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The performance of a prototype device designed to evaluate general quality parameters of X-ray equipment

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HIGHLIGHTS

- An instrument was developed to evaluate the performance of radiological equipment.
- The prototype containing solid detector was compared with commercial instruments.
- The prototype device shows comparable reproducibility and accuracy with commercial instruments.
- The prototype can be used for evaluate kVp, exposure time, and HVL using a single X-ray exposure.

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ABSTRACT

The performance of radiological equipment can be assessed using non-invasive methods and portable instruments that can analyze an X-ray beam with just one exposure. These instruments use either an ionization chamber or a state solid detector (SSD) to evaluate X-ray beam parameters. In Brazil, no such instruments are currently being manufactured; consequently, these instruments come at a higher cost to users due to importation taxes. Additionally, quality control tests are time consuming and impose a high workload on the X-ray tubes when evaluating their performance parameters. The assessment of some parameters, such as the half-value layer (HVL), requires several exposures; however, this can be reduced by using a SSD that requires only a single exposure. One such SSD uses photodiodes designed for high X-ray sensitivity without the use of scintillation crystals. This sensitivity allows one electron-hole pair to be created per 3.63 eV of incident energy, resulting in extremely high and stable quantum efficiencies. These silicon photodiodes operate by absorbing photons and generating a flow of current that is proportional to the incident power. The aim of this study was to show the response of the solid sensor PIN RD100A detector in a multifunctional X-ray analysis system that is designed to evaluate the average peak voltage (kVp), exposure time, and HVL of radiological equipment. For this purpose, a prototype board that uses four SSDs was developed to measure kVp, exposure time, and HVL using a single exposure. The reproducibility and accuracy of the results were compared to that of different X-ray beam analysis instruments. The kVp reproducibility and accuracy results were 2% and 3%, respectively; the exposure time reproducibility and accuracy results were 2% and 1%, respectively; and the HVL accuracy was ±2%. The prototype's methodology was able to calculate these parameters with appropriate reproducibility and accuracy. Therefore, the prototype can be considered a multifunctional instrument that can appropriately evaluate the performance of radiological equipment.

1. Introduction

Quality control tests are conducted periodically to assess the performance of radiological equipment using either a set of test instruments or a multifunctional instrument. This type of quality control is needed in order to avoid losses in image quality and unnecessary occupational or patient radiation exposure. Several technical parameters are examined when evaluating performance, including average peak voltage (kVp), exposure time, and half-value layer (AAPM, 2002; Costa et al., 2008). These parameters can be obtained in a single exposure using non-invasive methods and portable instruments. Several types of radiation detectors are used

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in these instruments. They can be classified into two categories: ionization chambers and solid state or semiconductor detectors (SSDs) (AAPM, 2002; DeWerd, 1999).

Ionization chambers measure radiation dosage and generate the same signals produced by X-ray equipment (DeWerd, 1999). However, two factors must be corrected for in the results. First, because the ionization chambers are unsealed, air density dependence must be corrected for using standard environmental conditions (temperature and pressure). Additionally, it is necessary to correct the chamber's sensitive volume to the measured quantity, i.e. exposure (C/kg) or absorbed dose (gray); this is known as energy dependence.

Solid state detectors, such as silicon photodiodes, operate by absorbing photons or charged particles. They can also generate current flow, proportional to incident power, in an external circuit that allows the detection of the presence or absence of minimal quantities of light. Consequently, SSDs can be calibrated to accurately measure intensities from below 1 pW/cm² to above 100 mW/cm². SSDs also use a class of photodiodes designed for additional sensitivity in the X-ray region of the electromagnetic spectrum. These photodiodes function without the use of any scintillation crystals or screens and possess a wide sensitivity range of 200 nm to 0.07 nm (6 eV to 17,600 eV). This creates one electron-hole pair per 3.63 eV of incident energy, a measure that corresponds to extremely high and stable quantum efficiencies (AAPM, 1998).

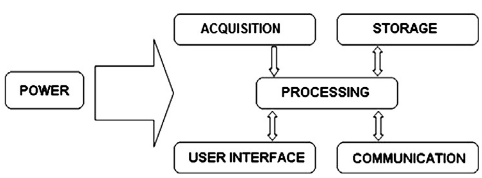

Fig. 1. Signal flow diagram of the sensors.

