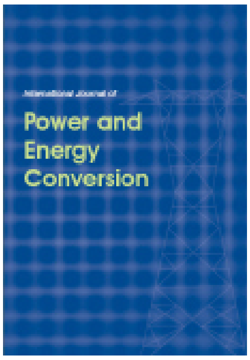

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Establishment of X-ray narrow spectrum beam energy according to the requirements of the new version of ISO 4037-2019 comparison with the previous version 1996

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Establishment of X-ray narrow spectrum beam energy according to the requirements of the new version of ISO 4037-2019 comparison with the previous version 1996

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Abstract: The primary aim of this study is to examine discrepancies resulting from the application of ISO 4037 standards. This investigation entails a comparative analysis between the 2019 and 1996 editions, focusing on the standard deviation between measured and normative values of the 1st Half Value Layer (HVL), as well as the ratio (1st HVL-measured / 1st HVL normative) for ISO 4037-1996. This research is conducted within Morocco's National Center for Nuclear Energy, Sciences, and Technology (CNESTEN) at the Gamma and X Calibration Laboratory. The laboratory employs a HOPPEWEL X80-225kV X-ray generator and TK-30 ion chamber for establishing standards beams. All obtained results are generally acceptable, except in the case of N-20 beam (with a ratio of 20% exceeding the 5% limit prescribed by ISO 4037-1996, and a standard deviation of 79 µm, falling below the 100 µm requirement for Hp(10), while surpassing 10 µm for Hp(3) according to ISO 4037-2019).

Keywords: air KERMA; Hp(10); Hp(3); radiation quality; half value layer; HVL; N-Series; narrow spectrum.

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1 Introduction

The use of X-rays in the medical and industrial fields became essential as soon as they were discovered in 1895 by the German doctor W. Röntgen (Röntgen, 1895) who performed the first X-ray of his wife's hand, from that time the use of X-rays became widely used in several fields, which required the calibration of equipment for quantification of these rays according to international standards, there are many sources of X-rays, such as using nuclear accelerator technology to generate intense X-rays (Winick, 2010). In order to offer calibration services to end users, every Secondary Standard Dosimetry Laboratory (SSDL) is required to establish identical reference beam characteristics, as employed for calibrating their respective reference instruments, in accordance with internationally recognised guidelines (IOS, 2019, 1996; IAEA, 2000). Furthermore, to guarantee traceability for end-user instruments, it is essential to replicate the same calibration conditions utilised for secondary standard calibration at the SSDL level, for these reasons, all countries must establish national references in accordance with current requirements, notably ISO 4037, as outlined in scientific articles.

In 2019, the ISO 4037 standard, concerning the requirements relating to reference X-rays and Gamma radiation for radiation protection instruments calibration, has been updated by changing several requirements relating to the validation and characterisation of X-rays beams, among which the validation of the N-Series beams by the criterion of the absolute deviation of the half-attenuation layers (IOS, 2019). Limited literature exists regarding the implementation of benchmark radiations through Monte Carlo simulation in calibration laboratories. However, there is a notable absence of publications addressing the comparative analysis between the two versions of ISO 4037 standard, namely 2019 and 1996.

This work is a very practical synthesis for all secondary calibration X-rays and Gamma laboratories, allowing them to setup the methodology required by the ISO 4037 standard for the validation and characterisation of X-rays beams and especially narrow spectrum N-Series, the most requested in the instrument calibration used in radiation protection of workers in the radio diagnosis field (IOS, 1996; IAEA, 2000).

