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Establishment and quality assessment of X-ray narrow spectrum series according to ISO 4037:2019 at SSDL of Center For Nuclear Technologies

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Abstract: The X-ray narrow spectrum series in the range from 40 to 120 kV were established according to the requirements of the ISO 4037:2019. This study was conducted by experimental measurements and the use of the SpekPy v2.0 – a software toolkit for modeling of X-ray spectra. The experiments were done to determine inherent filtration (0.332 mm and 0.492 mm Al at 100 cm and 250 cm, respectively). The HVL values obtained by experiment and simulation were biased 0.10 and 0.09 mm Al, respectively as compared with ISO 4037:2019. The homogeneity coefficient *h* ranged from 0.91 to 0.97 by experiment and from 0.89 to 0.96 by simulation. Contribution of the scattering component was evaluated less than 4.0%. Air kerma rate values at distances of 100 cm and 250 cm have also been determined with the uncertainties ranging from 3.85% to 5.18% by experiment and 3.41% to 4.19% by simulation. The obtained results revealed that the X-ray radiation field established at CNT providing that it meets the requirements of the ISO 4037:2019, which is fitting for the purpose of calibration of survey meters and personal dosimeters.

Keywords: *SpekPy v2.0; Inherent filtration; Narrow-spectrum; Half-value layer; Scattered radiation; Field uniformity; uncertainty.*

I. INTRODUCTION

Ionization radiation is widely used in industry, agriculture, medicine, and many other related fields. Therefore, radiometers are used more and more, and their calibration requires common standards. A network of Secondary Standard Dosimetry Laboratories (SSDLs) has been established since 1976 by the International Atomic Energy Agency (IAEA) and the World Health Organization (WHO). The ultimate aim is that these SSDLs should have the same qualities of radiation beams for calibrating instruments. In this work, the establishment and quality assessment of X-ray narrow spectrum series (N-series) according to ISO 4037:2019 at SSDL of CNT were done. N-series were selected for implementation because they demonstrate the radiation effectiveness at protection-level in medicine, as well as in life. Besides, this is one part of the content of the relevant ministerial-level science and technology project.

Based on ISO 4037:2019 [1-3], IAEA documents [4, 5] and the studies of other authors [6 - 14], Center for Nuclear Technologies (CNT) has developed and established the reference quality beams of the X-ray which conforms to this ISO standard . This paper presents the establishment and evaluation of narrow spectrum qualities from N-40 to N-120 at CNT. This is done experimentally and simulated by the software toolkit SpekPy v2.0. The specific tasks

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include: Determining the inherent filtration of the X-ray system; Establishing narrow spectrum qualities of X-rays from N-40 to N-120; Evaluation of the contribution of scattering, radiation field uniformity, and uncertainty of air kerma rates.

The software toolkit SpekPy v2.0 is free to use the software tool for calculating and manipulating x-ray tube spectra. The Python programming language is used to write the codes. Using Monte Carlo is for X-ray tube modeling. Bremsstrahlung and characteristic contributions to the spectrum are of interest. For all the above reasons, this software is used for the simulation in the work of this paper.

II. MATERIAL AND METHOD

A. Material

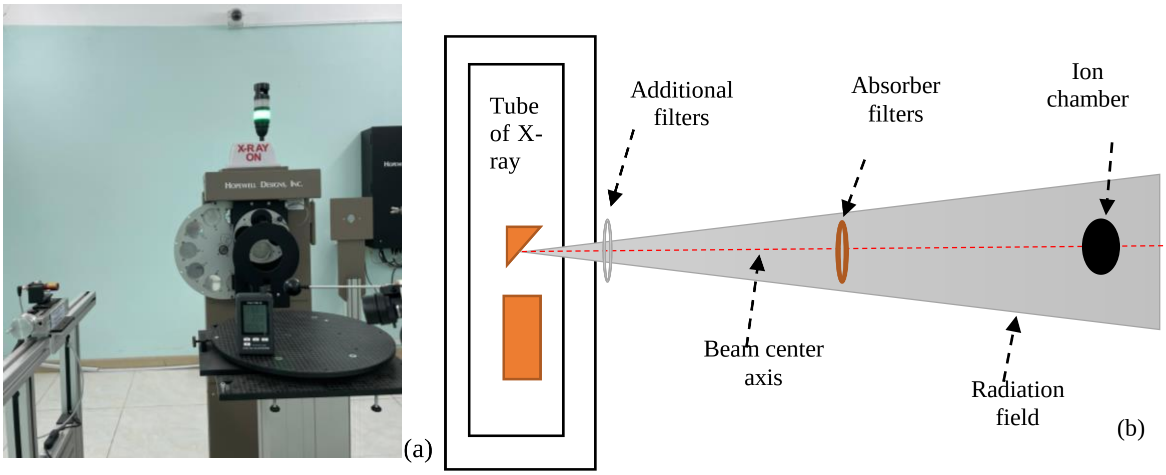


Fig. 1. X-ray system (a) and HVLs measurement diagram (b)

