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Development of a TL Personal Dosimeter Identifiable PA Exposure, and Comparison with Commercial TL Dosimeters

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A single-dosimeter worn on the anterior surface of the body of a worker was found to significantly underestimate the effective dose to the worker when the radiation comes from the back. Several researchers suggested that this sort of underestimation can be corrected to a certain extent by using an extra dosimeter on the back. However, use of multiple dosimeters also has disadvantages such as complication in control or incurrence of extra cost. Instead of the common multi-dosimeter approach, in this study, a single dosimeter introducing asymmetric filters which enabled to identify PA exposure was designed, and its dose evaluation algorithm for AP-PA mixed radiation fields was established. A prototype TL personal dosimeter was designed and constructed. The Monte Carlo simulations were utilized in the design process and verified by experiments. The dosimeter and algorithm were applicable to photon radiation having an effective energy beyond 100 keV in AP-PA mixed radiation fields. A simplified performance test based on ANSI N13.11 showed satisfactory results. Considering that the requirements of the International Electrotechnical Commission(IEC) and the American National Standards Institute(ANSI) with regard to the dosimeter on angular dependency is reinforced, the dosimeter and the dose evaluation algorithm developed in this study provides a useful approach in practical personal dosimetry against inhomogeneous high energy radiation fields.

KEYWORDS: ***TL dosimeter, dose evaluation algorithm, personnel dosimetry, angular dependency, $CaSO_4$***

I. Introduction

As an operational quantity for personnel monitoring, the International Commission on Radiation Units and Measurements(ICRU) recommended the personal dose equivalent, $H_p(d)$, which is the dose equivalent measured by a dosimeter placed on the surface of body and covered with soft tissue of thickness d millimeters[1)]. Accordingly, most personal dosimeters, including the thermoluminescence(TL) dosimeter badges, are designed and calibrated to measure the deep dose equivalent at a depth of 10 mm and the shallow dose equivalent at a depth of 0.07 mm[2)].

In present dosimetry system, Hp(10) provides a conservative estimate of effective dose for photons in most cases if the radiation comes from AP or near AP exposure mode. However, workers can be exposed to irregular radiation fields due to the geometry of source, the orientation of worker and source and movement of the workers. Especially, when a considerable portion of the radiation comes from the behind, significant underestimate of the personal dose equivalent may occur due to shielding effects by the human body itself.

Recently, several authors[3)-5)] suggested that this kind of underestimation can be corrected to a certain extent by using an extra dosimeter on the back. It is not unusual to use multiple dosimeters for a single task in a high dose-rate and complicated radiation field like a job at the PWR steam generator channel head[5)-6)]. However, multi-dosimeter approaches may subject to certain disadvantages like inconvenience in control and increased cost burden.

In this study, the personal dosimeter containing a new TL element, KCT-300[7)], was designed to solve the underestimation of a single dosimeter due to shielding effect by the body. Introduction of asymmetric filters was attempted to compensate the body shielding effects.

II. Materials and method

1. TL element and reader

The $CaSO_4$:Dy, P TL element of disc type, KCT-300, developed by the Korea Atomic Energy Research Institute is used in this study. Resources and details of the dosimetric properties of KCT-300 can be found in reference[7)]. The Teledyne system 310 TLD reader system is used.

2. Radiation fields

Only penetrating photon radiation like ^{137}Cs gamma rays and H150 X-ray spectra prescribed by the American National Institute of Standards[8)] was considered. Hence, the PA dose algorithm developed in this study is subject to limited applications to dosimeters worn by individuals working in gamma radiation field.

3. Phantom and dose conversion factors

The PMMA(polymethyl methacrylate) phantom (30×30×15 cm^3) recommended in ANSI N13.11 is used for calibration of personal dosimeter. The conversion factors,

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i.e. free air kerma-to-dose equivalent at 0.07 mm and 10 mm depth on the PMMA phantom are available for AP irradiation in the literature, but not for PA irradiation. Therefore, the conversion coefficients for PA irradiation are calculated with Grosswendt's conversion coefficients[9)-10)] by cubic spline interpolation and extrapolation and shown in **Table 1**.

Table 1. Conversion factors $H_p(10)/K_a$ at depth, d, of PMMA slab phantom.

