STUDY OF NON-INVASIVE INSTRUMENTS FOR THE MEASUREMENT OF PULSED X-RAY HIGH VOLTAGE TUBE

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Abstract. Non-invasive instruments (kVp meters) are widely used in radiology with diagnostic and guidance systems. Placed in the x-ray beam, they combine detectors and filters, to determine X-ray tube voltage and exposure time, which are the most important quantities in radiology and diagnostic quality control. Calibration of these instruments were limited by reference bench capabilities. General Electric Medical System France and LNE (The national metrology institute in France) have developed a reference bench for the characterization of kVp meters. The set up includes a fast high voltage generator associated with its internal measuring systems and an X-ray tube. The measurements are compared with an invasive reference standard. The set-up is installed in a Faraday cage, precautions have been taken in order to carry out accurate measurements and special adaptations have been made to avoid stray capacitances, which affect the dynamic performance of the generator. Results have shown a good agreement with the internal measuring system of the generator but the kVp meters have shown both good and bad results depending the exposure time, the current and the positioning.

1 INTRODUCTION

High voltage invasive reference measuring system, for the calibration of pulsed X-ray high voltage tube in radiology applications, has been recently developed within the frame of the EMPIR project UHV 15RNM02 [1] . This reference system has been developed in LNE (National Metrology Institute in France) FFII (National Metrology Institute in Spain), GEMS Buc (General Electric Medical Systems France Buc) and CEA Sacly (Commissariat à l'Energie Atomique et aux Energies Alternatives).

The reference system is composed of two compensated resistive high voltage dividers; the first is for anode voltage up to 75 kV and the second is for cathode voltage down to - 75 kV, the maximum voltage from anode to cathode is equal to 150 kV Peak. The standardized quantity used in radiology PPV (Practical Peak Voltage [4]) and its traceability have been already published in [2]. The procedure used for the characterisation of the reference system has been also discussed in [3]. The obtained uncertainties are 0,4 % for PPV (or peak voltage) and 1 % to 2 % for time parameters (rise time and time exposure). They are validated for every waveform with a rise time from 1 µs to 500 µs and a duration from 50 µs to few seconds.

Non-invasive instrument (kVp meters) are widely used in radiology for qualification and quality control of X-ray pulses [5]. They determine with a simple procedure kilovolts applied to the tube. In order to characterize accuracy of kVp meters , a test bench has been developed in GEMS. The comparison is done with the invasive reference system.

The advantages of kVp meters are that they do not modify the X-ray equipment configuration – equipment behavior remains unchanged. In comparison, external reference high-voltage dividers, physically connected to the X-ray equipment modify the equipment behaviour. Reference divider and connection cable to the equipment bring additional high-voltage capacitance, which slows down voltage rise time and fall time, and filters the ripple. Because rise time, fall time and ripple contribute to PPV calculation, a "minimally-invasive" configuration has been used for comparison between kVp-meter measure and reference divider PPV.

2 MINIMALLY-INVASIVE TEST BENCH

To perform short X-ray exposures with fast rise time and fall time, the X-ray source used comes by-design with a low capacitance: 330 pF total, spread in high-voltage transformer 210 pF, X-ray tube and high-voltage cable 120 pF (HV cable is very short, 70 cm only). The source is unipolar, anode grounded, operating down to -140 kVp. In the following experiments, exposures are limited to - 75 kVp.

The entire source is placed in a large faraday cage, as shown in figure 1, to allow required free air volume around the reference divider. Its connection to the source is provided between the X-ray tube and the HV generator. HV connector has been modified to receive a long open port receiving a copper wire up to the reference divider. This port is not shielded, resulting in around 1 pF additional capacitance. Insulation is provided by plastic parts filed with high-voltage oil – Figures 2 & 3.

