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DETERMINATION OF CALIBRATION X-RAY BEAM QUALITIES AND ESTABLISH A SET OF CONVERSION COEFFICIENTS FOR CALIBRATION OF RADIATION PROTECTION DEVICES USED IN DIAGNOSTIC RADIOLOGY[†]

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The use of X-ray facilities in calibrating radiation measuring equipment in diagnostic radiology requires an exact knowledge of the radiation field. X-ray spectrums are made narrow beam by proper filtration recommended by several international organizations. In the present study, the experimental determination of X-ray calibration qualities and analysis of conversion coefficients from air Kerma to ambient and personal dose equivalent is carried for X-ray beam irradiator X80-225kV as per ISO narrow spectrum series at Secondary Standard Dosimetry Laboratory (SSDL) in Bangladesh. The X-ray beam involved in half value layer, effective energy, beam homogeneity coefficient and consistency of X-ray production from the generator (kV and mA) is conducted. A discrepancy of half value layer has been observed for N200 beam code by -8.5% which leads to the deviation of effective energy by -7.7% with a standard deviation of 1.3%. The conversion coefficients from the air kerma to dose equivalent that satisfying the condition of ICRU sphere is established to obtain radiation qualities and compared with values referred by other standard laboratories. A deviation of 0.87% has been observed for *H*(10)* and *H′(0.07*) in between ISO and BCRU empirical relation which is insignificant. A set of conversion coefficients for *Hp(10)* and *Hp(0.07*) has also been calculated for ICRU four element tissue.
Keywords: X-ray qualities, radiation protection, ISO narrow beam, ambient dose equivalent, personal dose equivalent
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Radiation protection is based on the principle of monitoring with the aim of verifying how requirements of the system of limits in deriving dose equivalent. X-rays are highly penetrating radiation and are widely used as a calibration source at standard laboratories for the calibration of dosimeters used at diagnostic radiology for the convenient use of their expected energies and qualities. Kerma in air is the most common and widely used reference quantity for X-ray photon fields specified by different calibration laboratories. Most of the national recommendations for the calibration of dosimeters are derived from the recommendations of ISO-4037 [1], which specifies characteristics of calibration beams. To reproduce these beams strictly according to the International Organization for Standardization (ISO) recommendation is difficult and has to look a close compromise. For achievement of required air kerma rates and Half Value Layers (HVL) adjusting the filtration is necessary. Some of the laboratories also extended the number of calibration beams, i.e. the energy range beyond ISO-4037. All these lead differences in the specification of standard beams between different laboratories. This leads the characterization of X-ray beam used for the protection of radiation as a whole [2].

As early as in 1985, the International Commission on Radiation Units and Measurements (ICRU) presented a concept of radiation protection quantities for measurement in area and individual monitoring of external radiation. The concept of operational quantities is to provide a reasonable and conservative approximation to the effective dose for most photon energies. Effective dose is the radiation protection quantity assessed control purpose in respect of stochastic effects of ionizing radiation. In 1985, the concept of operational quantities was introduced in ICRU Report-39 [3] which was further elaborated in ICRU Report 43 and 47 [4, 5]. The quantities applied during the calibration of dosimeter for area monitoring in units of dose equivalents are ambient dose equivalent *H*(10)* & directional dose equivalent *H′(0.07)* and for individual monitoring it is represented by *Hp(10)* and *Hp(0.07)* [6, 7]. ISO-4037 also describes procedures for calibrating and determining the response of dosimeters and dose rate meters in terms of the ICRU operational quantities *Hp(10)*, *Hp(0.07)*, *H*(10)* and *H′(0*.07) for radiation protection.

