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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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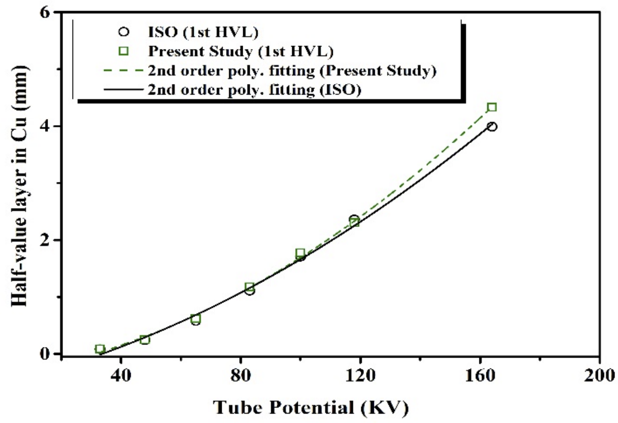

Figure 2. Experimental value of HVL in mm of Cu with ISO reference values

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;

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

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;

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

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.

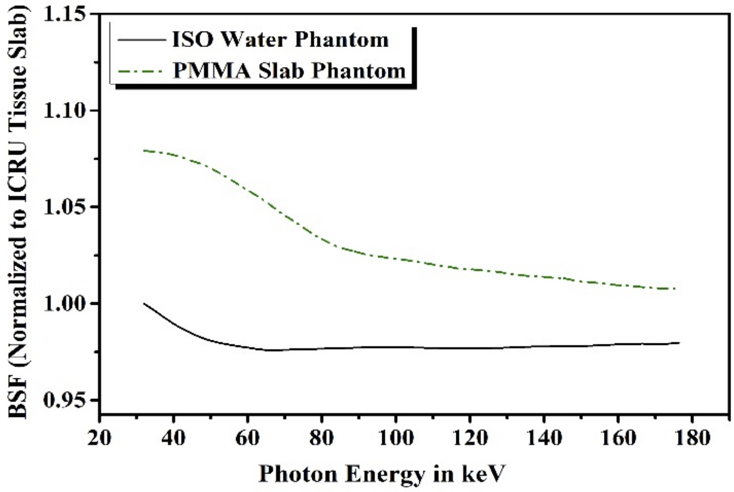

Figure 3. MCNP generated Backscattering Factor (BSF) for PMMA and ISO water phantom [25] that normalized with ICRU tissue slab

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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REFERENCES

[1] *X-ray and Gamma Reference Radiations for Calibrating Dosimeters & Dose rate meters and for determining their response as a Function of Photon Energy, Part-3: Calibration of Area and Personal Dosimeters and the Determination of Their Response as a Function and Angle of Incidence, ISO 4037-3* (International Organization for Standardization, Geneva, 1999).

[2] R.D. Evans, *X-Ray and Gamma-Ray Interactions;* in*: Radiation Dosimetry I*, edited by Attix and Roesch, 2nd Ed. (Academic Press, New York and London, 1968).

[3] *Determination of Dose Equivalents Resulting from External Radiation Sources, ICRU Report 39*, (International Commission on Radiation Units and Measurements, Bethesda, MD, 1985).

[4] *Determination of Dose Equivalents from External Radiation Sources, ICRU Report 43*, (International Commission on Radiation Units and Measurements, Bethesda, MD, 1988).
[5] *Measurement of Dose Equivalents from External Photon and Electron Radiation, ICRU Report 47*, (International Commission on Radiation Units and Measurements, Bethesda, MD, 1992).
[6] *Quantities and Units in Radiation Protection, ICRU Report 51*, (International Commission on Radiation Units and Measurements, Bethesda, MD, 1993).
[7] *Conversion Coefficients for Use in Radiological Protection against External Radiation, ICRP Publication 74*, Annals of the ICRP **26** (3-4), (International Commission on Radiological Protection, Oxford, Pergamon Press, 1996).
[8] *X-ray and Gamma Reference Radiations for Calibrating Dosimeters & Dose Rate Meters and for Determining their Response as a Function of Photon Energy, Part-2: Dosimetry for Radiation Protection Over the Energy Range 8keV to 1.3MeV and 4MeV to 9MeV, ISO 4037-2*, (International Organization for Standardization, Geneva, 1997).
[9] *Calibration of Radiation Protection Monitoring Instruments, Safety Report Series-16*, (International Atomic Energy Agency, Vienna, 1999).
[10] *Data for Use in Radiation Protection against External Radiation Report*, (International Commission on Radiological Protection, Oxford, Pergamon Press, 1987).
[11] S.R. Wagner, B. Grosswendt, J.R. Harvey, A.J. Mill, H.J. Selbach, and B.R. Siebert, Radiation Protection Dosimetry, **12**, 231 (1985), https://inis.iaea.org/search/search.aspx?orig_q=RN:17027979.
[12] I.M.G. Thompson, Journal of Radiation Protection, **9**(3), 203 (1989), https://doi.org/10.1088/0952-4746/9/3/007.
[13] Anon – BCRU, Radiation Protection Dosimetry, **14**, 337 (1986), https://doi.org/10.1093/oxfordjournals.rpd.a079667.
[14] *Data for Use in Protection against External Radiation, ICRP Publication 51*, (International Commission on Radiological Protection, Oxford: Pergamon, 1987).
[15] W.J. Iles, Conversion Coefficients from Air-kerma to Ambient Dose Equivalent for the International Standards Organizations Wide, Narrow and Low series of Reference Filtered X-Radiation, NRPB-R206 (1987).
[16] W.W. Seelentag, W. Panzer, G. Drexler, L. Plantz and F. Santer, A Catalogue of Spectra for the Calibration of Dosimeters, GSF Report 560 (1979).
[17] National Voluntary Laboratory Accreditation Program bulletin. Dosimetry, II:1, NVLAP (1995).
[18] *Personnel Dosimetry Performance – Criteria for Testing, McLean, ANSI/HPS N13 11*, (Health Physics Society, Virginia, 1993).
[19] R.J. Traub, J.C. McDonald, and M.K. Murphy, Radiation Protection Dosimetry, **74**, 13 (1997), https://doi.org/10.1093/oxfordjournals.rpd.a032176.
[20] H.M. Kramer, J. Böhm, W.J. Iles, and I.M.G. Thompson, Radiation Protection Dosimetry, **54**, 267 (1994), https://doi.org/10.1093/oxfordjournals.rpd.a082348.
[21] R.F. Nelson, and A.B. Chilton, *Low-energy Photon Dose Deposition in Tissue Slab and Spherical Phantoms, Report NUREG/CR-3425*, (Washington, DC; US Nuclear Regulatory Commission, 1983).
[22] D.T. Bartlett, P.J. Dimbylow, and T.M. Francis, Radiation Protection Dosimetry, **32**, 123 (1990), https://doi.org/10.1093/oxfordjournals.rpd.a080727.
[23] M.S. Rahman, *Report of MEXT Fellowship Program. Calibration and Standardization of Radiation Measuring devices*, (JAEA, 2003), pp. 23.
[24] Anon – BCRU, Radiation Protection Dosimetry, **14**(4), 337 (1986), https://doi.org/10.1093/oxfordjournals.rpd.a079667.
[25] M. Ginjaume, X. Ortega, and A. Barbosa, in: *IRPA-10: 10 International Congress of the International Radiation Protection Association*, (Japan Health Physics Society, Japan, 2000), pp. 1-7.

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 променів, 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