Journal of the Korean Nuclear Society
Volume 26, Number 3, September 1994

The Response Correction Function of TL Dosimeter for Shallow Dose Assessment in Tl-204 Beta Fields

Sang-Yoon Lee, Jang-Lyul Kim, and Kyung-Won Seo
Korea Atomic Energy Research Institute
(Received January 28, 1994)

Tl-204 베타선장에서의 피부선량평가를 위한 열형광선량계의 베타보정함수

이상윤 · 김장렬 · 서경원
한국원자력연구소
(1994. 1. 28 접수)

Abstract

Recently, the American National Standards Institute (ANSI) had made some changes in the radiation sources specified from those in the original performance test criteria ANSI N13. 11 – 1983. In case of beta category, in addition to the high-energy $^{90}Sr/^{90}Y$ beta source, the ^{204}Tl source was added because many workplaces have significant levels of lower energy betas. In this study, the performance of the Teledyne PB-3 personnel dosimetry system in the fields of ^{204}Tl and $^{90}Sr/^{90}Y$ beta was investigated using the PTB beta secondary standard sources. The new beta correction function of PB-3 personnel dosimetry system for ^{204}Tl beta was also developed in this response experiment. The results show that the Teledyne PB-3 personnel dosimetry system is very effective for $^{90}Sr/^{90}Y$ beta dose assessment. In case of ^{204}Tl beta radiation, however, the results of simple performance test indicated that the use of beta correction factor(= 2.088) which was recommanded by manufacturer may result in unexpectable over-estimation of delivered dose by about 60%, while the use of developed beta correction function could measure the delivered doses in errors of 15%.

요　약

방사선시설에서 작업자들의 피폭선량평가를 위해 개인선량계를 사용하는 경우에는 그 평가결과의 신뢰도를 우선적으로 확보하여야 한다. 최근, 미국 표준연구소에서는 기존의 개인선량계 성능검정 프로그램(ANSI N13. 11-1983)을 일부 개정하였으며, ^{204}Tl 베타선에 대한 성능시험항목이 추가 신설되었다. 본 연구에서는 열형광선량계가 베타방사선의 단일선장 및 혼합선장에서의 피부선량평가를 위해 사용되는 경우에 대한 성능검사를 실시하고 이에 따른 베타보정함수를 도출하였다. 실험에 사용된 열형광선량계는 한국원자력연구소에서 개인피폭관리용으로 사용되고 있는 Teledyne PB-3를 사용하였고, 선량계의 조사에 사용된 선원은 PTB 2차 베타표준선원을 사용하였다. 성능시험결과, Teledyne PB-3 선량계 시스템은 $^{90}Sr/^{90}Y$ 베타선장에서는 우수한 재현성을 나타내었다. 반면, ^{204}Tl 베타선이 기여하는 방사선장에 대한 PB-3 선량계의 재현성은, 기존 사용중인 베타보정인자를 적용하는 경우에는 최대 60%까지

의 상대오차를 보였다. 또한, 이러한 ^{204}Tl 베타선량산정의 오차는 본 연구에서 도출된 베타보정함수를 적용하는 경우에는 15%까지 감소하는 것으로 나타났다.

1. Introduction

Since the first commercial operation of nuclear power plant was started in Korea, the development of the technologies on the assessment of effective dose has been needed to enhance the reliability of personnel radiation monitoring. To do this, high quality radiation dosimetry is essential for workers who relay upon personnel dosimeters to record the amount of radiation to which they are exposed.

Recently, the Ministry of Science and Technology (MOST) issued a Ministerial Ordinance (No 1992-15) about the technical criteria on personnel dosimeter processors to reflect these problems and, the American National Standards Institute (ANSI) had made some changes in the radiation sources specified from those in the original performance test criteria ANSI N13. 11-1983 [1, 2, 3]. These include changes in the bremsstrahlung X-ray spectra, an additional beta source, and an additional neutron source. In the case of beta category, in addition to the high-energy ^{90}Sr/^{90}Y beta source, a lower energy of ^{204}Tl beta source had been added to category V of the standard. The ^{204}Tl source was added because many workplaces have significant levels of low energy betas, and because many dosimeters are extremely energy dependent when they are used in beta particle fields.