Air Kerma is widely used as reference quantities specified by different calibration laboratories and calibration of dosimeter used for individual and environmental monitoring requires the knowledge of conversion coefficients between the air Kerma and an appropriate protection quantity. The conversion coefficients (Sv/Gy) that relates ambient and personal dose equivalent to exposure and air kerma in free air is established by ISO for narrow spectrum in its publication 4037 [1, 8] as well as IAEA safety series-16 [9]. Conversion coefficients are the function of effective energy of the photon. The Conversion coefficients between the air kerma and these quantities have been calculated by different authors [10, 11]. The National

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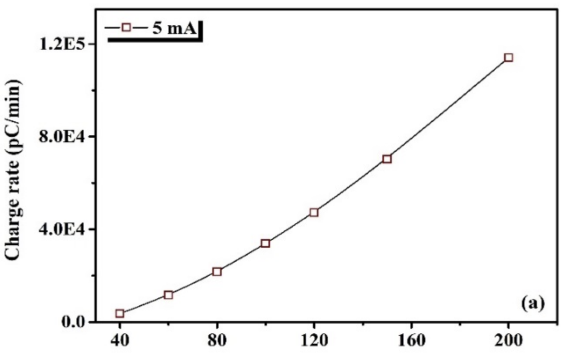
Measurement Accreditation Service (NAMAS) [12] recommended for the calibration of radiological instruments using ISO recommended conversion coefficients (Sv/Gy) in its publication. The radiation fields from these reference radiations are normally standardized by the measurement of the air kerma rates. Such conversion coefficients (Sv/Gy) for monoenergetic photon have been recommended by various authors and organizations such as British Committee on Radiation Units and Measurements [BCRU] [13], International Commission on Radiological Protection (ICRP) [14], National Radiological Protection Board (NRPB) [15], Physikalisch-Technische Bundesanstalt (PTB) [16] etc. The calculations of conversion coefficients are usually performed by Monte Carlo simulations in standard condition of exposure of a simplified phantom.

On the other hand, operational dosimetric quantity recommended for individual monitoring is the personal dose equivalent *Hp(10)* and *Hp(0.07)*, which would exist on a phantom approximately similar to a human body. The concept from which, 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 calibration phantom should provide a backscatter contribution similar to that of the part of the body where the dosimeter is worn. In several times, different phantoms recommended for and later were rejected due to raised difficulties. In 1992, the ICRU-47 [5] gave a list of five different phantoms that were being used by several laboratories, which is considered to be enough within the accepted overall uncertainty in most radiation protection measurement of 30%. In this recommendation, calibration of personal dosimeter should be carried out on a PMMA slab phantom of size 30 cm × 30 cm × 15 cm. Recently, a recommended phantom is proposed by the ISO in its report ISO-4037-3 [1] is named as ISO water phantom of same dimension, which is represented as the human torso with regard to backscattering of the incident radiation. For calibration, this definition is extended to include a phantom having the composition of ICRU tissue and the same size and shape as the calibration phantom (30 cm × 30 cm × 15 cm, ICRU four element tissue phantom) [17]. However, since ICRU tissue is not readily available, a phantom of alternative composition must be specified. Calculated and measured photon backscatter results for the ICRU tissue phantom and calibration phantoms have been reported [18-19]. Kramar, H.M. *et al.* studies of the PMMA rectangular phantom indicated that photon energies in the range from about 10-500 keV, the backscatter factor could be 8% high relative to ICRU tissue [20]. Nelson and Chilton [21], for instance, have calculated dose equivalents in plastic and ICRU tissue equivalent semi-infinite slab phantoms for photon energies range 10-150 keV. Backscatter factor and tissue kerma at the phantom surface have been published by Bartlett *et al.* [22] for photon energies 15-662 keV for an ICRU tissue equivalent cube phantom and PMMA slab. R. J. Traub *et al.* [19] calculated MCNP generated backscattering correction factor for PMMA and ISO water phantom for narrow beam spectrum for the photon energy from 10 keV-2 MeV.

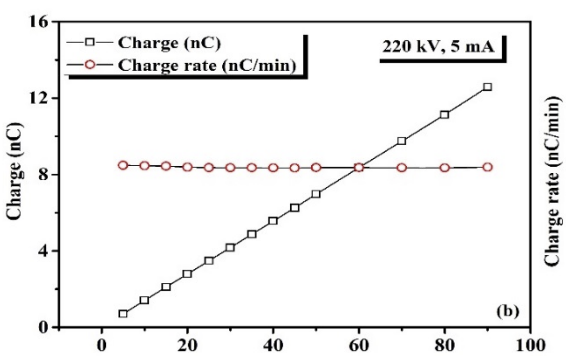
The aim of this work is to establish the calibration X-ray beam with a set of conversion factor for operational quantities for newly installed X-ray beam irradiator X80-225KV at Secondary Standard Dosimetry Laboratory (SSDL), Bangladesh Atomic Energy Commission.

