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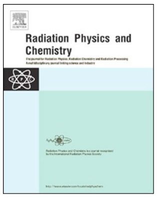

The performance of a prototype device designed to evaluate quality parameters of radiological equipment: Complementary study

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ABSTRACT

Quality control measurements in radiological equipment are essential to verify their achievable performance standards, as average peak voltage (kVp), practical peak voltage (kVpp), exposure time, radiation dose and half-value layer (HVL). In a recent study, a multifunctional prototype's partial results were presented using a solid-state detector to evaluate quality parameters as kVp, exposure time and HVL of radiological equipment. In the present work, the accuracy of these measurements was improved, and dosimetric parameters were developed aiming to comply with normative requirements. The prototype board hardware was built with four sensors PIN RD100 A and a dedicated software based on their signals. In a single exposure, these signals were used in settled polynomial functions to determine kVp, kVpp, exposure time, radiation dose, dose rate and HVL. Characterization tests were undertaken at an instruments calibration laboratory and at a clinical research laboratory. A mathematical function was fitted for 50–120 kVp range, with $R^2 = 0.999$. This new algorithm allowed improving the kVp accuracy from [0.3–2.3%] to [0.03–1.5%]. The reproducibility and accuracy of the radiation dose rate reached 0.94% and 0.34%, respectively. The dose range measurements varied from 0.01 to 40 mGy. In addition, calibration tests were performed in calibration laboratory at standard traceable radiation qualities of RQR6 and RQR8. The total uncertainty associated with this calibration did not exceed 2%. In conclusion, the prototype can be considered a multifunctional non-invasive instrument appropriate to evaluate radiological equipment performance with an effective range from 50 kV to 120 kV.

1. Introduction

The importance of a frequent radiological equipment evaluation in order to maintain its performance under control has been recognized. In Brazil, the quality assurance is based on national standards that intend to prevent wrong diagnoses, repeated exams and X-ray tube depreciation (BHM, 1998).

Control measurements in radiological equipment as average peak voltage (kVp), irradiation time, air kerma and half-value layer (HVL) are essential to verify the achievable performance standards. These measures are also compared with international normative references (AAPM, 2002; NCRP, 1988; EUR, 1996).

Invasive and methods, based on different techniques, have been used for peak voltage (kVp) measurement of radiological equipment, some of them presenting advantages for quality control routine tests in diagnostic radiology (Silva et al., 2000).

In general, devices that use ionization chambers and/or solid-state detectors (SSD) are applied to measure quality parameters in the X-ray equipment beams used for medical diagnostic radiological examinations (AAPM, 2002; DeWerd, 1999; IEC, 2013).

Ionization chambers as well as SSD present advantages and disadvantages related with energy dependence, environmental conditions, sensitive volume, and sensitivity characteristics (Owen et al., 2009).

Solid-state detectors have been used in radiation dosimetry since 1963. Their use are based on the production and motion of electron-hole pairs for detection and measurement of ionizing radiation (IEC, 2013). At the irradiation time, electron-hole pairs are created in the detector, and the current signal is due to charge carriers created in the

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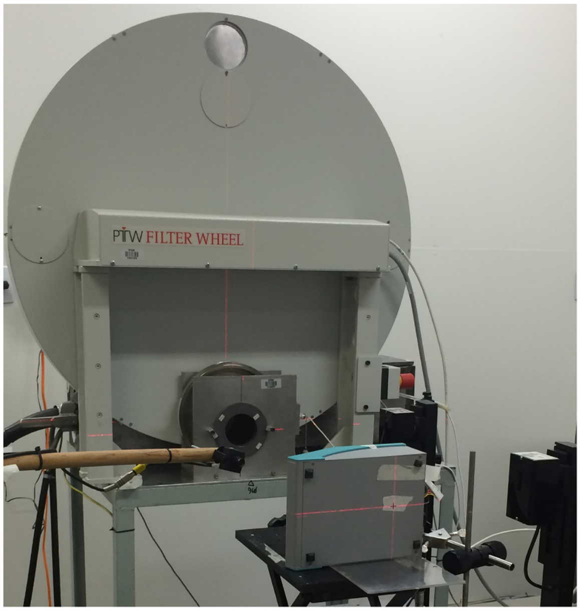

Fig. 1. PTW filter wheel and calibration set-up of LCI/IPEN.

depletion region and electrons in p-type silicon and holes in n-type created in the base material (Rikner and Grusell, 1986).