The reference X-ray system which was used included: X-ray generator, shielding post, high-voltage generator, cooling system, filters, laser positioner, Half-Value Stand, TK-30 reference ionization chamber (Based on ISO 4037-1:2019, for low energy radiation of the N-series, a larger diameter (> 3 cm) may be used. Useful energy ranges of ion chamber TK-30 are 25 keV ... 50 MeV, which is suitable for qualities N-40 to N-120 with mean energy of 33 keV to 100 keV. Ion chamber A3 should not be used despite its smaller diameter (< 3 cm) because the manufacturer's Report Calibration only calibrates with ^{137}Cs gamma sources, besides the manufacturer's manual is nominal calibration factors for greater energies than 200 keV.), SuperMax (electrometer), and safety devices. The X-ray tube model of the X-ray machine is Comet MXR 160/22, with inherent filtration of 0.8 ± 0.1 mm beryllium, focal spot d = 1.0 mm | d = 5.5 mm, provided by a 160 kV, 3000 watts Max., 40 kHz high-frequency high voltage generator, the tube voltage regulation range of 7.5 – 160 kV, with high stability, long continuous exposure time, long service life and other advantages. There is not a Monitor chamber in this X-ray system, because the stability of the air kerma rate during irradiation was not recorded. Based on the other method in order to investigate the variation of air kerma rate during time, Open Shutter Control was pressed after 120 s from the start of irradiation and the recording time of ion chamber TK-30 was selected to be 10 s for each measurement (Franciscatto selected 15 s for each charge reading [12]). This survey is not presented in this paper. The Aperture Wheel assembly is an aluminum disk with four holes. It is used to limit the diameter of the X-ray beam. In this paper, the diameter of X radiation shutter beam aperture was 7.36 cm. Filter wheels were 38 cm aluminum disks with 10 holes for filter material – each 7 cm in diameter. The filter set contained 99.99% pure Al, Cu filters and 99.95% for Sn. In this article, the software toolkit SpekPy v2.0 was used modeling for X-rays Tube - Comet MXR 160/22 in CNT. This software is a powerful and free software toolkit for calculating and manipulating x-ray tube spectra. The code is running in the Python programming language [6, 7].

Table I.a. Filters were used to establishthe quality of narrow-spectrum N-40 to N-120

X-ray narrow-spectrum qualities	**Filtration for modeling in Input (4 mm Al nominal inherent filtration)**			**Filtration for experiment**		
	mm Al	*mm Sn*	*mm Cu*	*Inherent filtration (mm Al)*	*Additional filtration for 4 mmAl nominal inherent filtration*	*Additional filtration (ISO 4037:2019) (mm Cu)*
N-40	4.0	0.0	0.21	0.332 and 0.492 at distance 100 and 250 cm from X-ray tube, resp.	3.665 and 3.505 at distance 100 and 250 cm from X-ray tube, resp.	0.21
N-60			0.6			0.6
N-80			2.0			2.0
N-100			5.0			5.0
N-120		1.0	5.0			5.0 + 1.0 mm Sn

Table I.b. Inputs data of the software toolkit SpekPy v2.0

Quantity	Value	Unit
Tube Voltage	depends on ray narrow-spectrum qualities	kVp
Anode Angle	20.0	degrees
Energy Bin	0.5	keV
Bin shift fraction	None	-
Physics Mode	spekpy-v2-casim	str
Mu Data Source	pene	str
Target	W	str
x	0.0	cm
y	0.0	cm
z	100 or 250	cm
Tube Load	1.00	mAs
Bremsstrahlung Emission	True	bool
Characteristic Emission	True	bool
Oblique	True	bool
Ref. Air Kerma rate	None	µGy/mAs
Ref. fluence	None	Photons cm^-2
Filtration (mmAl)	4.0	mm
Filtration (mmCu)	depends on ray narrow-spectrum qualities	mm
Filtration (mmSn)	1.0 for N-120	mm

B. Method

The experiment to establish and evaluateN-40 to N-120 narrow-spectrum radiation qualities according to ISO 4037:2019 standard was carried out with three steps: Determination of inherent filtration; Establishing the qualities of N-40 to N-120; Determining the uniformity of the radiation field, the contribution of scattering radiation and evaluating the uncertainty of the air kerma rates [1 - 5].

