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DOSE ASSESSMENT DURING THE COMMISSIONING OF FLAT DETECTOR IMAGING SYSTEMS FOR CARDIOLOGY

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Incident air kerma (IAK) and entrance surface air kerma (ESAK) have been measured for a range of copper (Cu) absorbers (1–10 mm) and polymethylmethacrylate (PMMA) slabs (12–28 cm) with kilovolt values ranging from 61 to 120 during the commissioning of an X-ray system equipped with a flat detector used in interventional cardiology procedures. Numerical parameters on image quality have also been measured for different X-ray beam qualities using the plastic wall of the ionisation chamber. When moving from 1 to 10 mm of Cu, IAK per frame increased to a factor of 38 for cine and 27 for fluoroscopy. A cine frame requires 60–116 times more IAK than a fluoroscopy frame. As for PMMA, when the backscatter factor is included (simulating real conditions with patients), and when moving from 12 to 28 cm, the increases in ESAK are 16 times for cine and 10 times for fluoroscopy. Because of the differences in X-ray beam quality for cine and fluoroscopy modes, the Cu thicknesses necessary to drive the generator to equivalent kilovolts resulted in the following values (cine and fluoroscopy, respectively): 12 cm of PMMA (1 and 1.5 mm Cu), 20 PMMA (2.5 and 3.5 mm Cu) and 28 cm PMMA (4.5 and 8.5 mm Cu). With the analysis of IAK, ESAK and image quality, one can verify the appropriate settings of the X-ray system and obtain baseline information for constancy checks and help cardiologists in the management of patient doses by knowing the dose increase factors and image quality changes when increasing patient thickness or using different C-arm projections.

INTRODUCTION

Modern interventional cardiology X-ray systems equipped with dynamic flat detectors use different curves for automatic exposure control (AEC) depending on the clinical protocols implemented. Some manufacturers use different spectral shaping filters (mainly copper (Cu) and aluminium (Al) ones) according to the X-ray beam attenuation (patient sizes), but others maintain the same filter thickness during the full protocol for the clinical application selected[(1)]. The experimental analysis of AEC curves mainly focuses on the evaluation of entrance surface air kerma (ESAK) or incident air kerma (IAK) to phantoms and detectors[(2)] and there is currently little information available on the simultaneous evaluation of numerical parameters related to the image quality obtained, such as the degradation of signal-to-noise ratio (SNR) when increasing the thickness of the absorber in the X-ray beam (and kilovolt values)[(3)].

During interventional cardiology procedures, and in order to maintain an acceptable level of image quality, some C-arm projections or thickset patients require a substantial increase in ESAK per frame. Manufacturers use different logics and AEC curves to maintain the image quality and changes in milliamperes, kilovolt and pulse time are then required. The increase in kilovolt[(4)] is the main factor linked with degradation of image quality (especially contrast) and measuring the dose per frame (IAK or ESAK) as well as the image quality parameters is usually part of the commissioning process for these systems. The European SENTINEL Concerted Action has recommended the evaluation of dose and image quality for the operation modes available during the commissioning of the new X-ray systems for angiography and cardiology units[(5)].

This paper intends to present a methodology to measure simultaneously the IAK (or ESAK) for different absorbers (Cu) or polymethylmethacrylate (PMMA) using a flat ionisation chamber, and parameters of the image quality when increasing thickness and kilovolt values. The method simplifies the ulterior checks as it avoids additional measurements on image quality. It also offers cardiologists some practical rules in the management of patient doses by giving information on the increases of dose per frame and the degradation on image quality for various patient thicknesses or C-arm angulations.

MATERIALS AND METHODS

An interventional X-ray system (Philips Integris Allura Xper FD10)[(6)] equipped with a flat detector and designed for interventional cardiology procedures was used for the measurements. Different Cu absorbers (from 1 to 10 mm) and PMMA plates (from 12 to 28 cm) were used to drive the AEC

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system from 61 to 120 kV. Low fluoroscopy (with constant added filtration of 0.9 mm of Cu and 1 mm of Al in the evaluated system) and cine modes (without added filtration in this system) were analysed. This experimental procedure is often used during the commissioning of cardiac laboratories to test the range of dose values per frame in fluoroscopy and cine as well as the logic of the AEC curves of the X-ray systems.

The IAK measurements were carried out placing a flat ionisation chamber (model 20 x 6-60) with a 2026C radiation meter from Radcal[7] over the mattress. Cu absorbers were placed at a distance of 15 cm over the ionisation chamber to avoid the influence of backscatter radiation during the measurements. The ionisation chamber was positioned at the interventional reference point, e.g. 15 cm down from the isocentre[8]. For the measurements with PMMA, the ionisation chamber was in the same position and in contact with the plates (with a support to avoid extra pressure on the chamber) to measure the backscatter radiation. In this case, ESAK values were measured.