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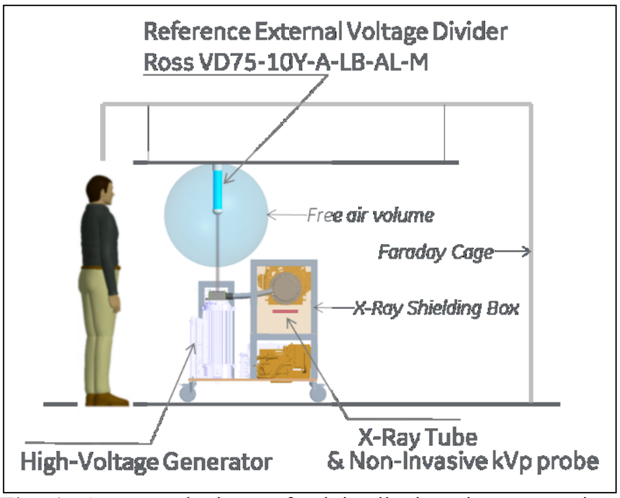

Fig. 1. Conceptual views of minimally invasive connection between high-voltage source and reference divider.

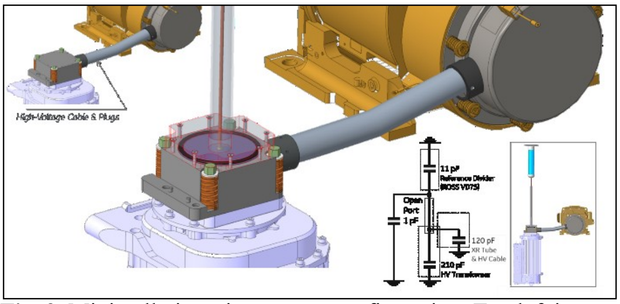

Fig. 2. Minimally invasive system configuration. Top left image shows the high-voltage cable standard configuration (before modification)

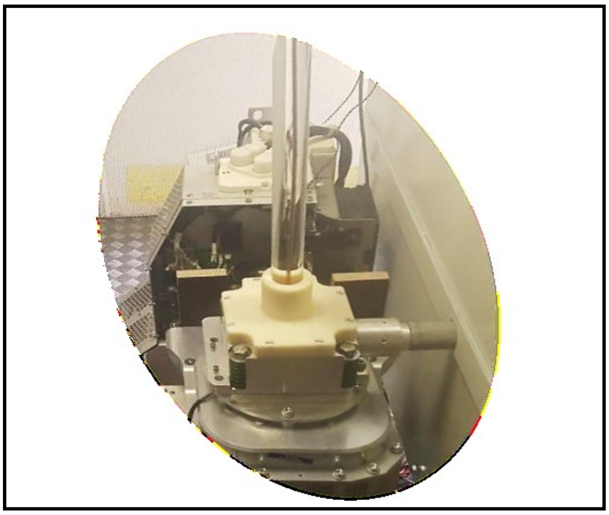

Fig. 3. Actual realization of the connection between high-voltage source and reference divider. (Connection add around 1 pF capacitance, compare to total X-ray source 330 pF and reference divider 11 pF).

The x-ray tube is surrounded by a lead box specially designed to respect very short high-voltage cable assembly configuration while totally shielding X-ray radiations. A door is provided to place the kVp-meter in the X-ray beam. Tube heat-exchanger is located out of the shielding box.

the bottom shielding plate (RaySafe-X2 in the front, RTI-Piranha in the back).

The principle of the measuring set is described in figure 4. It includes the reference divider associated with its 12 bits digitizer and its reference software. Exposure is trigged through X-ray generator control digital interface, tube voltage and kVp-meter data are acquired simultaneously.

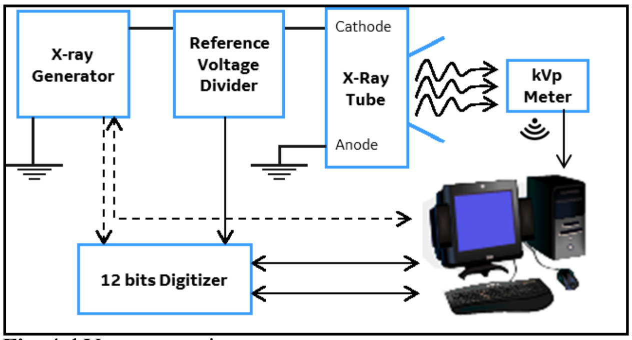

Fig. 4. kVp comparative measurement setup.