Source	Conversion factor	AP (α=0°)	PA(α=180°)
H150	$H_p(10)/K_a$	1.71	0.51
	$H_p(0.07)/K_a$	1.62	0.38
Cs	$H_p(10)/K_a$	1.21	0.61
	$H_p(0.07)/K_a$	1.21	0.55

4. Monte Carlo simulations and experiments

The Monte Carlo code, MCNP4C[11)], was used to simulate the dosimeter response under AP and PA irradiation situations. For a four-element TLD badge as shown in **Fig. 1**, the dosimeter responses were obtained by simulations for different values of variables such as type, thickness, and configuration of filters in order to save the time and cost needed to find promising designs. The F6 tally with maximum history of 8×10^7 was used to calculate the TL response under the assumption that TL output is proportional to the absorbed dose of dosimeter.

On the basis of calculated results, the proto-type TLD badge cases were fabricated as shown in **Fig. 2**. The experiments were conducted to confirm the final specifications of filters in the badge case. The calibration radiation fields established in KAERI were used for irradiation of the dosimeters.

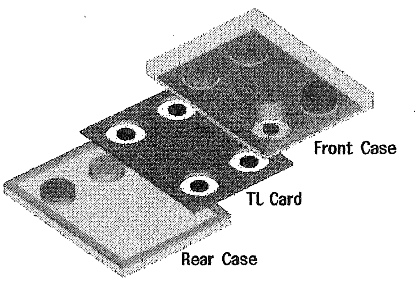

Fig. 1. The TL badge designed by MCNP4C for simulation of dosimeter response. It was rendered by the SABRINA visualization code.

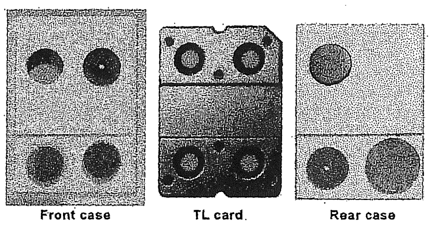

Fig. 2. The proto-type TL badge fabricated in this study for experiment to confirm the specification of filters.

III. Results and discussion

1. Final design of the badge

The principle of designing the dosimeter and the main idea of determining whether or not the radiation comes from PA exposure were described earlier[12)]. In brief, the badge design for KCT-300 TL elements by Kim[13)] was modified to facilitate identification of irradiation direction. There are four areas(hereinafter denoted as A1, A2, A3 and A4) containing TL elements and corresponding filters in one badge. Three of them, A1, A3 and A4, are for the dose algorithm to determine the personal dose equivalents resulting from regular AP irradiation mode. The remaining area A2 was specifically used for assessing contribution from PA irradiation mode by utilizing an asymmetric filter arrangement as shown in **Fig. 3**. If radiation comes from AP direction, the response of A2 is always higher than that of A3 due to the difference of the front filter thickness. In contrast, the response of A3 is higher than that of A2 for PA irradiation. The final filter design of the four areas is described in **Table 2**.

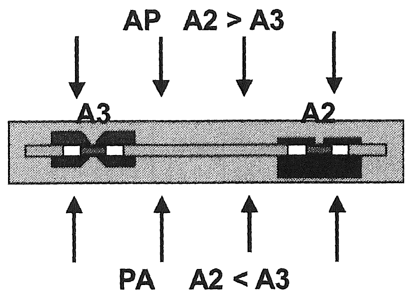

Fig. 3. Asymmetric filter design of A2 and A3 to change the response when radiation comes from the AP or PA direction.

2. Dose evaluation algorithm for PA mode irradiation

Dose evaluation is accomplished by applying the appropriate dose conversion factor to the response of A1 after determining by using the predetermined data if there is PA exposure and what the mixing ratio between AP and PA irradiation modes is. **Table 3** shows responses of the four TL elements obtained by theoretically mixing the measured responses. In cases of soley PA mode irradiation(row with mixing ratios of 0.0 to 1.0 in **Table 3**), A1 showed much lower responses than in cases of AP irradiation(row with mixing ratios of 1.0 to 0.0 in **Table 3**). The degree of underestimation exceeds 50% if evaluation of the dose for PA irradiation is made with the AP algorithm. To solve this problem, a separate dose evaluation algorithm for PA irradiation mode was introduced.

Figure 4 explains the PA mode dose evaluation algorithm. Firstly, the irradiation direction is determined by using A2/A3 ratio. If A2/A3 > 0.95, the irradiation direction is AP as expected from **Table 3**, otherwise the irradiation direction is PA or AP-PA mixed. If the irradiation direction

Table 2. Final specifications of filters for areas used on TL badge of this study.