The SSD PIN RD100A, with 100 mm^2 of active area and 6 ns of rise time, is a sensor with appropriated sensitivity for X-ray radiation fields. The manufacturer reports that all components should be enclosed in a metal box in order to decrease noise (OsiOptoelectronics, 2013).

In a recent study, a multifunctional prototype was presented using this SSD to evaluate voltage, exposure times and HVL of radiological equipment with a single exposure (Murata et al., 2014). In the present work, the dose and dose rate measurements were taken, and the accuracy of all parameters displayed in the prototype screen were improved according to normative requirements (AAPM, 2002; IEC, 2013).

This study proposed a further work on the original developed prototype, which turned it capable to evaluate the dosimetric parameters of the radiological equipment by non-invasive measurements, meeting the normative requirements.

2. Experimental

Two very important parameters, dose and dose rate, were introduced into the original described prototype as complementary measurements. The updated touch screen displays the following parameters: peak voltage (kVp), practical peak voltage (kVpp), ripple (%), dose rate (mGy/s), exposure time (ms), half-value layer (mmAl) and dose (mGy).

The same set of four sensors and filters of the original prototype was used for data acquisition. An AD converter with resolution of 12 bits and numerical accuracy in the processing routine of seven significant digits was used. The proportionality between 2 sensors data correlated with the voltage divider values, taken as reference, allowed the fitting of a 6th order polynomial function. This function was established in the floating-point processor with accuracy of 32 bits, following the IEEE 754 standard (IEEE, 1985).

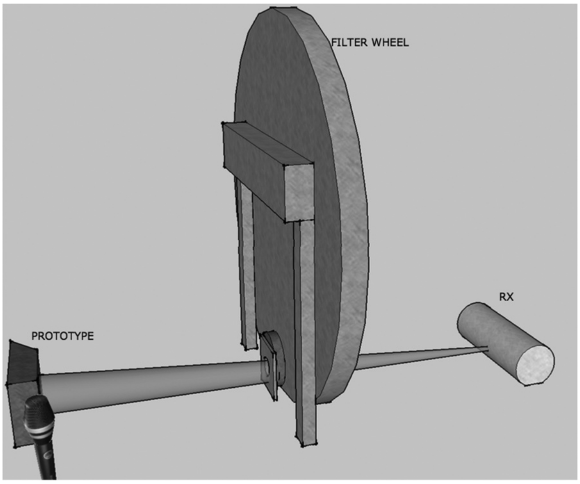

Fig. 2. Experimental set-up with the reference ionization chamber.

Characterization tests were performed at the Calibration Laboratory of Instruments of Nuclear and Energy Research Institute - LCI/IPEN using an industrial X-ray system (Pantak/Seifert, model ISOVOLT 160HS) with a PTW filter wheel (Fig. 1) to select the filtration according to the standard radiation qualities (RQR3, RQR5 and RQR8) (IEC, 2005).

These beam qualities and voltage range used to calibrate the parameters kVp, HVL and dose are shown in Table 1. A Radcal chamber RC6 (NS: 16675, sensitive volume of 6.0 cm^3) coupled to the PTW electrometer model Unidos-E, calibrated at the German standard laboratory of Physikalisch-Technische Bundesanstalt (PTB), was used as reference, as shown in Fig. 2.

The uncertainties of Type B are related mainly to the information about the use of the x-rays system for the standard radiation qualities for diagnostic radiology (RQR 3, RQR 5 and RQR 8), as the air kerma rates, positioning of the standard ionization chamber in the radiation beams, its traceable calibration factors for the different radiation qualities and the correction factor for the reference conditions of temperature and pressure. Taking into account all of these parameters, the maximum total uncertainty for LCI/IPEN set-up was determined as 2.3% (k = 1).