At present, there are many organizations capable of providing measurement results with good accuracy and precision in Korea. These organizations may provide personnel dosimetry services to their own facilities, or to others on a contractual basis. However, in today's climate, it is important to demonstrate and document that these systems and services to others meet national standards of quality.

The purpose of this study is to verify the performance of the Teledyne PB-3 personnel dosimeter when it would be used for personnel working in an area where they may be exposed to the beta radiation of different energies. The TL response experiments and performance test of this dosimetry system were carried out using the PTB beta secondary standards at the secondary standard dosimetry laboratory in KAERI(Korea Atomic Energy Research Institute).

The report begins with a general description and calibration of the PTB standard sources. It continues with a description of the PB-3 dosimetry system and irradiation conditions. The report concludes with an evaluation of relative response of PB-3 dosimeter, and a discussion of representative beta correction function.

2. Experimental Details

PTB Beta Secondary Standard Source

The PTB(Physikalisch-Technischen Bundesanstalt) beta secondary standard source is designed for calibration of β-particle dosimeters in terms of absorbed dose in tissue at the surface and at shallow depths within a tissue phantom. The span of about 60 to 800 keV in mean β-particle energy for calibration purposes is accomplished with three sources: ^{147}Pm, ^{204}Tl, and ^{90}Sr/^{90}Y. Source characteristics are described in Table 1 [4].

As summarized in Table 2, the sources are calibrated in several distances. The first three sources are used with matched "beam-flattening" filters consisting of polyethylene terephthalate (PTP) disks mounted coaxially with the source-receptor axis at a distance of 10 cm from the source. These filters are designed to "provide a uniform dose rate over an area of about 10 cm in diameter at calibration distances," as stated in the Buchler literature. The beam-flattening filters are as specified in ISO 6980-1984, the international standard that applies to these sources [5].

Table 1. Characteristics and Nominal Activities of the PTB Beta Secondary Standard.

Source Number	Nuclide	Half-life	E_{max} (keV)	E_{avg} (keV)	Frequency (percent)	Activity (MBq)
1	^{147}Pm	2.623 y	224.7	61.96	99.994	518
2	^{204}Tl	3.779 y	763.4	243.93	97.42	18.5
3 and 4	^{90}Sr	28.6 y	546.0	195.8	100.0	74 and 1850
	^{90}Y*	64.1 h	2283.9	934.8	99.988	

* Assumed to exist in equilibrium with the ^{90}Sr.

The PTB beta secondary standard is calibrated with the cavity absorbed dose rate $D_c(0)$ on the surface (depth 0) of a semi-infinitely extended soft tissue phantom of 1.0 g/cm^3 density. The cavity absorbed dose rate is the dose rate in an air-filled cavity surrounded by tissue. The tissue absorbed dose rate $D_t(0)$ at the surface is obtained by multiplying D_c by k_d, the ratio of the mass stopping power of tissue for electrons to that of air, averaged over the energy spectrum of the electron flux density. For monoenergetic electrons, k_d varies from 1.13 at 10 keV to 1.10 at 1 MeV for dry air and skeletal muscle [6]. The Buchler certification literature uses k_d values of 1.124, 1.121, and 1.110, respectively for ^{147}Pm, ^{204}Tl, and $^{90}Sr/^{90}Y$ sources [7].

Also provided with the PTB standard certification are transmission factors T(d), defined as the ratio of the cavity absorbed dose rate at depth d in soft tissue to that at depth 0, i.e., $T(d) = D_c(d)/D_c(0)$. Because k_d values are so nearly constant, T(d) is assumed to be equivalent to the ratio of tissue-absorbed dose rates $D_t(d)/D_t(0)$.

As the PTB beta secondary standard certification provides only nominal source activities (Table 1), the tissue dose rates have to be evaluated for experimental purposes, as is done in Table 2. This is necessary for qualitative comparison of calculated and measured dose rates.

Table 2. Nominal* Tissue Absorbed Dose Rates for PTB Beta Secondary Standard at KAERI.

