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Calculations of ISO Narrow and ANSI X–Ray Spectra, Their Average Energies and Conversion Coefficients

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ISO Narrow Series및 ANSI의 X선 스펙트럼, 평균에너지 및 선량환산인자의 이론적 계산

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Abstract – In spite of the prescriptions on the reference X-ray fields given by the International Organization of Strandard(ISO) and American National Standard Institute(ANSI), the measurement of X-ray spectrum is not only time consuming but very difficult, paticularly when significant corrections have to be applied to the measured pulse-height distributions of the observed spectra.

This paper describes the calculation method of ISO Narrow Series and ANSI X-ray filtered radiations by theoretical model which is modified Kramer's theory by target attenuation and backscatter correction. The X-ray spectra, average energies and conversion coefficients are calculated and compared with those obtained using the spectra prescribed by ISO and ANSI to assure good agreement.

Key words : ISO X-Ray, ANSI X-Ray, Spectrum Calculation, Mean Energy, Conversion Coefficients.

요약 – 중저준위 에너지 범위에서 방사선관리용측정기기의 에너지의존성에 대한 연구를 위하여 ISO에서는 ISO표준 X선장을 발간하였으며, 또한 ANSI에서도 개인방사선측정기기의 성능시험을 위하여 ANSI X선장을 제시하였다.

그러나 X선 스펙트럼의 측정은 많은 시간이 소요될뿐만 아니라 특히 측정 X선 스펙트럼에 unfolding이 수행된다면 매우 어려운 작업이 된다. 따라서 이론적인 방법에 의해 스펙트럼을 계산·예측하고 그 평균에너지 및 선량환산인자를 계산하는것은 X선 실험제작에 필요한 시간, 노력 및 비용을 최소화 할수 있을 것이다.

따라서 본 연구에서는 ISO Narrow Series 및 ANSI X선장에 대하여 이론적으로 스펙트럼을 계산하였으며, 그에 의한 평균에너지와 선량당량혼산인자를 계산하였다.

본 계산에 의한 평균에너지 및 선량환산인자는 측정스펙트럼에 의한 ISO 및 X선장의 값과 잘 일치하였다.

Key words : *ISO 표준방사선장, ANSI X선장, 스펙트럼 계산 평균에너지, 선량환산인자*

INTRODUCTION

The International Organization of Standard(ISO) recognized the need to study energy dependence of protection-level dosemeters, particularly photographic film and TLD, in the low and medium energy range. This led to the Narrow Spectrum Series of filtered X-radiations and fluorescence reference radiation. An ISO Standard[1], published in 1979, comprises of the Narrow and Wide Spectrum Series which included the fluorescence radiations. In addition, an amendment[2], addendum[3], and revision[4] of ISO 4037 were published and introduced the Low Rate and High Rate Serics of filtered X-radiations. The American National Standard Institute(ANSI) has also published the ANSI X-ray beams for personal dosimetry performance test[5, 6].

In the above documents, the average energy of X-radiations were determined from a spectral measurement. For the conversion coefficient between photon fluence or air kirma and the dose equivalents, Monte Carlo method has been used to calculate for monoenergetic radiation[7,8,9], but for a photon radiation which has a continous spectrum, a dose equivalent quantity has to be calculated by integrating the product of photon fluence, or air kirma, and the conversion coefficient for each energy over the entire energy range of the spectrum. This procedure assumes a detailed knowledge of the photon spectrum over the whole energy region.

The measurement of such spectrum can be both time consuming and difficult, paticularly when significant corrections have to be applied to the measured pulse-height distributions of the observed spectra. Therefore, the abilities to predict spectra and to calculate their conversion coefficients acculately by theoretical model can help to minimize the time, effort, and expenditure involved.

The purpose of this paper is the calculation of ISO Narrow Series and ANSI X-ray filtered radiations by theoretical model useful in the design of reference calibration spectra and in the determination of average energies and their conversion coefficients using caculated spectra.

