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Research Article

Characterization of X-Ray Reference Beam to Establish a Set of Conversion Coefficients for The Calibration of Radiation Measuring Equipment and Calculation of BSF with MCNP Code

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Abstract

X-ray beam characterization for the calibration of radiation measuring equipment is necessary to meet the requirements of the recommendations by international organizations. In the present study, characterization of X-ray beam generated from X-ray irradiator, Model: X80-225KV, Hopewell Design, Inc of Secondary Standard Dosimetry Laboratory (SSDL) has been performed in accordance with the ISO 4037-1 narrow–spectrum series. The beam characterization was done by the determination of half-value layer (HVL), the effective energy, homogeneity coefficient (HC), beam quality index and output air Kerma values. Experimentally measured HVL is compared with the values recommended by ISO-4037. The effective energy, Eeff, for ISO narrow spectrum series were calculated by empirical relation derived from Hubble mass attenuation coefficients. Hence, a set of conversion coefficients has been established for the effective energies Eeff of photon beam from air Kerma to dose equivalent (Sv/Gy) i.e., for ambient dose equivalent, $H^*(10)$ & directional dose equivalent, $Hp'(0.07)$ and personal dose equivalent, $Hp(10)$ & $Hp(7)$ for ISO beam code N40, N60, N80, N100, N120, N150 and N200 by empirical mathematical relationship applicable for the photons with energies between 10keV to 10MeV. An evaluation of backscattering factors for ISO water phantom and ICRU slab phantom has been conducted by MCNPX Code. The calculated values were compared with the values found in the literature.

Introduction

Radiation hazard is one of the critical issues at different medical centers, industries and nuclear facilities around the world. To protect radiation workers, public and environment, a reliable dose measurement system is required that should be complied with international recommendations. X-rays and gamma rays are a highly penetrating radiation and are widely used as a calibration source at different medical, industrial and nuclear facilities. Absorbed dose quantification of the extent of air Kerma to human body is a great challenge to optimize radiation protection. Human-body-related protection quantities are not measurable in practice; therefore, they cannot be used directly as quantities in radiation monitoring. Over the years, International Commission on Radiation Units and Measurements (ICRU) has developed definitions of operational quantities in radiation protection and has published corresponding values of conversion coefficients (Sv/Gy) from fluence to the operational quantities for mono-energetic photons and particles of several types (electrons, neutrons, and others) as well as conversion coefficients from total air Kerma to dose equivalent [1-3]. The ICRU set of operational quantities are ambient dose equivalent, $H^*(10)$ & directional dose equivalent $H'(0.07)$, Personal dose equivalent

$Hp(10)\&Hp(7)$ [4-8] for use in radiation measurements for external exposure to assess the protection quantities. These dose equivalent quantities are produced by the corresponding expanded and aligned field in the sphere of International Commission on Radiation Units and Measurements (ICRU) at a depth of 10 mm on the radius opposing the direction of the field [9]. The ICRU sphere is 30 cm in diameter and its density equals to 1 g/cm^3. This sphere consists of 4-elemental compositions of 76.2% oxygen (O), 11.1% carbon (C), 10.1% hydrogen (H), and 2.6% nitrogen (N) [10-11].

Most of the national recommendations for the calibration of dosimeters are derived from the recommendations of ISO-4037 [12], which specifies characteristics of calibration beams. To reproduce these beams strictly according to the ISO recommendation is difficult and has to look a close compromise. The ISO-4037 also describes procedures for calibrating and determining the response dose rate meters and personnel dosimeters in terms of the ICRU operational quantities $H^*(10), Hp(7)$ and $Hp(10)\&Hp(7)$ for radiation protection. This leads differences in the specification of standard beams between different laboratories. Hence, for analyzing the beam quality of X-ray irradiator is done by calculating several parameters such as Half value layer, effective energy, homogeneity coefficient and beam quality index. These values will be compared with ISO values. A set of conversion coefficients from air Kerma to $H^*(10), H'(0.07), Hp(10), Hp(7)$ is required to protect the radiation workers and patients in radiography exposure [13-14] and limit the stochastic effect of radiation (cancer and hereditary effect). This study is aimed to characterize calibration beam in terms of ISO qualities and establish a set of conversion coefficient from air Kerma to absorbed dose (Sv/Gy) for ambient and personnel dose equivalent.