Since commercial devices are not yet manufactured in Brazil, the currently available products are more expensive due to importation taxes. Additionally, quality control tests of radiological equipment are time-consuming and impose high workloads on their X-ray tubes. Acquiring measurements for the assessed parameters requires several exposures which heats the X-ray tubes. Multifunctional portable devices can quickly evaluate several parameters with fewer exposures which avoids thermal stress and addresses some of these concerns. In this study, we present a multifunctional prototype that uses a solid state detector to evaluate average peak voltages (kVp), exposure times, and half-value layers (HVL) of radiological equipment.

2. Methodology

A prototype board was developed that uses four PIN RD100 A sensors as radiation detectors and mathematical methods to calculate average peak voltages (kVp), exposure times, and half-value layers (HVLs) while using a single exposure. The software routine was established based on signals captured by the sensors. The following subsystems were also included: power source, signal acquisition, storage, processing, communication, and user interface. A signal flow diagram for the subsystems is shown in Fig. 1.

Tests were performed in a research laboratory using an installed X-Ray system (Compact Plus 500—VMI/Philips®; voltage range, 50–150 kVp; current range, 50–500 mA; total attenuation, 2.3 mmAl). The X-Ray equipment was connected to a Minipa MO-310 oscilloscope (100 MHz; accuracy, 3% mV; sensibility, 1 mV; error base time, ±1%) for invasive measurements. The Heel Effect was eliminated during the data acquisition by using the setup shown in Fig. 2a and b shows the prototype.

A set of four sensors with different copper attenuators (0.25, 0.5 and 0.75 mmCu) was used to measure the average peak voltage from 50 to 120 kVp. The attenuators were placed above

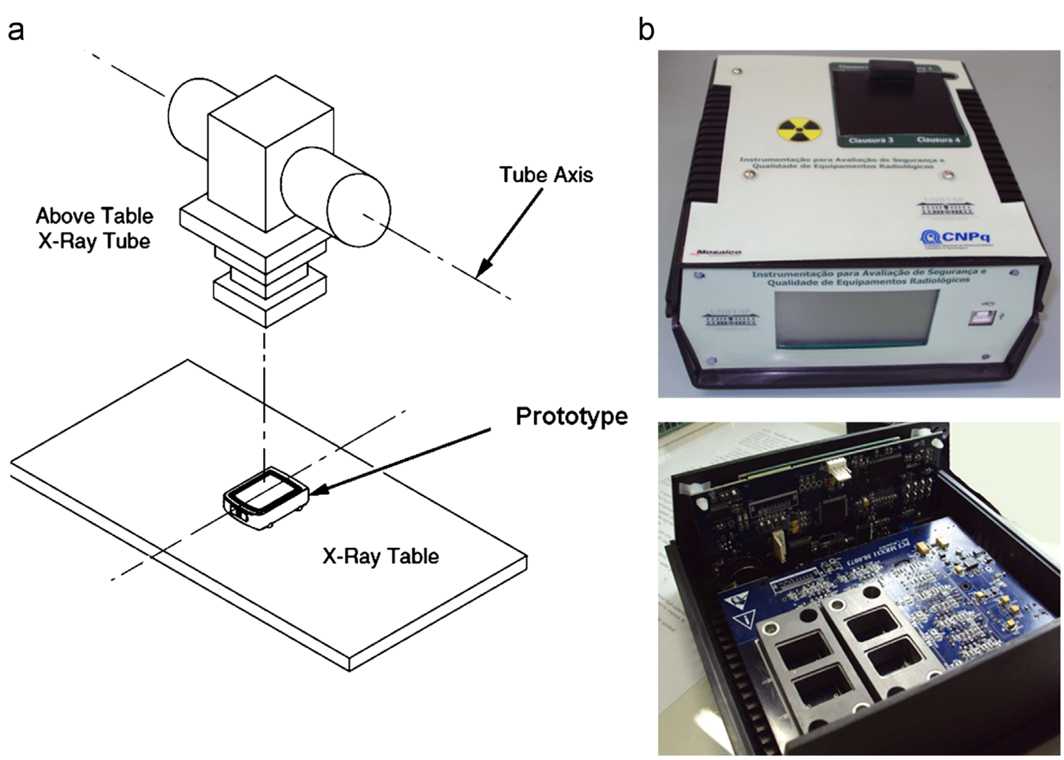

Fig. 2. (a) Diagram of the instruments aligned with the X-ray tube axis with a spot sensor distance (focal length) of 1 m. Adapted from reference 7; (b) Photograph of the prototype.