MATERIALS AND METHODS

I. Calibration of X-ray Machine: The X-ray beam irradiator X80-225KV has been used to generate X-ray that permits its variable tube potentials 15-225 kV in 0.2 kV increments with accuracy ±1% kV drift as a function of temperature is <100 ppm/^{0}C and current selectable from 0-50 mA in 0.05 mA increments with a current accuracy ±0.2% of set value for standard focal spot ±0.2% for fine focuses. The quality of the X-ray production is checked in order to get of the desired uniformity of narrow beam. The linearity of tube voltage and tube current is tested for stability of the X-ray generator. The measurement is performed using secondary standard ionization chamber NE2575 coupled with an electrometer TW10002. Dose measurements were performed for each recommended beam quality of ISO narrow spectrum series at constant tube voltage varying tube current from 0-15 mA with an increment of 0.1 mA and vice versa. The stability of the X-ray generator was found to be good in agreement with SD variation of less than 1%. Output linearity is checked and found to be linearly increased with mAs and exposure time, beam output per unit time was also constant with exposure time which is shown in Figure 1.



(a)



(b)

Figure 1. Variation of beam output with (a) Tube potential kVs and (b) Exposure time.

II. Half Value Layer (HVL) and Beam Homogeneity Coefficient: Attenuation measurements of a monoenergetic (monochromatic) beam of X- or gamma ray depends on the number of photons incident on an absorber, the number of photons transmitted through the absorber, and the absorber thickness. The expression; $\mu = \Delta N/\Delta x$. If ΔN and Δx are very small, they are known as differentials and the differential equation is solved by using calculus giving the following equations;

$$I = I_0 e^{-\mu x} \text{ and } N = N_0 e^{-\mu x} \tag{1}$$

where I_0 is beam intensity at an absorber thickness of zero, *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 attenuation coefficient, *N* = number of transmitted photons, and N_0 = 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 1evels 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 ;

$$h = \frac{1^{st}\, HVL}{2^{nd}\, HVL}. \tag{2}$$

Effective energy, E_{eff} of narrow beam X-rays are calculated by the empirical relation obtained from the interpolation value from Hubble mass attenuation coefficients [23];

$$E_{eff} = 76.48 \cdot t^{0.356} + 2.543 \cdot t^{2.00}, \tag{3}$$

where *t* is the filter thickness in mm of Cu.

III.Measurement of Air Kerma Rate: The term dosimetry is used to describe the method by which the value of physical quantity characterizing the interaction of the radiation field with matter, which is measured in a given point by the use of a calibrated standard instrument. Dosimetry is the basis for calibration of radiation protection instruments and the determination of their response as a function of energy of interest. The output of calibration X-ray beam is measured by using a secondary standard ionization chamber NE2575 coupled with an electrometer TW10002. The chamber was previously calibrated at the National Physical Laboratory as well as from IAEA laboratory in terms of air kerma.

The air kerma rate at the reference point in air is given by simple relationship;

$$K_a' = M_u \cdot N_K, \tag{4}$$

where, M_u is the reading of the electrometer per unit time corrected for the influence quantities and N_K is the calibration factor in terms of air kerma. The corrected electrometer reading M_u, which is derived from the uncorrected instrument reading, *M*, by applying a number of measurement corrections;

$$M_u = M.K_{tp}.P_s.P_{pol}.C_k, \tag{5}$$

where, K_{tp} is the temperature and pressure correction factor, P_s 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

