy. This

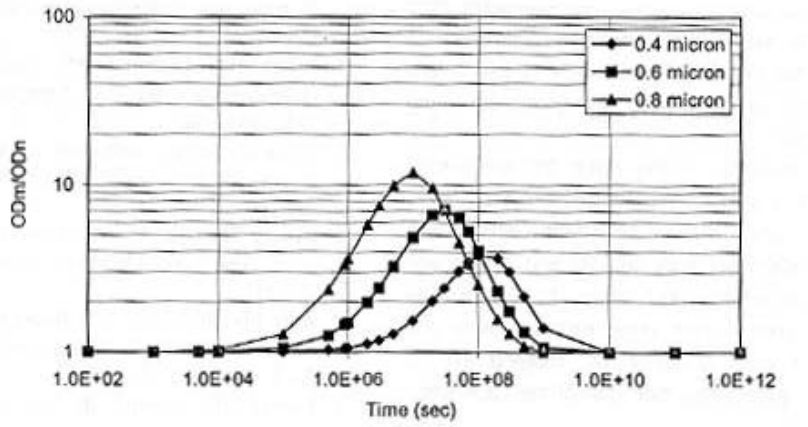

Fig. 5. The relative trend of the ratio of OD with scintillator/OD without scintillator to exposure time as gain size changes : A computational result E_γ=1,45 MeV and m=3 in eq. (16). The scintillator screen BC400 was used. Three exemplary grain diameters were 0.4, 0.6, and 0.8μ. The first diameter represents the CEA TVS film relatively, whereas the second diameter does represent the Kodak XV film.

implies that the average grain size of the latter is larger than that of the former because at the same dose environment the grain size is the term which determines

the shape of the H-D curve (see eq.s (5), (8) or (9)). This fact is also supported by Fig. 4 for mixed exposures. It shows higher threshold dose for the CEA film: the higher threshold dose corresponds to the smaller grain size, because at a low dose environment, smaller grains are not as likely to be hit

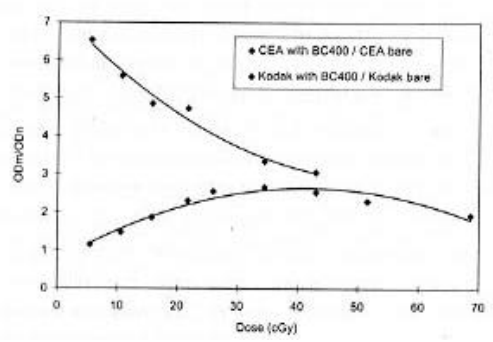

Fig. 6. Comparison in the increase in OD by scintillation for the Kodark and CEA V films. ODm/ODn-OD with scintillator screens (BC400) /OD with no scintilltor screens. The curve for Kodak film has its peak below 1 cGy.

as larger grains. This grain size difference affects the shape of the H-D curves for mixed radiation exposure at a low dose region: the OD of the Kodak film of larger grains as an average is higher than that of the CEA film. However, as the dose increases, the OD of the CEA film exceeds that of the Kodak film because it inherently contains higher silver bromide content. This finding on the grain sizes of the films is in agreement with what Table 2 shows.

The trend in the H & D curve of the CEA film is the typical shape for the film under multiple hit environment, as the H & D curve of x-ray film responding to visible light was analytically explained previously in chapter I. The threshold dose for the Kodak film is too low to be seen in this figure (We have identified from other experiments that the threshold dose for the Kodak film is in the very low dose range, less than 1 cGy).

We can also observe the same finding on the grain size of the films in a different fashion from the Fig. 5 and 6. Fig. 5 is an exemplary plot describing eq. (16). The three films representative of the Kodak V films are exposed under the same environment, defined by the total fluence, namely. The only difference between them is on the grain size. Thus, the curves for OD_m/OD_n are shown to be dependent on the grain size; as the grain size increases, the peak exposure time decreases and the magnitude of OD_m/OD_n increases. This fact has been predicted by eq. (16), especially at low doses: the ratio is very sensitive to grain size and exposure time.

This computational finding helps the analysis of Fig. 6 which is an experimental result of OD_m/OD_n. This figure also shows the trend which was predicted mathematically by eq. (16) and agrees well with

the trend of the ratio shown by Fig. 5. The Kodak film shows lower peak exposure time and much higher value of OD_m/OD_n, implying that its grain size is quite larger than that of the CEA film.

CONCLUSION

In this study, we derived the H and D curve differently from the traditional one (eq. (5)). The new derivation related optical density to reaction rate between the grains and the incoming particles, while the traditional one related optical density to the dose the film has received (the overall shape of the formulation employing an exponential function is unchanged though by this new derivation). Using this new derivation (eq. (5)), we were able to additionally derive an analytical formula for the optical density of the film exposed in the mixed radiation field consisting of photons, electrons, and visible light quanta (eq. (15)). By these new derivations, this study provided an analytical and experimental basis for understanding the response of X-ray film to the mixed radiation. The new derivations also demonstrated the sensitivity of the film to the emulsion properties such as grain size and silver-bromide content. Comparative understanding of the emulsion properties for the two film, the Kodak and the CEA film, was achieved.

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= 국문 초록 =

X-선 Verification 필름의 반응 특성에 관한 연구

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목 적 : 본연구는 상용되는 CEA TVS 필름의 감성과 현탁재질을 Kodak X-Omat V 필름과 비교하여 이해하는 것을 목표로 한다.

대상 및 방법 : 이 목표를 위해 전자, 광자, 및 가시광선의 복합방사선에 노출된 X 선 필름의 특성커브(H & D curve)에 대한 해석적 표현식을 유도해 내었다. 이 수학적 공식은 반응율 및 target-hit 이론에 근거하여 전개되었다. 기존의 표현식과는 다르게 이것은 필름의 광밀도를 AgBr 입자크기 및 함유량과 같은 현탁재질과 관련시킨다. 또한 광자와 전자에 대한 것과 상대하여 필름의 가시광선에 대한 반응성을 특징짓는 정량적 인자(양자)를 유도해 내었다. 즉, 우리는 필름의 현탁재질을 그것의 감성을 근거로 알게 해 주는 수식과 양자를 유도해 내었다. 이러한 해석적인 연구의 사용을 보이기 위하여 CEA와 Kodak Verification 필름을 전자, 광자, 및 가시광선으로 이루어진 복합방사선에 노출시키고 그 실험결과를 적절히 해석하였다.

결 과 : 우리는 아래를 논증하였다. (1) 임계밀도는 AgBr 함유량이 증가함에 따라 증가한다. (2) 필름이 가시광선에 노출되었을 때 문턱선량까지 도달하는 데에 걸리는 시간은 AgBr입자크기가 증가함에 따라 감소한다. (3) Kodak 필름이 보다 더 큰 입자를 함유한 반면 CEA 필름은 더 많은 양의 AgBr을 함유하고 있다. 이러한 결과는 차후에 필름제작자가 제공한 자료로 뒷받침 되었다.

결 론 : 본 연구는 X선 필름의 반응성을 그 현탁재질에 관련하여 이해하기 위한 해석적, 실험적인 도구를 제시하였다.