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■論 文■

Development of TLD Algorithms by Monochromatic Fluorescence Radiations and Continuous Spectrum X-rays

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단일에너지 형광 X선 및 연속 스펙트럼 X선장에 의한 TLD 알고리즘 개발

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Abstract - Personal dosimetry system is required to measure the personal dose equivalent accurately in a wide range of radiation fields, but the dose evaluation algorithms have been developed with the X-ray fields described in MOST Ordinance (equivalent to the ANSI N13.11) from which the actual fields to be monitored may be significantly different. To evaluate the dose more accurately when workers are exposed to the non-ANSI N13.11 radiation fields, two algorithms for monochromatic radiations (one algorithm was used for various ratios of TL dosimeter and the other for matrix approximation) were developed with the experimental data of the energy responses of the $CaSO_4$:Dy TL materials irradiated by monochromatic X-ray fields recently established in KAERI, and compared with the another algorithm developed on the basis of the ANSI N13.11 continuous spectrum X-ray fields. Then it follows the discussions for some results of the algorithm testing including mixed fields irradiations and angular response conducted in IAEA/RCA intercomparison as well as ANSI and ISO continuous spectrum X-ray and monochromatic radiation fields. The developed algorithms were successfully performed the test not only in the continuous spectrum X-ray fields given by MOST Ordinance but also in the several non-MOST Ordinance radiation fields which could be encountered in the practical working environments.
Keywords : TLD algorithm, monochromatic radiation, continuous spectrum X-ray

요약 - 개인방사선측정시스템은 광범위한 에너지의 방사선에 대하여 정확한 개인선량당량을 측정할 수 있어야 하지만 현재 사용중인 선량평가 알고리즘은 ANSI N13.11의 방사선장과 거의 유사한 과학기술부 고시에 명시되어 있는 X-선장을 기준으로 개발되었고 이는 실제 측정이 요구되는 방사선장과 상당한 차이가 있을 수 있다. 방사선작업종사자가 ANSI N13.11의 방사선장과 다른 형태의 방사선에 피폭되었을 경우 좀더 정확한 선량을 평가하기 위하여 한국원자력연구소에 설치되어 있는 단일에너지 X-선장에 $CaSO_4$:Dy 열형광체를 조사시켜 에너지반응도를 실험적으로 구한 후 두 가지 형태의 알고리즘을 개발하였으며 이를 ANSI N13.11의 연속스펙트럼 X-선장에 기본을 두고 개발한 알고리즘과 비교하였다. 알고리즘 개발후 ANSI, ISO의 연속 스펙트럼 X-선 및 단일에너지 X-선장과 IAEA/RCA 상호비교시험시 사용되었던 혼합방사선장 및 각도변화 실험데이타를 이용하여 이를 검증하였다. 검증결과 개발된 알고리즘들은 과학기술부 고시에 나타나 있는 X-선장뿐만 아니라 방사선작업환경에서 피폭될 수 있는 다른 종류의 방사선장에서도 매우 정확한 선량평가를 하고 있음을 확인하였다.
중심어 : TLD 알고리즘, 단일에너지 방사선, 연속에너지 스펙트럼 X-선

INTRODUCTION

The basic requirements of personal dosimetry are to provide a reliable measurement of the operational quantities, $H_p(10)$ and $H_p(0.07)$ for almost all practical situations independent on the type, energy and direction of incidence of the radiation with a prescribed overall accuracy. General guidance on these requirements will be given by IAEA Safety Guide[1]. Additional information is provided by the ICRP Publication 60 and 75[2,3], the ICRU Publication 39, 43 and 47[4,5,6], and the Report of the Joint Task Group of the ICRU and ICRP[7,8]. Of these requirements, particularly important problem of the measurement of personal dose equivalent is the dependence of the dosimeter response on the energy of radiation[9].

The energy responses of TLD to the low energy photon (10 ~ 300 keV) are very different from those of the high energy photons (^{137}Cs, ^{60}Co), because most of TL detectors are not tissue equivalent. So the response of TL materials is a function of photon energy. This energy dependence of the response depends on the material, thickness and encapsulation of detector. The characteristics test of the TL materials for low energy photon range is usually performed by using the continuous X-ray spectra but the energy responses for those spectra are also different from those for the monochromatic photons. Above the energy of 100 keV of the photons, the calculated dose conversion coefficients based on the continuous distribution of X-ray spectra have not big differences with those of spectrum averaged energy which can be obtained by interpolation of the values represented in the ICRU and ICRP Publication[6,8,10], but for the X-ray energy below 100 keV this difference can not be negligible and in this case the monochromatic radiations become useful for calibrating of TLD. For X-ray spectra below about the energy of 50 keV the predominant contribution of the air kerma comes from the low energy part of the photon fluence spectrum, but conversely personal dose equivalent, $H_p(10)$, is predominantly determined by the high energy part of the spectrum. This means that any modification of the spectrum shape or monochromatic spectrum will result in different effects on air kerma and personal dose equivalent compared with those from the continuous X-ray spectrum which are mostly used to develop TLD algorithm.

In practice, radiation fields to which workers are exposed are unlikely to be monochromatic, and also unlikely monodirectional relative to the workers. Even direct exposure to a gamma ray source, such as ^{137}Cs will result in irradiation by a range of photon energies due to scattering from the source material, the source holder, collimating system, air scatter and scatter from the walls of the room and its contents. And workers are to be exposed by multiple sources involved in many cases. But also workers do not seem to be exposed to the same energy spectra described in ANSI N13.11[11] which includes the basic information to construct the dose evaluation algorithm by personal dosimeter processors in Korea according to the MOST Ordinance 96-6[12].

So in this paper the energy dependences of $CaSO_4$:Dy TL materials, which are currently being used for the personal monitoring in Korea Atomic Energy Research Institute (KAERI), were measured using ANSI N13.11 continuous X-ray spectra and monochromatic fluorescence X-rays described in previous papers[13,14]. Based on the results for energy dependences of two kinds of X-ray fields, three different algorithms were developed (two of them are based on the "Table-of-Ratio" for continuous spectrum X-ray and monochromatic X-ray fields, respectively and the other is matrix approximation[15] for monochromatic X-ray fields) and compared their performances by irradiating TLD to the ANSI, ISO, monochromatic X-ray fields and other radiation qualities. The developed algorithm based on the monochromatic radiation is confirmed to use in the radiation work places in which the radiation qualities are not known or in low energy photon mixed fields.