3 RESULTS OF CHARACTERIZATION

3.1 Comparison Measurements

In a first measurement session, kVp-meter outputs are compared to reference voltage divider and generator analog output "base" value reported by the digitizer. Base value defined as "the value of most probable lower state" of the signal (excluding rise and fall sections). An additional reference divider from North Star and generator kV digital output have been included in the comparison. Six exposures are recorded: 10 ms, 100 ms and 1000 ms at 70 kV – 100 mA, and 10 ms , 100 ms , 1000 ms at 75 kV – 100 mA. Results of measurements at 70 kV are reported in figure 5, they show around 2 % difference between reference divider base value and RTI Black Piranha (old generation kVp-meter), around 0.5% between reference divider base value and RaySafe X2 (new generation kVp-meter). Invasive system from North Star and from GEMS internal measuring system (generator Analog and Digital outputs) show an error of about 0,5 %.

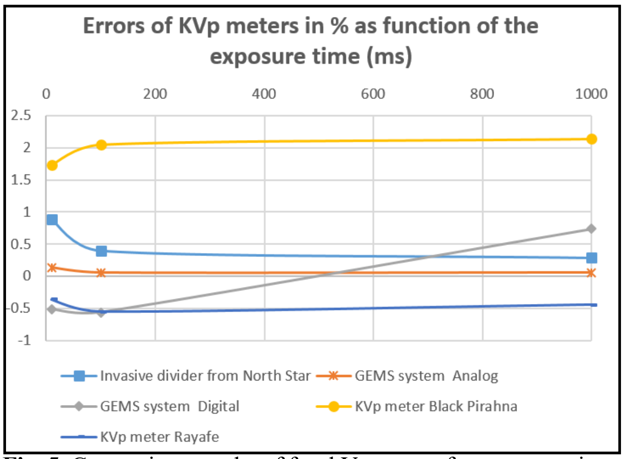

Fig. 5. Comparison results of few kVp meters for exposure time from 10 ms to 1000 ms at 70 kV.

3.2 Dynamic Measurements

Dynamic records has been performed by the kVp meter which has shown the lowest errors (Raysafe X2). The figure 6, highlight response time limitation of the kVp-meter measure chain. Intended use of kV-meters is actually non-invasive PPV measurement, not real-time voltage acquisition. The results show about 3 ms response delay versus the reference invasive standard. It could be concluded that the non-invasive instrument does not allow transient voltage recordings.

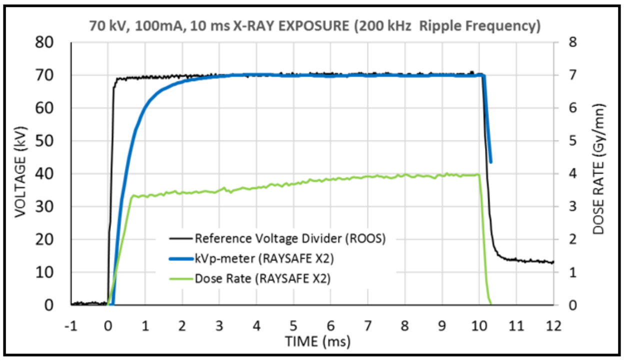

Fig. 6. Comparative kVp dynamic record for a 10 ms exposure at 70 kV – 100 mA

3.3 mA sensitivity – 100 ms exposure

In this section, the objective is to compare kVp-Meter measure and PPV value computed from reference divider voltage records, for different exposure parameters. RaySafe X2 kVp meter has been compared to the calibrated reference divider. Exposure voltage is set at 75 kV, exposure duration is set at 100 ms and tube current (mA) varies from10 mA to 590 mA (11 experimental records at 10 mA, 100 mA, 200 mA, 250 mA, 300 mA, 350 mA, 400 mA, 450 mA, 500 mA, 550 mA and 590 mA). Around 600 mA the kVp-meter is saturating in current experimentation conditions (200 mm source to kVp-meter distance).