The average peak voltage measures were collected in steps of 2 kV selected at the LCI/IPEN X-ray equipment.

Differently from the first prototype, where three different polynomial functions were used for three voltage ranges (50–70 kVp, 71–90 kVp and 91–120 kVp), in this case, one polynomial mathematical function described at Eq. (1) (regression coefficient = 0.9997), that allows calculating the voltages between 50 kV and 120 kV, was implemented, taking as reference the nominal voltage values obtained from the voltage divider.

$$y_i = \sum_{n=0}^{6} m_n.\, x_i^n \quad i = 1,\ \ 2,\ \ 3,\ \ldots 36 \tag{1}$$

where y_i are peak voltage values, $m_{0,}$ m_1,..m_6 are coefficients and x_i are the acquired data from the proportionality between the differential absorption of X-ray between two sensors (with 0.25 and 0.75mmCu

Table 1
X-rays beam characteristics established by LCI (IEC, 2005).

Radiation Quality	Tube voltage (kV)	HVL (mmAl)	Filtration (mmAl)	Tube current (mA)	Voltage range (kV)	Air kerma (mGy/min)
RQR 3	50	1.78	2.4	10	50 – 69	22.4 ± 0.5
RQR 5	70	2.58	2.8	10	70 – 99	38.6 ± 0.9
RQR 8	100	3.97	3.2	10	100–120	69.3 ± 1.5

Table 2
Coefficients of Eq. (1) for kVp measurements, with $R^2 = 0.9997$.

Order (n)	Coefficient value
Null[a]	(7.12 ± 0.16) E02
1st	(−5.76 ± 0.13) E02
2nd	(2.203 ± 0.051) E02
3rd	(−4.52 ± 0.10) E01
4th	5.19 ± 0.12
5th	(−3.122 ± 0.072) E − 01
6th	(7.70 ± 0.18) E − 03

[a] Residual value.

Table 3
Coefficients of Eq. (2) for HVL measurements, with $R^2 = 0.9994$.

Order (n)	Coefficient value
Null*	(−1.757 ± 0.040) E02
1st	(1.627 ± 0.037) E01
2nd	(−5.38 ± 0.12) E − 01
3rd	(9.09 ± 0.21) E − 03
4th	(−8.35 ± 0.19) E − 05
5th	(3.984 ± 0.092) E − 07
6th	(−7.74 ± 0.18) E − 10

- residual value.

filtration). Table 2 shows the coefficients values and respective polynomial orders.

The practical peak voltage was calculated according to the equation in Annex B of IEC 61676 (IEC, 2002).

The HVL measures were collected in steps of 10 kV selected in the LCI/IPEN X-ray equipment. The HVL values were estimated using the HVL_{Al} (mmAl) calculated with the reference ionizing chamber and correlated with HVL_{Cu} (mmCu) calculated from the displayed values of the four sensors. A mathematical function described at Eq. (2) ($R^2 = 0.9994$) that allows calculating HVL was used through the HVL_{Al}/HVL_{Cu} ratio and the nominal voltage values of the X-ray equipment obtained from the voltage divider. Table 3 shows the coefficients and respective polynomial orders.

$$y_i = \sum_{n=0}^{6} m_n.\, x_i^n \quad i = 1,\ 2,\ 3,\ \ldots 8 \tag{2}$$

where y_i are HVL_{Al}/HVL_{Cu} ratio values, m_0, m_1,..m_6 are coefficients and x_i are the peak voltage values, calculated in Eq. (1). The y_i multiplied by HVL_{Cu} results in HVL_{Al}.

The dose rate was calculated in steps of 10 kV using the ionizing chamber (Radcal RC6) as reference placed next to the prototype (Fig. 2). For this purpose, just the sensor without copper filtration was used in order to avoid the beam attenuation effect. A third order polynomial function ($R^2 = 0.9999$) that allows calculating radiation dose between 50 kV and 120 kV was used correlating the ionization chamber values with this sensor for each nominal voltage value of the X-ray equipment. The data were collected at each radiation quality considering the X-rays beam characteristics established by LCI (Table 1).