THEORY

Theoretical spectra of Kramer[10] made use of many simplifying assumptions. Namely, the backscattering of electrons in the target was neglected, the bremsstrahlung cross sections were assumed to be independent of electron energy, and the absorption of photons in the target itself was ignored. Because the factors for X-ray absorption and for electron backscattering are now known to a much higher degree of accuracy, a more accurate evaluation of the X-ray continuum from target is possible.

The number of photons within the energy interval k + dk in the continuum of a filtered X-ray beam produced from a target per incident electron may be written as

$$N_k\,dk = I_{A,k} \cdot F_{B,k/T_i} \cdot F_{C,k/T_i} \cdot \exp(-\sum \mu_i \rho_i x_i)\,dk / 4\pi D^2 \qquad (1)$$

where N_k = number of photons $cm^{-2}s^{-1}$ in the energy interval k to k + dk per incident electron

$I_{A,k}$ = intensity of X-ray photons of energy k per incident electron

$F_{B,k/T_i}$ = back-scatter factor

$F_{C,k/T_i}$ = target attenuation factor

k = photon energy in keV

T_i = initial eletron energy in keV

$\exp(-\sum \mu_i \rho_i x_i)$ = attenuation due to filters of mass attenuation μ, density ρ and thickness x

D = distance of point of measurement from X-ray tube focus in cm.

Where appropriate, the contribution from characteristic X-ray has to be added to the above.

Intensity of continuum of X-ray from a solid target

The continuum energy intensity at photon energy k generated by an electron travelling a distance in the target element is given by

$$I_{A,k} = \frac{\rho N}{A} \int_k^{T_i} Q(dT/dx)^{-1}\, dT \qquad (2)$$

where N is the Avogadro's number, ρ is the density, A is the atomic weight, dT/dx is the relative stopping power, and Q is the X-ray energy intensity per unit energy interval per incident electron flux per atom. The Q value can be obtained from Morin[11] and the stopping power data from ICRU 37[12], and equation 2 can be rewritten as

$$I_{A,k} = F_{A,k}(T_i - k) \qquad (3)$$

Eq.(3) gives the energy intensity and must be divided by the photon energy to give the number of photons per energy interval. The numerical values of $F_{A,k}$ is given in Table 1 for a tungsten target.

Target attenuation

To determine the effect due to the attenuation of X-ray produced within the target, it is necessary to know both the relative number and energy distribution of the electrons therein. The Thomson-Whiddington Law has frequently been used to calculate the maximum depth at which a photon of energy k can be produced by an incident electron of energy T_i. This stated that after penetrating a distance x into the material along with the incident direction, the electrons have their energy related to k as

$$k = (T_i^2 - \rho C x)^{\frac{1}{2}} \qquad (4)$$

where C is the Thomson-Whiddington constant and ρ is the density of the target material.

The mean depth of X-ray production is considerably less than the range given by T-W Law, and Green[13] concluded that, based on experimental measurements, the mean depth of X-ray production was approximately one quarter of the T-W range. Illes[14] offers the similar method with the T-W Law using the Continuous Slowing Down range Approximation(CSDA). If the mean range of the electron is expressed as a fraction of $R_{W,Ti}$, the CSDA, the attenuation correction factor $F_{C,k/Ti}$ for photons of energy k/T_i is given by

$$F_{C,k/Ti} = \exp\{-[(f_{C,k/Ti} R_{W,Ti})\, \mu_{wk} \cot\theta]\} \qquad (5)$$

where $R_{w,Ti}$ = the CSDA range in g/㎠ of an electron energy T_i in tungsten

$f_{C,k/Ti}$ = values of the mean depth of production as a fration of the CSDA range

μ_{Wk} = mass attenuation coefficient in tungsten for photons of energy k

θ = tube angle in degrees

A graph of $f_{C,k/Ti}$ versus k/T_i is shown in Fig. 1. The values for $R_{w,k/Ti}$ were taken from the data of ICRU 37[12].

Table 1. Values of $F_{A,k}$ used for calculation of the spectra.