MATERIALS AND METHODS

Teledyne 300 TLD Reading System

The personal dosimetry system for the development of TLD algorithms was Teledyne 300 automatic TLD reading system and C-300-A badge (Teledyne Co., USA). The phosphor of dosimeter is $CaSO_4$:Dy that is known to be highly sensitive to photons. The badge case is divided into four areas, each with a different set of dosimetric properties depending on the filters presented. The filter materials and thickness are given in Table 1. A description of the filters in the badge is that the open window, area 1, has 7 mg/cm^2 of mylar covering for beta response. The second filter, area 2, is the area for attenuating most of the betas. Thus if area 2 which includes gamma only is subtracted from area 1 which includes both beta and gamma, a net beta response can be determined. A simple subtraction can not be made if the badge case is also exposed to low energy photons, so a correction has to be applied to the other areas to obtain the correct beta response. Area 3 and 4 include thick filter materials for measuring high energy photons. The copper filter has a hole in it to provide a relative flat response for the $H_p(d)$. Three algorithms were developed to evaluate personal dose equivalent $H_p(d)$ for the TLD system using ANSI N13.11 X-ray fields[13] and monochromatic fluorescence radiations[14] established in KAERI. The basic concept of the first two algorithms was used for various ratios of the reading values with the 4 different filter areas and energies using 5 ANSI N13.11 continuous spectrum X-ray fields and 8 monochromatic radiations respectively, these ratios could represent the characteristic fields of X-ray and gamma ray or mixed fields. Another concept for the third algorithm was the matrix approximation using the results of TL energy response for monochromatic radiations. The TLD system was calibrated at Secondary Standard Dosimetry Laboratory of KAERI before development of algorithms.

Table 1. Filter materials for each area of P-300-AS badge system.

Element	Filter material and thickness
P1 & S1	7 ㎎/㎠ black polyethylene
P2 & S2	Badge case + Plastic plate 0.04″ ×2 + 647 ㎎/㎠ = 863 ㎎/㎠
P3 & S3	Badge case + Al 0.04″ × 2 + 650 ㎎/㎠ = 866 ㎎/㎠
P4 & S4	Badge case + Al +Cu + Sn/Pb 0.04″ ×2 + 34 ㎎/㎠ + 434.5 ㎎/㎠ + 560.4 ㎎/㎠ = 1245 ㎎/㎠

Radiation Sources and Irradiation Conditions

Continuous and monochromatic X-radiations were obtained by HF-75c (Pentak, UK) for low energy M30 of ANSI X-ray and MG325 (Phillips, Germany) for the other radiation qualities. Energies for the first algorithm were the ANSI N13.11 spectrum X-rays which are currently being used for the performance test in Korea as shown in Table 2, and those for the other two algorithms were the monochromatic fluorescence radiations as shown in Table 3.

The air kerma rates were determined by Shonka A3 (3.6 ml, Exradin) chamber for ANSI beams and by NE2530/1 (35 ml, NE) chamber for monochromatic radiations. Detailed methods for calibration are in the references[14,16], and the air kerma rates are also indicated in the Table 2 and 3.

The reference dosimeters for algorithms were irradiated on a tissue equivalent phantom constructed of polymetylmethacrylate (PMMA) having a dimension of 30 x 30 x 15 cm according to the suggestion of ICRU and ANSI N13.11[6,11]. Four dosimeters were attached to the phantom surface at each irradiation. These

Table 2. Characteristics of ANSI N13.11 Photon Fields and Conversion Coefficients.

Radiation Sources							C.C. (Sv/Gy)		Air Kerma Rate
Beam Code	Add Filter(mm) Al	Cu	Sn	HVL (mmAl)	Homogeniety $\left(\frac{\text{1st HVL}}{\text{2nd HVL}}\right)$	Average E.(keV)	$H_p(10)$	$H_p(0.07)$	mGy/min
M30	0.5			0.36	0.64	20	0.42	1.02	14.37
M60	1.51			1.68	0.68	34	1.00	1.21	10.65
M100	5.0			5.03	0.73	51	1.52	1.49	10.53
M150	5.0	0.25		10.25	0.89	70	1.78	1.64	12.58
H150	4.0	4.0	1.51	17.0	1.0	117	1.71	1.60	0.52
Cs-137						662	1.21	1.21	4.50

Table 3. Characteristics of Monochromatic Radiations and Conversion Coefficients.

Target	Filter	$E_{K\alpha}$ (keV)	H.V. (kVp)	Current (mA)	Conversion Coefficients(Sv/Gy)* $H_p(10)$	$H_p(0.07)$	Air Kerma Rate mGy/h
Zn	Cu	8.64	50	10	0	0.93	11.71
Mo	Zr	17.5	80	20	0.44	1.01	54.52
Sn	Ag	25.3	100	20	0.89	1.14	35.69
Nd	Ce	37.4	110	20	1.40	1.39	9.74
Er	Gd	49.1	120	20	1.75	1.62	10.50
W	Yb	59.3	170	15	1.89	1.72	9.05
Au	W	68.8	170	15	1.90	1.73	2.87
Pb	Au	75	200	15	1.90	1.73	7.77

*Data from Ref. 7, 8 and 19.

dosimeters facing the source were mounted with their back planes directly to the surface of the phantom, and the distances between center of the source and the phantom surface varied 1 to 2 m with the air kerma rates at which the field may be assumed to be aligned and expanded. At each energy 10 dosimeters were irradiated and repeated 3 times to reduce the statistical deviation.

CONSTRUCTION OF THE ALGORITHMS

Energy Responses

If a TL material is to be used for dosimetric applications in the field of photon radiation, one of the main characteristics that must be known is its energy response. This energy response is defined as a measure of the energy absorbed in the TL material to the energy absorbed in a material taken as the reference (normally air) when irradiated at the same exposure. The energy response is therefore characteristic of each TL material and a direct measurement is obtained when the material is under electronic equilibrium conditions.

Bassi *et al.*[17] calculated the energy responses with the monoenergies for various type of TL materials. Because below 100 keV of photon energy the photoelectric effect becomes important and accounts for the energy dependence of most dosimeters, high atomic number material such as $CaSO_4$ with an over-estimation of about a factor of more than 10 at around 50 keV are preferably used in personal monitoring in order to estimate radiation quality.

