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■ 論　文 ■

Development of Dose Evaluation Algorithm for Film Badge Using ISO Reference Radiations

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ISO 표준방사선장을 이용한 필름배지의 선량평가 알고리즘 개발

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Abstract – Since provisions on the technical criteria for personnel dosimetry was amended three years ago, several improvements in the technique of monitoring personnel doses by TLD have taken place, but for the photograpfic film as a personnel monitor, additional investigations should be carried out for its accuracy of dose estimates because of its wide use in the radiation involved industries. So, this paper describes the methods to develope dose evaluation algorithm for photographic film using ISO reference radiations by i) empirical formula, ii) degree-of-fit method, and iii) matrix approximation. These methods show a good agreement between irradiated and calculated dose within tolerance level represented in ANSI N13.11, and can be used for the dose evaluation of X, γ and/or mixed radiation fields.

Key words : *Personal monitoring, Photographic film, Algorithm, Empirical formular, Degree-of-fit, Matrix, ISO reference radiation*

요약 – 과학기술처의 개인방사선피폭선량평가에 관한 기술기준이 제정된 이후, TLD에 의한 개인피폭선량평가 기술은 많은 발전이 있었으나, 우리나라 대부분의 방사선관련 산업체에서 방사선피폭관리용으로 사용되고 있는 필름배지의 정확한 선량평가기술을 확보하기 위한 연구는 아직도 미진한 상태이다. 따라서 본 연구에서는 ISO 표준방사선장을 이용하여 i) 실험식에 의한 방법, ii) Degree-of-fit에 의한 방법, 그리고 iii) Matrix에 의한 방법으로 필름배지에 의한 선량평가 알고리즘 개발방법을 제시하였다. 이러한 방법들에 의한 계산값은 조사량과 ANSI N13.11에서 제시하고 있는 성능지수 이내에서 잘 일치하였으며, 이는 X, γ 혹은 혼합방사선장에서 선량평가에 유용하게 활용될 수 있을 것이다.

중심단어 : 개인방사선피폭선량평가, 알고리즘, 필름배지, 실험식, Degree-of-fit, 매트릭스, ISO 표준방사선장

INTRODUCTION

Individial monitoring constitutes an integral part of any radiological protection programme and serves as such the overall function of achiving and/or maintaining acceptably safe and satisfactory radiation condition in the workplace.

The requirements for personnel dosimeters are based on the above objectives of individual monitoring, and to provide a reliable measurement of the appropriate quantities, i. e. Hp(10) and Hp(0.07) for almost all practical conditions, independent of type and energy of radiation with a prescribed overall accuracy. The general guidance on the basic requirements for personnel dosimeters, in relation to the dose quantities that should be measured, the overall accuracy that should be obtained, and the degree of monitoring that should be exercised, is given by ICRP in publications 26, 35 and 60[1, 2, 3], by ICRU in reports 39, 43 and 47[4, 5, 6], by IAEA in safety series No. 84[7].

Under such an environment of the increasing emphasis on personnel dosimetry performance, the Ministry of Science and Technology(MOST) issued guidelines[10] on the technical criteria for personnel dosimetry, which is very similar to the ANSI N13.11[8, 9], to encourage dosimeter processors to evaluate personnel radiation dose more accurately.

Since the guidelines was issued 3 years ago, the technique of monitoring personnel doses particularly using TLD has been assessed[11, 12], but as regards the photographic film as a personnel monitor, additional investigations should be carried out for its accuracy of dose estimates by end users.

Because of the energy dependence of photographic film, it is necessary, for proper dose evaluation, to separate the radiation into some energy groups. This separation is especially important for energies around 50 keV where the relative response of the bare film may be 30 to 50 times greater than that for energies of 200 keV and higher. Energy separation can be accomplished by the use of filters which selectively attenuate radiations in the desired range.