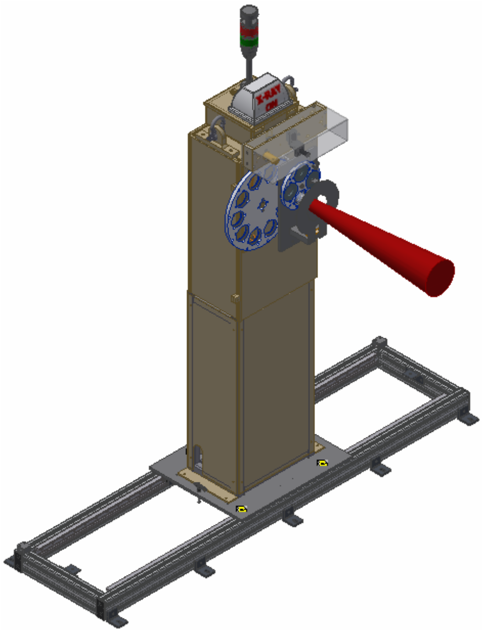
In this work, the validation of the different beam qualities is based on half value layer (HVL) measurements produced by a X-rays generator ‘HOPEWELL’, X80-225kV at the CNESTEN calibration laboratory (National Center for Energy, Sciences and Nuclear Techniques) and by applying the validity criteria of the both version of the ISO 4037 standard, 2019 and 1996 version’s (IOS, 2019, 1996; IAEA, 2000; Hopewell Designs Inc., 2016).

The experiments were carried out using the PTW TN32005 ionisation chamber which the leakage current is measured in the same HVL measurement setup condition, and it was less than 0.02%. This ion chamber is positioned at 100 cm from the focus of the X-rays tube and connected to a SUPERMAX electrometer, the value of the HVL are measured by applying the attenuation law, including their uncertainties. The experimental results obtained were compared with the HVLs values defined by the ISO 4037-1 (1996 and 2019) standard, checking the maximum absolute deviation.

2 Materials and methods

This study aimed to establishing the X-rays narrow-spectrum series beams used to calibrate radiation protection instrument, in Gamma and X Calibration Laboratory (LEGX) of National Center for Nuclear Energy, Sciences and Technology (CNESTEN) in Morocco. The irradiator used in this work is an X-rays generator model X80-225 kV, Hopewell Designs Inc. (COMET, 2010). The set of filters designed to modify the spectral characteristics of the X-ray beam to meet the different beam codes needed for instrumentation calibration (according to the 4037 standard). It consists of an aluminium disc of at least 38 cm, mounted on the front of the shielded enclosure with at least ten holes and at least 7 cm in diameter. The disc is electrically driven, and the holes in the disc are designed to hold filters ranging in thickness from 0.1 mm to 15 mm. The disk is easily removed, and another disk installed when more than ten beam codes are used (COMET, 2010), the generator used is shows in Figure 1.

Figure 1 X-rays generator model X80-225kV (see online version for colours)



The validation method is based on the measurement of the half-attenuation layer of narrow-spectrum N-Series beams as defined in ISO 4037-2019, using a graphical method by determining the attenuation factor of the filters attenuators (copper) (Osama and Aziz, 2007).

The beam validity criteria established by X-ray calibration laboratories are based on the absolute deviation of measured HVL and normative HVL for the different types of operational quantities personal dose equivalent Hp(10), personal dose equivalent Hp(0.07), personal dose equivalent Hp(3) and ambient dose equivalent H*(10), but is different for etch version. And that is the main purpose of this work to compare the validity of this beams developed with the both versions 1996 and 2019 of ISO 4037, for that only the first HVL is measured (Osama and Aziz, 2007; IOS, 2019, 1996).

For all measurement, the beam area is large enough to ensure that all the ion camber's area is completely irradiated, indeed the operational quantity included in this work is the air KERMA rate K_{air} can be given by the following equation (IAEA, 1996):

$$K_{air} = N_R \cdot (L - L_0) \cdot K_d \cdot K_S \cdot K_{TP}$$

where

K_{air} air KERMA (R)

N_R ion chamber calibration coefficient (R/C)

L reading of the reference ion chamber (R)

L_0 reading of the background of the reference ion chamber (R)