On the other hand, the operational dosimetric quantity recommended for individual monitoring is the personal dose equivalent $Hp(d)$ [15], which would exist on a phantom approximately in human body. From this concept, the calibration of personal dosimeter should be carried out on a suitable phantom surface as recommended by different international organizations related to the radiation protection standard. The use of the phantom is based on dose contribution of incidence beam with backscatter contribution as the replacement of human body considered that as soft tissue. The ICRU soft tissue is a hypothetical material, and it is hard to find a material with the same composition (76.2% O, 11.1% C, 10.1% H and 2.6% N by weight) [15]. Various alternative phantom types are in use. Water is an excellent substitute for these radiation energies but must be encapsulated in some non-tissue equivalent material. Moreover, for the practical works ICRU slab phantom, Alderson Rando Phantom, ISO water phantom are widely used as calibration phantom.

Backscatter factor (BSF) is defined as the ratio of the collision Kerma of a phantom material; at the surface of a full scatter phantom located at a point in the beam axis, to the collision Kerma of the same material; at the same point in the primary beam, with no phantom present [16-17]. Backscatter factors are difficult to measure experimentally, and tabulated values are based largely on Monte Carlo Calculations [18]. In this work, we have calculated back scattering factor using Monte Carlo N-Particle (MCNP) Code (version 2.6.0). These calculated values are compared with the values found in the literature [19-23].

Method and Materials

X-ray Beam Irradiator

The X-ray beam irradiator with variable tube potential 15-225kV in 0.2kV, ± 1% kV drift as a function of temperature is <100ppm/^{0}C and current selectable from 0-50mA in 0.05mA increments with a current accuracy ± 0.2% of set value for standard focal spot ± 0.2% for fine focuses made by Hopewell Design Inc, USA is used in this study. To achieve the desired uniformity of desired narrow beam for the produced X-ray, hence the stability of tube current, tube voltage represents the stability of generator. The determination of air Kerma, 1st and 2nd half-value layer (HVL), the effective energy and homogeneity coefficient are determined with a reference class electrometer (IB Dose-1) and an ionization Chamber (NE2575) of volume 600cc.

Effective Energy and Homogeneity Coefficients Measurement of X-Ray Beam

Attenuation measurements of a monochromatic photon beam depends on the number of photons incident on an absorber, the number of photons transmitted through the absorber, and the absorber thickness. The expression; $\mu = \Delta T/\Delta x$. If ΔT and Δx is very small, they are known as differentials and the differential equation of following.

$$I = I\_0e^{\wedge}(-\mu X)\, and\, T = T\_0e^{\wedge}(-\mu X) \quad (1)$$

where I_0 is the intensity of the beam without absorber, X absorber thickness, I is the beam intensity transmitted through an absorbent of thickness of X, e is base of the natural logarithm system, μ is the attenuation coefficient, T = number of transmitted photons, and T = number of incident photons.

The penetrating ability or quality of an X-ray beam is described explicitly by its spectral distribution, which indicates the energy present in each energy interval. However, the HVL or half-value thickness is the concept used most often to describe the penetrating ability of X-ray beams of different energy levels and the penetration through specific materials.

The HVL of an X-ray beam is obtained by measuring the exposure rate from the X-ray generator for a series of attenuating materials or attenuators placed in the beam. The HVL can be easily calculated from the linear attenuation coefficient for a monoenergetic photon beam and vice versa. The measurement of HVL is related to the Hubble's mass attenuation coefficient by relation; HVL= ln2/μ, where μ is linear attenuation coefficient of the material.