In the measurement of personnel dose equivalent due to photon radiation, a correction must be made for the response of the photographic film relative to the actual dose equivalent in tissue. For photon energies exceeding 200 keV, this correction is essentially unity, while for low energy photons, the necessary factor, expressed as a multiplier, may range as low as 0.1. In practice, it is straightforward to generate a family of energy dependent correction factor and choose the most appropriate factor for each readout of the film. Using the response of several different filter materials that are significantly different with respect to the photon field, the correction factor to convert the element response to the dose to tissue can be calculated. This is done by using empirical data for the relative element responses as a function of photon energy.

Therefore, the purpose of this paper is to develope the algorithm for evaluating the personnel dose equivalent by photographic film using reference radiation fields.

EXPERIMENT

Film Badge

Film badge case PS1[13] used in the Center of Atomic Energy in France was selected for the development of the algorithm. The

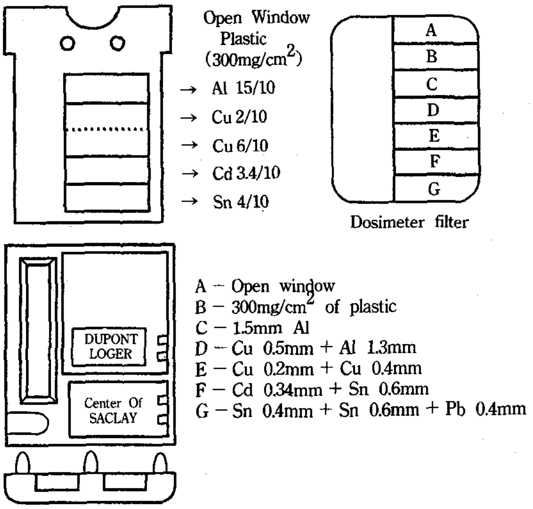

Fig. 1. PS1 film badge case.

configuration of PS1 badge case is shown in Fig. 1. It has six filter areas and an open window areas. The filter materials and thicknesses are as follows:

- Filter B : plastic, 300 mg/cm^2 equivalent
- Filter C : 1.5 mmAl, 400 mg/cm^2 equivalent
- Filter D : 0.2 mmCu + 1.3 mmAl, 528 mg/cm^2 equivalent
- Filter E : 0.6 mmCu, 530 mg/cm^2 equivalent
- Filter F : 0.34 mmCd + 0.6 mmSn + 0.4 mmPb, 1091 mg/cm^2 equivalent
- Filter G : 1 mmSn + 0.4 mmPb, 1027 mg/cm^2 equivalent

Agfa film Model 301 was used to set up the algorithm. Packing thickness of the film is equivalent to 20mg/cm^2. In each film, there are 2 emulsions: the 1st emulsion is for low dose(under 10 mGy), the 2nd emulsion for high dose(over 10 mGy).

Radiation Sources

X-radiations were obtained by Pentak 420 kV X-ray generator. The specifications of this generator are:

- output power : 4.2 kW maximum
- output voltage : 420 kV maximum
- current : 0.1 – 30 mA
- stability : < 0.05 %
- focus : 3.5 × 3.5 mm
- beam angle : 40°
- inherent filtration : 7 mmBe

Energies used were the ISO narrow series and fluorescent radiations[14] which are listed in Table 1.

The air kerma rates were calibrated by a Free Air Ion Chamber for the ISO narrow series and MESH type ion chamber for fluorescent radiations. Detailed method for using these detectors is described in reference[15].

Co-60 γ sources of 0.2 TBq and 1.1 TBq were used to obtain calibration curve of photographic film.

Irradiation Conditions

For the purpose of individual monitoring, ICRU 39[4] recommended two quantities, the individual dose equivalent, penetrating, Hp(d) and the individual dose equivalent, superficial, Hs(d). Both quantities should be measured with dosimeters on the surface of an appropriate phantom under a well known set of standard conditions. When dosimeters are calibrated on the ICRU sphere, the conversion factors for Hp(d) and Hs(d) can be used. Although a new name, personnel dose equivalent, is used in ICRU 47[6], the quantity itself is the same. Hence the conversion

Table 1. Energies used in this experiment.