But currently used TL algorithm is usually

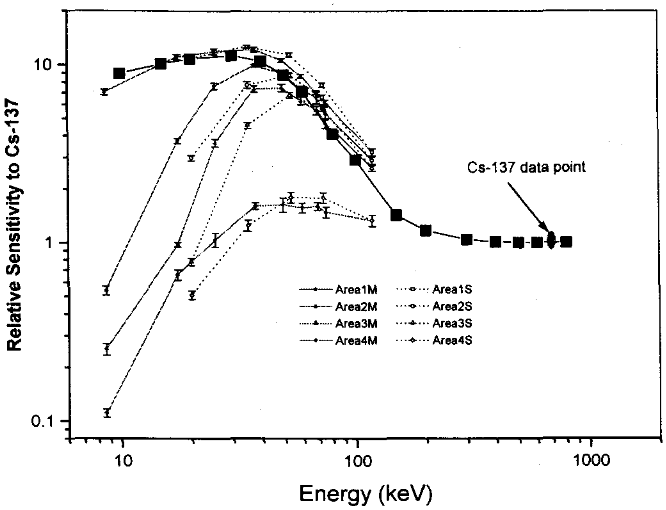

Fig. 1. Energy Responses of $CaSO_4$:Dy for ANSI N13.11 Continuous Spectrum(···) and Monochromatic Fluorescence Radiation(—). The calculation results by Bassi for $CaSO_4$:Dy[17] are represented by ■. Area1M and Area1S mean the response data of filter area 1 for monochromatic fluorescence radiation and continuous spectrum, respectively.

constructed with the aid of the continuous spectrum radiation fields, it must be investigated the differences of the energy response with the monochromatic radiations.

Fig. 1 shows the energy responses for the above two types of radiation qualities. In open area (area 1) the responses are nearly same for the both radiation qualities. Also the calculated results by Bassi in open area are very consistent with the experimental results. But the responses for the monochromatic radiations are usually higher than those of spectrum X-rays in other filter areas because the filter materials in TLD badge case cut off low energy parts of the X-ray spectrum. These differences in responses would be led a wrong dose evaluation result when radiation worker is irradiated to the some different types of radiations with the continuous spectrum.

Dose Evaluation Algorithms

1. Degree-of-Fit Method

If the TL dosimeter 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, the reference 'Table-of-Ratio' for continuous spectrum algorithm and mono-energy algorithm were produced by four filter areas using above energy response data. Table-of-Ratio consisted of R10 to R16 and conversion coefficients CF1 and CF2 for reference is shown in Table 4, 5 for two types of radiations.

When personal data of the four filter areas are read, these data are transformed to relative ^{137}Cs dose by reader calibration factor, 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.

$$DOF = \sum_{i=10}^{16} \frac{R_{i,ref} - R_{i,meas}}{R_{i,ref}} \quad \text{------------} \quad (1)$$

Table 4. Table-of-Ratio for Algorithm of the ANSI X-Ray Fields.

Radiation	X-ray	Cs-137	R10*	R11	R12	R13	R14	R15	R16	CF1	CF2	CF3
M30	1	0	5.85	3.64	22.38	3.82	1.53	124.62	1078	1.39	2.43	3.64
(20keV)	1	0.33	3.95	3.38	11.79	2.99	1.32	52.64	453.8	1.17	1.73	3.38
	1	0.5	3.45	3.26	9.4	2.72	1.27	38.87	325.88	1.12	1.58	3.26
	1	1	2.64	2.98	5.91	2.24	1.18	20.77	156.11	1.06	1.37	2.98
	0.5	1	1.99	2.58	3.57	1.79	1.11	10.2	61.32	1.01	1.21	2.58
	0.33	1	1.7	2.31	2.69	1.58	1.08	6.68	33.13	0.99	1.15	2.31
M60	1	0	6.18	1.64	10.45	1.69	3.65	62.68	46.25	1.43	1.21	1.64
(35keV)	1	0.33	5.1	1.62	8.38	1.65	3.1	41.95	35.34	1.29	1.15	1.62
	1	0.5	4.7	1.6	7.63	1.62	2.89	35.37	31.4	1.24	1.13	1.6
	1	1	3.88	1.57	6.07	1.57	2.47	23.56	23.42	1.16	1.09	1.57
	0.5	1	2.99	1.51	4.43	1.48	2.02	13.5	15.24	1.08	1.06	1.51
	0.33	1	2.51	1.46	3.56	1.42	1.77	9.21	11.08	1.04	1.04	1.46
M100	1	0	4.89	1.3	6.32	1.29	3.78	31.01	13.85	1.35	0.98	1.3
(53keV)	1	0.33	4.28	1.29	5.48	1.28	3.34	23.62	11.71	1.26	0.98	1.29
	1	0.5	4.04	1.28	5.15	1.27	3.17	20.92	10.86	1.23	0.99	1.28
	1	1	3.5	1.27	4.39	1.26	2.78	15.49	8.95	1.17	0.99	1.27
	0.5	1	2.84	1.24	3.48	1.23	2.31	10.01	6.69	1.1	0.99	1.24
	0.33	1	2.44	1.22	2.94	1.2	2.03	7.3	5.37	1.06	0.99	1.22
M150	1	0	3.68	1.17	4.24	1.15	3.2	15.89	6.8	1.15	0.92	1.17
(73keV)	1	0.33	3.27	1.16	3.73	1.14	2.86	12.4	5.86	1.11	0.94	1.16
	1	0.5	3.1	1.16	3.53	1.14	2.72	11.11	5.49	1.09	0.94	1.16
	1	1	2.72	1.15	3.07	1.13	2.41	8.5	4.65	1.06	0.95	1.15
	0.5	1	2.27	1.13	2.52	1.11	2.04	5.81	3.65	1.03	0.97	1.13
	0.35	1	2	1.12	2.19	1.1	1.82	4.45	3.06	1.01	0.97	1.12
H150	1	0	2.18	1.11	2.41	1.11	1.97	5.28	3.33	0.89	0.94	1.11
(118keV)	1	1	1.94	1.1	2.13	1.09	1.78	4.17	2.85	0.9	0.95	1.1
	1	0.5	1.86	1.1	2.02	1.09	1.7	3.78	2.67	0.9	0.95	1.1
	1	1	1.67	1.08	1.8	1.08	1.55	3.04	2.3	0.91	0.96	1.08
	0.5	1	1.47	1.07	1.56	1.06	1.39	2.31	1.9	0.92	0.97	1.07
	0.35	1	1.36	1.06	1.43	1.05	1.3	1.95	1.68	0.93	0.98	1.06
Cs-137	1	1	1	1	1	1	1	1	1	0.94	1	1
Sr/Y-90	1	0	1.3	38.22	2.02	1.55	0.84	65.04	112931	0	0	38.22
	1	0.35	1.02	3.89	1.05	1.03	0.99	4.04	61.83	1	3.85	3.89
	1	0.5	1.01	2.96	1.03	1.02	0.99	3.04	26.8	0.98	2.88	2.96
	1	1	1.01	2.01	1.02	1.01	1	2.03	8.22	0.96	1.94	2.01
	0.5	1	1	1.51	1.01	1	1	1.52	3.47	0.95	1.47	1.51
	0.33	1	1	1.34	1.01	1	1	1.34	2.41	0.95	1.31	1.3+4

* R10 = A2/A4, R11 = A1/A2, R12 = $A2^2$/A3*A4, R13 = A2/A3, R14 = A3/A4
R15 = A1*A2/$A4^2$, R16 = $A1^3$/A2*A3*A4

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.