To maintain a constant distance of 100 cm from the focus to the flat detector, it was necessary to move down the table when thicknesses of 24–28 cm of PMMA were used. The dose values measured were later normalised at a distance of 63 cm from the focus.

The standard distance from the ionisation chamber to the focus was 63 cm (see Figure 1). The measurements were made for a field of view (FOV) of 25 cm (diagonal dimension). The default acquisition protocol selected was: 'cardiology' and the application and procedure: 'stereotaxis electrophysiology (EP)' at 7.5 frames per second; the patient type selected was: 'medium' (from 70 to 90 kg). This range of weight is related to the AEC curve selected by the system. This protocol is the most common for EP cardiac procedures. The range of Cu and PMMA thicknesses selected enabled one to drive kilovolt values to the maximum value. The experiment was carried out with low fluoroscopy and cine as they are the acquisition modes most frequently used in the cardiac laboratory where the measurements were done.

Along with the dose measurements, all the series of images for cine and fluoroscopy were archived in DICOM format in order to measure the changes in image quality occurring when kilovolt was increased as a consequence of larger Cu or PMMA thicknesses.

This methodology allowed one to evaluate the relative degradation of SNR with the increase in kilovolt values using the plastic wall of the ionisation chamber as a 'low-contrast object'. Thus, it was not necessary to use a test object in the beam. A region of interest (ROI) selected in the wall of the ionisation chamber was used to measure the degradation in image quality. The dispersion of the results when changing the size and position of the ROI was tested and the mean values and standard deviation were calculated. Three measurements were done each time in an attempt to reproduce similar ROI sizes (650–750 pixels).

Figure 2 shows the ROIs selected for the numerical analysis of the images[9–12]. The SNR is defined as:

$$\mathrm{SNR} = \frac{[\mathrm{BG} - \mathrm{ROI}]}{\sqrt{\mathrm{STD}^2_{\mathrm{ROI}} + \mathrm{STD}^2_{\mathrm{BG}}/2}}, \tag{1}$$

where

- BG is the background value, in the case here the mean value of the pixel contained in the ROI

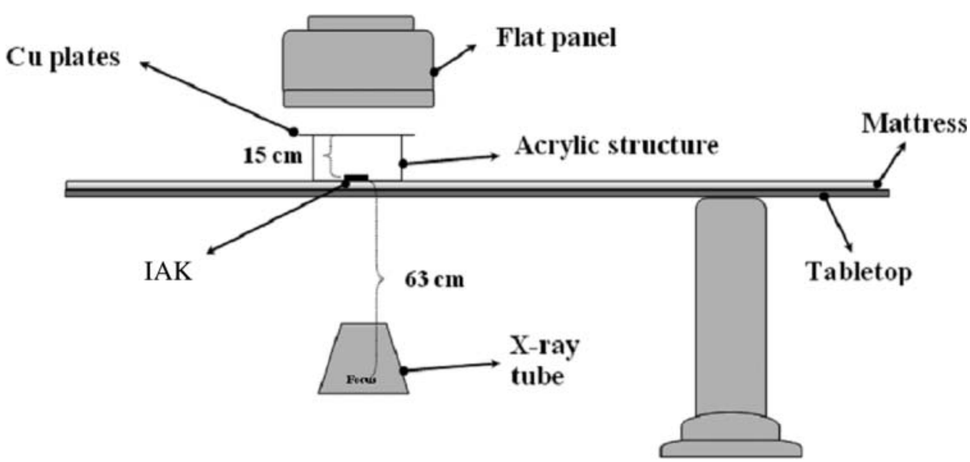

Figure 1. Experimental arrangement to measure IAK and image quality for different kilovolts.