Mean Energy (keV)	Tube Potential (kV)	Additional Filter(mm)[1]			1st HVL (mm Cu)	Radiator[2]	2nd Filter (g/cm^2)
		Pb	Sn	Cu			
16	100					Zr	Sr 0.02
23	150					Cd	Ag 0.05
33	40			0.21	0.084		
48	60			0.6	0.23		
65	80			2.0	0.58		
83	100			5.0	1.11		
100	120		1.0	5.0	1.71		
208	250	3.0	2.0		5.19		
1250	Co-60						

1) The total filtration consists, in each case, of the additional filtration plus the inherent filtration adjusted to 4mm of Al.

2) Fluorescent radiation

coefficients for ICRU sphere by Grosswendt [16] were used in this paper. Test dosimeters were irradiated with a tissue equivalent phantom constructed of polymetacrylate (PMMA) having a dimension of 30 × 30 × 15 cm according to the suggestion of ANSI N13.11[8].

Four dosimeters were attached to the phantom surface at each irradiation. The test dosimeters facing the source were mounted with their back planes parallel to the surface of the phantom, and the distances between center of the source and the phantom surface varied 1m to 1.5m with the exposure rates.

RESULTS AND DISCUSSIONS

Response characteristics

To transform the reading values of optical density of the film to dose quantity, the dosimeters should be irradiated to the reference radiation for which the dose rate is known. Reference radiation used was a Co-60 calibrated in BNB(National Calibration Bureau), France.

Fig. 2 shows the calibration curves for Agfa film. From these calibration curves, it is possible to transform the density of the other X-ray energies to relative dose of Co-60 called 'apparent dose'. The relative responses to Co-60 are shown in Fig. 3 and 4. If the photon energy is similar to that of Co-60 (above~200 keV), the dose equivalent is close to the calibration curve of the Co-60. If the energy is very different from the Co-60, the response of the dosimeters to the energy under consideration must be determined. As shown in figures 3 and 4, the response of the film at 50 keV is 30~50 times greater than that of the energies of 200 keV and higher. This difference is due to the photoelectric effect which causes the following corrections:

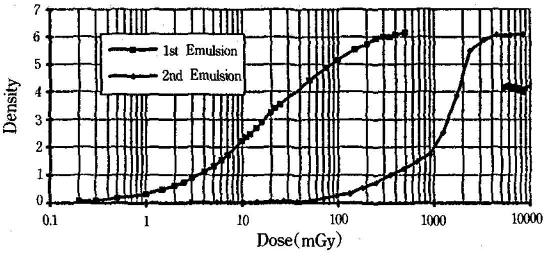

Fig. 2. Calibration curve of Co-60 for Agfa film

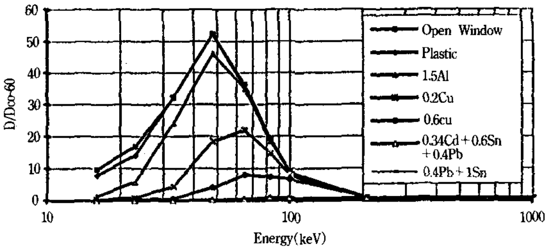

Fig. 3. Relative response to Co-60(1st emulsion)

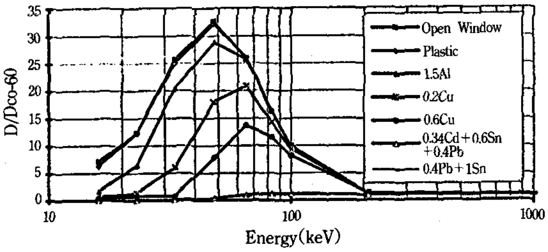

Fig. 4. Relative response to Co-60(2nd emulsion)

$$\frac{D_{emulsion}}{D_{tissue}} = [\frac{Z_{emulsion}}{Z_{tissue}}]^4 \qquad (1)$$

where D is the apparent dose and Z is the effective atomic number.

Dose Algorithm

1) Empirical formula

In Fig. 3 and 4, the first three filter groups can be used for calculating the low energy region and the 4th and 5th filter areas for medium energy, the 6th and 7th filter areas for strong energy.