Source	Calibration Distance(cm)	Tissue Dose Rate (μGy/sec) at a Depth of d (mg/cm^2)			
		d = 0	d = 7	d = 20	d = 100
1 (^{147}Pm)	20	2.666×10^{-2} (0.07)**	4.798×10^{-2} (0.07)	–	–
2 (^{204}Tl)	30	2.191×10^{-1} (0.004)	2.147×10^{-1} (0.004)	1.775×10^{-1} (0.004)	–
3 ($^{90}Sr/^{90}Y$)	30	2.773 (0.004)	2.889 (0.004)	3.011 (0.004)	2.917 (0.004)
4 ($^{90}Sr/^{90}Y$)	11	5.527×10^{-2} (0.004)	5.903×10^{2} (0.004)	6.329×10^{2} (0.004)	6.340×10^{2} (0.004)
4 ($^{90}Sr/^{90}Y$)	30	76.37 (0.004)	81.57 (0.004)	87.45 (0.004)	87.60 (0.004)
4 ($^{90}Sr/^{90}Y$)	50	27.33 (0.004)	28.59 (0.004)	30.01 (0.004)	28.78 (0.004)

* PTB certification applies to evaluate dose rates, not source activities.

** The values in parentheses are the relative errors.

PB-3 Personnel Dosimetry System

Thermoluminescence dosimeter (TLD) and film badge has been considered to be suitable for use as personnel dosimeters, and recently the use of TLD is increasing because of its high accuracy and convenience. The whole-body dosimeter used for this study was the Teledyne Isotopes PB-3 multi-element dosimeter, and these personnel dosimetry system consists of a badge case containing a phosphor impregnated Teflon card to detect gammas, betas and neutrons. The phosphor in the whole body card is thermoluminescent $CaSO_4$: Dy that is known to be highly sensitive to gamma rays but to have little sensitive to thermal neutrons. The badge case is divided in four areas, each with a different set of dosimetric properties depending on the filters presents. The filters in the badge are given in Table 3 [8].

A description of the filters in the badge is as follows. The open-window of the area 1 has a mylar layer of 14 mg/cm^2 to measure betas. In the area 2, 3 mm of Teflon attenuates most of betas. Thus if area 2, which includes gamma only is subtracted from area 1, which includes both betas and gammas, a net beta response can be determined. A simple subtraction cannot be made if the badge is also exposed to low energy photons, so a correction has to made to area 2 to obtain the correct beta response.

Table 3. Filter Materials and Thickness for the PB-3 Badge System.

Area	Front	Back
E 1	7mg/cm^2 mylar film Plastic case	Plastic case
E 2	3.2 mm of Teflon Plastic case	Plastic case
E 3	Plastic case 2.64 mm of slotted Cu 0.81 mm of Al Plastic case	Plastic case 1.02 mm of Cu 0.81 mm of Al Plastic case
E 4	Plastic case 2.64 mm of slotted Cu 0.81 mm of Al Plastic case	Plastic case 0.13 mm of slotted Cu 0.81 mm of Al 0.81 mm of Cd Plastic case

Area 3 and 4 both include an identical aluminum and copper filter. The copper filter has a hole in it to provide a relative flat response for the deep dose Since the deep response in area 3 or area 4 is not flat, a correction has to be made to the measured deep dose response to properly correct for over-response of the deep dose in area 3 and area 4 when the badge case has been exposed to low energy photons. The filtration is identical in area 3 and 4 to provide a redundant measurement for the deep dose.

Irradiation Condition

Test dosimeters were irradiated with a tissue equivalent phantom constructed of polymethyl methacrylate (PMMA) having a thickness of 5 cm, and a face of 30 cm × 30 cm. Two dosimeters were attached to the phantom surface at each irradiation, and six dosimeters were irradiated in each dose level. The test dosimeters were mounted with their backplanes parallel to the surface of the phantom facing the source. The phantom was positioned so that a line through the source perpendicular to its front face shall pass through the center of the face.

The distance between the center of the beta sources and the phantom surface to which the dosimeters are attached was 30 cm. For all beta irradiation, field flattening filters were used to extend the useful area of the beam at the phantom position. These beam flattening filters were centered on the source-to-dosimeter axis and mounted perpendicular to it 10 cm from the source surface.

As the purpose of this study is to enhance the performance of the PB-3 personnel beta dosimetry system and to meet the tolerance level of ANSI performance test, most of the irradiation range of experiments were selected from the beta test ranges of ANSI[3]. The range of test irradiation levels in ANSI performance test generally resulted from a compromise between considerations based on the principles of personnel dosimetry for radiation protection recommended by the NCRP[10].