I. X-ray Beam Qualities: The experimentally measured and ISO reference values of HVL with tube potential (KV) for the ISO recommended filter combination for narrow beam spectrum is shown in Figure 2. The variation of HVL of measured value lies within 2 to -8.5% to ISO values with a standard deviation of 1.3%. The Beam homogeneity coefficients lie within 0.84 to 1.04 that meets well in agreement with ISO values (0.75 to 1.00). The experimental values of second HVL varies by -10.9% and -12.9% with ISO values for the beam code N150 and N200. It can be mentioned here that the deviation between the experimental and reference values of second HVL lies within 2% for five other beam codes. The effective energy (keV) is then calculated by established empirical relation which is obtained by the interpolation value from Hubble mass attenuation coefficients (Eqn. 3). It is shown that the -8.5% discrepancy of HVL for the beam code N200 leads to an effective energy deviation of -7.7%. The experimental measured 1st and 2nd HVL for ISO recommended filter combination with the reference values are summarized in Table 1.

II. Conversion Coefficients *(Sv/Gy)* for Reference Photon Radiation: The conversion coefficient enables calibration in terms of operational quantities to be derived from those the quantity currently determined by primary standardization laboratories. A set of conversion coefficients *(Sv/Gy)* for ambient dose equivalent *H*(10)* and *H′(0.07)* and personal dose equivalent *Hp(10)* and *Hp(0.07)* has been calculated for ISO narrow beam spectrum series.

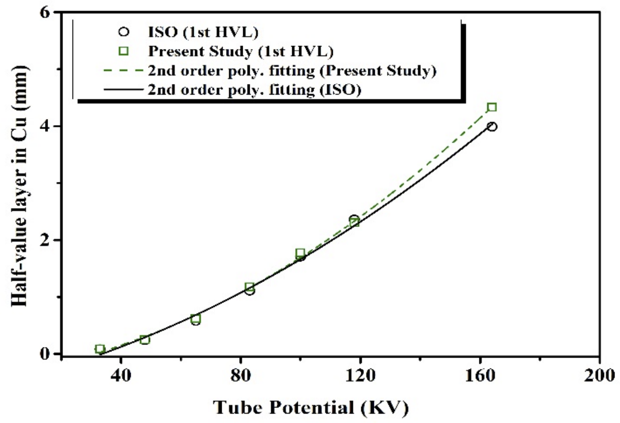


Figure 2. Experimental value of HVL in mm of Cu with ISO reference values

Table 1. Established radiation qualities and air kerma rate of X-ray beam irradiator X80-225KV

Beam code	Tube voltage in kV	Additional Filtration thickness in mm			1st HVL in mm of Cu		HC	Effective photon energy in keV	Air kerma rate in mGy/h
		Pb	Sn	Cu	ISO reference	Experimental Value			
N40	40			0.21	0.084	0.088	0.957	32.21	37.12
N60	60			0.60	0.24	0.25	0.961	46.85	79.94
N80	80			2.00	0.58	0.62	1.016	65.49	14.28
N100	100			5.00	1.11	1.18	1.044	84.66	7.08
N120	120		1.00	5.00	1.71	1.775	0.947	102.00	10.45
N150	150		2.50	--	2.36	2.31	0.843	116.61	58.14
N200	200	1.00	3.00	2.00	3.99	4.33	0.947	176.544	22.20

II (a). Ambient Dose Equivalent *H*(10)* and *H′(0.07)*: The conversion coefficient for ambient dose equivalent is calculated from the fitted value of photon energy vs Conversion coefficient recommended by ISO and is given in Table 2 (SSDL, Bangladesh). The empirical mathematical functions for photon energy have been fitted from the data recommended by the British Committee on Radiation Units and Measurements (BCRU) for narrow spectrum series which is adopted under the condition of ICRU-39. These functions are convenient for user as their derivation is discussed elsewhere [23].