Hence beam homogeneity coefficient (h) has been obtained by using the relation stated below.

$$h = \frac{1^{st}\ HVL}{2^{nd}\ HVL} \qquad (2)$$

The effective energy E_{eff} (keV) of X-rays are calculated by the empirical relation obtained from the interpolation value from Hubble mass attenuation coefficients [24];

$$E_{eff} = 76.48.t^{0356} + 2.543.t^{2.00} \qquad (3)$$

Where t is the filter thickness in mm of Cu

The beam quality index (*QI*) is obtained from effective energy (keV) for tube potential by using the formula,

$$QI = \frac{E_{eff}}{Tube\ potential\,(kV)} \qquad (4)$$

Air Kerma Rate Measurement

The output air Kerma rate of calibration X-ray beam is measured by using a secondary standard ionization chamber NE2575 (600cc) coupled with an electrometer (IBA Dose-1). The chamber was previously calibrated at IAEA laboratory in terms of air Kerma.

The air Kerma rate at the reference point in air is given by simple relationship.

$$K_a^{'} = M_C.N_K \qquad (5)$$

where, M_C is the reading of the electrometer per unit time corrected for the influence quantities Pressure and Temperature N_K and is the calibration factor of the ionization chamber in terms of air Kerma. The corrected electrometer reading M_C, which is derived from the uncorrected instrument reading, *M*, by applying a number of measurements corrections:

$$M_C = M.k_{TP}.P_F.\,P_{pol} \qquad (6)$$

where, k_{TP} is the temperature and pressure correction factor, P_F is the recombination correction factor, P_{pol} is the correction factor for polarity effects in the user's beam and C_k is the correction factor for any difference in relative humidity between the reference conditions and conditions during measurement.

Results and Discussion

Measurement of X-ray Qualities

The 1st and 2nd HVL for each beam code N40, N60, N80, N100, N120, N150 and N200 for ISO narrow spectrum was with 99.99% Cu filter. The measured HVL is compared with ISO values is shown in Figure 1. The variation of experimental HVL lies within 0 to -12.5% to ISO values. The Beam homogeneity coefficients lie within 0.84 to 1.104 is given in Table 1. The effective energy E_{eff}, is calculated from the HVL is summarized with ISO recommended values in Table 2 (Figure 1) (Tables 1,2).

Table 1: Experimental values of HVL with ISO-4037 reference values, HC and air Kerma rate

Beam Quality	Tube Potential (kV)	Measured 1st HVL in mm (Cu)	ISO-4037 1st HVL in mm (Cu)	Percentage of Deviation	Measured 2nd HVL mm (Cu)	ISO-4037 2nd HVL mm in Cu	Percentage of Deviation	HC	Air Kerma mGy/h
N40	40	0.09	0.08	-12.50%	0.09	0.091	1.11%	1	32.16
N60	60	0.24	0.24	0%	0.27	0.26	-3.85%	0.89	66.77
N80	80	0.58	0.58	0%	0.6	0.62	3.23%	0.97	34.43
N100	100	1.13	1.11	-1.80%	1.04	1.17	11.11%	1.087	16.92
N120	120	1.8	1.71	-5.26%	1.63	1.77	7.90%	1.104	18.06
N150	150	2.2	2.36	6.77%	2.62	2.47	6.07%	0.84	140.5
N200	200	4	3.99	-0.25%	4.01	4.05	0.99%	0.998	53.7

.

Table 2: Derived values of effective energy *(E_{eff})* from HVL in comparison with ISO-4037 and beam Quality Index (QI).

Beam Quality	Tube Potential (kV)	Tube Current (mA)	1st HVL in mm of Cu	Experimental Values of Effective Energies (keV)	ISO-4037 Values of Effective Energies (keV)	Percentage of Deviation	Quality Index (QI)
N40	40	10	0.09	32.45	33	1.67	0.811
N60	60	10	0.24	46.17	48	1.83	0.77
N80	80	10	0.58	65.1	65	-0.15	0.814
N100	100	10	1.13	83.13	83	-0.16	0.831
N120	120	10	1.8	102.52	100	-0.03	0.854
N150	150	10	2.2	113.57	118	3.75	0.757
N200	200	10	4	165.97	164	-1.2	0.83

Table 3: Calculated values of conversion coefficient for ambient dose *H*(10)*.