2. Matrix Approximation

If we need more accurate information for irradiated radiation energies, we can use matrix approximation[15]. 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 as

$$D_j = k_{1,j}d_1 + k_{2,j}d_2 + \ldots k_{i,j}d_i \ldots + k_{n,j}d_n \text{ ------- } (2)$$

where d_1, d_2, ... d_i, ... d_n are doses from

Table 5. Table-of-Ratio for Algorithm of the Monochromatic X-Ray Fields.

Radiation	X-ray	Cs-137	R10	R11	R12	R13	R14	R15	R16	CF1	CF2	CF3
ZnCu	1	0	4.85	13.11	8.32	1.72	2.82	307.97	18734	0	0	13.11
(8.6 keV)	1	0.33	1.97	8.51	2.66	1.35	1.46	32.96	1634.23	1.26	3.32	8.51
	1	0.5	1.7	7.28	2.17	1.28	1.33	21.01	835.46	1.15	2.53	7.28
	1	1	1.38	5.24	1.62	1.17	1.18	10.04	232.8	1.05	1.77	5.24
	0.5	1	1.2	3.57	1.32	1.1	1.1	5.16	59.89	0.99	1.38	3.57
	0.33	1	1.14	2.83	1.21	1.07	1.06	3.65	27.37	0.98	1.25	2.83
MoZr	1	0	5.65	2.95	21.65	3.83	1.48	94.45	558.42	1.71	2.3	2.95
(17.5 keV)	1	0.33	4.1	2.8	12.78	3.11	1.32	47.08	279.24	1.35	1.68	2.8
	1	0.5	3.65	2.72	10.47	2.87	1.27	36.26	211.62	1.27	1.54	2.72
	1	1	2.85	2.54	6.83	2.4	1.19	20.66	112.2	1.15	1.34	2.54
	0.5	1	2.16	2.27	4.15	1.93	1.12	10.56	48.77	1.06	1.2	2.27
	0.33	1	1.83	2.08	3.1	1.69	1.09	6.98	27.81	1.02	1.14	2.08
SnAg	1	0	7.31	1.56	15.3	2.09	3.5	83.65	58.51	1.33	1.28	1.56
(25.3 keV)	1	0.33	5.79	1.54	11.6	2	2.9	51.71	42.37	1.21	1.19	1.54
	1	0.5	5.26	1.53	10.32	1.96	2.69	42.38	36.89	1.18	1.17	1.53
	1	1	4.22	1.5	7.83	1.86	2.27	26.68	26.35	1.11	1.12	1.5
	0.5	1	3.16	1.45	5.39	1.7	1.85	14.45	16.31	1.05	1.08	1.45
	0.33	1	2.61	1.4	4.17	1.6	1.64	9.59	11.52	1.02	1.05	1.4
NdCe	1	0	6.16	1.23	8.32	1.35	4.56	46.77	15.6	1.31	0.99	1.23
(37.4 keV)	1	0.33	5.28	1.23	7.05	1.34	3.95	34.17	12.99	1.23	0.99	1.23
	1	0.5	4.93	1.22	6.55	1.33	3.72	29.76	11.96	1.2	1	1.22
	1	1	4.18	1.21	5.47	1.31	3.19	21.18	9.74	1.14	1	1.21
	0.5	1	3.3	1.19	4.21	1.28	2.59	12.99	7.16	1.08	1	1.19
	0.33	1	2.79	1.18	3.48	1.25	2.23	9.16	5.7	1.04	1	1.18
ErGd	1	0	5.5	1.18	6.64	1.21	4.55	35.58	10.86	1.07	0.93	1.18
(49.1 keV)	1	0.33	4.74	1.17	5.69	1.2	3.95	26.34	9.15	1.04	0.94	1.17
	1	0.5	4.44	1.17	5.31	1.2	3.72	23.07	8.48	1.04	0.94	1.17
	1	1	3.79	1.16	4.49	1.18	3.2	16.67	7.01	1.02	0.96	1.16
	0.5	1	3.02	1.15	3.52	1.16	2.6	10.47	5.29	0.99	0.97	1.15
	0.33	1	2.58	1.13	2.96	1.15	2.24	7.52	4.3	0.98	0.98	1.13
WYb	1	0	4.68	1.18	5.48	1.17	4	25.83	8.97	0.95	0.91	1.18
(59.3 keV)	1	0.33	4.04	1.17	4.7	1.16	3.48	19.14	7.54	0.95	0.93	1.17
	1	0.5	3.79	1.17	4.39	1.16	3.27	16.79	6.98	0.95	0.93	1.17
	1	1	3.25	1.16	3.73	1.15	2.83	12.22	5.78	0.95	0.95	1.16
	0.5	1	2.62	1.14	2.96	1.13	2.32	7.83	4.39	0.94	0.96	1.14
	0.33	1	2.26	1.13	2.52	1.12	2.02	5.74	3.6	0.94	0.97	1.13
AuW	1	0	4.09	1.07	4.84	1.18	3.45	17.82	5.88	0.97	0.91	1.07
(68.8 keV)	1	0.33	3.56	1.06	4.18	1.17	3.04	13.49	5.03	0.96	0.93	1.06
	1	0.5	3.35	1.06	3.92	1.17	2.87	11.96	4.7	0.96	0.93	1.06
	1	1	2.9	1.06	3.35	1.16	2.51	8.92	3.98	0.96	0.95	1.06
	0.5	1	2.38	1.05	2.7	1.13	2.09	5.93	3.13	0.95	0.96	1.05
	0.33	1	2.07	1.05	2.32	1.12	1.85	4.48	2.65	0.95	0.97	1.05
PbAu	1	0	3.61	1.15	4.13	1.14	3.16	15.01	6.27	0.89	0.91	1.15
(75 keV)	1	0.33	3.14	1.14	3.56	1.13	2.77	11.24	5.28	0.9	0.93	1.14
	1	0.5	2.96	1.14	3.34	1.13	2.62	9.93	4.9	0.9	0.93	1.14
	1	1	2.56	1.13	2.86	1.12	2.29	7.39	4.08	0.91	0.95	1.13
	0.5	1	2.11	1.11	2.33	1.1	1.92	4.96	3.17	0.92	0.96	1.11
	0.33	1	1.86	1.1	2.02	1.09	1.71	3.79	2.66	0.92	0.97	1.1
Cs-137	0	1	1	1	1	1	1	1	1	0.94	1	1

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. 1 for monoenergy responses 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. 2 with the error function d'_j to find maximum or minimum total dose D_j,

$$D_j = \sum_{i=1}^{n} k_{i,j}\, d_i \pm d'_j. \qquad (3)$$

To minimize errors in Eq 3, we can use the objective function C

$$C = \sum_{i=1}^{n} \alpha_i d_i + \sum_{i=1}^{4} \beta_i d'_j. \qquad (4)$$

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. 3 and 4, the computer program 'Simplex[18]' was used and its sample results for M60 (35 keV) 10 mGy shows in Table 6.