So the following empirical equation is effective to calculate the dose.

$$D = A(D_{Pl} - D_{Al}) + B * D_{0.6Cu} + C * D_{Sn-Pb} \qquad (2)$$

where D = dose in tissue and

Table 2. Coefficients A, B and C to calculate dose according to the equation 2.

Coefficient	1st emulsion	2nd emulsion
A	0.13	0.18
B	0.03	0.01
C	0.90	0.90

D_{Pl}, D_{Al}, $D_{0.6Cu}$, D_{Sn-Pb} = apparent doses on the filter of Pℓ, Aℓ, 0.6Cu and Sn−Pb respectively.

The coefficients which were determined experimentally are shown in Table 2. Calculation results using these coefficients for various radiation doses are in Table 3. From this table, the differences between irradiated and calculated values are within ±25 %. It means that these coefficients can be used for algorithm in case of monoenergetic radiation.

Degree-of-fit method

The situation of mixed radiation field(X-ray and gamma-ray) is complicated and it is not possible to evaluate doses by simple em-

Table 3. Performance index* of the irradiated and calculated dose for AGFA film by empirical equation.

Energy (keV)	Irrad. Dose(mGy) 1.5	2	3	10	20	30
16	−1.3	−0.11	0.12	−0.11	−0.14	−0.13
23	−0.01	0.11	0.22	0.22	0.11	0.03
33	0.16	0.10	0.25	0.21	0.01	0.13
48	−0.17	0.13	−0.12	−0.02	0.05	−0.15
65	−0.15	−0.12	−0.12	0.05	0.12	0.11
83	0.17	0.15	0.15	0.19	0.21	0.24
100	−0.05	−0.01	0.05	0.23	0.16	0.22
208	−0.09	0.19	−0.23	−0.13	−0.10	−0.03
1250	−0.01	−0.02	0.03	−0.11	−0.05	−0.01

* Bias B + performance quotient P

P = [H'−H]/H, H'=Irradiated dose and H=Reported dose

B = $\bar{P}$

Table 4. Table of ratios for film badge algorithm(2mGy, 1st emulsion of AGFA film).

E	Percent		mGy Co Equi.1)				Deliv.(mSv)			Ratios2)							CF3)	
keV	X	Co	A1	A2	A3	A4	mGy	Deep	Sha.	R10	R11	R12	R13	R14	R15	R16	CF1	CF2
16	100	0	19.4	0.98	0.03	0.03	2.00	0.60	1.96	32.7	19.8	1070	32.7	1.00	2.1E4	8.3E6	1.63	3.27
	100	33	20.1	1.68	0.73	0.73	2.67	1.36	2.71	2.30	12.0	5.30	2.30	1.00	6.3E1	9.1E3	1.23	1.99
	100	50	20.5	2.04	1.09	1.02	3.00	1.74	3.08	2.00	10.0	3.74	1.87	1.07	4.0E1	3.8E3	1.17	1.77
	100	100	21.5	3.09	2.14	2.16	4.00	2.88	4.20	1.43	6.96	2.07	1.44	0.99	1.4E1	7.0E2	1.07	1.46
	50	100	11.8	2.60	2.13	2.15	3.00	2.58	3.22	1.21	4.55	1.48	1.22	0.99	6.7E0	1.4E2	1.01	1.25
	33	100	8.58	2.44	2.12	2.14	2.67	2.48	2.90	1.14	3.52	1.31	1.15	1.00	4.6E0	5.7E1	0.98	1.17
	0	100	2.11	2.11	2.11	2.13	2.00	2.28	2.24	1.00	1.00	1.00	1.00	1.00	1.0E0	1.0E0	0.93	0.98

1) A1 : Open Window, A2 : Cu 0.2mm+Al 1.3mm
A3 : Cd 0.34mm+Sn 0.6mm+Pb 0.4mm, A4 : Sn 1.0mm+Pb 0.4mm

2) R10 : A2/A4, R11 : A1/A2, R12 : (A2*A2) / (A3*A3), R13 : A2/A3
R14 : A3/A4, R15 : (A1*A2) / (A4*A4), R16 : (A1*A1*A1) / (A2*A3*A4)

3) CF=Conversion Factors
CF1 : A2/DEEP, CF2 : SHALLOW/DEEP

pirical formula. There is a significant technique to solve this problem. If the photographic film is exposed to a low energy photon field, the response of the areas under thick filters will be a smaller portion of the response of the areas under thin filters than that if exposed to a higher energy photon field. Therefore, various ratios of the reading values for different filters and energies can represent the characteristics of X-ray, gamma-ray or mixed fields.