The first step was to determine the inherent filtration of the X-ray system. This determination was done by measurements HVL mm Al of X-ray system at 60 kV, 1 mA, consisting of taking 10 charge readings of 10 seconds each and then interpolating the X-ray system's half-value layer mm Al according to table 9 of ISO 4037-1:2019 pages 17-18 [1, 12]. The X-ray system and experimental diagram for measuring HVLs are depicted in Fig.1. According to the recommendation of ISO 4037:2019, the experiments in this report were done at distances of 100 cm and 250 cm (when using phantom). Inherent filtration for X radiation qualities was determined with 4 mm Al nominal inherent filtration. According to the guidance of ISO 4037:2019, determination of the inherent filtration for X radiation qualities with 4 mm Al nominal filtration inherent by HVL measurement (pages 16, 17, 18 ISO 4037-1:2019) [1], the experiments were conducted at 60 kV to measure the radiation attenuation through the Al filter and make a matching equation to determine the HVL1 mm Al value Eq. 1. From this HVL_1 result, through the interpolation of the inherent filtration equation (according to ISO 4037-1:2019 data) Eq.2, the inherent filtration (I) for X-ray system value could be determined.

$$HVL_1 = A + B.\exp(Cx^D) + E.x^2 + F.x^3 \qquad (1)$$

$$I = a + b.\exp(cX^d) + e.X^2 + f.X^3 + g.X^4 + h.X^5 \quad (2)$$

Where, the fitting coefficients are A, B, C, D, E, F, a, b, c, d, e, f, g, h; and values x=0.5, X = HVL_1 (mm Al) Eq.1.

Establishment of the quality of N-40 to N-120 radiation was the second experiment to be performed after determining inherent filtration. The quantities to be determined included: the Additional filter (according to ISO 4037-1:2019 or adjusting accordingly), HVL_1 and HVL_2 from which the homogeneity factor h and deviation could be calculated and then the radiation quality suitable with ISO 4037-1, 2, 3:2019 [1 – 3, 8 - 11, 13, 14] was evaluated. In this step, the voltage of the X-ray system was adjusted from 40 to 120 kV depending on the quality of N-40 to N-120 radiation, the tube current of 1 mA and taking 10 charge readings of 10 seconds each.

In the last step, the method used for this determination is described in references [1-5], where the experiment determined the contribution of scattering, radiation field uniformity, and uncertainty of air kerma rates. The field uniformity of the radiation is defined as the value of the air kerma rate on the plane perpendicular to the center of the radiation beam axis that varies by no more than 5.0% [1]. For example, at a distance of 250 cm, the field uniformity was experimentally determined by measuring the air kerma rate at the radiation beam axis, then the appropriate measurement step was selected and measurements in the left - right and top - bottom directions were carried out. The field uniformity is the area of the beam axis and has a variation of no more than 5.0%. The contribution of scattering was made with 2 tests: attenuation with distance and the contribution of the scattering component of radiation, value not exceeding 5.0% [1]. According to ISO 4037:1-2019, the scattering component of radiation at a distance to be determined, e.g. at 250 cm, is determined by the

% air kerma rate measured in a plane perpendicular to the axis of the beam and the distance from the beam axis is equal to twice the beam radius plus its penumbra at that distance (understood as the ion chamber diameter TK-30 used in the experiment), with air kerma rate on the central axis. The contribution of the scattering component of radiation is understood as radiation that is deflected from the beam axis of the X-rays tube, or the radiation is deflected from the beam axis due to objects collision along the path of the radiation beam. For example, the interaction of the X-ray beam from the emitter onto the rim of the X-ray tube window, Aperture Wheel assembly, Filters, room, etc. The uncertainties of air kerma (rate) are referenced following parts 2 and 3 of ISO 4037:2019 [2, 3], document of IAEA No.16 [4] and the evaluation guidelines Uncertainty for the IAEA Level 2 dosimetry laboratory [5].