VERIFICATION OF THE ALGORITHMS AND DISCUSSIONS

The calculation results using developed three algorithms are in Fig. 2 to 4 for ANSI[13], ISO[19] and monochromatic fluorescence radiation fields[14]. The algorithm based on the ANSI continuous spectrum X-ray shows a little better results for ANSI and ISO X-ray fields than those of the other two algorithms because reference Table-of-Ratio of this algorithm is generated from the continuous spectrum X-ray data. In contrast the results of two algorithms based on the monochromatic radiation and matrix approximation have very similar fashion and are very consistent with the conventional true irradiation doses for the monochromatic radiations. It means that because the radiation

Table 6. Results for M60 (35 keV), 10 mGy by Matrix Approximation.

```
*********************************************************************
*                  APPARENT DOSE TO Cs-137                          *
*               ******************************                      *
*       14.401      10.316       5.697       1.453                  *
*                INTERPRETATION OF  LECTURES                        *
*             **********************************                    *
*      CALCULATED TOTAL MINIMUM EXPOSURE   =   1.208  R             *
*      CALCULATED TOTAL MAXIMUM EXPOSURE   =   1.209  R             *
*********************************************************************
* RADIATIONS        MIN. AD-E   MAX. AD-E   MIN. AD+E    MAX. AD+E  *
* ***********       **********  **********  **********   ********** *
* 11    28 KEV        1.001       1.001        .990         .990    *
* 12    30 KEV         .188        .188        .198         .198    *
* 15    36 KEV         .019        .019        .020         .020    *
*                                                                   *
*     TOTAL           1.209       1.209       1.208        1.208    *
*                        VARIABLES OF VALUE                         *
*                     **********************                        *
*  1   *               .018        .018        .000         .000    *
*  2   *               .000        .000        .008         .008    *
*********************************************************************
*   DOSE EQUIVALENT     Hp(0.07)  MIN. =   1.267    MAX. =   1.267  *
*       (mSv)           Hp(10)    MIN. =   1.106    MAX. =   1.106  *
*********************************************************************
```

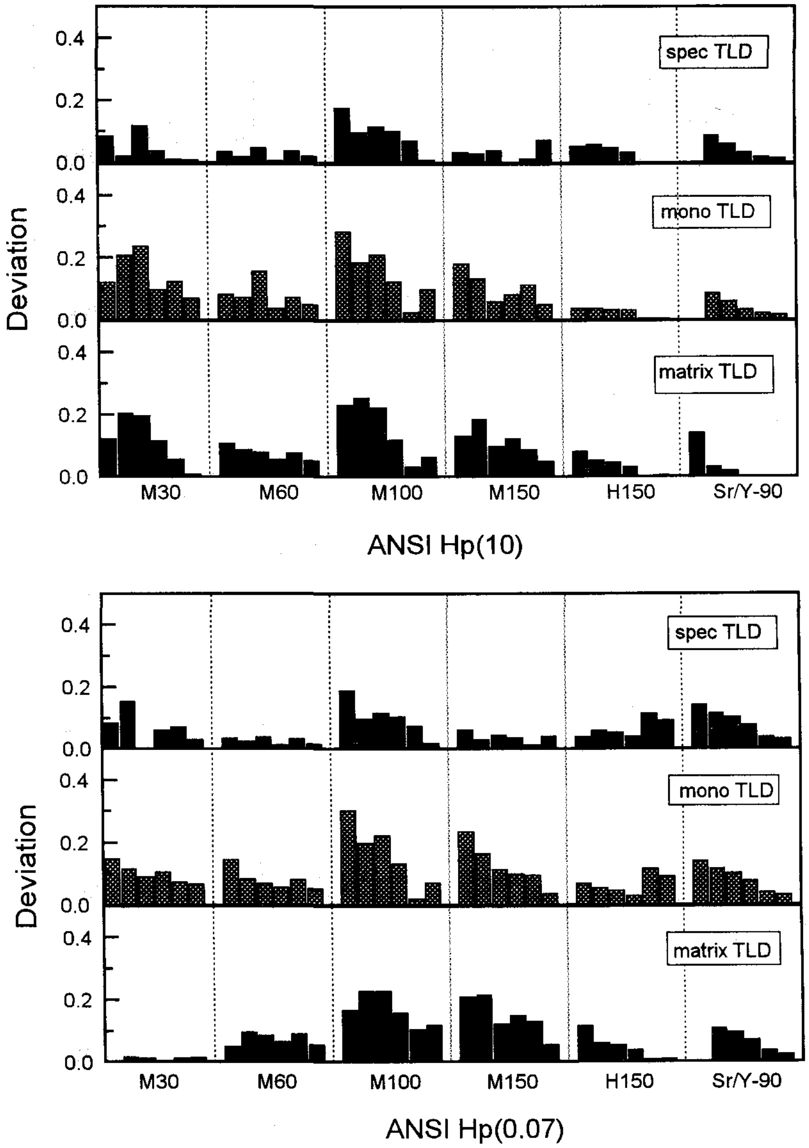

Fig. 2. Deviation(| (Measured Dose-Delivered Dose)/(Delivered Dose) |) for ANSI N13.11 Radiation Fields Calculated by Spectrum Based Algorithm(Spec TLD), Monochromatic Radiation Based Algorithm(Mono TLD) and Matrix Based Algorithm(Matrix TLD). The six bars in each radiation quality represent the mixture ratios of X-ray : ^{137}Cs as 1:0, 1:0.33, 1:0.5, 1:1, 0.5:1 and 0.33:1, respectively.