the lead housing used to protect the sensors from scattered radiation. Mathematical functions to improve measurement accuracy were determined for the following voltage ranges: 50–70 kVp, 71–90 kVp, and 91–120 kVp. Three readings for each kVp were taken as a standard, and the oscilloscope was used as a reference. These measurements were compared with two devices, the TNT 12000 Fluke® and the Innovision Victoreen 4000 M+®.

Exposure time was calculated using the waveform stored in the microprocessor memory. 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. Five readings at 50 ms, 100 ms, 200 ms, 400 ms, and 800 ms were taken as a standard.

HVL was estimated using the signal ratio of the waveform between the aluminum and copper attenuators. Five readings for each five units of voltage were taken as a standard.

The accuracy and reproducibility of the average peak voltage, exposure time, and HVL were compared to values obtained from reference instruments.

3. Results and discussion

Average peak voltage measurements were taken using a pair of closely spaced solid state detectors (SSDs) filtered by differing thicknesses of attenuating material. The methodology used to the X-ray tube voltages produced during X-ray exposure provided a direct measurement of the kVp. This method of using a set of attenuators was introduced by Ranallo (1993), but a silicon PIN photodiode, such as the one used in this study, and the Bremsstrahlung spectrum can also be used (Silva et al., 2000; Terini et al., 2004). For conventional diagnostic systems instruments, a kVp reproducibility of 0.5% and an accuracy of 2–3% are required (AAPM, 1998; IEC, 2002; Brazilian Health Ministry, 1998).

Fig. 3 compares the kVp measurements taken by the prototype to those of the reference instruments. There were no significant statistical differences between the responses of the solid state detectors (TNT® and Prototype) and the ionization chamber (Innovision®). The reproducibility and accuracy of the average peak voltage data from 50 to 120 kVp is also shown in Table 1. Both the reproducibility and accuracy of the prototype were comparable to that of reference instruments after correcting for each instrument's calibration factors.

Exposure time measurements taken by the prototype were compared to those of the reference instruments (Fig. 4). There were no significant statistical differences between exposure times measured by the solid state detectors (TNT® and Prototype) and the ionization chamber (Innovision®). Table 2 shows the reproducibility and

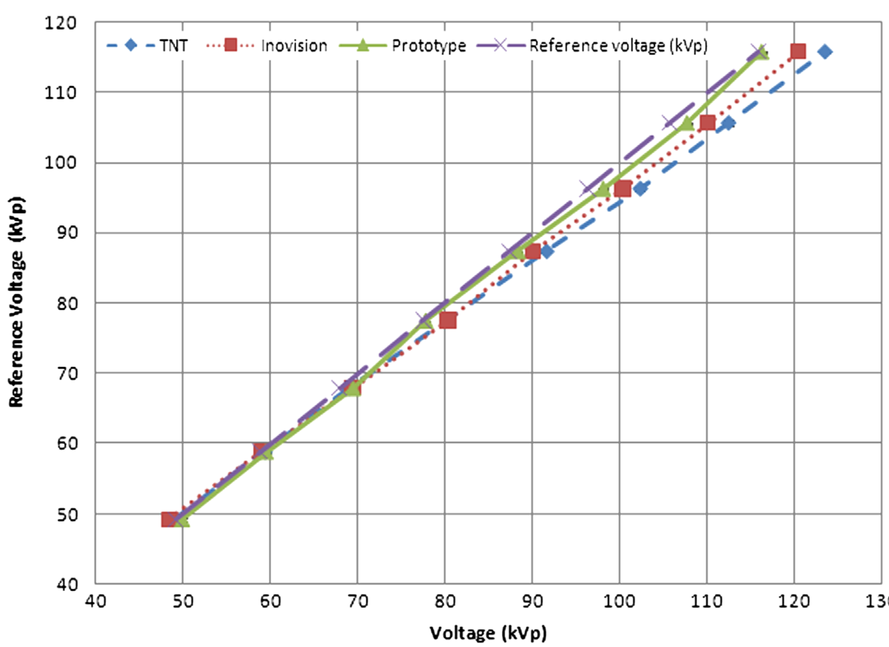

Fig. 3. Comparison of the kVp measurements taken by the prototype to that of the reference instruments.