Beam Quality	Mean Energy in keV	Effective Energy in keV	Present Study $H^*(10)$/Ka ($Sv.Gy^{-1}$)	ISO-4037 $H^*(10)$/Ka ($Sv.Gy^{-1}$)	Percentage of Deviation ISO Values
N40	33	32.63	1.19	1.18	0.84
N60	48	44.73	1.57	1.59	1.27
N80	65	64.84	1.75	1.73	1.14
N100	83	85.57	1.7	1.71	0.59
N120	100	102.52	1.64	1.64	0
N150	118	116.33	1.58	1.58	0

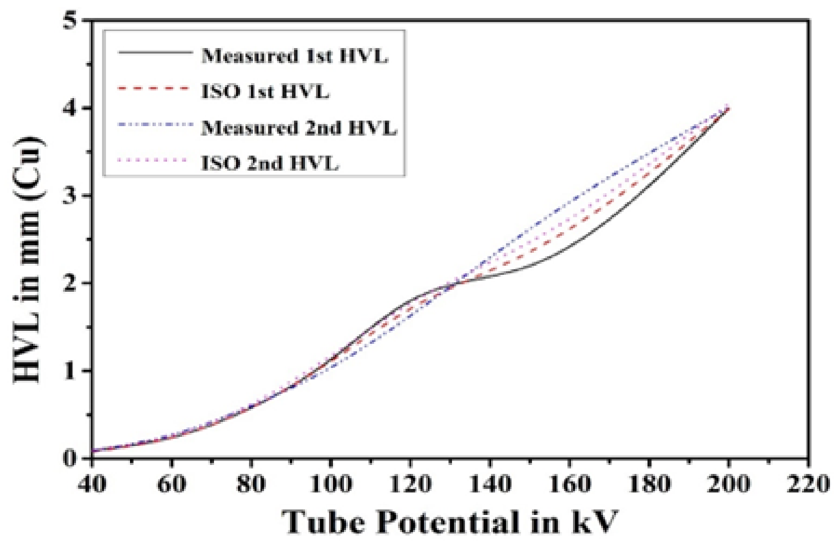

Figure 1: Experimental values of HVL (mm of Cu) with ISO-4037 [12] recommended values.

Conversion Coefficients (Sv/Gy) for Reference X-ray

Radiation survey instruments and personnel protection devices for photons should be reference radiations from X-ray generators or from radio-isotopic sources, described in ISO 4037-3 [12]. The ISO narrow-spectrum series is frequently used for calibration of radiation protection instruments and dosimeters. In radiation protection, the effective dose, E is the protection quantities describe by whole-body exposure. Effective dose cannot be measured directly hence the measuring instrument such as dosimeters and survey instruments should be calibrated in terms of operational quantities recommended by ICRU-26 that introduces two quantities for whole body exposure, ambient dose $H^*(10)$ for area monitoring and personal monitoring $Hp(10)$. Fluence or Kerma-to-dose conversion coefficients for these spectra can be tabulated for operational quantities $Hp(10)$ *and* $H^*(10)$ in [25-26].

The conversion coefficients (Sv/Gy) from Kerma to dose equivalent for X-ray spectrum can be described by the equation given in [27]. A set of conversion coefficients *(Sv/Gy)* for ambient dose equivalent, $H*(10)$ and directional dose equivalent, $H'(0.07)$ and personal dose equivalent, $Hp(10)\,and\,Hp(0.07)$ has been calculated as a function of E_{eff} *(keV)* of the X-ray beam has been established.

Ambient Dose Equivalent $H*(10)\,and\,H'(0.07)$

The ambient dose equivalent, $H*(10)$ at a point in a radiation field is the product of the particle fluence, $\Phi(E)$, at that point and a conversion coefficient relating the particle fluence to the maximum value of the effective dose, Emax, that would be produced by that field, calculated for whole-body exposure in the ICRP reference phantoms [2]. The general expression of conversion coefficients from Kerma to dose equivalent can be describe by Wills formula given in [28]. The conversion coefficient for ambient dose equivalent is derived by the empirical mathematical relation for photon energy have been fitted from the data recommended by the British Committee on Radiation Units and Measurements (BCRU) for narrow spectrum series [27] which is adopted under the condition of ICRU-39 is given in Table 3.