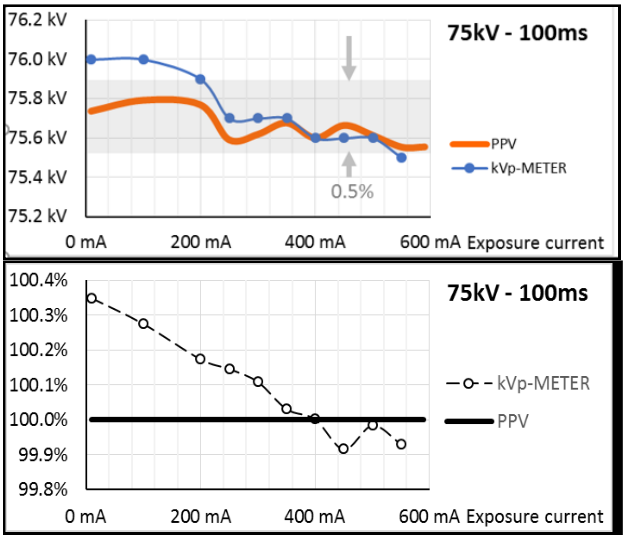

Fig. 7a & 7b. Reference PPV compared with PPV measured by the kVp meter.

For 100 ms exposure, kVp-meter calibration is better at high mA (0.1 % in 300-600 mA range), lower mA kVp-meter values shifting up to 0.4 % (worse case) compare to PPV values from reference divider (figure 7a & 7b).

Additionally, calculated PPV is compared to kV average values at 75 % of max voltage, kV average values at 90 % of max voltage, and “base” value (i.e. most probable lower state) - Figure 7c. Base value is shifted by 0.1 % to 0.3 % without correlation with mA. For long exposures (100 ms) Average values stays within +/- 0.1 % of PPV value. Difference can be attributed to mA effect on fall time (fall time is longer at low mA due to less discharge current) and to mA effect on voltage ripple, ripple being lower at low mA (2.5 % ripple at 10 mA versus 6 % at 600 mA).

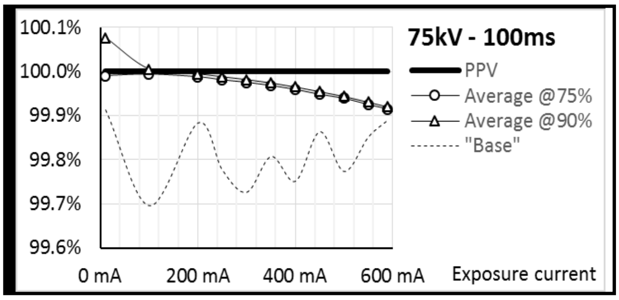

Fig. 7c. Reference PPV compared with kV average values and digitizer “base” value.

3.4. Exposure duration sensitivity

Exposure voltage has been set at 75 kV, exposure duration and tube current (mA) vary respectively from 100 ms to 0.7 ms and from 10 mA to 550 mA (18 experimental records, 6 exposure duration stations, 100 ms, 10 ms, 5 ms, 2 ms, 1 ms, 0.7 ms, and 3 tube current stations, 10 mA, 300 mA, 550 mA).

Experimental results highlight kVp-meter sensitivity to dose (figure 8a). In current experiment conditions kVp-meter did not operate when jointly mA and exposure durations are high, and when jointly mA and exposure durations are low. Comparative analysis is here possible for 300 mA stations only.

