Establishment of ANSI N13.11 X-ray Radiation Fields for Personal Dosimetry Performance Test by Computation and Experiment

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This paper describes establishment by computational and experimental methods of the American National Standard Institute (ANSI) N13.11 X-ray radiation fields by the Korea Atomic Energy Research Institute (KAERI). These fields were used in the standard irradiations of various personal dosimeters for the personal dosimetry performance test program performed by the Ministry of Science and Technology of Korea in the autumn of 1995. Theoretical X-ray spectra produced from two KAERI X-ray generators were estimated using a modified Kramers’ theory with target attenuation and backscatter correction and their spectral distributions experimentally measured by a high-purity germanium semiconductor detector through proper corrections for measured pulse height distributions with photpeak efficiency, Compton fraction, and K-escape fraction. The average energies and conversion coefficients obtained from the computational and experimental methods, when compared with ANSI N13.11 and the recently published National Institute of Standards and Technology X-ray beams, appeared to be in good agreement—a 3% between corresponding values— and thus, could be satisfactorily applied in the performance test of personal dosimeters. — Environ Health Perspect 105(Suppl 6):1417–1421 (1997)

Key words: personal dosimetry, ANSI X-ray, spectrum calculation, spectrum measurement, average energy, conversion coefficients

Introduction

The International Organization for Standardization (ISO) recognized the need to study the energy dependence of protection-level dosimeters, particularly photographic film and thermoluminescent dosimeters, in the low and medium energy ranges. This led to the narrow spectrum series of filtered X-radiations and fluorescence reference radiation. An ISO Standard (1) published in 1979 is comprised of narrow and wide spectrum series that included the fluorescence radiations. In addition, an amendment (2), addendum (3), and revision (4) of ISO 4037 were published and introduced the low- and high-rate series of filtered X-radiations. The American National Standard Institute (ANSI) has also published the ANSI X-ray beams for personnel dosimetry performance tests (5,6).

In the above documents, average energies of X-radiations were determined from spectral measurement. The Monte Carlo method has been used to calculate monoenergetic radiation for the conversion coefficients between photon fluence or air kera and the dose equivalents (7–9). However, for photon radiation, which has a continuous spectrum, a dose equivalent quantity must be calculated by integrating the product of photon fluence, or air kera, and the conversion coefficient for each energy level over the entire energy range of the spectrum. This procedure requires detailed knowledge of the photon spectrum over the whole energy region.

This paper describes establishment of ANSI N13.11 X-ray-filtered radiations by computations based on Kramers’ theory but include target attenuation and backscatter correction, and by experiments that measured spectral distributions with a high-purity germanium (HPGe) semiconductor detector. The average energies and conversion coefficients were calculated from the above computational and experimental X-ray energy spectra.

Theory

Kramers’ formula (10) gives the bremsstrahlung energy emission, Nk(E), per unit energy interval per electron as

\[ N_k(E) = CZ(E_0 - E) \]  \[ 1 \]

where \( E_0 \) is the energy of the bombarding electrons, \( Z \) is the atomic number of the target material, and \( C \) is a constant \( (2.76 \times 10^{-6} \text{ keV interval electron}^{-1}) \). But Kramers’ theoretical spectra incorporated many simplifying assumptions. For example, the backscattering of electrons in the target was neglected. Because the factors for X-ray absorption and electron backscattering are now known to a much higher degree of accuracy, a more accurate evaluation of the X-ray continuum from the target is possible.

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

\[ N_k = I_{AA} \cdot F_{BA/T_i} / C_{CA/T_i} \cdot \exp \left( -\sum_{i} \mu_i p_i x_i \right) dk / 4\pi D^2 \]

\[ 2 \]

where \( N_k \) = number of photons/cm²·sec⁻¹ in the energy interval \( k \) to \( k + dk \) per incident electron; \( I_{AA} \) = intensity of X-ray photons of energy \( k \) per incident electron; \( F_{BA/T_i} \) = backscatter factor; \( F_{CA/T_i} \) = target
attenuation factor; $k =$ photon energy in keV; $T_1 =$ initial electron energy in keV; $\exp(-\Sigma \mu_\rho x_1) =$ attenuation due to filters of mass attenuation $\mu$, density $\rho$, and thickness $x_1$; and $D =$ distance of point of measurement from X-ray tube focus, in cm.