Personal Dose Equivalent $Hp(10)\,and\,Hp(0.07)$

The ICRU [29] and ICRP [30] recommended the operational quantities $Hp(10)\,and\,Hp(0.07)$ as the quantities to be determined for personal dose equivalent evaluations for highly penetrating and weakly penetrating radiations. These quantities are not measurable, hence, to measure on a suitable phantom and it is very sensitive for effective dose measurement of radiation worker. The general formalism of air Kerma to dose equivalent (Sv/Gy) is given by Wills [28] as;

$$\frac{H_P(d)}{K_{air}} = BSF \times T^S(d)\left(\frac{\mu_{en}}{p}\right)_{air}^{PMMA} \qquad (7)$$

Where $BSF = K^s_{air}(0)/K_{air}$ _air is the back-scattering factor; $T^s(d) = K^s_{air}(d)/K^s_{air}(0)$ is the dose factor at depth d, $\left(\frac{\mu_{en}}{p}\right)_{air}^{PMMA}$ is the ratio of mass energy absorption coefficient of the polymethyl methacrylate (PMMA) tissue to that for the air, averaged over the photon spectrum at the phantom depth, d. A set of conversion coefficients of $Hp(10)$ and $Hp(0.07)$ for ISO narrow beam series derived from the fitting values given in ref [31] and is presented in Table 4 (Table 4).

Table 4: Calculated conversion coefficient for personal dose equivalent H_p*(10)* and H_p*(0.07)* for various phantom.

Beam Quality	Effective ‘ Energies in keV	Conversion Coefficient H_p *(10)* (Sv. Gy^{-1})			Conversion Coefficient H_p *(0.07)* (Sv. Gy^{-1})		
		ICRU Tissue Slab	PMMA Slab	ISO water Phantom	ICRU Tissue Slab	PMMA Slab	ISO Water Phantom
N40	32.63	1.34	1.541	1.298	1.261	1.161	1.253
N60	44.73	1.631	1.504	1.657	1.531	1.407	1.557
N80	64.84	1.885	1.793	1.932	1.723	1.608	1.766
N100	85.57	1.877	1.824	1.912	1.718	1.669	1.729
N120	102.52	1.805	1.765	1.847	1.665	1.628	1.704
N150	116.33	1.74	1.709	1.782	1.617	1.588	1.646

Backscatter Factor and Monte Carlo N-Particle (MCNP) Simulation

The dose measured by any detector in any medium depends on the gamma photon energy, density of the medium and material characteristics. When the absorbed dose is measured in air in terms of air Kerma (K_{air}), and when a phantom is placed instead of air it provides the dose quantity in terms of equivalent dose. The concept of the BSF on a phantom is to simulate practical wearing of dosimeter on the chest, backscattered photons contribute to the dose estimation.

The X-ray spectrum that satisfied the quality to ISO narrow spectrum series N40-N200 generated from Model: X80-225KV, Hopewell Design, Inc, USA installed at Secondary Standard Dosimetry Laboratory, Bangladesh Atomic Energy Commission is therefore simulated with Monte Carlo N Particle Transport Code. This code is a powerful geometry package by which a complex geometry that described by unions, intersections and compliments of cells that can be defined by the user's plan. A photon history terminated when it reaches an energy 1 keV. The energy loss of electrons for the X-ray production by collision can be expresses by Bethe-Bloch formula [32]. In the present study, MCNP is run with default parameters that counts for photoelectric Effect, Compton

Effect and Pair Production including Fluorescence. The Thomson effect is accounted from modification of cross section and Compton cross section is modified by the incoherent scattering cross section that corrects the electron binding effects.