Photon Energy(keV)	$F_{A,k}$ X 10^{-4}
15	2.15
30	2.02
60	1.78
100	1.51
150	1.25
200	1.04
300	0.73

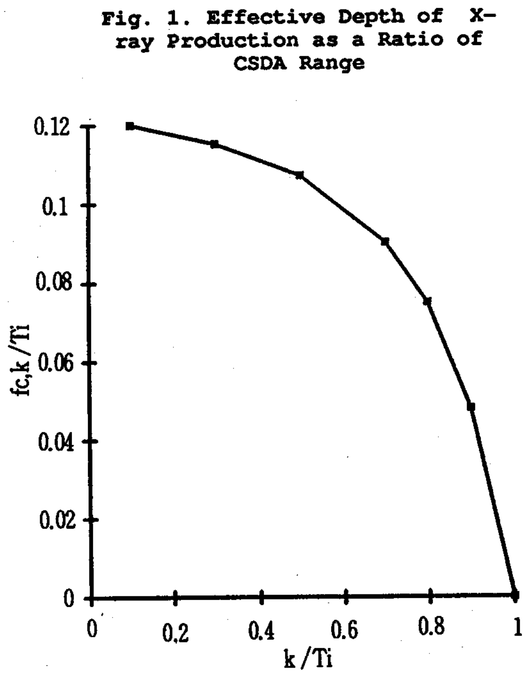

Fig. 1. Effective Depth of X-ray Production as a Ratio of CSDA Range.

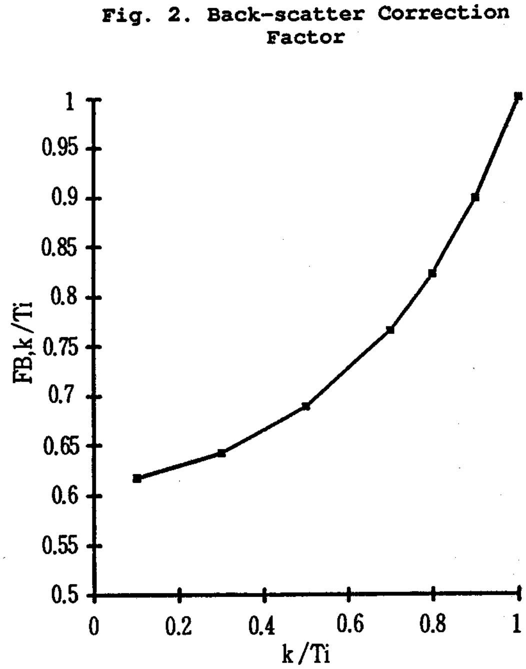

Fig. 2. Back-scatter Correction Factor.

Back-scatter correction

Antolak[15] has performed Monte Carlo calculations for the wide range of incident electron energies, angle of incident and atomic number. His results is to confirm that, for a given target material, the back-scatter gactor is almost independent of the initial electron energy and varies typically by less than 10% for the angle of incidence between 0° and 45°, and the electron back-scatter correction factor $F_{B,k/Ti}$ may be expressed as

$$F_{B,k/Ti} = 1 - \frac{\int_{w=k/T_i}^{w=1} \frac{dn}{dw}(w-k/T_i)\,dw}{1-(k/T_i)} \qquad (6)$$

in which the number of back-scattered electrons of relative energy w is represent- ed by the differential dn/dw.

Fig. 2 shows $F_{B,k/Ti}$ as a function of k/T_i.

Characteristic X-rays from the target

In addition to the X-ray continuum, the- re will be a contribution from characteristic fluorescence X-rays produced by the tungsten target. This relationship can be found elsewhere[16,17]. In this paper, Birch's work[18] was used to calculate the number of characteristic K- and L- series X-ray:

$$N_k = 9.535 \times 10^4 \frac{R}{A_r \cdot C}\{U_0 \cdot 1nU_0 - (U_0 - 1)\}$$
$$\approx 9.535 \times 10^4 \frac{R}{A_r \cdot C} 0.365(U_0 - 1)^{1.63} \qquad (7)$$

where N_k = number of characteristic K-X-ray of tungsten produced by an incident electron

A_r = mass number of target

C = costant ≈ 1

R = correction of back-scatter of election ≈ 1

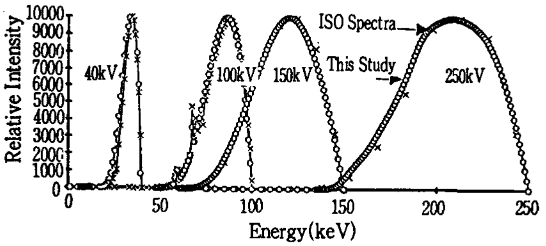

Fig. 3. Comparison of ISO Narrow Series(x) and Calculated Spectra(o).