Dose and dose rate values were estimated and displayed for an exposure time lower or equal to 1 s Table 4 presents the coefficients of Eq. (3) for dose measurements and respective polynomial orders.

$$y_i = \sum_{n=0}^{3} m_n.\, x_i^n \quad i = 1,\ 2,\ 3,\ \ldots .6 \tag{3}$$

where y_i are dose values, m_n are coefficients and x_i are the acquired data from the sensor without filtration.

Table 4
Coefficients of Eq. (3) for dose measurements, with $R^2 = 0.9999$.

Order n	Coefficient value
Null[a]	(1.930 ± 0.044) E − 01
1°	(6.98 ± 0.16) E − 03
2°	(1.429 ± 0.033) E − 05
3°	(−9.32 ± 0.21) E − 09

[a] Residual value.

The peak voltage measurements were repeated 5 times in each step of 2 kV in order to improve the mathematical function fit. In the case of HVL and dose rate the measurements were repeated 5 times in each step of 10 kV.

The tests for exposure time measurements were performed using clinical X-ray equipment installed for research purposes at the Federal University of São Paulo, supported by FAPESP and Project of Technology and Science National Institutes (INCT) – Radiation Metrology in Medicine. This X-ray equipment is a Compact Plus 500 – VMI/Philips® system with: voltage range of 50–150 kV; current range of 50–500 mA and total attenuation of 2.3 mmAl. The exposure time was determined using the stored waveform in the prototype microprocessor memory. The exposure time was defined as the time interval between the first peak after the rising edge and the last peak before the falling edge of the sampled signal (Fig. 3). Five readings at 50 ms, 100 ms, 150 ms, 200 ms, 250 ms and 800 ms were compared with the measured values using the Minipa MO-310 oscilloscope (100 MHz; accuracy of 3% mV; sensibility of 1 mV; error base time of 71%), connected to the X-ray tube generator system.

The same X-ray equipment was used to compare the prototype performance with two other commercial devices (Unfors model Mult-O-Meter and Radcal model AGMS-D), both non-invasive instruments. The measurements were repeated 5 times in each step in order to obtain reproducibility and accuracy of data (Unfors, 1997; RTI, 2008).

The reproducibility and accuracy of the obtained data were calculated according to Eqs. (4) and (5).

$$Reproducibility(\%) = [2^*(maximum - minimum)/(maximum + minimum)]^*100 \tag{4}$$

$$Accuracy(\%) = [(nominal - measure)/nominal]^*100 \tag{5}$$

Uncertainties of A type were considered for the results presented in this study, with coverage factor of k = 1 (confidence level of 68.3%). The standard deviations of the mean measures were considered (INMETRO, 2008).

The prototype calibration was performed at the Ionizing Radiation Metrology Laboratory of the Federal University of Pernambuco - LMRI-DEN/UFPE, according to the standard radiation qualities of RQR6 and RQR8. The calibration qualities are traceable to the secondary standard

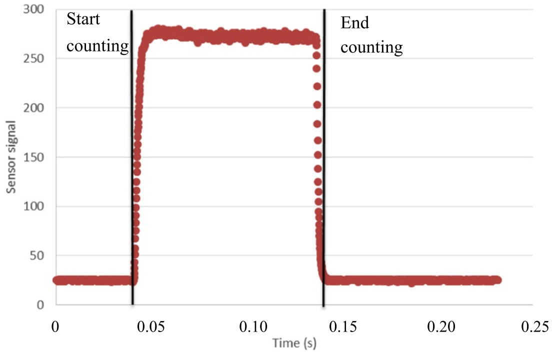

Fig. 3. Representation of exposure time calculation.

Table 5
Average voltage values and standard deviations obtained at 50 kV and 25 mA (RQR 3).

SSD (cm)	kVp (kV)	kVpp (kV)	HVL (mmAl)
50	50.02 ± 0.13	50.02 ± 0.13	2.20 ± 0.11
100	51.13 ± 0.54	51.13 ± 0.54	2.20 ± 0.11
Difference (%)	− 2.2	− 2.2	ND

ND: not detectable.

dosimetry laboratory named National Ionizing Radiation Metrology Laboratory of the Dosimetry of the Radiation Protection and Dosimetry Institute of Brazilian Nuclear Energy Commission – IRD/CNEN/Brazil.