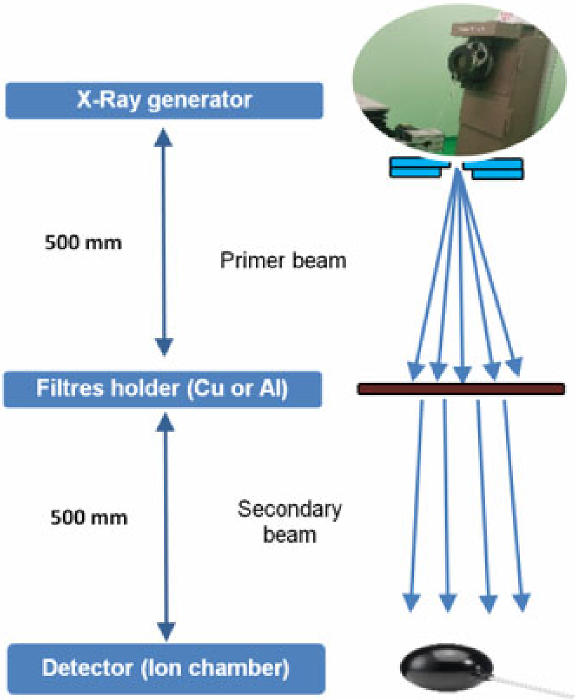
K_d distance correction factor

K_s recombination factor

K_{TP} correction factor for pressure and temperature.

Figure 2 illustrates the configuration used for half-value layer (HVL) measurements. By manipulating the wheels and adjusting the high voltage, it is possible to achieve radiation beam qualities of any desired magnitude. The distance between the generator and the detector (PTW TK-30 Type 32005) is maintained at 1 metre. Aluminium and cooper are utilised as the absorber for both the measurement of inherent filtration and the HVL assessment (Osama and Aziz, 2007).

Figure 2 Experimental setup used (see online version for colours)



3 Results and discussion

3.1 Assessment of inherent filtration in order to establish narrow beam radiations qualities

The first step to establish the national standard for radiation protection instruments is to regularly provide the inherent filtration of the X-ray generator. Because this specific filtration will constitute the total filtration necessary for the etch radiation qualities (IOS, 2019, 1996; IAEA, 2000).

To be compliant with the ISO 4037 standard, the determination of the inherent filtration of the X-ray generator is mandatory using the recommended HVL graphic method. The determination method is described by standard ISO 4037-1 Part 1, is the subject of evaluation of the half-attenuation layer compared to aluminium, in the case of irradiation at 60 KV without any additional filtration. From the measured HVL and using Table 1, the inherent filtration can be determined (IOS, 2019, 1996; IAEA, 2000).

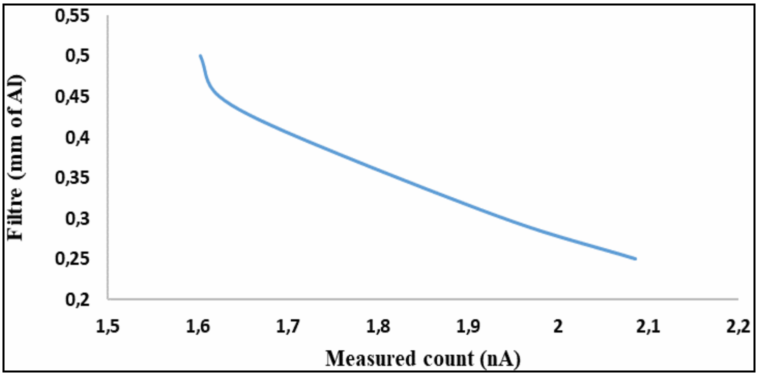
Table 1 Correlation between HVL for 60 kV and inherent filtration of the X-ray tube (ISO 4037-2019)

First HVL (mm) of Al at 60 kV	*Inherent filtration (mm)*
0.33	0.25
0.38	0.3
0.54	0.4
0.67	0.5
0.82	0.6
1.02	0.8
1.15	1
1.54	1.5
1.82	2
2.11	2.5
2.35	3
2.56	3.5
2.75	4
2.94	4.5
3.08	5
3.35	6

The provided table (Table 1) shows the correspondence between the first HVL assessed and the inherent filtration that should be subtracted from the total filtration to establish the desired radiation quality.