Through the survey, the measurement uncertainty of the air kerma rate includes 2 groups: there is a calibration certificate or reference manual and the group is calculated from the measurement results during the experiment. 16 components measurement uncertainty of the air kerma rate: Group 1 includes Simplified air kerma rates calculation, SupperMAX (electrometer), zero shift (SupperMAX), long-term stability (SupperMax), Bias (SupperMAX_TK-30), calibration of Ion chamber TK-30, chamber orientation in the beam (The quantities in this group are found in the calibration certificate or referenced from the manufacturer's manual.); Group 2 includes: Setting the reference X-ray system voltage, Setting the reference X-ray system generation current, charge, Air temperature, thermometer resolution, Air pressure, barometer resolution, beam attenuation depending on the distance, Inhomogeneity_ion chamber, calibration distance (d distance) (The quantities in this group are derived from experimental measurements, or instrument resolution. For example, Setting X-ray system voltage on system software has the smallest division 0.1 kVp.). This uncertainty is calculated by Eq. (3). In addition, the air kerma $\dot{K}_a$ rate is calculated by the Eq. (4).

$$U = k.\sqrt{\sum_{i=1}^{16}\left(c_i u_i\right)^2} \tag{3}$$

$$\dot{K}_a = N_k \times \frac{Q_{raw}^{ref}}{\tau} \times \frac{p_0 \times (t + 273.15)}{(t_0 + 273.15) \times p} \times k_{elec} \tag{4}$$

Where, k is coverage factor, c_i is the sensitivity, u_i is the measurement uncertainty of each component, N_k is air kerma calibration coefficent of ion chamber TK-30, τ is the time for each charge reading, Q_{raw} is the measured charge, k_{elec} is the standard coefficient of the electrometer - SupperMAX, p_0 and t_0 are the reference pressure and temperature, p and t are the experimentally measured pressure and temperature, h_k is the conversion coefficient.

III. RESULTS AND DISCUSSION

A. The inherent filtration of the X-ray system

Based on the guidance of ISO 4037-1:2019 in part II above (from the Eq.1 and Eq.2), two inherent filter values are determined, 0.332 & 0.492 mm Al at two distances of 100 and 250 cm respectively, resulting in Table II. Thus,if the device is calibrated at any distance, the filter must be changed to add 4 mm Al corresponding to each distance.

Table II. Inherent filtration by distance to the X-ray tube

Beam center axis distance (cm)	Inherent filtration (mm Al)
100	0.332
250	0.492

B. Establishment of narrow spectrum qualities of X-rays from N-40 to N-120

The results of establishing the quality of narrow-spectrum N-40 to N-120 radiation are presented in table 3.a and 3.b. In these tables the reference values according to ISO 4037-1:2019 (In the 1996 version, there is a presentation of the air kerma rate with values in the range of 1000 - 10 000 µGy/h at 1m. However, in the 2019 version, the air kerma rate was not shown.); experimental values and values through modeling using the software toolkit SpekPy v2.0 were given. From the results presented in Tables III3.a and III.b, we can see that the values of HVL_1, HVL_2, h from experiment and simulation are good response to the values given by ISO 4037-1:2019. Uncertainty of the air kerma rate's values are 3.85% to 5.18% in the experiment and 3.41% to 4.19% for modeling (not exceed 10.0%, ISO 4037:2019).

Table IIIa. The quality of narrow-spectrum N-40 to N-120 radiation versus the experiment's results

X-ray narrow spectrum qualities	**d (cm)**	**Establishingthe quality of narrow-spectrum (a)**							
		ISO 4037:2019				***Experiment***			
		HVL_1	*HVL_2*	*h*	*$\bar{E}$ keV*	*HVL_1*	*HVL_2*	*h*	*$\dot{K}_a$ (μGy/h) ± %U*
N-40	100	2.63	2.83	0.88-1	33.3	2.690	2.878	0.93	4630.1±3.85
	250	2.65	2.84			2.726	2.872	0.95	736.2±3.87
N-60	100	0.234	0.263		47.9	0.239	0.269	0.95	6642.9±5.17
	250	0.235	0.264			0.236	0.264	0.93	1061.4±5.18
N-80	100	0.578	0.622		65.2	0.592	0.614	0.97	3387.0±5.12
	250	0.580	0.623			0.600	0.624	0.96	540.3±5.15
N-100	100	1.09	1.15		83.3	1.14	1.20	0.95	1712.9±5.10
	250	1.09	1.15			1.11	1.22	0.91	266.6±5.18
N-120	100	1.67	1.73		100	1.73	1.83	0.95	1899.2±5.06
	250	1.67	1.74			1.66	1.79	0.93	301.2±5.09