3. Results and discussion

The results are dependent of the photodiode characteristics and the signals acquisition methodology (Murata et al., 2014). The recommended features were established for different dynamic voltage ranges for testing the clinical ranges of kVp and mA settings at exposure times as short as 50 ms. Minimal dependence on variations in positioning according to the detector orientation and the source-detector distance were observed. The differences between the measurements obtained for the prototype considering 50 cm and 100 cm (source-detector distance-SDD) were 2.2% for kVp and kVpp; and they were not detectable for HVL (Table 5).

The differences between the measurements obtained at 0° and 90° rotation displayed for the prototype were 0.5% for kVp and kVpp, and not detectable for dose rate and HVL values (Table 6).

The differences among measurements obtained for the prototype between 0° (reference) and 5°, 10°, −5°, −10° angulations are shown in Table 7.

The prototype instrument presents low dependence on these geometric parameters providing to users more reliability in their results and less concern regarding the set-up during the measurements. For commercial instruments used in diagnostic radiology, a reproducibility of the average peak voltage of 0.5% and an accuracy of 2–3% are required (IEC, 2002; AAPM, 1998).

The reproducibility and accuracy of the average peak voltage data from 50 to 120 kVp were compared with results of two other commercial instruments: Unfors model Mult-O-Meter and Radcal model AGMS-D, as shown in Table 8. These results show that the prototype has similar reproducibility and accuracy when compared with both commercial devices.

For the X-ray exposure time, the AAPM requires a range from 0.001 to 10 s, accuracy of 1 ms, minimum resolution of 0.1 ms (AAPM, 1998). Table 9 shows the reproducibility and accuracy for the exposure time measurements comparing the three instruments. These results were obtained with clinical equipment and for this reason, the maximum tested value was 800 ms. These results show that the response of all three instruments was better than 1% for all measurements, which is in accordance to the AAPM requirements.

Unlike radiological equipment used clinically, the industrial equipment (Pantak/Seifert) generates a continuous X-ray beam with low tube current values (10–30 mA). This feature enables higher beam stability during exposure allowing a superior accuracy at kVp, HVL and

Table 7
Average peak voltage values and standard deviations obtained at 70 kV, 25 mA and 1 m (SDD).

Rotation angle (deg.)	kVp (kV)	kVpp (kV)	Dose Rate (mGy/s)
0	69.55 ± 0.06	69.57 ± 0.10	1.500 ± 0.008
5	69.27 ± 0.10	69.27 ± 0.10	1.500 ± 0.008
10	69.04 ± 0.11	69.04 ± 0.11	1.500 ± 0.008
− 5	69.67 ± 0.13	69.67 ± 0.13	1.500 ± 0.008
− 10	69.77 ± 0.05	69.77 ± 0.05	1.500 ± 0.008
Differences taking 0° as reference (%)			
5	− 0.4	− 0.4	ND
10	− 0.7	− 0.8	ND
− 5	0.2	0.1	ND
− 10	0.3	0.3	ND

ND: not detectable.

Table 8
Reproducibility and accuracy of kVp measurements, from 50 kVp to 120 kVp. (100 mA, SDD = 1 m).

Nominal voltage (kVp)	Reproducibility (%)			Accuracy (%)		
	Unfors	Radcal	Prototype	Unfors	Radcal	Prototype
50	0.73	0.30	0.42	1.80	0.38	0.32
60	0.44	0.43	0.37	0.93	0.67	2.30
70	0.65	0.13	0.28	0.52	0.45	2.06
80	0.51	0.16	0.53	1.11	0.28	1.75
90	0.45	0.25	0.44	1.46	0.13	1.22
100	0.29	0.28	0.48	1.66	0.83	0.18
110	0.41	0.18	0.35	2.68	1.50	0.87
120	0.41	0.07	0.18	4.57	2.47	1.40

Table 9
Reproducibility and accuracy of exposure time measurements (80 kV, 100 mA, SDD = 1 m).