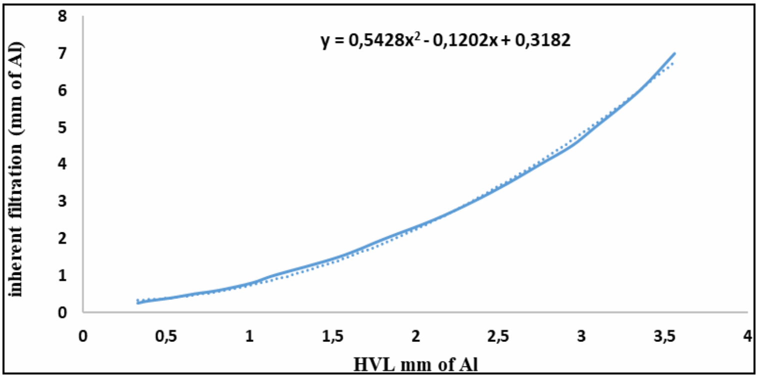
We have measured the variation of air KERMA (K_{air}) rate for the beam obtained without any additional filtration at 60 kV. Figure 3 illustrates the variation of air KERMA rate as a function of aluminium filter thickness. The HVL obtained is 0.431 mm of aluminium, between 0.38 mm and 0.54 mm of Al.

Figure 3 Attenuation curve without using additional filtration and at 60 kV (see online version for colours)



In order to determine the inherent filtration equivalent to the HVL value of 0.431 mm, we need to approximate it through extrapolation. The extrapolated value obtained from Figure 4 is 0.37 mm of aluminium (Al).

Figure 4 Inherent filtration according to ISO 4037-2019 standard (see online version for colours)



3.2 Narrow-spectrum beams validation

3.2.1 The half-attenuation layer measurement

The measurements of the half-attenuation layer make it possible to determine the quality of the X-ray beam filtered according to the ISO 4037-1 standard, by using the experimental setup described in Figure 2.

The results found are plotted in the curve below, which represents the variation of the transmission rate of the beams (%) as a function of the thickness of the copper filter (mm). The attenuation curves are established by applying Aluminium filters for the N-20, N-30 and N-40 beams. And copper filters for the N-60, N-80, N-100, N-150 and N-200 beams. For all the measurement points, five measurements were made with a counting time of 60 seconds.

The given graph shows the different attenuations curves for aluminium (N-20 to N-40) and copper (N-60 to N-200), the results of the curve above make it possible to deduce the thicknesses which correspond to the transmission rate of 50 and 25% (1st and 2nd HVL) (Osama and Aziz, 2007).

$$K_{air} = K_{air0} \cdot e^{-\mu x}$$

where

K_{air0} initial air KERMA (R)

μ attenuation factor (mm^{-1})

x filters thickness (mm).

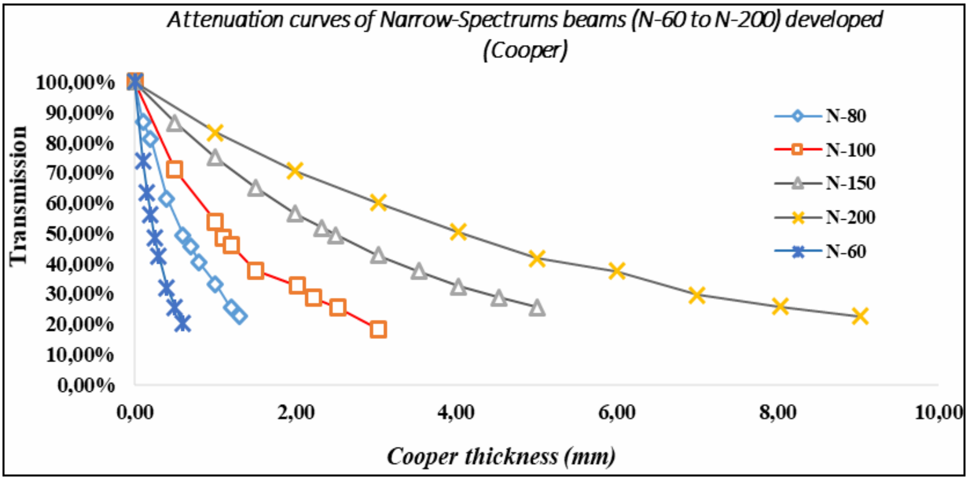
At a thickness equivalent to the 1st half attenuation layer, the counting is reduced to half, which makes it possible to write:

For x = 1st HVL

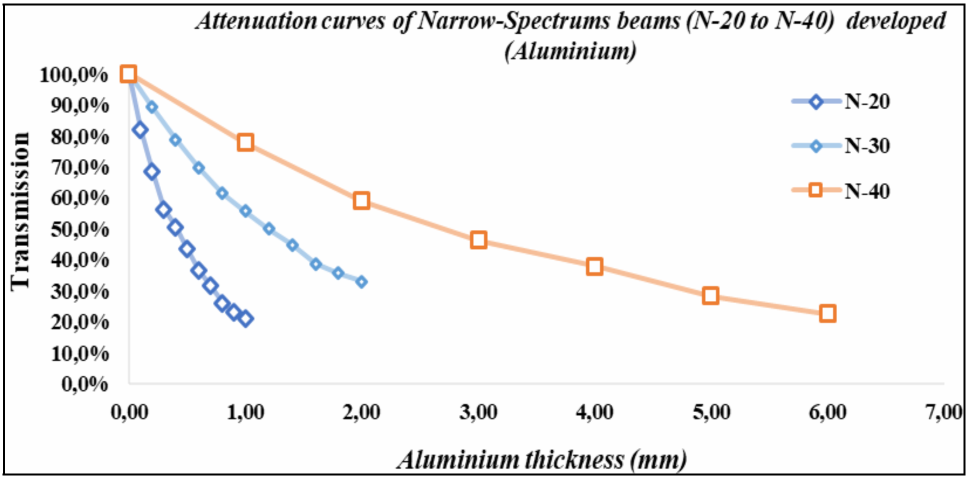
$$\frac{K_{air}}{K_{air0}} = 0.5$$

$$1\text{st } HVL = \frac{\ln(2)}{\mu}$$

Figure 5 Attenuation profiles for N-20 to N-200 established in LEGX, (a) for cooper (b) for aluminium (see online version for colours)



(a)



(b)

3.2.2 Assessment of half attenuation layer uncertainty HVL

The half-attenuation layer is determined as follows:

$$\text{1st } HVL = \frac{\ln(2)}{\mu}$$

Next, in order to calculate the uncertainties of the HVL values, it is crucial to determine the uncertainties related to the attenuation coefficient μ. The attenuation coefficient μ is defined as the ratio of the natural logarithm of the air KERMA to the thickness of the attenuating filters, at a specific thickness of applied filters, the variation of air KERMA as a function of this thickness is governed by the attenuation coefficient.

$$\mu = \frac{\ln\left(\frac{K_{air}}{K_{air0}}\right)}{x}$$

This equation demonstrates that the estimation of the measurement uncertainty associated with the attenuation coefficient is primarily dependent on the measurement uncertainty of air KERMA and the thickness of the attenuating filters.

This enables the estimation of the measurement uncertainty associated with the attenuation coefficient by applying the appropriate law of propagation.

$$u_C(\mu) = \sqrt{u^2(K_{air}) + u^2 x}$$

where

$u_C(\mu)$ relative uncertainty associated with the attenuation coefficient (%)

$u_C(K_{air})$ relative uncertainty associated with the air KERMA (%)

$u_C(x)$ relative uncertainty associated with the thickness of the filters (%).

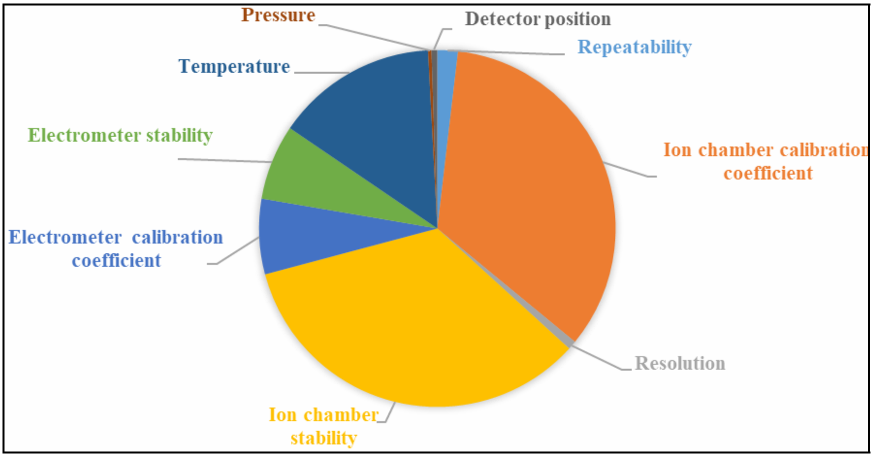
In order to determine the uncertainty associated with the air KERMA rate and the attenuation factor, we conducted a comprehensive analysis of all the sources of uncertainty that impact the measurements (IAEA in Collaboration with WHO, 2009). The results of this analysis are presented in Table 2.