X-ray Spectra that generated by the experimental condition satisfied with ISO radiation quality were determined by the attenuation analysis method which gave spectra in terms of photon fluence and exposure. The simulated geometry (2-D view) of the X-ray machine is shown in Figure 2. The calculated spectrum generated from experimental condition by MCNP code and are used in the present Monte Carlo calculations for back scatter factors on ISO water phantom and ICRU slab phantom of 30 cm × 30 cm × 30 cm. The MCNP generated Back Scattering Factor (BSF) for ICRU slab phantom and ISO water phantom from the present study is summarized with literature values and is given in Table 5 and Table 6. It is seen that present values are close comparable with the data generated by IPEMB data [19] and *N. Petoussi-Henss et al.* [20] for ISO water phantom (Figure 2) (Tables 5,6).

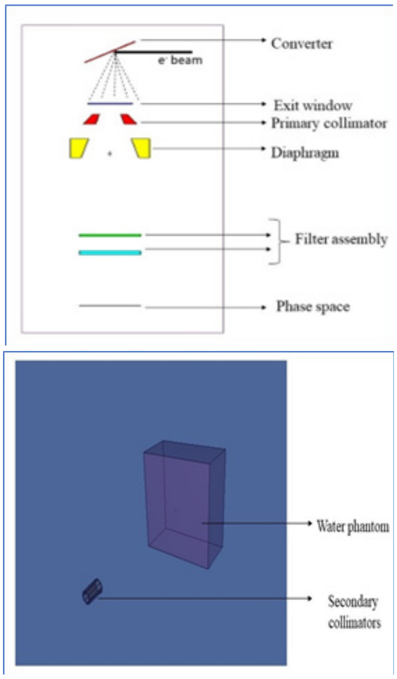

Figure 2: Simulated geometry (2-D view) of X-ray machine.

Table 5: MCNP calculated BSF values with literature values data for ISO water phantom of 10cm diameter radiation field.

Tube Potential (kV)	**Backscattering Factor (BSF)**				
	MCNP Generated BSF calculated in the Present Study	**IPEMB Data [19]**	***N Petoussi-Henss, et al.*[20]**	***Shukor, et.al.* [21]**	***Eaton, et al.* [22]**
40	-	-	-	-	-
60	-	-	-	-	1.185
80	1.3665	1.238	1.32	1.089	-
100	1.2974	1.343	1.34	1.145	-
120	1.2536	1.335	1.37	1.147	1.309
150	1.206	1.35	-	-	1.369
200	1.1577	1.292	-	-	1.296

Table 6: MCNP calculated BSF values with literature values data for 30cm×30cm×30cm ICRU Slab phantom of 10cm diameter radiation field.

Tube Potential (KV)	Backscattering Factor		
	Current Study	IPEMB Data [19]	*Coudin, et al.* [23]
40	-	0.945	1.035
60	-	-	-
80	1.3698	0.926	1.147
100	1.2975	0.905	1.216
120	1.2543	-	-
150	1.2027	-	-
200	1.1596	-	-

Conclusion

The present work was aimed to characterize calibration X-ray beam at SSDL, Bangladesh Atomic Energy Commission as per international recommended protocols. The X-ray beams are characterized as per ISO narrow spectrum series. The beam characterization is conducted with the recommended filtration by ISO. To achieve the ISO qualities half value layer, effective energy, beam homogeneity coefficient is determined. In this study, the variation of HVL of measured value lies within 0 to -12.5% to ISO values with a standard deviation of 1.3%. The effective energy (keV) is then calculated by established empirical relation which is obtained by the interpolation value from Hubble mass attenuation coefficients. A set of conversion coefficients (Sv/Gy) for ambient dose equivalent $H^*(10)$ and $Hp'(0.07)$ and personal dose equivalent $Hp(10)$ and $Hp(0.07)$ has been calculated empirical mathematical function developed by BCRU. The conversion coefficient for ambient dose equivalent $H^*(10)$ is calculated for mono-energetic photon lies within 0.00% and 1.27% with ISO reference values which shows a very good in agreement. The personnel dose equivalent $Hp(10)$ and $Hp(0.07)$ was also derived for various phantom as a function of photon energy. Backscattering factors for are generated with Monte Carlo N Particle (MCNP) transport code for ISO water phantom and ICRU slab phantom. The calculated values are compared with the values found in the literature that shows good in agreement.

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