Where appropriate, the contribution from characteristic X-ray must 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 penetrating a distance in the target element is given by

$$I_{Ak} = \frac{dN}{dA} \int dT \frac{dT/dx}{dT} dT$$  \[3\]

where $N$ is Avogadro’s number, $\rho$ is the density of the target, $A$ 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 et al. (11) and the stopping power data from the International Commission on Radiation Units and Measurements (ICRU) (12), and Equation 2 can be rewritten as

$$I_{Ak} = F_{Ak} (T_i - k)$$  \[4\]

Equation 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 $F_{Ak}$ are given in Table 1 for a tungsten target.

**Target Attenuation**

To determine the effect of the attenuation of X-ray produced within the target, it is necessary to know both the number and energy distribution of the electrons in the target. The Thomson–Whiddington (T–W) Law (13) frequently is used to calculate the maximum depth at which a photon of energy $k$ can be produced by an incident electron of energy $T_i$. The law states that, after penetrating a distance $x$ into the material along with the incident direction, the electrons have their energy related to $k$ as

$$k = (T_i^2 - \rho C x)^{1/2}$$  \[5\]

where $C$ is the T–W constant and $\rho$ is density of the target material.

Iles (14) uses a method similar to the T–W Law: the continuous slowing down range approximation (CSDA). If the mean range of the electrons is expressed as a fraction of $R_{W,T_i}$, the CSDA, the attenuation correction factor $F_{C/k,T_i}$ for photons of energy $k/T_i$ is given by

$$F_{C/k,T_i} = \exp \left(-\int f_{C/k,T_i} du \right)$$  \[6\]

where $R_{W,T_i}$ is the CSDA range in g/cm² of an electron energy $T_i$ in tungsten; $f_{C/k,T_i}$ = values of the mean depth of production as a fraction of the CSDA range; $\mu_{a,k}$ = mass attenuation coefficient in tungsten for photons of energy $k$ and $\theta$ = tube angle in degrees (45°).

A graph of $f_{C/k,T_i}$ versus $k/T_i$ is shown in Figure 1. The values for $R_{W,k,T_i}$ were taken from the data of ICRU 37 (12).

**Backscatter Correction**

A backscatter term should be included to correct for electrons scattered back from the focal spot. Antolak and Williamson (15) performed Monte Carlo calculations for a wide range of incident electron energies, angles of incidence, and atomic number. Their results confirm that for a given target material the backscatter factor is almost independent of the initial electron energy and varies typically by less than 10% for the angle of incidence, between 0 and 45°; the electron backscatter correction factor $F_{B,K/k,T_i}$ may be expressed as

$$F_{B,K/k,T_i} = 1 - \frac{\int \frac{dN}{d\omega} (w-k/T_i) d\omega}{\int 1 d\omega}$$  \[7\]

in which the number of backscattered electrons of relative energy $w$ is represented by the differential $dn/d\omega$. Figure 2 shows $F_{B,K/k,T_i}$ as a function of $k/T_i$.

**Characteristic X-rays from the Target**

In addition to the X-ray continuum, characteristic fluorescence X-rays are produced by the tungsten target. This relationship is discussed elsewhere (16,17). Birch and Marshall’s work (18) was used in this paper to calculate the number of characteristic $K$- and $L$-series X-rays:

$$N_k = 9.535 \times 10^4 \frac{R}{A_k \cdot C} \{U_0 \cdot \ln U_0 \}$$

$$= 9.535 \times 10^4 \frac{R}{A_k \cdot C} \cdot 0.365(U_0-1)^{63}$$  \[8\]

where $N_k =$ number of characteristic $K$-X-rays of tungsten produced by an incident electron; $A_k =$ mass number of target; $C =$ constant = 1; $R =$ correction of backscatter of electron $= 1$; $U_0 =$ $T_i/E_k$; and $E_k =$ $K$-absorption energy of target.