Table 2 Air KERMA standard uncertainty

Source of uncertainty	*Value of quantity*	*Uncertainty type*	*Uncertainty (k = 1)*
Repeatability	7.66 mGy/h	A	0.007
Ion chamber calibration coefficient	1.354E+08 R/C	B	1.25
Ion chamber stability	/	B	1.25
Electrometer calibration coefficient	1.354E+08 R/C	B	0.25
Electrometer stability	/	B	0.25
Pressure	1,006.15 hPas	B	0.01
Temperature	19.9°C	B	0.54
Detector position	1,000 mm	B	0.02
Resolution	7.66 mGy/h	B	0.03
Expanded uncertainty (*k* = 2)		3.77%	

Figure 6 illustrates the graphical representation of all the sources of uncertainty in the air KERMA rate, clearly demonstrating that the overall uncertainty depends primarily on the calibration of the ionisation chamber used as a reference standard in this study.

Figure 6 The uncertainty budget of K_{air} for the N-40 beam, including all standard uncertainties (see online version for colours)



3.2.3 *Compliance of HVL results according to the ISO 4037 standard (1996 and 2019)*

All results fond in laboratory is subject to validation through their comparison with the ISO 4037 standard 1996 and 2019 are showing in Table 3.

Table 3 Result obtained for narrow-spectrum beams developed at LEGX

Beam qualities	*Added filtration (mm)*				*1st HVL_{std} ISO (mm) (2019)*	*1st HVL (mm)*	*Deviation (µm)*
	Pb	*Sn*	*Cu*	*Al*			
N-20	/	/	/	1.0	0.344 (Al)	0.423 ± 0.03	79
N-30	/	/	/	4.0	1.16 (Al)	1.21 ± 0.04	46
N-40	/	/	0.2	4.0	2.63 (Al)	2.65 ± 0.06	20
N-60	/	/	0.6	4.0	0.234 (Cu)	0.246 ± 0.007	12
N-80	/	/	2.0	4.0	0.578 (Cu)	0.609 ± 0.03	31
N-100	/	/	5.0	4.0	1.09 (Cu)	1.09 ± 0.06	18
N-150	/	2.5	/	4.0	2.30 (Cu)	2.44 ± 0.13	140
N-200	0.9	3.0	2.0	4.0	3.92 (Cu)	3.09 ± 0.14	170

The HVL measured for each radiation qualities, are compared to the HVL published by the ISO 4037 for each version 2019 and 1996:

- For ISO 4037-1996: We calculated the difference between the HVL measured and HVL_{std} as a standard deviation percentage (%), this standard deviation must be less than 5%.

- For ISO 4037-2019: We calculated the difference between the HVL measured and the HVL_{std} as a standard deviation in µm, these standard deviations must meet the conditions listed in Table 4.

Table 4 Requirements for the determination of HVL according to ISO 4037-2019

Radiation qualities	*Maximum allowed of HVL measured and HVL_{std} (aluminium)*			*Maximum allowed of HVL measured and HVL_{std} (cooper)*		
	0.07 mm µm	*3 mm µm*	*10 mm µm*	*0.07 mm µm*	*3 mm µm*	*10 mm µm*
N-10	50	/	/	/	/	/
N-15	50	/	/	/	/	/
N-20	100	10	/	/	/	/
N-25	300	30	10	/	/	/
N-30	500	50	30	/	/	/
N-40	500	200	100	/	/	/
N-60	/	/	/	100	20	20
N-80	/	/	/	200	200	100
N-10 to N-400	/	/	/	200	200	200

The validity criteria for the 2019 version of the ISO 4037 standard are based on the operational quantity intended to be measured, specifically the radiation penetration depth. This measurement is conducted using various phantoms that simulate the human body (and can also be simulated numerically (Bardane et al., 2019).