The reference PPV calculated value as a function of exposure duration and mA. Curve inflection toward low exposure durations can be attributed to contribution of rise and fall time in PPV calculation (rise and fall time getting relatively higher when exposure duration reduces). The drop is accentuated at very low mA as fall time become longer due to low discharge current.

The results show a good correlation (<0.3%) between kVp-meter and PPV values for 300 mA exposures for the different exposure duration stations.

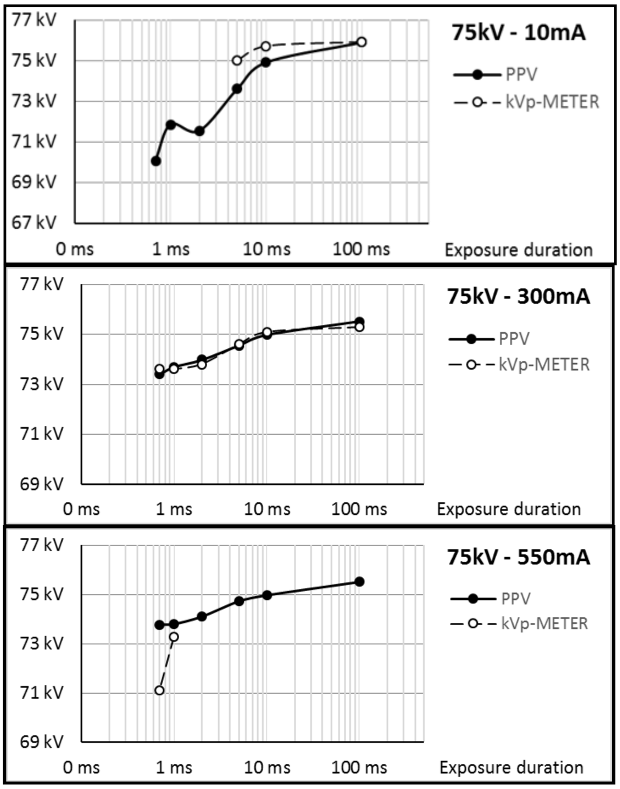

Fig. 8a. Exposure duration sensitivity performed at 75 kV and a current from 10 mA to 550 mA.

Additional comparison between PPV and kV average values shows up to 2 % drift below 5 ms exposure duration (figure 8b). Average kV at 75%, which is often used in X-ray exposure specifications, cannot be considered as a "fair estimation" of PPV for short exposures.

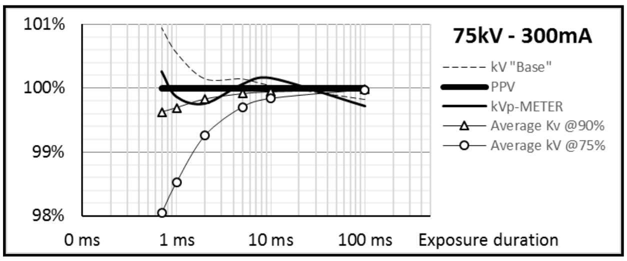

Fig. 8b. Exposure duration sensitivity performed at 75 kV 300mA.

3.5 Positioning of the kVp-meters

kVp meters positioning in confined environment is very important. kVp meter is significantly shifted from the central position under the X-ray source. The 10 positions of kVp-meter (two vertical shifting high and low, each one has 5 positions as described in figure 9) relative to lead-box, X-ray source and expected X-ray beam location.

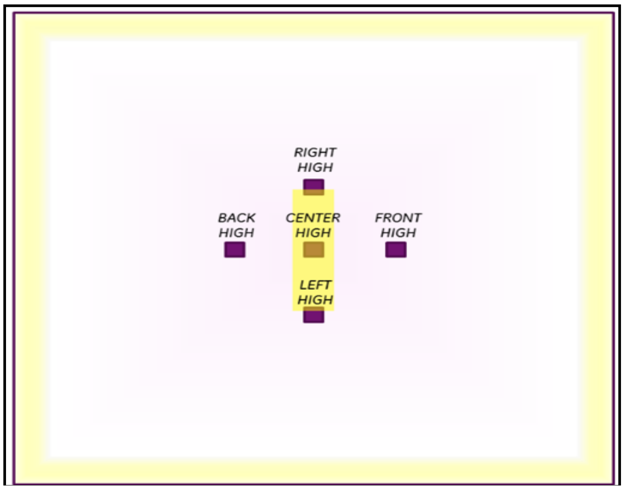

Fig. 9. Top view of high position, relative to lead-box, X-ray source and expected X-ray beam.