Area	Front side filters	Back side filters
Open window area (A1)	None	0.7mm ABS*
PA exposure detection area (A2)	2.2mm ABS 0.3mm Cu(ϕ=10mm) hole(ϕ=1.5mm)	0.5mm ABS 4.0 mm Pb(ϕ=10mm)
Energy information area (A3)	0.9mm ABS 1.2mm Cu(ϕ=10mm) hole(ϕ=1.3mm) with 60° angle of taper	2.5mm ABS 1mm Cu(ϕ=10mm) hole(ϕ=1.5mm) with 60° angle of taper
Energy compensation area (A4)	3.7mm ABS 0.9mm Pb(ϕ=10mm) hole(ϕ=1.3mm) with 60° angle of taper 0.2mm Al(ϕ=10mm)	2.5mm ABS 1mm Cu(ϕ=13mm)

*ABS: acrylonitrile butadiene styrene

Table 3. Summary of the theoretical responses of the TL elements exposed to 1R($2.58x10^{-4}$C/Kg) photon radiation fields at having teo different energies of 117 and 662 keV. A1, A2, A3, and A4 represent the TLD readout of the 4 badge areas in mSv. D and S represent the actual deep and shallow doses delivered during exposure. All results are relative to Cs-137 photons. The related quantities for different AP-PA mixed fractions are also included.

Ave. E [keV]	Mix. ratio* AP	PA	mSv Cs Equivalent A1	A2	A3	A4	CFD** A1/D	CFS+ S/D	Response ratio A2/A3	(A1×A1)/(A3×A4)	(A1×A3)/(A2×A2)	(A1×A4)/ (A2×A2)
H150 [117]	1.00	0.00	**40.45**	**29.77**	**28.54**	**13.30**	2.70	0.95	1.04	4.31	1.30	0.61
	1.00	0.33	56.72	32.71	36.76	20.23	2.84	0.90	0.89	4.32	1.95	1.07
	1.00	0.50	64.88	34.18	40.89	23.71	2.89	0.88	0.84	4.34	2.27	1.32
	1.00	1.00	89.31	38.60	53.25	34.13	2.98	0.85	0.72	4.39	3.19	2.05
	0.50	1.00	138.16	47.42	77.96	54.96	3.07	0.81	0.61	4.46	4.79	3.38
	0.33	1.00	187.01	56.24	102.67	75.79	3.12	0.80	0.55	4.49	6.07	4.48
	0.00	1.00	**14.57**	**2.63**	**7.37**	**6.21**	3.26	0.75	0.36	4.64	15.50	13.07
Cs [662]	1.00	0.00	**10.62**	**10.62**	**10.62**	**10.62**	1.00	1.00	1.00	1.00	1.00	1.00
	1.00	0.33	13.93	12.84	13.69	13.45	0.98	0.98	0.94	1.05	1.21	1.08
	1.00	0.50	15.52	13.91	15.18	14.81	0.98	0.97	0.92	1.07	1.30	1.12
	1.00	1.00	20.42	17.19	19.73	18.99	0.97	0.95	0.87	1.11	1.51	1.19
	0.50	1.00	30.47	23.93	29.07	27.58	0.96	0.93	0.82	1.16	1.78	1.27
	0.33	1.00	40.40	30.59	38.29	36.06	0.95	0.93	0.80	1.18	1.95	1.32
	0.00	1.00	**5.00**	**3.35**	**4.65**	**4.28**	0.93	0.90	0.72	1.26	2.63	1.49

*Mix. ratio: mixing ratio between AP and PA exposure mode
** CFD: conversion factor from the response at A1 to the deep dose, + CFS: conversion factor from D to the shallow dose

is detrmined to be PA or AP-PA mixed, the PA algorithm has to be applied. Secondly, the energy of radiation is determined by using (A1×A1) /(A3×A4) ratio. Thirdly, the mixing ratio of irradiation direction is determined by using (A1×A3)/(A2×A2) or (A1×A4)/(A2×A2) ratio. Finally, the corresponding conversion factor is selected and $H_p(d)$ is evaluated by applying this conversion factor to the response at A1.

3. Performance test and comparison with commercial TL dosimeters

To assure acceptable performance of the dosimeter and the dose algorithm, a performance test was conducted. Since a performance requirement for PA irradiation mode was not available, an ad-hoc performance requirement for PA irradiation which reflects the test concept given in ANSI N13.11 was established. **Table 4** shows the performance test results. In all test categories, the performance indicator, [B] + S as defined in ANSI N13.11, were satisfactorily within the tolerance levels.