fields for personal dosimeter proficiency test are the continuous spectrum X-ray the results for the two algorithms based on the monochromatic radiation fields are a little worse than those of spectrum X-ray based algorithm, when radiation worker, however, is exposed to the radiation except for the continuous X-rays these two algorithms can perform the more accurate dose evaluation. Also the spectrum based algorithm is very difficult to distinguish between X-ray and beta particle in low energy X-ray (less than 20 keV) as shown in Fig. 3, so this algorithm would be caused a severe reading error in this energy range. In the condition that the energy

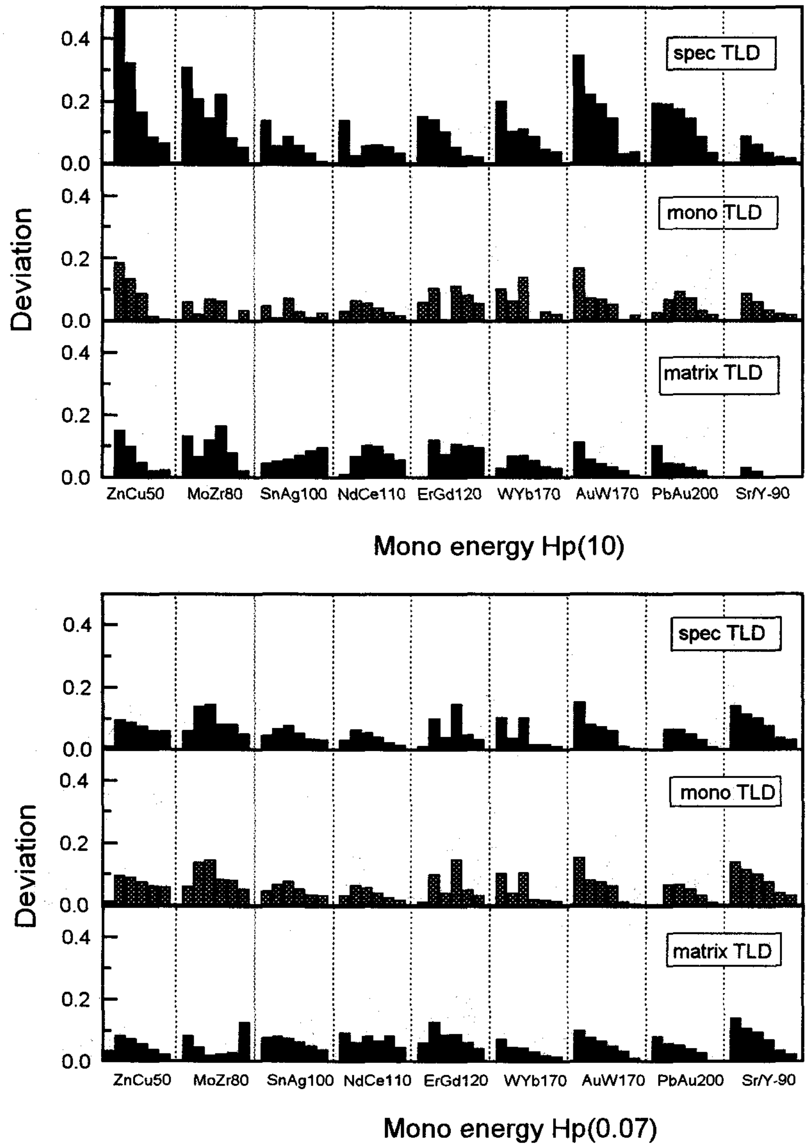

Fig. 3. Deviation for Monochromatic Fluorescence Radiations. The notations are same as the Fig. 2.

ranges under which a personal dosimetry is required to perform are widely expanding, the accurate measurement of the discrete set of radiation fields defined by the MOST Ordinance [12] based on the ANSI standard[11,20] was just seen as the goal of a dosimetry program, but it should be stressed that ANSI radiation fields only defined the minimum legal standard[21]. To satisfy the regulation as currently enforced, a dosimetry program must accurately measure the radiation fields of the MOST Ordinance, but the ability to measure the doses of interest in other radiation fields presented in work environment is also important. So personal dosimeter processors can use several dose calculation algorithms to measure the doses for the various X-ray fields in which dosimeter is used, and the algorithm derived from the use of energy dependence by the monochromatic radiation should be effective in this case.

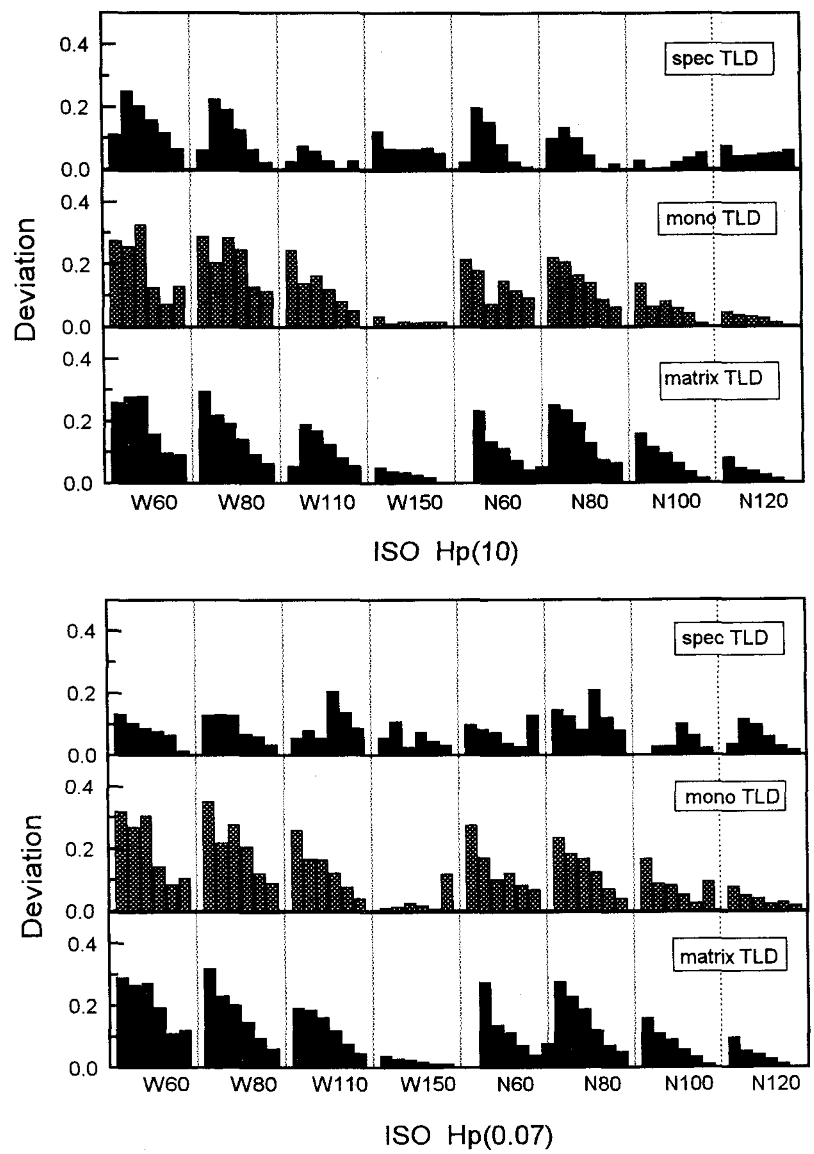

Fig. 4. Deviation for ISO Wide and Narrow Series X-Ray Fields. The notations are same as the Fig. 2.