kVp-meter values are compared with PPV values. Results are summarized in tables 1 and 2.

Table 1: kVp-meter 5 locations – position HIGH

EXPOSURE PARAMETERS			REF. DIVIDER ROSS VD75 (N°1)	Non-Invasive Raysafe (X2)		
VOLTAGE	CURRENT	DURATION	PPV (kV)	POSITION	kVp-METER (kV)	
75 kV	10 mA	100 ms	75.693	CENTER HIGH	75.900	0.27%
75 kV	100 mA	100 ms	75.675		75.600	-0.10%
75 kV	500 mA	100 ms	75.466		No feedback	NA
75 kV	10 mA	100 ms	75.641	FRONT HIGH	No feedback	NA
75 kV	100 mA	100 ms	75.858		No feedback	NA
75 kV	500 mA	100 ms	75.567		53.600	-29%
75 kV	10 mA	100 ms	75.742	BACK HIGH	No feedback	NA
75 kV	100 mA	100 ms	75.866		No feedback	NA
75 kV	500 mA	100 ms	75.478		No feedback	NA
75 kV	10 mA	100 ms	75.929	RIGHT HIGH	No feedback	NA
75 kV	100 mA	100 ms	75.911		No feedback	NA
75 kV	500 mA	100 ms	75.564		49.300	-35%
75 kV	10 mA	100 ms	75.980	LEFT HIGH	No feedback	NA
75 kV	100 mA	100 ms	75.721		No feedback	NA
75 kV	500 mA	100 ms	75.561		53.000	-30%

Table 2: kVp-meter 5 locations – position LOW

EXPOSURE PARAMETERS			REF. DIVIDER ROSS VD75 (N°1)	Non-Invasive Raysafe (X2)		
VOLTAGE	CURRENT	DURATION	PPV (kV)	POSITION	kVp-METER (kV)	
75 kV	10 mA	100 ms	75.675	CENTER LOW	76.000	0.43%
75 kV	100 mA	100 ms	75.745		76.100	0.47%
75 kV	500 mA	100 ms	75.586		75.700	NA
75 kV	10 mA	100 ms	75.820	FRONT LOW	No feedback	NA
75 kV	100 mA	100 ms	75.788		51.400	NA
75 kV	500 mA	100 ms	75.694		51.600	-32%
75 kV	10 mA	100 ms	75.821	BACK LOW	No feedback	NA
75 kV	100 mA	100 ms	75.800		No feedback	NA
75 kV	500 mA	100 ms	75.677		52.200	NA
75 kV	10 mA	100 ms	75.870	RIGHT LOW	No feedback	NA
75 kV	100 mA	100 ms	75.838		60.900	NA
75 kV	500 mA	100 ms	75.542		60.600	-20%
75 kV	10 mA	100 ms	75.785	LEFT LOW	66.600	NA
75 kV	100 mA	100 ms	75.757		66.600	NA
75 kV	500 mA	100 ms	75.694		66.600	-12%

Without surprise, only central positions give a good correlation with PPV reference with a deviation of about 0.6 % between High and Low positions. Also, when located too close to the source (~20 cm), kVp-meter saturates at high mA (550 mA, 75 kV, 100 ms).

In confined environment, when significantly shifted from central position kVp-meter sometimes reports misleading values (mainly at high mA), underestimating PPV by around 30%.