Table 1
Reproducibility and accuracy of kVp measurements taken by the three instruments from 50 to120 kVp.

Nominal voltage (kVp)*	Reference voltage (kVp)**	Reproducibility (%)			Accuracy (%)		
		TNT	Innovision	Prototype	TNT	Innovision	Prototype
50	49.20 ± 0.44	0.8	0.1	1.0	0.1	1.6	−1.4
60	58.80 ± 0.44	0.5	0.1	0.5	−0.9	−0.2	−1.1
70	67.87 ± 0.79	1.0	0.0	0.1	−1.6	−2.2	−2.3
80	77.47 ± 1.47	0.4	0.0	0.1	−3.5	−3.7	−0.3
90	87.33 ± 1.06	0.5	0.3	0.2	−4.8	−3.1	−1.1
100	96.27 ± 0.65	0.6	0.0	0.2	−6.2	−4.2	−1.8
110	105.60 ± 1.01	0.8	0.0	0.2	−6.4	−4.2	−1.9
120	115.73 ± 0.83	0.2	0.2	0.1	−6.6	−4.0	−0.3

* Nominal voltage selected by the X-ray system Compact Plus 500—VMI/Philips®.
** Reference voltage measured with oscilloscope.

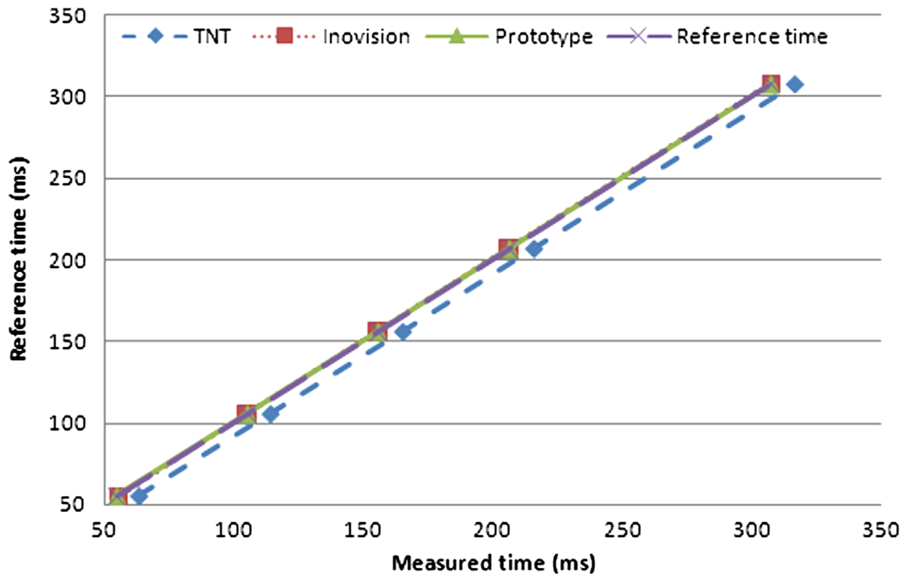

Fig. 4. Exposure time measured using the three instruments. Maximum uncertainty was 1.5 ms (not shown).

Table 2
Reproducibility and accuracy of exposure time measurements taken by three instruments from 50 to 800 ms.

Nominal time (ms)	Reference time (ms)*	Reproducibility (%)			Accuracy (%)		
		TNT	Innovision	Prototype	TNT	Innovision	Prototype
50	55	2.55	4.33	0.92	−14.6	−0.82	0.95
100	105.5	0.53	0.38	0.38	−8.1	0.66	0.45
150	156	0.12	0.06	0.06	−6.0	0.35	0.22
200	207	0.05	0.15	0.24	−4.4	0.41	0.23
300	308	0.09	0.10	0.06	−3.0	0.08	0.04

* Reference time measured with oscilloscope.