Table 5 Compliance results according to the ISO 4037 standard 1996 and 2019

Beam quality	*Added filtration*				*1st HVL ISO (2019) (mm)*	*1st HVL ISO (1996) (mm)*	*1st HVL measured (mm)*	*Deviation according to ISO 2019 (µm)*	*Percentage according to ISO 1996 (%)*
	Pb	*Sn*	*Cu*	*Al*					
N-20	/	/	/	1.0	0.344 (Al)	0.32 (Al)	0.423 ± 0.03 (Al)	79	20
N-30	/	/	/	4.0	1.16 (Al)	1.15 (Al)	1.21 ± 0.04 (Al)	46	5
N-40	/	/	0.20	4.0	2.63 (Al)	0.084 (Cu)	2.65 ± 0.06 (Al) 0.081 ± 0.001 (Cu)	20	4
N-60	/	/	0.6	4.0	0.234 (Cu)	0.24 (Cu)	0.246 ± 0.007 (Cu)	12	2
N-80	/	/	2.0	4.0	0.578 (Cu)	0.58 (Cu)	0.609 ± 0.03 (Cu)	31	5
N-100	/	/	5.0	4.0	1.09 (Cu)	1.11 (Cu)	1.07 ± 0.06 (Cu)	18	4
N-150	/	2.5	2.5	4.0	2.30 (Cu)	2.36 (Cu)	2.44 ± 0.13 (Cu)	140	3
N-200	0.9	3.0	2.0	4.0	3.92 (Cu)	3.99 (Cu)	3.80 ± 0.14 (Cu)	120	5

The provided in Table 5 shows the result of validity criterion found for the narrow spectrum series qualities developed at calibration laboratory of CNESTEN, bay using, on the one hand the ratio of the HVL given by the ISO 4037-1996 standard and the HVL measured, and the standard deviation between standard HVL given by the ISO 4037-2019 standard and HVL measured in our laboratory on the other hand.

It is important to note that the significant variation between the two versions of the ISO 4037 standard relates to low energy beams (N-20, N-30, and N-40) by increasing validity criteria, and this is particularly evident in our N-20 beam, which does not conform to the ISO 4037-1996 standard (deviation of 20%) but is valid according to the ISO 4037-2019 standard (deviation of 79 μm) for the quantity H'(0.07). It is also important to note that the validity criteria in ISO 4037-2019 are classified according to the quantity of operation, which depends on the depth of penetration of the radiation. We propose to optimise these discrepancies through a Monte Carlo simulation of appropriate phantoms for operational quantities such as the dose equivalent Hp(10) and Hp(0.07) (Bardane et al., 2019; Krzanovic et al., 2017; Franciscatto and Potiens, 2009; Arectout et al., 2022).

4 Conclusions

In this study, we have conducted the procedure for establishing standard narrow beam radiation qualities used in radiation protection. This was achieved by determining the HVLs for X-ray photons with energies up to 200 keV. The measurements were performed by placing copper or aluminium absorbers of varying thicknesses equidistantly from the focal point of the X-ray tube and the detector (ion chamber). The first remark that we can see is that the smallest HVL deviation corresponds to N-60, and it increases as the high voltage exceeds 60 kV, and this was probably because hard-X-ray hardening, but all result obtained are acceptable except N-20 for the ISO 4037-1996 most likely due to the use of the PTW 32005 ionisation chamber which has an energy range of 25 keV to 50 MeV indeed, all beams qualities have been successfully established and can be used of instrument calibration in X-ray and Gamma Calibration Laboratory at CNESTEN. However, those X-ray beams developed in our laboratory can be optimised through the use of simulation methods like MCNP for determination of personal and ambiance conversion factor in order to reduce the associated uncertainties.

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