3.6 Other influence quantities

Other influence quantities have not yet been studied Temperature and humidity, amplitude and frequency of ripples, radiofrequencies disturbances and electrical field. This study has been performed in real conditions of use. The temperature was varying from 20 °C to 26 °C The amplitude of ripples was varying from 2 % to 6 % in 100 kHz to 300 kHz frequency range. Radio frequencies and disturbances have been also shown and acquired by the reference divider, they include also several spikes and overshoots (figure 10).

The kVp meters errors obtained in this study could also due to these influence quantities.

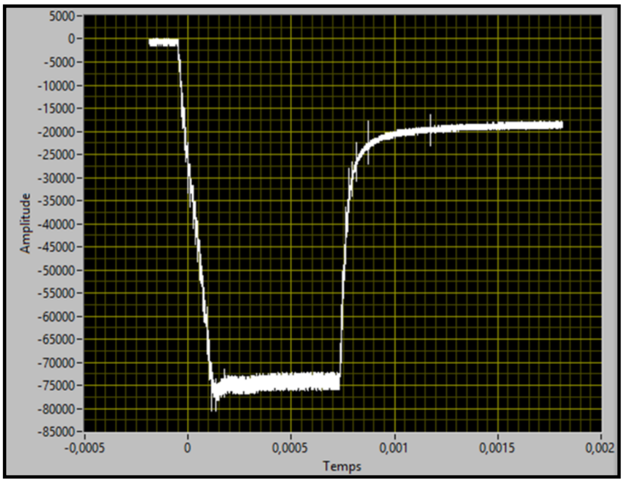

Fig 10. Reference divider voltage record for 75 kV, 550 mA, 0.7 ms exposure, 150 µs rise time. Overshoot and peaks are visible at the end of kV rise (located bottom left on the picture).

4 RECOMMENDED LIMITS OF THE USE OF KVP METERS.

Approaching kVp-meter reading capability limits, significant divergences with reference PPV have been observed – at high mA short exposure duration before saturation, and at low mA short exposure before loss of reading capability. Limits may vary between manufacturers and between technologies. PPV calibration based on reference divider measurements should allow to better define usage limits without being too much restrictive. kVp meters must be calibrated by comparison to an invasive system to check their accuracy within the condition of use such the exposure time, rise time, fall time, current, ripples and level of voltage. Theses parameters could affect the accuracy of kVp meters.

Only central positions give a good correlation with PPV reference. Also, when located too close to the source (~20 cm), kVp-meter saturates at high mA (550 mA, 75 kV, 100 ms). In confined environment, when significantly shifted from central position kVp-meter sometimes reports misleading values (mainly at high mA), underestimating PPV by around 30%. Calibration of X-ray tube must be performed with central position in the front of the voltage tube. Also distance range between central position and X-ray source must be specified according to exposure parameters (kV, mA) for each kVp meters.

Dynamic records highlight response time limitation of the kVp-meter measure chain. Intended use of kV-meters is actually non-invasive PPV measurement, they should not be used for real-time voltage acquisition, until new technologies bring them this capability.

The characterisation of kVp meters, before their use as standard for the qualification of X-ray tubes, is necessary to avoid inappropriate results. It could be performed by comparison to an invasive standard in the real condition of use.

5 CONCLUSION

A test bench has been developed to check the accuracy and the limits for the use of kVp meters. The measurements have been performed by comparison to a reference invasive system. For long X-ray exposure duration (above 10 ms), errors between kVp-meters and reference voltage "base" value were found within 2 %.
Considering new technology kVp-meter and reference PPV value (computed from reference voltage record), errors are found within 0.5% over a large range of mA and down to short exposure duration below 1 ms, provided kVp-meter is used in its beam intensity range (mAs). kVp meters have shown inappropriate results depending on beam intensity (mAs) and kVp meter probe positioning. Errors could sometimes reach 30 % depending how kVp meters are used. Calibration and verification of the kVp meter to check their accuracy in the same condition of use by comparison to a calibrated invasive standard is essential to avoid undesirable errors.

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