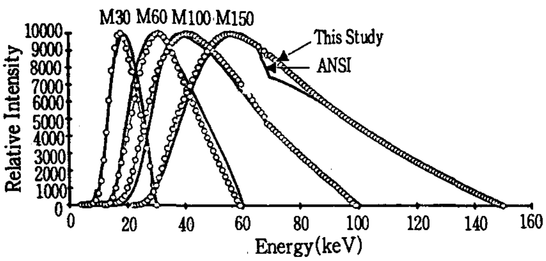

Fig. 4. Comparison of ANSI(–) and Calculated X-Ray Spectra(o).

$U_0 = T_i / E_k$
E_k = K-absorption energy of target

The number of L-X-ray is given by

$$N_L \sim 8/3\ (E_K/E_L)^2 N_K \qquad (8)$$

Results and Discussions

Average energy

Calculated spectra are presented in Fig. 3 and 4 and compared to the ISO Narrow series filtered X-radiations and the ANSI N13.11 [11] X-ray beams. The calculated spectra satisfactorily approximates the prescribed spectra. Small deviations are moticed for ANSI M60 spectrum where the calculated spectrum is narrower than the prescribed, and the sump appeared on the prescribed M150 spectrum near 70keV is smoothen out

Table 2. Comparison of average photon energies for ISO Narrow Series.

Tube Voltage (kV)	Average Photon Energy(keV)			
	ISO	GSF	Hawell	KAERI[1)]
40	33	32.5	33.1	33.1
60	48	47.3	47.8	47.2
80	65	64.5	65.2	64.6
100	83	82.6	83.3	82.9
120	100	100	100.2	99.9
150	118	117	118.2	117.2
200	161	164	164.3	164.8
250	205	207	207.0	205.5

1) Present calculation work

Table 3. Comparison of average photon energies for ANSI N13.11 X-ray.

Tube Voltage (kV)	Average Photon Energy(keV)		
	ANSI	KAERI[1)]	ANSI /KAERI
M30	20	19.4	1.03
M60	34	35.2	0.97
M100	51	51.2	0.997
M150	70	73	0.96
H150	117	118.3	0.99

1) Present calculation work

on the calculated spectrum.

ISO standard 4037 defines average energy, E_{ave} as

$$E_{ave} = \frac{\int_o^{E_{max}} \phi_E E\, dE}{\int_o^{E_{max}} \phi_E\, dE} \qquad (9)$$

where $\phi_E = d\phi_E/dE$ is the quotient of the fluence $d\phi(E)$ of the primary photons (main continuous spectrum) with energies between E and E + dE and the energy interval dE. The average energy for each spectrum was calculated by dividing the spectrum into 1keV energy interval and reading the numbber of photons associated with energy interval from the calculated spectrum.

The average energies from the calculateda spectra are compared to the ISO Narrow series of filtered radiation, measured values by Seelentag et al.[19], and by Peaples et [20] in Table 2, and also compared to the ANSI N13.11 X-ray becams in Table 3. There is very good agreemint between the corresponding values.

Conversion coefficients

The spectrum weighting calculation were done by using the calculated X-ray spectral data, the conversion factors for monoenergetic radiation of ICRU sphere[9] and PMMA slab[8], and the values for the attenuation coefficients μ(E) from Hubbel[21]. The cubic spline interpolations were used to complete the following summations.

$$\frac{H(d)_{spectra}}{K_a} = \frac{\sum \frac{H(d)}{K_a} \varphi(E)\mu(E)\triangle E}{\sum \varphi(E)\mu(E)\triangle E} \quad (10)$$

where the bin width, $\triangle$E, for the summations were 1 keV.