Nominal time (ms)	Reproducibility (%)			Accuracy (%)		
	Unfors	Radcal	Prototype	Unfors	Radcal	Prototype
50	0.19	0.11	0.16	− 0.39	0.35	− 0.56
100	0.01	0.06	0.08	0.77	0.86	− 0.06
200	0.42	0.39	0.40	0.16	− 0.08	− 0.19
400	0.03	0.03	0.01	0.18	0.20	0.01
800	0.02	0.02	0.02	0.01	0.04	− 0.08

Table 10
Reproducibility and accuracy of HVL measurements of the present study (25 mA, SDD = 1 m).

Nominal Voltage (kV)	HVL (mmAl)	Accuracy (%)	Reproducibility (%)
50	2.2 ± 0.1	1.79	1.83
60	2.5 ± 0.1	2.84	0.40
70	2.9 ± 0.1	− 1.07	0.69
80	3.2 ± 0.2	− 1.03	0.31
100	3.9 ± 0.2	− 3.84	2.86
120	4.4 ± 0.2	− 3.20	0.23

Table 6
Average voltage values and standard deviations obtained at 70 kV, 25 mA and 1 m (SDD).

Rotation (deg.)	kVp (kV)	kVpp (kV)	Dose Rate (mGy/s)	HVL (mmAl)
0	68.97 ± 0.22	68.97 ± 0.22	1.500 ± 0.008	2.90 ± 0.11
90	69.30 ± 0.09	69.31 ± 0.09	1.500 ± 0.008	2.90 ± 0.11
Difference (%)	0.5	0.5	ND	ND

ND: not detectable.

Table 11
HVL measurements comparing two devices (100 mA, SDD = 1 m).

Nominal voltage (kVp)	HVL (mmAl)	
	Radcal	Prototype
50	2.101 ± 0.002	2.114 ± 0.090
60	2.519 ± 0.002	2.602 ± 0.004
70	2.947 ± 0.002	3.002 ± 0.004
80	3.391 ± 0.002	3.380 ± 0.045
90	3.775 ± 0.002	3.702 ± 0.004
100	4.203 ± 0.002	4.060 ± 0.055
110	4.623 ± 0.001	4.402 ± 0.004
120	5.031 ± 0.001	4.702 ± 0.004

Table 12
Reproducibility and accuracy of dose rate. (25 mA, SDD: 1 m).

Nominal Voltage (kV)	Dose Rate (mGy/s)	Reproducibility (%)	Accuracy (%)
50	0.876 ± 0.004	0.94	− 0.17
60	1.291 ± 0.006	0.61	0.34
70	1.520 ± 0.007	0.66	− 0.06
80	1.97 ± 0.01	0.58	− 0.19
100	2.77 ± 0.01	0.61	0.08
120	3.88 ± 0.02	0.65	− 0.01

Table 13
Dose rate measurements for three devices. (100 mA, SDD: 1 m).

Nominal voltage (kVp)	Dose Rate (mGy/s)		
	Unfors	Radcal	Prototype
50	1.765 ± 0.007	1.604 ± 0.015	1.800 ± 0.009
60	2.855 ± 0.006	2.568 ± 0.004	3.000 ± 0.015
70	4.078 ± 0.015	3.645 ± 0.009	4.220 ± 0.045
80	5.373 ± 0.011	4.821 ± 0.004	5.500 ± 0.028
90	6.739 ± 0.026	6.093 ± 0.011	6.850 ± 0.055
100	8.098 ± 0.013	7.388 ± 0.005	8.200 ± 0.041
110	9.461 ± 0.021	8.711 ± 0.018	9.460 ± 0.055
120	10.848 ± 0.029	10.077 ± 0.014	10.700 ± 0.054

dose rate. For this purpose, the software was adapted so that the dose rate values were calculated and displayed for each second. However, the X-ray equipment for clinical use was essential for testing short exposure time measurements (< 1 s).

Table 15
Calibration factors of the prototype: Calibration Report LMRI-DEN/UFPE N° 0236 kV/0816.