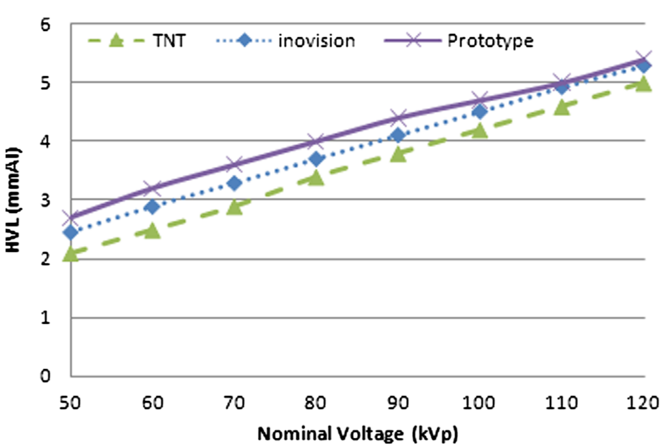

Fig. 5. HVL measurements taken by the prototype to that of the reference instruments.

Table 3
Values of HVL measurements taken by three instruments at 60, 80 and 100 kVp.

Nominal voltage (kVp)	HVL (mmAl)		
	TNT	Innovision	Prototype
60	2.5	2.9	3.2
80	3.4	3.7	4.0
100	4.2	4.5	4.7

accuracy for the exposure time measurements after correcting for each instrument's calibration factors.

A comparison of HVL measurements taken by the prototype compared to those of the reference instruments are shown in Fig. 5. Again, there were no significant statistical differences between the solid state detectors (TNT® and Prototype) and the ionization chamber (Innovision®). It is important to mention that determining HVL using the ionization chamber requires several exposures with attenuators of different aluminum thicknesses; determining HVL using solid state detectors requires only a single exposure. The differences we observed can be attributed to the methods used in the calculation of HVL, and they are not relevant since nominal values were registered as baseline values. The Brazilian Health Ministry requires a minimal HVL value in its 453/98 directive (Brazilian Health Ministry, 1998).

Table 3 shows the reproducibility and accuracy of HVLs estimated at 60, 80, and 100 kVp. The uncertainty of HVLs estimated by the prototype was much lower than that of with the reference instruments. This difference can likely be explained by the calculation method the prototype uses.

A summary comparing all measurements taken by the prototype to those of the reference instruments is shown in Table 4.

Further tests are being developed with the aim of expanding the range of kVp and exposure time measurements. Additionally, it is important to note that measurements by the prototype corresponded to direct data and were not yet corrected for any calibration factors.

Table 4
Measurement characteristics of the three portable instruments.

	TNT*	Innovision*	Prototype
		kVp measurements	
Quantity unit	Average kVp	Average kVp	Average kVp
Range	40 kV to 150 kV	27 to 155 kVp	40 kV to 130 kV
Accuracy	± 2% or ± 1 kV, whichever is greater	± 2%	± 2.3%
Reproducibility	± 1% (standard deviation of 5 readings)	**	± 1%
		Exposure time	
Method	Calculated between the first and last zero crossings of the kV waveform	Measured during entire exposure; corrected to 90% rise/fall kV time	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	the kV waveform	1 msto, 10 s.	1 msto, 1000 ms
Accuracy	1% or 0.5 ms	Within 2% or 2 ms, whichever is greater	2%
Reproducibility	1% or 0.5 ms	**	3%
	Half-value layer (HVL)		
Range (mm Al)	1.2 to 10 (equivalent)	**	2 to 6 (equivalent)
Accuracy	± 10% or 0.2 mm Al (equivalent)	**	± 2%

* Data from manufacturer manual (TNT 12000® X-Ray Test Tools Manual, 2011; Victoreen® 4000M+ X-Ray Test Device (Innovision), 2006).
** Data not informed in the manufacturer manual.

4. Conclusions

It was possible to determine the average peak voltage (kVp), exposure time, and the half-value layer (HVL) of radiological instrument using a prototype device containing the solid sensor detector PIN RD100 A. The methodology used to estimate kVp, exposure time, and HVL also showed reproducibility and accuracy when compared that of commercial instruments. The prototype analyzed in this study can be considered a multifunctional instrument that possesses similar features to commercial devices that are currently used to evaluate radiological equipment performance.

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