3. Results and Discussions

The linearity of the TL response of PB-3 with delivered doses was first investigated. Linearity is defined as the closeness to which a curve approximates a straight line. In the TLD measurements, the linearity is a function of the light output from a dosimeter versus exposure. As shown in Figure 1, the response of the PB-3 badge system is linear for $^{90}Sr/^{90}Y$ betas and the measured doses show a good agreement with the delivered doses. In case of ^{204}Tl, however, the statues are somewhat different. The response of the PB-3 to the ^{204}Tl was linear to the increase of delivered dose, but it can be seen that the results are under-estimate the delivered doses. The adoption of BCF(Beta Correction Factor=2.088) which was recommended by Teledyne Isotopes Inc. to reduced the errors on estimation of ^{204}Tl doses, result in same errors[9]. The BCF corrected response is also shown in Figure 1 as a Tl-204(BCF), and it is shown that the reponses over-estimate the delivered doses.

According to the Teledyne PB-3 dose calculation algorithm, the beta dose is derived by the expression; (E1-E2) ×BCF. E1 and E2 in this expression are

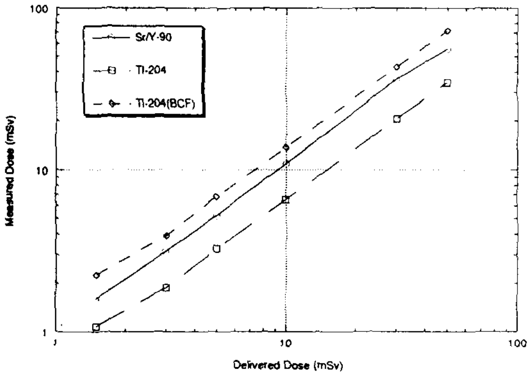

Fig. 1. Linearity of the PB-3 in Different Beta Fields

defined as the measured responses of the area 1 and 2 of an unknown dosimeter and BCF(ratio of delivered dose to measured dose)is defined by results from standard irradiations. If the dosimeter/badge case combination were exposed to a beta only, area 2 with a Teflon filter would not respond to a beta. In this expression, therefore, the response of area 1 is only used for pure beta radiation field.

In order to solve the problems in present BCF, we investigated the TL response of PB-3 for ^{204}Tl beta dose. To meet the tolerance levels of ANSI performance test, response experiments were carried out in the range of 15 mSv to 50 mSv which is same to the test ranges of ^{204}Tl beta[3]. The evaluation of beta correction factor for each delivered dose was also conducted. As illustrated in Figure 2, the PB-3 dosimeter does not show a uniform response for delivered doses and the maximum difference between BCFs was about 20% especially in low doses. So, It is not proper to use BCF constantly to calculate the ^{204}Tl beta dose for all ranges of delivered dose. To represent the beta correction factor curve in Figure 2 precisely, the exponential interpolation technique was used and evaluated function of the curve is descirbed as follows;

$$BCF' = 1.5141 \times e^{(-8.3059E\text{-}4 \times X)} \tag{1}$$

$$H_{Beta} = (E1\text{-}E2) \times BCF' \tag{2}$$

where, X is net beta response of dosimeter(=E1-E2) and H_{Beta} is calculated shallow dose equivalent from beta radiation.

The usefulness of a new BCF' is clearly shown in Figure 3. As illustrated in this figure, PB-3 measured shallow doses show a good agreement with the delivered doses for $^{90}Sr/^{90}Y$ beta radiation field. The differences between delivered and measured doses are less than 20% for all dose levels. In case of ^{204}Tl beta field, the results of shallow dose assessment were under-estimated by about 40% without response correction. The old BCF corrected data in Figure 3 also show that present BCF is not proper to