Practical Peak Voltage (kVpp)		
Reference (kVpp)	**Instrument Indication (kVpp)**	**Calibration Factor**
53.2	53.9	0.99
70.5	71.37	0.99
90.97	92.47	0.98
Maximum Peak Voltage (kVp)		
Reference (kVp)	**Instrument Indication (kVp)**	**Calibration Factor**
56.02	53.57	1.05
74.64	71.23	1.05
98.18	93.63	1.05
Exposure Time (ms)		
Reference (ms)	**Instrument indication (ms)**	**Deviation (ms)**
208.87	209.63	0.77
110.17	112.43	2.27
57.55	60.7	3.15

Tables 10, 11 show the reproducibility and accuracy of the HVL values calculated by the prototype instrument and from the results with two other devices. The differences of results, when compared with the first study, can be attributed to Radcal ionization chamber RC6 used as reference (Murata et al., 2014). It is important to mention that in the HVL measurements in quality control tests the values are registered as baseline and there is no reference levels in the Brazilian normative (BHM, 1998).

The AAPM recommends measurement instruments with 17.4 µGy to 86.9 Gy of dose range and 173.8 µGy/min to 5.7 kGy/s of dose rate range with accuracy better than 1% (AAPM, 1998).

Table 12 shows the reproducibility and accuracy for the dose rate with maximum values of 0.94% and 0.34%, respectively in a dose rate range of 0.88 mGy/s to 3.88 mGy/s for 100 mA. Once the prototype's purpose is to measure X-ray output from radiological equipment it was necessary to perform tests using clinical equipment and realistic technical conditions. In these conditions, the dose range varied from 0.01 mGy to 50 mGy. This range is consistent with the dose values received by patients in radiographic exams.

A dose rate measurements comparison for three devices is presented in Table 13. It is possible to observe a great similarity between Unfors and the prototype responses in terms of dose rate.

Table 14 shows the doses obtained at different technical conditions compared with two other commercial instruments. The prototype reproducibility was better than 1%, which it is considered acceptable (IEC, 2013). The prototype accuracy was similar of Unfors' device. Although, the prototype accuracy was better than 1%, as recommended (IEC, 2013), both commercial devices were also with higher accuracy.

The prototype was submitted to the calibration procedure in the

Table 14
Dose measurements using different technical parameters.

Reference dose (µGy)	Reproducibility (%)			Accuracy (%)		
	Unfors	Radcal	Prototype	Unfors	Radcal	Prototype
13.7 ± 0.1	1.40	0.21	0.63	10.8	− 1.78	17.2
83.2 ± 0.5	0.44	1.13	0.79	9.85	− 0.64	11.8
135.7 ± 0.2	0.27	0.23	0.54	9.31	− 2.31	13.3
193.3 ± 1.1	0.30	0.30	0.33	9.69	− 2.29	12.3
256.8 ± 0.7	0.13	0.06	0.39	8.72	− 2.61	10.7
326.6 ± 1.0	0.34	0.24	0.29	7.50	− 3.00	8.00
398.4 ± 1.9	0.16	0.17	0.36	6.03	− 3.26	6.03
471.1 ± 2.9	0.22	0.21	0.34	4.77	− 3.36	3.88
504.2 ± 1.8	0.17	0.16	0.10	9.00	− 1.96	11.0
544.6 ± 2.6	0.18	0.16	0.29	3.82	− 3.24	1.76
997.0 ± 4.4	0.46	0.49	0.50	8.36	− 2.16	10.7
$1.9.10^3$ ± 1.0	0.14	0.10	0.10	8.15	− 2.08	10.8
$3.8.10^3$ ± 1.5	0.01	0.02	0.04	8.03	− 2.04	10.8
$6.0.10^3$ ± 2.8	0.14	0.25	0.21	9.22	− 1.40	11.6
$1.3.10^4$ ± 7.1	0.20	0.03	0.01	7.13	− 1.85	8.25

Table 16
Calibration factors of the prototype: Calibration Report LMRI-DEN/UFPE N° 0967RX/0816.