Table IIIb. The quality of narrow spectrum from N-40 to N-120 radiation versus the modeling's results

X-ray narrows pectrum qualities	**d (cm)**	**Establishing the quality of narrow-spectrum (b)**								
		ISO 4037:2019				***Modeling***				
		HVL_1	*HVL_2*	*h*	*$\bar{E}$ keV*	*HVL_1*	*HVL_2*	*h*	*$\bar{E}$ keV*	*$\dot{K}_a$ (μGy/h) ± %U*
N-40	100	2.63	2.83	0.88-1	33.3	2.640	2.826	0.93	33.1	3423.6±3.54
	250	2.65	2.84			2.640	2.826	0.93		547.2±3.53
N-60	100	0.234	0.263		47.9	0.232	0.260	0.95	47.6	5853.6±4.09
	250	0.235	0.264			0.232	0.260	0.89		936.0±3.45
N-80	100	0.578	0.622		65.2	0.575	0.618	0.93	64.9	2970.0±3.41
	250	0.580	0.623			0.575	0.618	0.93		475.2±3.41
N-100	100	1.09	1.15		83.3	1.093	1.152	0.95	83.0	1350.0±3.61
	250	1.09	1.15			1.093	1.152	0.95		216.0±3.5
N-120	100	1.67	1.73		100	1.683	1.746	0.96	100.0	1490.4±4.13
	250	1.67	1.74			1.683	1.746	0.96		237.6±4.19

* *$HVL_{1,2}$ of N-40 [mm Al], others [mm Cu]; U-uncertainty of air kerma rate with k = 2, P = 95%.*

In Table IV, the experimental quantities HVL_1, HVL_2, *h* and the maximum deviation of the HVL values compared to ISO 4037-1:2019 are all satisfied. The homogeneity coefficient *h* fully responds well, h values are 0.91 to 0.97, between in ISO 4037 range (0.88 - 1). The values of HVL_1, HVL_2 respond well. Criteria for validation by HVL determination is based on requirements on HVL determination for matched reference fields, that is maximum absolute deviation of measured HVL, $|\Delta HVL_{max, abs}|$, nominal value for aluminium or copper depends on qualities N-40 to N-120 and definition phantom depth d of 0.07 mm, 3 mm, 10 mm. This means that the maximum deviation of the experimental HVL values from the corresponding ISO 4037-1:2019 values must be less than the reference values given in table 14, page 23 of this document. Then the dose calibration field is established and it is suitable to use the $H_p(0.07)$, $H_p(3)$, $H_p(10)$ values of this dose calibration field for related work. In Table IV, the maximum deviation of the measured HVLs values, all achieved, is no more than 0.1 mm Al; and modeling does not exceed 0.09 mm Al. Compared with the reference values in ISO 4037-1:2019 page 23 [1], the narrow spectrum qualities of N-40 to N-120 which were achieved at CNT completely responded well and can be well applied to the research and development related to $H_P(0.07)$, $H_P(3)$, $H_P(10)$. Likewise, the results from simulations using SpekPy v2.0 (Table 5) are also completely compatible with ISO 4037:2019 (in particular, mean energy, HVL_1, HVL_2 (HVLs values are slightly smaller than ISO 4037:2019), *h* and the maximum deviation of the HVL values).

Table IV. HVLs values for N-40 to N-120 radiation quality establishment by experiment/ ISO 4037:2019