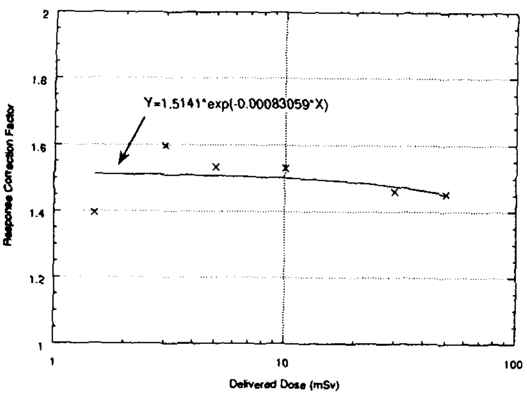

Fig. 2. Beta Correction Factors of PB-3 in Different ^{204}Tl Doses

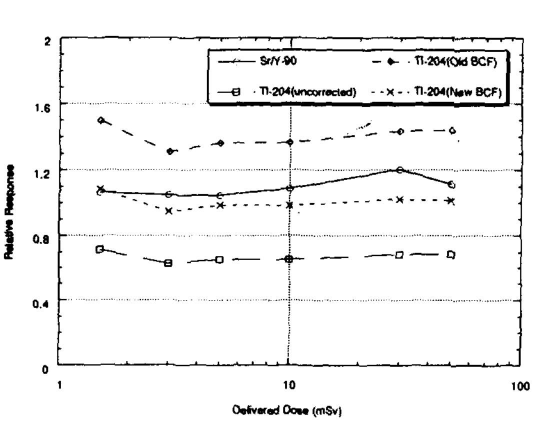

Fig. 3. Relative Response of the PB-3 in Different Beta Fields

compensate the ^{204}Tl response. From Figure 3, it is clear that more accurate calculation of ^{204}Tl shallow dose can be done by new beta correction factors from Eq. (1). The results from new BCF show a good agreement with delivered doses and differences between calculated and delivered ^{204}Tl beta shallow doses were below 10%.

To verify the effectiveness of newly developed beta correction function, a simple performance test was conducted. The test categories and delivered doses specified in Table 4 was selected from ANSI test categories and the ratio of the dose equivalents of the radiation components in mixed categories VC and VII had been restricted to values between 1:3 and 3:1[3]. The test results are also summarized in Table 4, and the related performance indices in the table were calculated as follows;

$$\text{Performance quotient} \quad P_i = \frac{[\,H_i' - H_i\,]}{H_i}\,, \tag{3}$$

where H_i is the delivered dose and H_i' is the measured dose,

$$\text{Bias} \quad B = \overline{P} = \frac{1}{n}\sum_{i=1}^{n} P_i\,. \tag{4}$$

$$\text{Standard deviation} \quad S = \sqrt{\frac{[\sum_{i=1}^{n}(P_i - \overline{P})^2]}{(n-1)}} \tag{5}$$

The lower limit of detection(LLD) for test dosimeter was also evaluated in this test. Generally, LLD is used to predict if a radiation induced signal added to the background can be measured with some degree of probability. Determination of the LLD is not a separate test category, but it was recommended by ANSI that the maximum value for the LLD in each category should not exceed one half of the minimum dose level in test irradiation. A determination of the lower limit of detection (LLD) for test dosimeter was evaluated with formula as follows;

$$LLD = \frac{2(1.8S_0 + FH_B)}{(1-F)} \tag{6}$$

$$F = [\frac{1.8S}{(1-B)}]^2 \tag{7}$$

where, S_0 is standard deviation of unirradiated control-dosimeters and H_B is the calculated mean value of the background dose[3].

As summarized in Table 4, the PB-3 personnel dosimetry system shows a good performance in categories VA, VIIA and VIIB without correction of beta response. For these categories, test results are all meet the performance test criteria include the additional limit on bias and standard deviation. In case of category VB, however, the result from old BCF

Table 4. Results of Performance Test of the PB-3 Badge System.