Radiation Quality	Tube Voltage (kV)	HVL (mmAl)	Air Kerma Rate (mGy/s)	Instrument Indication (mGy/s)	Calibration Factor	Total Uncertainty (%)
LMRI-RQR6	80	3.01	0.670	0.643	1.04	2.5
LMRI-RQR8	100	3.97	0.962	0.887	1.09	2.5

Table 17
Prototype technical specification compared with Unfors - Mult-O-Meter and Radcal - AGMS-D (Unfors, 1997; RTI, 2008).

	Unfors - Mult-O-Meter	Radcal - AGMS-D	Prototype
	kVp measurements		
Quantity Unit	Average kVp	Average kVp	Average kVp
Range	50–150 kV	40–160 kVp	50–130 kV
Accuracy	± 2%	± 2%	± 2%
Reproducibility	± 1%	N/A	± 1%
	Exposure time		
Method	Measured during entire exposure; corresponding to 75% rise/fall average kVp.	N/A	Calculated between the first peak after the rising edge of the signal and the last peak before the falling edge of the sampled signal.
Range	1 ms - 9999 s	1 ms to 300 s	1–1000 ms
Accuracy	0.5% or 3 digits	± 0.1% or ± 0.2 ms	0.5%
Reproducibility	0.5% or 3 digits	N/A	0.5%
	Half-Value Layer (HVL)		
Range	N/A	1.3–10 mmAl	2–10 mmAl
Accuracy	N/A	± 10% or ± 0.2 mm Al. whichever is greater	± 5%
	Dose		
Range	1 nGy - 9999 Gy	150 nGy - 100 Gy	0.01–50 mGy
Accuracy	± 5%	± 5%	± 20%
Reproducibility	< 1.0% for > 1microGy/s < 5.0% for < 1microGy/s	N/A	1.0%
	Dose Rate		
Range	0.1–500 mGy/s	150 nGy/s - 350 mGy/s	0.5–10 mGy/s
Accuracy	± 5%	± 5%	± 20%

laboratory LMRI-DEN/UFPE with the aim to verify its performance as multifunction device for use in diagnostic radiology applications. In these laboratory assays, uncertainties A and B types were considered. Tables 15, 16 show the calibration factors obtained. The total uncertainty associated with the instrument calibration did not exceed 2%.

Table 17 shows the prototype's technical specifications compared with two commercial devices. The reproducibility and accuracy for all parameters evaluated were similar considering the prototype operating range.

In order to obtain lower uncertainties, spectrometers can be non-invasive alternative methods to measure peak tube voltage, as described by some researchers (Silva et al., 2000; Krmar et al., 2005; Abbene et al., 2012). This methodology requires a precise calibration, presenting reliability of results and better accuracy for kVp measurements. The spectrometry will be better utilized in laboratory, in the verification of the secondary calibration of voltage dividers or tertiary calibrations of kVp meters (Silva et al., 2000).

X –ray spectroscopy in mammography with silicon PIN photodiode has been studied and the results showed that this photodiode could be used in mammography beam dosimetry with better accuracy. Uncertainties evaluated for voltages in the range 20–35 kV from the measured spectra are better than 0.13% (Kunzel et al., 2004). Another work showed that uncertainties were evaluated for a peak voltage of X-ray tube in mammography, and they were better than 0.22% (k = 1) (Abbene et al., 2012). The low uncertainties point out that this method can be useful for calibration of kVp meters. This application at a clinical system is able to evaluate X ray spectrum precisely but it consumes time and requires methodology domain.

4. Conclusions

The average peak and practical peak voltages (kVp and kVpp), exposure time, radiation dose, dose rate and the half-value layer (HVL) of a radiological instrument were determined using a non-invasive electronic device containing the solid sensor detector PIN RD100 A. The methodology applied showed results with acceptable reproducibility and accuracy based on the AAPM standards and similar the commercial devices.

The prototype developed in this study can be considered a multifunctional non-invasive instrument appropriate to evaluate radiological equipment performance used at diagnostic radiology applications with an effective range from 50 kV to 120 kV.

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