The data for seven categories and fifteen dosimeters at each category according to the MOST Ordinance were run through the three algorithms to check of the accuracy and precision. The irradiation levels were selected with the aid of random number, ρ, between 0 and 1, and the dose equivalents, H, were represented as

$$\log H = \log(H)_l + \rho[\log(H)_u - \log(H)_l] \quad (5)$$

where $(H)_l$ and $(H)_u$ are the lower and upper limits of the range of the test irradiation levels in the Ordinance. The results of this test are contained in Fig. 5. As seen in the Fig, the performances of the spectrum X-ray based algorithm are a little better than those of the other two algorithms as expected, but the performances of the three results are better

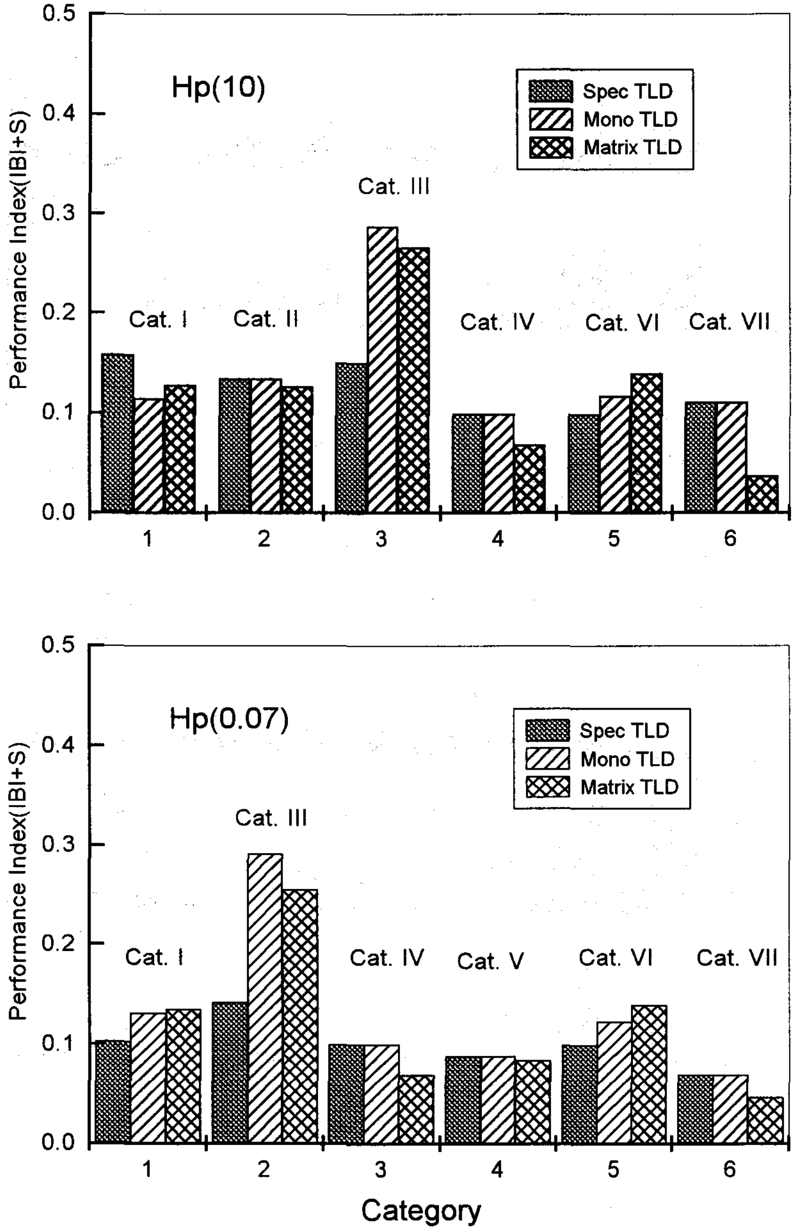

Fig. 5. Results of the Performance Test According to the MOST Ordinance by 3 Different Algorithms. Radiation qualities in each category are given in Ref. 12.

than 30 % in all cases. According to the suggestion of the ICRP[3,22] that the accuracy in the routine individual monitoring for external radiation should be in the acceptable uncertainty, the ratios of the measured personal dose equivalent to the conventional true dose are illustrated by the trumpet curves[23] in Fig. 6 and 7. It can be seen that for all irradiation categories all of the values evaluated by the three algorithms fall within the limits of the trumpet curves.

To verify the capability of the algorithms to evaluate the irradiation doses for the non ANSI radiation fields, doses by three algorithms were calculated from the reading values of the IAEA Regional Cooperation of Agreement (IAEA/RCA)

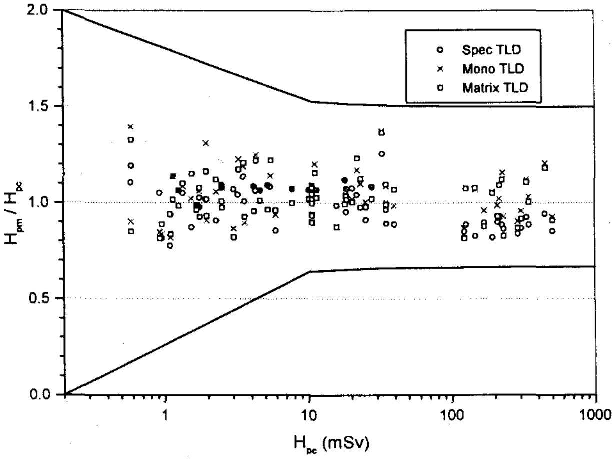

Fig. 6. Results of the Performance Test for $H_p(10)$ Represented by Trumpet Curves Using the Same Data in Fig. 5. H_{pc} and H_{pm} mean the conventional true dose of personal dose equivalent and the measured personal dose equivalent, respectively.