Test Category	LLD (mSv)	(Delivered Dose) Reported Dose (mSv)	Test Results		
			|B|	S	L
	Shallow	Shallow	Shallow	Shallow	Shallow
VA. $^{90}Sr/^{90}Y$	0.0162	(1.50)[1] 1.60	0.0667	0.0133	0.0800
VB. ^{204}Tl	0.0164[2] (0.0226)[3] (0.0174)[4]	(5.0)[1] 3.27[2] (6.82)[3] (4.93)[4]	0.3465[2] (0.3645)[3] (0.0132)[4]	0.0288[2] (0.0602)[3] (0.0434)[4]	0.3753[2] (0.4247)[3] (0.0566)[4]
VC. $^{90}Sr/^{90}Y$ + ^{204}Tl	0.0162[2] (0.0288)[3] (0.0163)[4]	(4.5)[1] 3.51[2] (7.31)[3] (5.22)[4]	0.2193[2] (0.6252)[3] (0.1564)[4]	0.0158[2] (0.0361)[3] (0.0146)[4]	0.2350[2] (0.6613)[3] (0.1709)[4]
VIIA. $^{90}Sr/^{90}Y$ + ^{137}Cs	0.0165	(40)[1] 40.54	0.1349	0.0214	0.1563
VIIB. ^{204}Tl + ^{137}Cs	0.0163[2] (0.0183)[3] (0.0166)[4]	(40)[1] 30.09[2] (51.26)[3] (39.63)[4]	0.2479[2] (0.2815)[3] (0.0097)[4]	0.0192[2] (0.0399)[3] (0.0280)[4]	0.2671[2] (0.3214)[3] (0.0377)[4]

[1] The values in the parentheses are delivered doses to test dosimeter.
[2] The results are derived without any beta response correction.
[3] The values in the parentheses are results from BCF(= 2.088).
[4] The values in the parentheses are results from BCF'.

correction fails in bias limit of 0.35. And we can see that BCF uncorrected results are also close to additional limit of bias. The problems in adoption of old BCF for ^{204}Tl dose assessment are clearly shown in the result of category VC. In this category, the BCF uncorrected result is below the tolerance level but is almost close to the bias limit, and old BCF corrected results are fail in all limits.

As shown in Table 4, the beta correction function developed by this study was very useful for shallow dose assessment in the fields of mixed and non-mixed betas. The results of simple performance test indicated that the use of BCF may results in over-estimation of delivered dose by about 60%, while the use of beta correction function could measure the delivered doses in error bound of 15%.

In conclusions, the Teledyne PB-3 personnel dosimetry system showed its usefulness for $^{90}Sr/^{90}Y$ beta dose assessment. It has a good low detection limit (below 0.03 mSv) and its responses present a performance quotient of less than 0.3. In case of ^{204}Tl, however, the results showed that PB-3 personnel dosimetry system is not proper to assess the shallow doses if it would be used without beta response correction. It was also known that the beta correction factor(=2.088) from revised version of dose algorithm recommended by Teledyne Isotopes may cause unexpectable errors in shallow dose measurements. Therefore, It is recommended that the users of PB-3 personnel dosimetry system who want to assess the ^{204}Tl shallow doses more precisely, have to consider the use of beta correction function developed by this study.

References

1. 과학기술처, "개인방사선피폭선량평가에 관한 기술기준," 과학기술처고시 *1992-15*, 1992.
2. American National Standards Institute, "American National Standard for Dosimetry-Personnel Dosimetry Performance-Criteria for Testing," *ANSI N13. 11, ANSI,* 1983.
3. American National Standards Institute, "American National Standard for Dosimetry-Personnel Dosimetry Performance-Criteria for Testing," *ANSI N13. 11, ANSI,* 1992.
4. R.E. Faw et al., "Simulation of Angular and Energy Distributions of the PTB Beta Secondary Standard," *Health Physics*, 59, 311 (1990)
5. International Organization for Standardization, "Reference Beta Radiations for Calibrating Dosemeters and Doseratemeters and for Determining Their Response as a Function of Beta Radiation Energy," *ISO Report* 6980, 1983.
6. International Commission on Radiation Units and Measurements, "Measurement of Dose equivalents from External Photon and Electron Radiations," *ICRU Report* 47, 1992.
7. Physikalisch-Technische Bundesanstalt, "Certification of Beta Secondary Standard BSS No. 90," PTB, 1992.
8. Alan S. Klotz et al., "Gamma and X-ray Response of the Teledyne Isotopes PB-3 Whole Body Dosimeter," Health Physics Society Annual Meeting, 1983.
9. Teledyne Isotopes, "PB-3 Badge Case Algorithm Revision 1. 5," Teledyne Isotopes Inc., 1989.
10. National council on Radiation and Measurements, "Instrumentation and Monitoring Methods for Radiation Protection," *NCRP Report* 57, 1978.