Comparisons with commercial TL dosimeter, P-300-AS of Teledyne and TLD-8814 of Harshaw, were made in

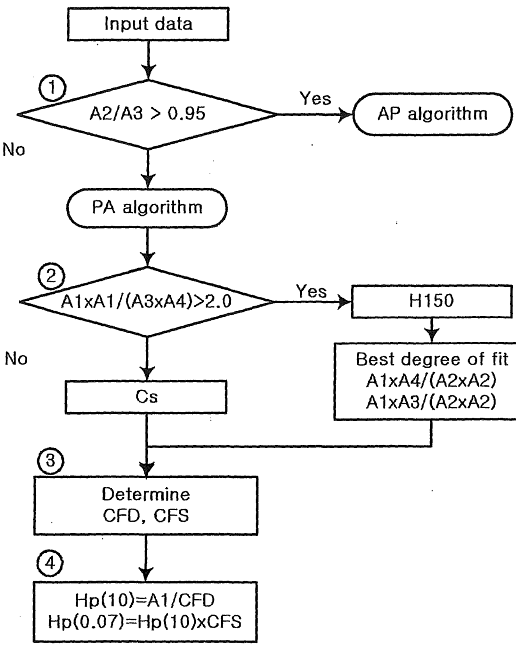

Fig. 4. Dose evaluation algorithm for PA or AP-PA mixed irradiation mode.

order to demonstrate utility of the dosimeter developed in this study. Three kinds of dosimeters were exposed in PA and AP-PA mixed irradiation modes at two energies of 117 and 662 keV. As shown in **Fig. 5**, the new dosimeter reproduced the delivered dose accurately while the rest two commercial dosimeters underestimated the delivered dose. The new dosimeter was superior to the two dosimeters compared in evaluating doses both in PA exposure mode and AP-PA mixed exposure mode for penetrating photon radiation.

Table 4. Results of performance testing for PA or AP-PA mixed fields of H150 and ^{137}Cs.

Test Category	Performance level					
	Deep			Shallow		
	B*	S**	[B] + S	B	S	[B] + S
Ⅰ. Low energy photon (H150)	0.007	0.045	0.052	0.013	0.045	0.058
Ⅱ. High energy photon (Cs)	0.039	0.049	0.088	-0.007	0.044	0.051
Ⅲ. Low energy photon mixture	-0.024	0.048	0.072	0.022	0.067	0.089
Ⅳ. High energy photon mixture	-0.011	0.047	0.058	-0.018	0.058	0.076

*B: Bias defined in ANSI 13.11.
**S: Standard deviation defined in ANSI 13.11.
Tolerance level, 0.4, was applied to all categories.

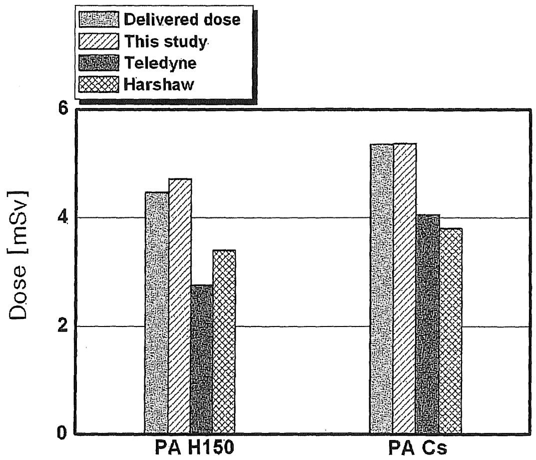

Fig. 5. Comparison of readings of the new dosimeter, P-300-AS(Teledyne) and TLD-8814(Harshaw) exposed in PA irradiation mode at two energies, H150(117keV) and Cs(662keV).

Ⅳ. Conclusion

A single TLD badge enabling identification of PA exposure by penetrating photon radiation was designed by introducing asymmetric filters. Monte Carlo simulations were utilized as a convenient design tool and the resulting design was verified by experimental measurements with proto-type TLD badges. The dosimeter and the associate dose algorithm are applicable to photon radiation having an effective energy of 100 keV and above in AP-PA mixed radiation fields. They showed performance well within the tolerance levels similar to those prescribed in ANSI N13.11 and provided far better dose estimates than the commercial dosimeters compared for applicability in PA or AP-PA mixed irradiation modes. Considering the requirement of the International Electrotechnical Commission(IEC) and the American National Standards Institute(ANSI) with regard to dosimeter on angular dependency, the new dosimeter design and the dose evaluation algorithm presented here are of worth of further development to broaden the energy range. The performance test including high energy photons should be followed. It is expected that they can be applied to dosimetry of workers exposed to complicated gamma radiation fields.

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