Table 2. Calculated values of Conversion Coefficients for ambient dose equivalent *H*(10)*

Beam Quality	Effective Energy in keV	HVL in mm	Conversion Coefficients *H*(10)* (Sv/Gy)						
		Cu	ISO	BCRU	NPL	PTB	NRPB	AERE	NAMAS
N40	32.21	0.088	1.192	1.194	1.134	1.180	1.164	1.145	1.148
N60	46.85	0.250	1.615	1.618	1.547	1.579	1.579	1.528	1.558
N80	65.49	0.620	1.741	1.748	1.733	1.743	1.742	1.743	1.732
N100	84.66	1.180	1.713	1.704	1.706	1.706	1.705	1.706	1.706
N120	102.00	1.775	1.647	1.637	1.635	1.646	1.645	1.647	1.635
N150	116.61	2.305	1.599	1.585	1.587	1.597	1.697	1.598	1.588
N200	176.544	4.330	1.449	1.437	1.431	1.442	1.442	1.420	1.423

For monoenergetic photons with energies between 10 keV and 10 MeV, the relationship [24] between ambient dose equivalent *H*(10*) at 10 mm depth in ICRU tissue and air kerma free in air, K_a is given by;

$$\frac{H^{*}(10)}{K_a} = \frac{x}{ax^2+bx+c} + d.\arctan(gx), \tag{6}$$

where a = 1.465, b = -4.414, c = 4.789, d = 0.7006, g = 0.06519, arctan in radians and $x = \ln (E/E_0)$ where E is the photon energy in keV and E_0= 9.85keV.

From this relationship (Eqn. 6) the *H*(10)* is calculated for the radiation quality obtained by the experiment is summarized in Table 2. For unidirectional monoenergetic photons with energies between 10 keV and 250 keV, the relationship [24] between directional dose equivalent at 0.07 mm depth in the ICRU sphere on the radius opposing the direction of the incident radiation, *H′(0.07)*, and air kerma free in air, K_a, is given by;

$$\frac{H'(0.07)}{K_a} = a + bx + cx^d . \exp(gx^2) \; Sv/Gy \qquad (7)$$

Where, a = 0.9505, b = 0.09432, c = 0.2302, d =5.082. g = -0.6997 and x = ln *(E/E0)*, where *E*= photon energy (keV), and E_0= 9.85 keV.

From this relationship (Eqn. 7) the *H′(0.07)* is calculated for the radiation qualities obtained by the experiment which is shown in Table 3. A comparison of *H*(10)* and *H′(0.07)* for the obtained photon energies measured by SSDL, Bangladesh and other standard laboratories are also presented.

Table 3. Calculated Conversion Coefficients for directional dose equivalent *H′(0.07)*

Beam Quality	Effective Energy in keV	HVL in mm	Conversion Coefficients *H′(0.07)* (Sv/Gy)					
		Cu	ISO	BCRU	NPL	PTB	AERE	NAMAS
N40	32.21	0.088	1.263	1.266	1.238	1.258	1.220	1.243
N60	46.85	0.250	1.497	1.499	1.465	1.478	1.456	1.470
N80	65.49	0.620	1.600	1.609	1.602	1.592	1.582	1.602
N100	84.66	1.180	1.603	1.596	1.597	1.588	1.578	1.598
N120	102.00	1.775	1.546	1.547	1.546	1.547	1.536	1.545
N150	116.61	2.305	1.507	1.502	1.506	1.506	1.495	1.496
N200	176.544	4.330	1.369	1.371	1.369	1.377	1.366	1.369

The conversion coefficient for ambient dose equivalent *H*(10)* is calculated for monoenergetic photon by the mathematical equation stated above lies within -0.16% and 0.87% with ISO reference values shows a very good in agreement. It is made clear that *H*(10)* calculated by mathematical equation provides a conservative approximation of effective dose equivalent at lower energies up to 65.49 keV than ISO but above this energy ISO showed the similar. However, the deviation between the calculated values for ISO and BCRU are insignificant. Compared to the values by other laboratories, ISO and BCRU values provide us more conservative estimation which is an important concept in radiation protection.

For directional dose equivalent, *H′(0.07)* the calculated values by mathematical equation lies within -0.13% to 0.43% showed a very good in agreement. In comparison with the measured values by other laboratories i.e. NPL, PTB, AERE, NAMAS, it can be stated that ISO values are more conservative estimation for the measurement of dose equivalent.