The number of $L$-X-rays is given by

$$N_L = \frac{8}{3} \left(\frac{E_k}{E_i}\right)^2 N_k$$  \[9\]

Table 1. Values of $F_{Ak}$ used for calculation of the spectra.

| Photon energy, keV | $F_{Ak} \times 10^{-4}$ |
|-------------------|-------------------------|
| 15                | 2.15                    |
| 30                | 2.02                    |
| 60                | 1.78                    |
| 100               | 1.51                    |
| 150               | 1.25                    |
| 200               | 1.04                    |
| 300               | 0.73                    |

Figure 1. Effective depth of X-ray production as a ratio of the CSDA range.

Figure 2. Backscatter correction factor.
Experiment

Spectral Measurements

X-radiations were obtained using an HF75C generator (Pantak, UK, 3.0 kW) for low-energy radiations and an MGN325 generator (Philips, Germany, 3.2 kW) for medium-energy radiations. Spectral photon measurements were determined at a distance of 2 m from the focus using a HPGe planar semiconductor (GLP 32340, Ortec, USA, detector thickness 13 mm).

The detector was placed in lead shielding 10 mm thick with an 0.8-mm hole in the front to protect against saturation of the detector (Figure 3). $^{133}$Ba, $^{241}$Am, and $^{137}$Cs gamma sources were used to calibrate the detector and its pulses were registered on a portable multichannel analyzer (PMCA-7500, Ortec). The pulse data were processed in a personal computer after saving on magnetic tape. Then the correction for K-escape photons, Compton continuum, and detector efficiency were made.

For detectors thicker than 4 mm, the K-escape for a pencil beam is significant only through the entrance surface and is independent of the detector dimension and geometry. K-escape fractions were obtained based on the work of Chen et al. (19).

For a thick detector and photon energies between the Ge–K-edge (11.1 keV) and approximately 50 keV, it is assumed that K-escape is the only significant source of loss. The full energy peak efficiency, $P(E)$, was therefore calculated from the K-escape fraction $K(E)$ to be

$$P(E) = 1 - K(E) \quad \text{[10]}$$

For energies below approximately 15 to 20 keV, absorption in the detector window will be significant. The correction factor was calculated from absorber thickness. For energies above approximately 50 keV, the full energy peak efficiency strongly depends on the detector dimension, so it was measured with $^{133}$Ba, $^{241}$Am, and $^{57}$Co radioactive sources emitting X- and gamma-rays of known energies and emission rates.

The Compton continuum arises from the partially absorbed photons registered in the energy channel, particularly those above the 50-keV energy range. This can be fitted with a second-order polynomial and an additional triangle to account for multiple scattering. When stripping continuous spectra, however, the assumption of a uniform Compton continuum with a triangle that allows for multiple scattering was proven sufficient (19). In Figure 4, the rectangular shape sufficient for continuous spectra as the effect of the distribution near the Compton edge is smoothed in the polyenergetic spectrum. The effect is cumulative, however, at the low energies. This is accounted for by the additional triangle at energies $0 < E < E_{c}$, and the multiple Compton scattering is accounted for by the triangle at $0 < E < 4E_{c}$, where $E_{c}$ is the Compton edge energy in keV.

Unfolding Method

In the high-energy range, which requires only a photopeak correction, the corrected spectrum, $I(E)$, can be calculated from the measured spectrum, $M(E)$, by

$$I(E) = \frac{M(E)}{P(E)} \quad \text{for } E_{\text{max}} - E < E \leq E_{\text{max}} \quad \text{[11]}$$

where $P(E)$ is the photopeak efficiency at energy $E$, $E_{\text{max}}$ is the maximum energy of the measured spectrum, and $E_{c}$ is the K-fluorescence energy of Ge.

In the medium-energy range, the K-escape correction is included

$$I(E) = \frac{M(E) - I(E + E_{c})K(E + E_{c})}{P(E)}$$

for $E_{\text{cmax}} < E < E_{\text{max}} - E_{c} \quad \text{[12]}$

where $K(E)$ is the K-escape fraction at energy $E$ and $E_{\text{cmax}}$ is the Compton edge energy corresponding to the maximum incident X-ray energy, $E_{\text{max}}$.
Results and Discussions

Average Energy

Calculated and measured spectra are presented in Figure 5 and compared to the ANSI N13.11 (6) X-ray beams. The calculated and measured spectra satisfactorily approximated the prescribed spectra. Small deviations were noticed for ANSI M60 spectrum, where the calculated spectrum was narrower than the prescribed, and the bump appearing on the prescribed M150 spectrum near 70 keV smoothed out on the calculated spectrum.