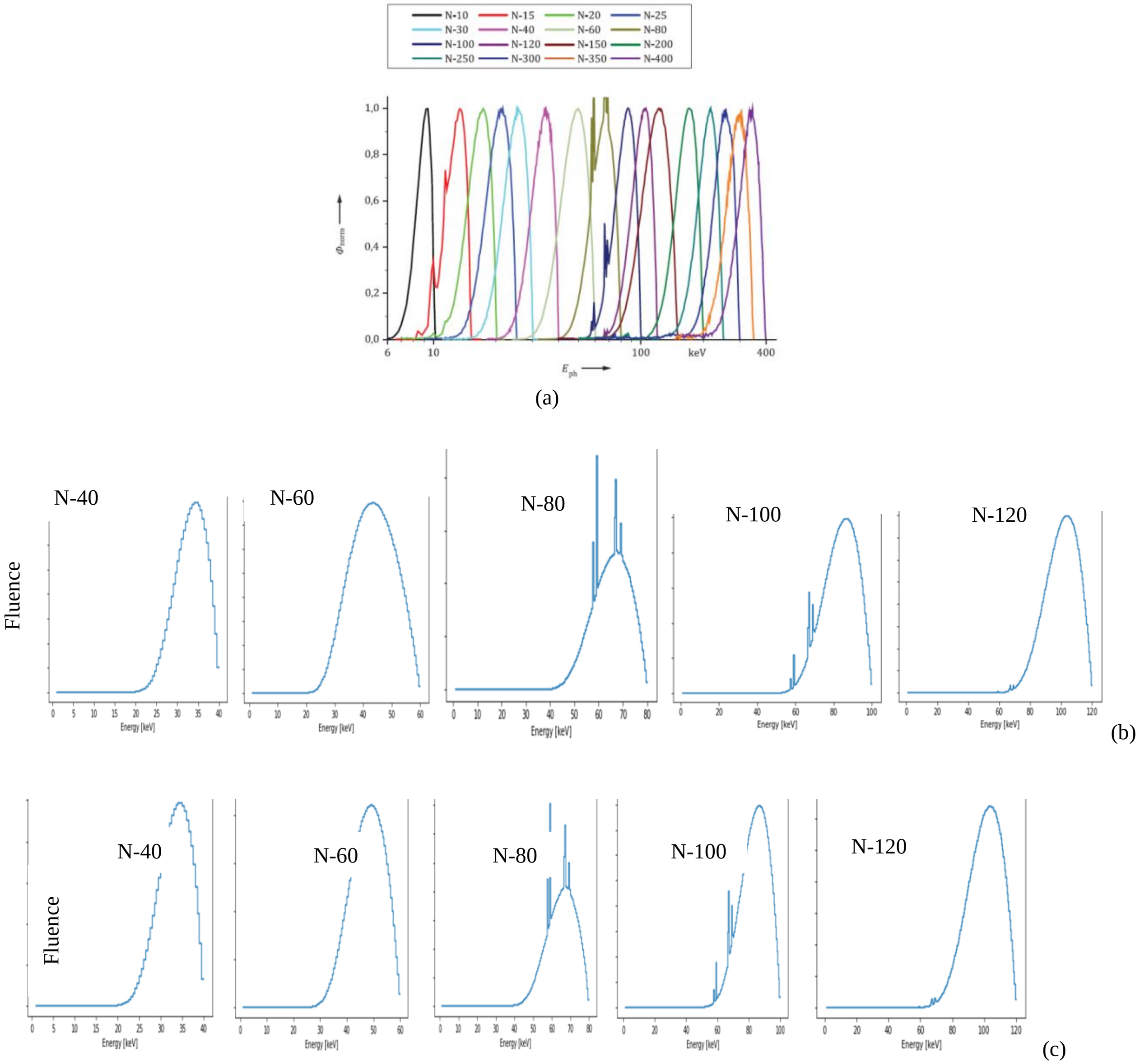
X-ray narrow-spectrum qualities	**Distance 100 cm**				**Distance 250 cm**			
	ΔHVL_1 (%)	*ΔHVL_2 (%)*	*$\Delta HVLs_{max}$, abs (mmAl)*	*h*	*ΔHVL_1 (%)*	*ΔHVL_2 (%)*	*$\Delta HVLs_{max}$, abs (mmAl)*	*h*
N-40	2.28	1.70	0.06	0.93	2.87	1.13	0.08	0.95
N-60	2.14	2.28	0.01	0.95	0.43	0.00	0.00	0.93
N-80	2.42	-1.29	0.01	0.97	3.45	0.16	0.02	0.96
N-100	4.59	4.35	0.05	0.95	1.83	6.09	0.07	0.91
N-120	3.59	5.78	0.10	0.95	-0.60	2.87	0.05	0.93

Table V. HVLs values for N-40 to N-120 radiation quality establishment by SpekPy v2.0/ ISO 4037:2019