In this paper, four filter areas were selected to make the 'Table-of-Ratio' for reference. An example of Table-of-Ratio consisted of R10 to R16 and conversion coefficients CF 1 and CF2 for reference is shown in Table 4 for the case of monoenergetic energy and calculated mixed field for 16 keV X-ray, and reference 'Table of Ratio' for other energies can be generated by same method as 16 keV seperately.

When personnel optical densities of the four filter areas are read, these optical density are transformed to relative Co-60 dose by calibration curve, then calculate conversion coefficients CF1 and CF2. To determine CF1 and CF2, it is used the measured ratios R10 to R16 and compared to the ratios R10 to R16 in the reference 'Table-of-Ratio' to obtain the best fit. The following formula is used to calculate the degree-of-fit.

$$DOF = \sum_{i=10}^{i=16} \frac{R_{i,\ ref} - R_{i,\ meas}}{\mathrm{R}_{\mathrm{i,\ ref}}} \qquad (3)$$

where $R_{i,ref}$ is the ratio R10 to R16 in the reference 'Table-of-Ratio' and $R_{i,meas}$ is the ratio calculated from the readings of dosimeters to be evaluated.

The calculation results using this method for various radiation doses are in Table 5. From this Table, the differences between irradiated and calculated doses show a good agreement within ±30 %.

Table 5. Performance index[1)] of the irradiated and calculated dose for AGFA film by degree of fit method: Hp(10).

Energy	Irrad. Dose(mGy) for Hp(10)				
(keV)	1.5[2)]	3	10	20	30
16	0.01	−0.01	−0.07	0.00	−0.05
23	0.05	−0.32	0.01	0.00	−0.06
33	0.13	0.11	0.01	0.00	−0.08
48	−0.11	0.05	0.09	0.00	−0.06
65	−0.07	0.12	0.06	0.00	−0.05
83	0.05	0.15	0.07	0.00	0.11
100	−0.05	0.10	−0.05	0.00	−0.08
208	0.01	0.06	−0.03	0.00	0.04
1250	−0.01	0.04	−0.06	0.00	0.03

1) Basis B+performance quotient P
P=[H′−H]/H, H′=Irradiated dose and
H=Reported dose
$B=\overline{P}$

2) Irradiated dose(mGy) was converted to mSv for calculating Hp(10).

Matrix Approaximation

If we need more accurate informations for irradiated radiation energies, we can use matrix approximation. Here the brief descriptions of this method is demonstrated.

The apparent dose D_j under the filter j can be represented as the sum of the doses due to the individual radiation energy E_i

$$\begin{aligned} D_j = {} & k_{1,j}d_1 + k_{2,j}d_2 + \cdots\cdots \\ & k_{i,j}d_i \cdots\cdots + k_{n,j}d_n \end{aligned} \qquad (4)$$

where d_1, d_2, …… d_i, …… d_n are doses from radiation of energy E_1, E_2, …… E_i, …… E_n and $k_{i,j}$ is (apparent dose / real dose) for filter j and energy E_i

To obtain the coefficient $k_{i,j}$, the curves of Fig. 3 and 4 are divided into 40 bands of energy(E_1 to E_{40}) between 10 keV to 1 MeV. The size of the energy interval can be varied with the shape of curve.

From the above divided energy groups, we have 6 equations with 40 unknowns of d_i values. So we can rewrite Eq. 4 with the error function d'_j to find maximum or minimum total dose D_j.

Table 6. Result for AGFA film by matrix approximation(33 keV X-ray 3 mGy).