II (b). Personal Dose Equivalent *Hp(10)* and *Hp(0.07)*: A set of conversion coefficients of *Hp(10)* and *Hp(0.07)* for ISO narrow beam series is presented in Table 4. As personal dosimeter has more or less significant sensitivity to backscattering component of radiation; therefore the suitability of the calibration phantom as compared with theoretical MCNP generated backscatter factor [25] for PMMA and ISO water phantom was used in this study is shown in Figure 3.

Table 4. Calculated conversion coefficient for personal dose equivalent *Hp(10)* and *Hp(0.07)*

Beam Quality	Effective Energy in keV	HVL in mm Cu	Conversion Coefficients *Hp(10)* (Sv/Gy)			Conversion Coefficients *Hp(0.07)* (Sv/Gy)		
			ICRU Tissue Slab	PMMA Slab	ISO water slab phantom	ICRU Tissue Slab	PMMA Slab	ISO water
N40	32.21	0.088	1.139	1.0551	1.1388	1.253	1.1607	1.2528
N60	46.85	0.250	1.623	1.5131	1.6511	1.531	1.4273	1.5575
N80	65.49	0.620	1.885	1.7925	1.9315	1.723	1.6384	1.7655
N100	84.66	1.180	1.877	1.8239	1.9217	1.718	1.6694	1.7589
N120	102.00	1.775	1.805	1.7651	1.8473	1.665	1.6282	1.7040
N150	116.61	2.305	1.740	1.7085	1.7820	1.617	1.5877	1.6560
N200	176.544	4.330	1.542	1.5323	1.5739	1.469	1.4598	1.4994

DISCUSSION

The fundamental requirements for an adequate characterization of reference radiations for ISO narrow beam spectrum is established based on experimental condition. All radiation qualities should be chosen in accordance with the relevant standard which generally is useful to select an appropriate radiation quality taking into account the specified energy range and range of dose equivalent or dose equivalent rate of the device to be calibrated. To reproduce calibration X-ray beams in experimental condition differs, which is difficult to maintain strictly the ISO recommendation which leads to make in radiation protection optimization. Half value layer, air Kerma, photon energy could vary in experimental condition at different laboratory which leads the differences in producing standard beams. The process analyzed obtained by this experiment could give the message in minimizing the difficulties to standardize the calibration X-ray beam at different laboratories. The discrepancies of experimental value of HVL lies within -8.5% which leads the variation of effective energy -7.64% to ISO values.

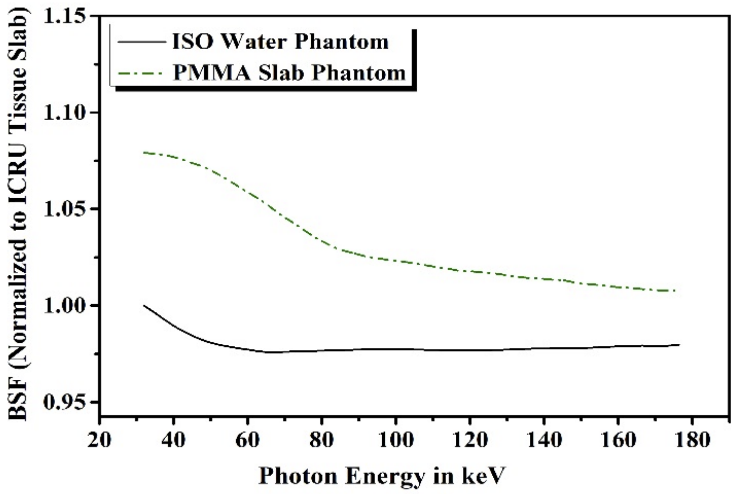


Figure 3. MCNP generated Backscattering Factor (BSF) for PMMA and ISO water phantom [25] that normalized with ICRU tissue slab

The conversion coefficients $H^*(10)/K_a$ and $H'(0.07)/K_a$ for ISO narrow beam series have been calculated from ISO data and compared with the value recommended by different laboratories. Empirical mathematical functions have been fitted from the data recommended by the BCRU for narrow spectrum series which is adopted under the condition ICRU-39. It is seen that ISO values meets very good in agreement with calculated value by empirical mathematical equation. This leads the use of these functions convenient for users as their derivation of ambient and directional dose equivalents. It is also observed that ISO value provides us more conservative approximation for the dose equivalent compared to other laboratories.