X-ray narrow-spectrum qualities	**%E mean energy**	**Distance 100 cm**				**Distance 250 cm**			
		ΔHVL_1 (%)	*ΔHVL_2 (%)*	*$\Delta HVLs_{max}$, abs (mmAl)*	*h*	*ΔHVL_1 (%)*	*ΔHVL_2 (%)*	*$\Delta HVLs_{max}$, abs (mmAl)*	*h*
N-40	-0.60	-1.86	-1.81	0.05	0.93	-3.15	-1.60	0.09	0.93
N-60	-0.63	-2.93	-3.35	0.01	0.95	-1.69	-1.52	0.00	0.89
N-80	-0.46	-2.87	0.65	0.02	0.93	-4.17	-0.96	0.03	0.93
N-100	-0.36	-4.12	-4.00	0.05	0.95	-1.53	-5.57	0.07	0.95
N-120	0.00	-2.72	-4.59	0.08	0.96	1.39	-2.46	0.04	0.96

Table VI. HVLs values for N-40 to N-120 radiation quality establishment by SpekPy v2.0/experiment

X-ray narrow-spectrum qualities	**Distance 100 cm**				**Distance 250 cm**			
	ΔHVL_1 (%)	ΔHVL_2 (%)	$\%h$	$\% \dot{K}_a$	ΔHVL_1 (%)	ΔHVL_2 (%)	$\%h$	$\% \dot{K}_a$
N-40	-1.86	-1.81	0.00	-26.05	-3.15	-1.60	-2.11	-25.85
N-60	-2.93	-3.35	0.00	-11.87	-1.69	-1.52	-4.30	-11.86
N-80	-2.87	0.65	-4.12	-12.33	-4.17	-0.96	-3.12	-11.41
N-100	-4.12	-4.00	0.00	-21.22	-1.53	-5.57	4.40	-18.92
N-120	-2.72	-4.59	1.05	-21.59	1.39	-2.46	3.23	-21.43



(a)

(b)

(c)

Fig. 2. Normalized fluence spectra of the N-series.

(a) ISO 4037-1:2019; (b), (c) simulation by SpekPy v2.0 at 100 cm and 250 cm from X-ray tube respectively

Besides, in this paper, there is also a comparison between the simulation results by SpekPy v2.0 compared with the experimental results in Table VI. From this comparison table, we c see that the simulation and experimental results are similar. However, there are some differences as follows: The value of HVLs in simulation is mostly lower than that in experiment; Lower air kerma rate value from 11.41 % to 26.05 %. These differences can be explained by the fact that the simulation is in an unobstructed infinite space and describes only the x-ray tube and ion chamber [6], not the surrounding peripherals while the experimental reality is the room size limit (6 m x 4 m x 4 m) and related equipment such as racks, lifting tables, etc.

The energy-to-energy flux from simulation results using SpekPy v2.0 and from ISO 4037-1:2019 is described in Fig.1. From Fig.1 we can see that the spectral form obtained from the simulation results is similar to the spectral form of ISO 4037-1:2019.

C. Evaluating the contribution of scattering, radiation field uniformity, and uncertainty of *air kerma* rates

Table VII. Experimental results of evaluating the contribution of scattering, radiation field uniformity, and measurement uncertainty of *air kerma* rates

X-ray narrow-spectrum qualities	**Beam center axis distance 100 (cm)**			**Beam center axis distance 250 (cm)**		
	Radiation field uniformity (cm)	*Scattering radiation, %*	$U(\dot{K}_a)$ *(1mA, 10s), %*	*Radiation field uniformity (cm)*	*Scattering radiation, %*	$U(\dot{K}_a)$ *(1mA, 10s), %*
N-40	12.5	3.38	5.56	35.5	1.3	4.65
N-60	11.0	1.10	5.87	31.5	1.2	3.02
N-80	10.0	1.8	4.46	29.0	2.5	3.96
N-100	9.0	3.6	8.36	26.5	2.5	8.18
N-120	8.5	4.0	9.03	24.5	3.5	4.59

The final step in establishing the qualities N-40 to N-120 is to evaluate the contribution of scattering, radiation field uniformity, and measurement uncertainty of air kerma rates. This is done by the experimentation in accordance with the guidance of ISO 4037-1:2019, IAEA guidelines and related documents [1, 4, 5]. The results obtained from this assessment are presented in Table VII below. Radiation field uniformity at distances of 100 cm and 250 cm was calculated for each quality N-40 to N-120 (*air kerma* rate deviation of no more than 5 %, ISO 4037-1:2019). The radiation field images of narrow spectral qualities are similar in shape, but different in size (diameters of radiation field uniformity are shown in Table VII). In this paper, the N-80 radiation field image is presented in Figure 3 below.