<table>
<tr><td colspan="6">Apparent Dose to Cobalt-60</td></tr>
<tr><td>281.900</td><td>273.700</td><td>213.000</td><td>61.050</td><td>7.750</td><td>1.000</td></tr>
<tr><td colspan="6">Interpretation of Lectures</td></tr>
<tr><td colspan="6">Exposure total Minimum Calcule = 2.887 mGy
Exposure total Minimum Calcule = 3.392 mGy</td></tr>
<tr><td>Radiations</td><td>Min. AD-E</td><td>Max. AD-E</td><td>Min. AD+E</td><td colspan="2">Max. AD+E</td></tr>
<tr><td>7 18 KEV</td><td>1.813</td><td>.000</td><td>.000</td><td colspan="2">0.000</td></tr>
<tr><td>14 35 KEV</td><td>.401</td><td>2.569</td><td>2.887</td><td colspan="2">2.887</td></tr>
<tr><td>16 45 KEV</td><td>.730</td><td>.603</td><td>.000</td><td colspan="2">.000</td></tr>
<tr><td>Total</td><td>2.944</td><td>3.392</td><td>2.887</td><td colspan="2">2.887</td></tr>
<tr><td>Dose Equivalent</td><td>Hp(S)</td><td colspan="2">MIN. = 3.551</td><td colspan="2">MAX. = 4.172</td></tr>
<tr><td>(mSv)</td><td>Hp(D)</td><td colspan="2">MIN. = 3.309</td><td colspan="2">MAX. = 3.901</td></tr>
</table>

Table 7. Performance index* of the irradiated and calculated dose for AGFA film by matrix approximation.

Energy	Irradi. Dose		Performance Index	
(keV)	Hp(10)	Hp(0.07)	Hp(10)	Hp(0.07)
16	0.6	1.96	0.08	0.12
23	1.64	2.14	0.186	0.14
33	2.29	2.46	0.05	0.05
48	3.09	3.92	−0.03	−0.07
65	3.48	3.16	0.136	0.17
83	3.43	3.16	0.25	0.21
100	3.30	3.09	0.137	0.09
208	2.74	2.66	−0.033	−0.03
1250	2.28	2.24	−0.04	−0.01

* Bias B+performance quotient P
P=[H'−H]/H, H'=Irradiated dose and
H=Reported dose
$B=\bar{P}$

$$D_j = \sum_{i=1}^{n} k_{i,j}\, d_i \pm d'_i \tag{5}$$

To minimize errors in Eq 5, we can use the objective function C

$$C = \sum_{i=1}^{n} \alpha_i d_i + \sum_{i=1}^{n} \beta_i d'_j \tag{6}$$

For the total minimum dose, the coefficients α and β are always positive, and for the total maximum dose, these values are always negative. To optimize the algorithm of Eqs. 5 and 6, the computer program 'Simplex [13]' was used and its sample results for 33 keV 2 mGy show in Table 6.

The calculation results for various radiation energies are in Table 7.

CONCLUSIONS

Prior to the conclusion, it should be stressed that good QA/QC programme can assure good results. It means that sensitivity and contrast of a photographic emulsion are materially influenced by the type of developing agents, their age and temperature, as well as by the developing time, the type of film developing rack, and the mode of agitation during the developing process. Processing condition should therefore be kept as nearly constant as possible and calibration films should be processed along with the monitoring film to adjust the calibration curve in such a ways as to compensate for any change in processing conditions.

Bear in mind the above conditions, we must always make use of an energy dependent correction to overcome the problem of the strongly energy dependent film sensitivity in the dose evaluation from film badge readings, and the experimental results contained in this paper enable the following conclusions to be drawn.

(1) The PS1 film badge dosimeter is suitable for the measurement of both Hp(10) and Hp(0.07) within the accuracy of ±30 % over the photon energy 16 keV∼1,250keV.

(2) The performance in (1) above was obtained using empirical equation 2 for unmixed X-or γ-ray fields.

(3) To obtain more accurate results in mixed radiation fields, degree-of-fit method and matrix approximation could be used within the performance level of (1) above.

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