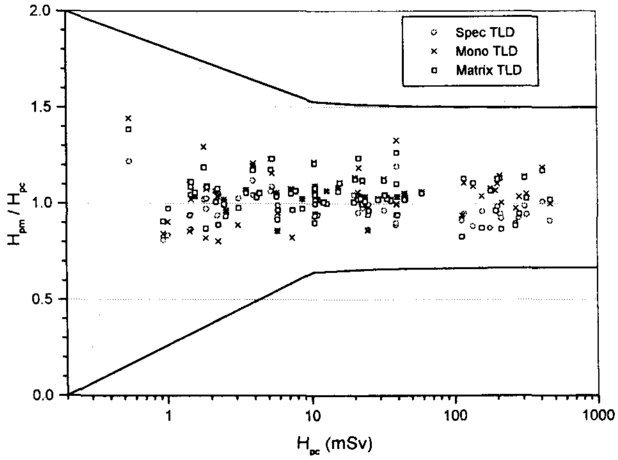

Fig. 7. Results of the performance test for Hp(0.07) represented by trumpet curves using the same data of Fig. 5. H_{pc} and H_{pm} mean the conventional true dose of personal dose equivalent and the measured personal dose equivalent, respectively.

personal dosimeter intercomparison study conducted from 1996 to 1997[24]. In this intercomparison six radiation categories ranged from 19.7 keV (ISO H30) to 1.25 MeV (^{60}Co) were offered including two categories with mixed fields (high energy ^{60}Co and 134 keV (ISO W200) X-ray plus low energy 45 keV (ISO W60) X-ray and one category with the dosimeters irradiated at the angle of 60° by 79 keV (ISO W110) X-ray. The calculation results are in Fig. 8. On the contrary to the other tests, two algorithms based on the mono-chromatic radiations show more precise results as compared with the spectrum based algorithm. It could be said that the radiation fields used are the mixed fields or nonperpendicular to the source from which the radiation fields are far from the energy responses for the spectrum

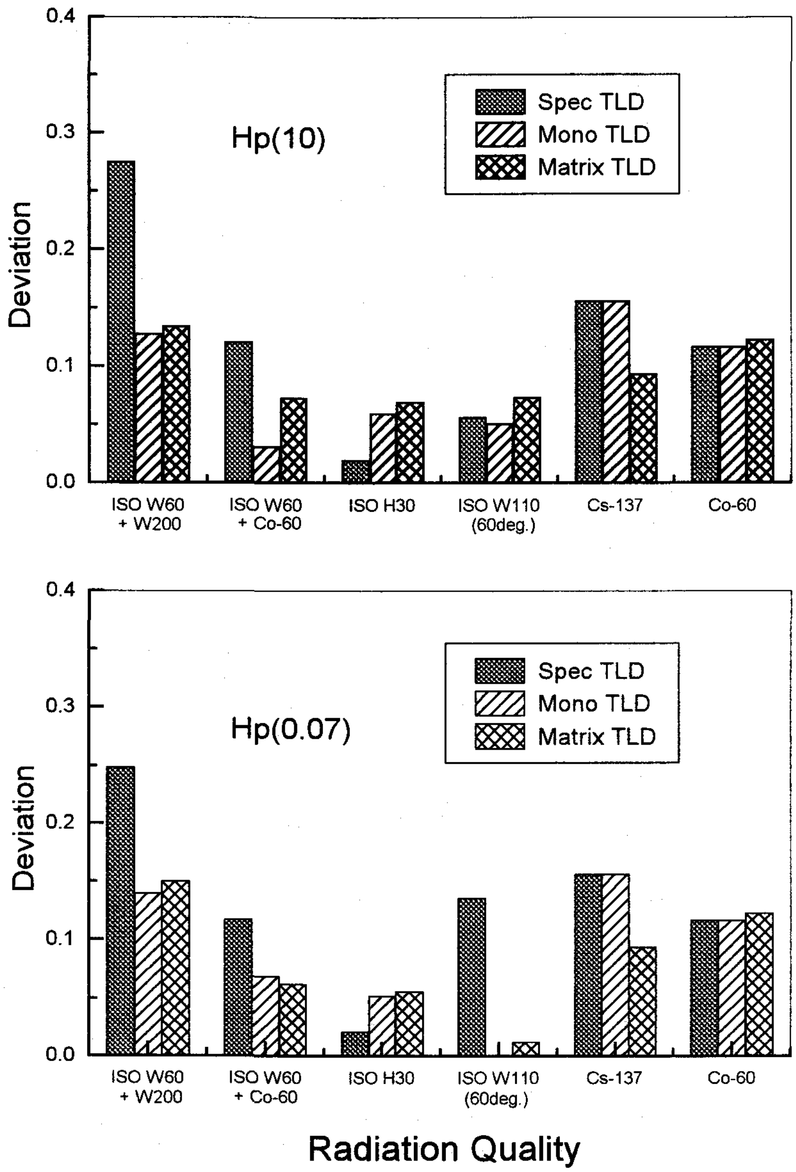

Fig. 8. Deviation for IAEA/RCA Intercomparison Study Conducted from 1996 to 1997 for 6 Radiation Qualities Calculated by three Different Algorithms.

based algorithm, then this algorithm might not distinguish the correct irradiation energies. In these cases it is clear that the monochromatic algorithm can calculate irradiation doses more effectively.

CONCLUSIONS

Personal dosimetry system is required to perform the measurement of personal dose equivalent in many different radiation fields. Though the categories specified in the MOST Ordinance should be accurately evaluated to satisfy legal requirements, more important capability in personal dosimetry is to measure the dose in the real working environments where the dosimeter is used because the radiation fields are often very different from the categories given in the Ordinance.

For evaluating the dose more accurately in this case, the energy dependence of $CaSO_4$:Dy phosphore was measured by monochromatic radiations established in KAERI and compared it with the results of ANSI N13.11 continuous spectrum X-ray fields. Usually monochromatic radiations show higher responses than spectrum X-ray fields because of a cut off in low energy parts of the spectrum X-ray. By using energy responses for two types of radiation fields, three kinds of dose evaluation algorithms were developed, one algorithm was used to the response data of spectrum X-ray, and the other two were based on the data of monochromatic radiations. It was verified that all of the developed algorithms in this study were satisfied with the prescribed overall accuracy in all cases of radiation types or mixtures. But spectrum based algorithm has advantage to evaluate the dose for the proficiency test of the MOST Ordinance because the radiation fields of this test are the continuous spectrum X-ray. On the while radiation fields in the working place are quite different from the ANSI X-ray fields, then monochromatic radiation based two algorithms are preferable to evaluate the dose more accurately.

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