The contribution of scattering has a maximum value 4.0 % (< 5 %, ISO 4037-1:2019 standard). Radiation field uniformity of N-40 to N-120 are 12.5, 11.0, 10.0, 9.0, 8.5 cm at 100 cm distance; and 35.5, 31.5, 29.0, 26.5, 24.5 cm at 250 cm distance. Measurement uncertainty of air kerma rates value at positions with qualities that differ by no more than 10 %, with a coverage factor k = 2, confidence 95 % (ISO 4037-2,3:2019 standard). Thereby, the narrow spectrum qualities of N-40 to N-120 at CNT have characteristics that are well compatible with ISO 4037:2019.

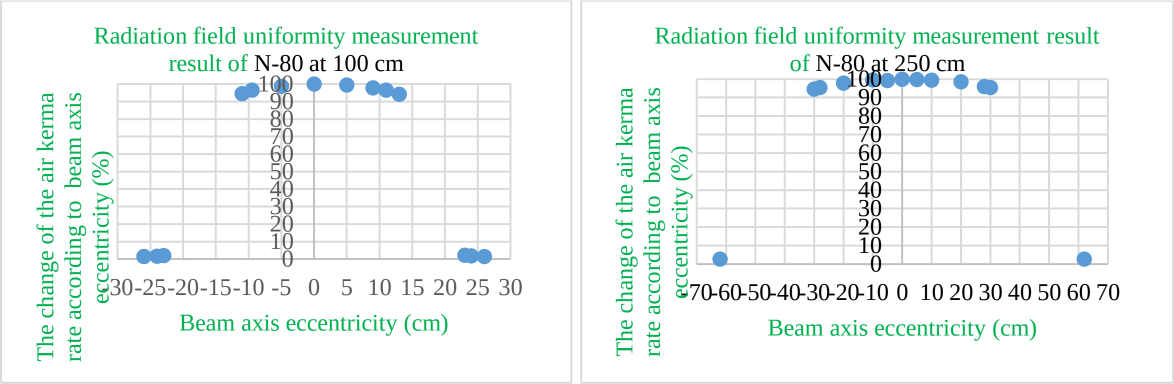


Fig. 3. Experimental results of uniformity of radiation field N-80 at distance 100 cm and 250 cm at CNT

IV. CONCLUSIONS

The inherent filtration values of the reference X-ray at SSDL of CNT were experimentally determined to be 0.332 mm and 0.492 mm Al-thickness at 100 cm and 250 cm positions, respectively. Because the emitter will age over time and the smallest available Al filter thickness is 0.005 mm Al, the inherent filtration value was chosen for the two positions, 0.335 mm and 0.495 mm Al, respectively. From these results, an additional inherent filtration value of 3.665 and 3.505 mm Al (with 4 mm Al nominal inherent filtration) was determined, respectively.

The narrow-spectrum N-40 to N-120 qualities of X-rays have been established. The values of HVL_1, HVL_2, homogeneity factor h from experiment and simulation with the software toolkit SpekPy v2.0 are very compatible with ISO 4037:2019, the narrow spectrum qualities of N-40 to N-120 achieved at CNT completely responded well and can be well applied to research and development related to $H_P(0.07)$, $H_P(3)$, $H_P(10)$. The value of air kerma rate which was calculated by using SpekPy v2.0 software is smaller from 11.41 % to 26.05 % depending on the radiation qualities. It is resulted by the fact that the simulation uses infinite space, while the experiment uses finite space. In general, the values of HVL_1, HVL_2 from the experiment are slightly larger than ISO 4037:2019, and by contrast, the values when simulated by SpekPy v2.0 are slightly smaller than the value according to ISO 4037:2019 standard.

The contribution of scattering, radiation field uniformity, and uncertainty of air kerma rates were experimentally evaluated, thereby, the narrow spectrum qualities of N-40 to N-120 at SSDL of CNT have the features that meet the requirements of ISO 4037:2019. Therefore, the X-ray radiation field at SSDL of CNT has been well established in compliance with the ISO 4037:2019 and can be used as a photon standard radiation field for calibrating survey meters and personal dosimeters.

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