MCNP generated backscattering correction factor for PMMA and ISO water phantom for narrow beam spectrum is also used to derive conversion coefficients for individual monitoring *Hp(10)* and *Hp(0.07)*.

CONCLUSION

In this work calibration X-ray beam was characterized by determining half value layer, effective energy, beam homogeneity coefficient and consistency of X-ray production from the generator (kV and mA) and also a set of conversion factor for operational quantities was established for newly installed X-ray beam irradiator X80-225KV at Secondary Standard Dosimetry Laboratory (SSDL), Bangladesh Atomic Energy Commission following recommendations from ISO-4037. In this study, the variation of HVL of measured value lies within 2 to -8.5% 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 *H′(0.07)* and personal dose equivalent *Hp(10)* and *Hp(0.07)* has been calculated for ISO narrow beam spectrum series. The conversion coefficient for ambient dose equivalent *H*(10)* is calculated for monoenergetic photon lies within -0.16% and 0.87% with ISO reference values which shows a very good in agreement. It is made clear that *H*(10)* calculated by mathematical equation provides a conservative approximation of effective dose equivalent at lower energies up to 65.49 keV than ISO but above this energy ISO showed the similar. For directional dose equivalent, *H′(0.07)* the calculated values by mathematical equation lies within -0.13% to 0.43% showed a very good in agreement. A set of conversion coefficients for individual monitoring *Hp(10)* and *Hp(0.07)* has also been established using the MCNP generated backscattering factor for PMMA and new ISO water slab phantom. The result obtained from this work could be used in characterizing radiation beams at different laboratories.

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ВИЗНАЧЕННЯ ЯКОСТІ КАЛІБРУВАННЯ РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ ТА ВСТАНОВЛЕННЯ НАБОРУ КОЕФІЦІЄНТІВ ПЕРЕТВОРЕННЯ ДЛЯ КАЛІБРУВАННЯ ПРИСТРОЇВ РАДІАЦІЙНОГО ЗАХИСТУ, ЩО ВИКОРИСТОВУЮТЬСЯ В ДІАГНОСТИЧНІЙ РАДІОЛОГІЇ

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Використання рентгенівських апаратів для калібрування радіаційно-вимірювального обладнання в діагностичній радіології вимагає точного знання радіаційного поля. Спектри рентгенівського випромінювання робляться вузько-променевими шляхом належної фільтрації, рекомендованої кількома міжнародними організаціями. У цьому дослідженні було проведено експериментальне визначення якостей рентгенівського калібрування та аналіз коефіцієнтів перетворення з повітряної керми в еквівалент дози для навколишнього середовища та персональної дози при використанні рентгенівського опромінювача X80-225 кВ відповідно до стандарту ISO для серії вузьких спектрів у Лабораторії Вторинної Стандартної Дозиметрії (SSDL) у Бангладеш. Були проведені дослідження рентгенівського пучка промінів, що задіяні у шарі половинного значення, ефективної енергії, коефіцієнту однорідності пучка та послідовності рентгенівського випромінювання від генератора (кВ та мА). Для коду пучка N200 спостерігалася розбіжність шару половинного значення на 8,5%, що призводить до відхилення ефективної енергії на 7,7% зі стандартним відхиленням 1,3%. Коефіцієнти перетворення з повітряної керми в еквівалент дози, що задовольняє умовам сфери ICRU встановлюються для отримання радіаційних якостей та порівнюються із значеннями, зазначеними іншими стандартними лабораторіями. Для *H*(10)* та *H□(0.07)* спостерігалося відхилення 0,87% між емпіричним співвідношенням ISO та BCRU, яке є незначним. Набір коефіцієнтів перетворення для *Hp (10)* та *Hp (0,07)* також був розрахований для чотирьохелементної тканини ICRU.

Ключові слова: якості рентгенівського випромінювання, радіаційний захист, вузький пучок промінів згідно з ISO, еквівалент дози для навколишнього середовища та еквівалент персональної дози