The operational quantities for area monitoring, as recommended in ICRU Report 39[22], are defined in the 'ICRU Sphere'. Two quantities are specified by ICRU: the ambient dose equivalent H*(d) and directional dose equivalent H′(d). In unidirec- tional radiation field the quantity H′(d,0) = H*(d). The conversion coefficients for ambient dose equivalent which have been calculated for ISO Narrow Series according to the Eq.(10) are shown in Table 4 using the monoenergetic conversion coefficients by Grosswendt[9], and compared to the ISO values in ISO 4037 (1992), measured values by Harwell[20], and calculated value by Illes[14]. There are good agreements between the sets of values within 0.5%.

The operational quantity for individual monitoring is the personal dose equivalent, Hp(d). This is the dose equivalent in soft tissue below a specified depth on the ICRU sphere. For practical reasons a 30 X 30 X 15 cm tissue equivalent slab is recommended as the phantom to be used for type testing dosemeters in ICRU47[23]. A difficulty arises from the fact that ICRU tissue equivalent material cannot be made exactly. Therefore, ICRU suggested that, for irradiation of the dosemeters, a PMMA slab phantom be used. The backscatter characteristics of the PMMA slab are acceptably close to those of

Table 4. Conversion coeffieients from air kirma K_a to H*(0.07) for ISO Narrow Series.

Tube Voltage (kV)	Average E. (keV)	Conversion Coefficients ISO[1)] H*(10)	ISO[1)] H*(0.07)	KAERI[2)] H*(10)	KAERI[2)] H*(0.07)
40	33.1	1.17	1.23	1.165	1.232
60	47.2	1.55	1.47	1.543	1.459
80	64.6	1.74	1.58	1.736	1.581
100	82.9	1.71	1.58	1.713	1.581
120	99.9	1.65	1.54	1.648	1.546
150	117.2	1.59	1.49	1.583	1.498
200	164.8	1.45	1.39	1.443	1.384
250	205.5	1.38	1.33	1.373	1.335

1) Data from Harwell[20].
2) Present calculation work.

Table 5. Conversion coefficients from air kirma K_a to Hp(0.07) for ANSI N13.11 X-ray.

Tube Voltage (kV)	Average E. (keV)	Conversion Coeffieients ANSI N13.11 H*(10)	ANSI N13.11 H*(0.07)	KAERI[1)] H*(10)	KAERI[1)] H*(0.07)
M30	19.4	0.47	1.04	0.44	1.03
M60	35.2	1.07	1.30	1.17	1.38
M100	51.2	1.65	1.62	1.61	1.59
M150	73.0	1.92	1.78	1.90	1.76
H150	118.3	1.80	1.73	1.80	1.68

1) Present calculation work

the human trunk for photon, but the response of the dosemeter should still be interpreted in terms of conversion coefficients for the tissue equivalent slab phantom. Meanwhile ANSI N13.11(1992) uses the phantom made of PMMA and conversion coefficients corrected by the ratio of backscattering factor between a PMMA slab and the reference ICRU tissue cube phantom. Present calculation follows the procedures of ANSI N13.11 and the results show in Table 5. Good agreement between values of the ANSI N13.11 and of this study was achived with a few exceptions: due to the wide spectrum of M60 the present value is about 9% higher than that of ANSI N13.11 particularly in Hp(10).

CONCLUSIONS

The average energies and the conversion coefficients of X-rays calculated by theoretical spectra of this study were in good agreement within ±1.0% for the ISO beams, and within ±9.0% for the ANSI beams.

The reason of this little higher difference of the ANSI X-ray beams with the calculated seemed to be resulted from that the ANSI adopts much wider beam than the ISO, which would cause not only the uncertainties in spectrum measurements in detectors because of their different energy responses but also the difficulties in unfolding the measured spectrum.

However, the agreements between the theoretical data of this study and measured data for the ISO and ANSI beams seemed to be fairly acceptable, and therefore, it may be concluded that the model of this study is quite adequate over a wide range of experimental conditions of X-ray generators with high digree of confidence.

The most prominent advantages of this theoretical approach would be its easiness in calculation of the operational quantities, which has to be inevitably based on computation method at the moment, and its easy applicability to another X-ray spectrum.

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