ISO standard 4037 (4) defines average energy, \( E_{ave} \), as

\[
E_{ave} = \frac{\int_0^{E_{max}} \phi_E(E) dE}{\int_0^{E_{max}} \phi_E dE}
\]

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 0.2 keV energy intervals and reading the number of photons associated with energy intervals from the calculated spectrum.

The average energies from the calculated and measured spectra are compared to the ANSI N13.11 X-ray beams (6) in Table 2. Agreement between the corresponding values is generally good, with one exception; because of the wide spectrum of M150, the present measured value is about 5\% higher than that of ANSI N13.11.

Conversion Coefficients

The spectrum weighting calculations were done by using the calculated and measured X-ray spectral data, the conversion factors for monoenergetic radiation of ICRU slab (8), and the values for the attenuation coefficients \( \mu(E) \) from Hubbell (21). The cubic spline interpolations were used to complete the following summations.

\[
H(d)_{spectra} = \frac{\sum \frac{H(E)}{K_d \mu(E) \Delta(E)}}{\sum \frac{\phi(E)\mu(E)\Delta(E)}}
\]

where the bin width, \( \Delta(E) \), for the summations were 0.2 keV.

ANSI N13.11 used the phantom made of polymethylmetacrylate (PMMA) and conversion coefficients corrected by the ratio of backscattering factor between a PMMA slab and the reference ICRU tissue cube phantom. This posed some serious problems, one of which was the relatively large increase in some of the photon conversion coefficients. Another argument is that no dosimeter can ever respond perfectly to backscatter because of the necessity for package material of the dosimeter (22). A metrologically more satisfying solution has been adopted by the ISO (23) in specifying that dosimeter irradiations below 300 keV be performed on a water-filled phantom. Such a phantom reproduces the backscatter characteristics of ICRU tissue to within 2\% (24). This study, therefore, uses the monoenergetic conversion coefficients of ICRU slab (8) and the results are shown in Table 3. Good agreements between the values of the recently published conversion coefficients of ANSI N13.11 (22) and those in this study were achieved within 3\%.

Conclusions

The average energies and the conversion coefficients of calculated and measured X-ray spectra in this study were in good agreement (within \( \pm 3\% \)) with those for the ANSI beams. An exception was the average energy of M150, about a 5\% difference. The reason for this slightly higher difference appeared to be that the ANSI adopts a wide beam, 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.

The agreements between the theoretical and measured data of this study and those of ANSI beams appear acceptable; therefore it is concluded that ANSI N13.11 X-ray radiation fields have been set up successfully and could be satisfactorily applied in performance tests of personal dosimeters.

Figure 5. Comparison of ANSI (solid line), calculated (circle), and measured (dashed line) X-ray spectra.

Table 2. Comparison of average photon energies for ANSI N13.11 X-ray.

| Tube voltage, kV | Average photon energy, keV | ANSI* | Calculated | Measured |
|-----------------|---------------------------|-------|------------|----------|
| M30             | 20                        | 19.4  | 19.9       |
| M60             | 35                        | 35.2  | 34.6       |
| M100            | 53                        | 51.3  | 54.2       |
| M150            | 73                        | 73    | 76.7       |
| H150            | 118                       | 118.3 | 118.7      |

*Data from the American National Standard Institute (6).

Table 3. Conversion coefficients from air kerma \( K_d \) to Hp (10) and Hp (0.07) for ANSI N13.11 X-ray.

| Tube voltage, kV | ANSI N13.11* | Calculated | Measured |
|-----------------|--------------|------------|----------|
| M30             | 0.42         | 1.40       | 1.43     | 1.02     |
| M60             | 1.00         | 1.03       | 0.98     | 1.21     |
| M100            | 1.52         | 1.49       | 1.52     | 1.51     |
| M150            | 1.78         | 1.76       | 1.82     | 1.68     |
| H150            | 1.71         | 1.71       | 1.74     | 1.82     |

*Data from the American National Standard Institute (6). \( \text{Hp (10)} \) and \( \text{Hp (0.07)} \) are personal dose equivalents at depths of 10 and 0.07 mm from skin layer.
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