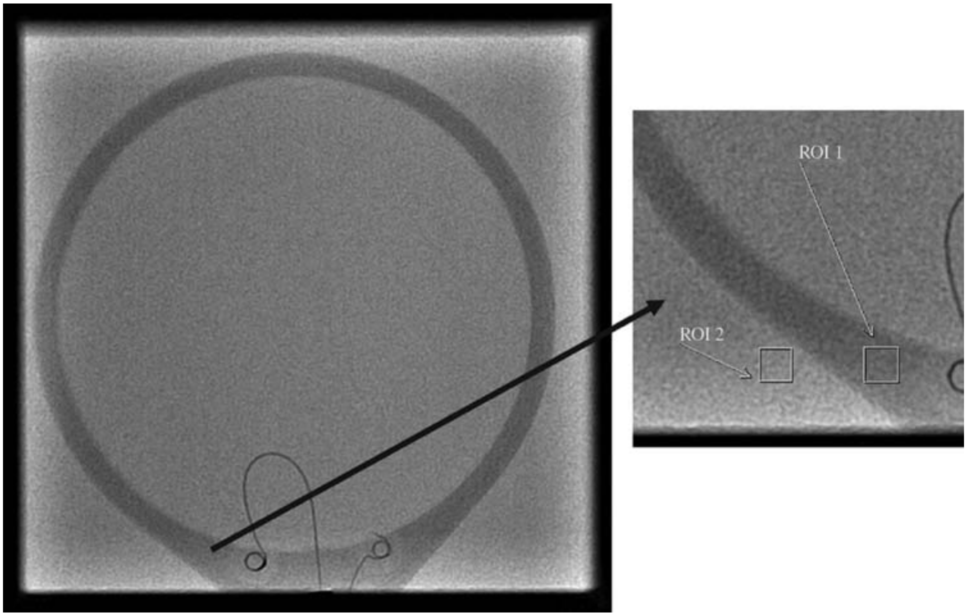

Figure 2. Example of the selected ROIs. The above image corresponds to the semitransparent ionisation chamber during cine mode, FOV 25 cm, Cu absorber thickness 1 mm. ROI 1 was used for the 'signal' and ROI 2 for the background.

selected from a rectangular ROI outside the wall of the chamber and of the same size as ROI 1 selected inside the wall of the chamber (see Figure 2).

- ROI is the mean value of the pixel contained in the ROI selected from a rectangular ROI 1 inside the wall of the chamber.
- STD is the corresponding standard deviation for the pixel contained in the selected ROIs, inside and outside the wall of the chamber.

The results reported for SNR are mean values and standard deviations of the pixel contents for the single image archived for the fluoroscopy runs (in low-dose mode) and image number 15 for each series in cine mode. The images, in the case here, were archived and evaluated in 1024 × 1024 pixels and 12 bits. The selection of image number 15 for the cine series ensures that the AEC was stabilised and the image quality was constant in the series.

RESULTS

Tables 1 and 2 show the numerical values of dose (ESAK and IAK) and SNR (mean values and standard deviations for a set of three measurements for each result) obtained in the modes of operation evaluated together with the most relevant radiographic parameters adjusted by the X-ray system. For IAK values, inaccuracies could be estimated to 5–7 % when taking into account the calibration factor of the ionisation chamber.

Figures 3 and 4 show ESAK (for PMMA) and IAK (for Cu) values (per frame) for fluoroscopy (low-dose) and cine modes.

Figures 5 and 6 show the values of SNR with their standard deviations in fluoroscopy and cine modes for the different Cu and PMMA thicknesses and adjusted kilovolts.

Figures 7 and 8 show the ratio between IAK and ESAK for cine frame and for fluoroscopy frame (low mode) for the different thicknesses of Cu (IAK) and PMMA (ESAK) used as absorbers.

DISCUSSION

Figures 3 and 4 (dose/frame values) can help medical physicists in the dosimetric characterisation of the X-ray systems and cardiologists in the management of patient doses during the procedures. Cardiologists should be aware of the important increase in dose per frame (ESAK) when moving from low (12 cm) to high (28 cm) PMMA thicknesses: a factor of 16 for cine and 10 for fluoroscopy. Note that the increase in IAK measured using Cu absorber is more important in the region of a low absorber thickness (1–4 mm of Cu) than in the last part of the curve (5–10 mm of Cu). The second relevant aspect to help cardiologists in the management of patient dose is the important save in dose

Table 1. Tube potential (kV_p), tube current (mA), IAK at 63 cm from the focus and SNR, for fluoroscopy low-dose (FL) and cine (CI) modes and all the Cu thicknesses used in the experiment, FOV 25 cm.

Acquisition mode	Absorber (mm Cu)	Tube potential (kV_p)	Tube current (mA)	Frame rate (pulses s^{-1})	IAK (μGy fr^{-1})	SNR
FL	1	67	2	15	0.40	1.55 ± 0.04
FL	2	74	4	15	1.11	1.37 ± 0.01
FL	3	79	5	15	2.19	1.13 ± 0.02
FL	4	85	6	15	3.63	1.11 ± 0.03
FL	5	92	5	15	4.76	0.79 ± 0.03
FL	6	98	5	15	6.00	0.78 ± 0.01
FL	7	104	5	15	7.18	0.61 ± 0.02
FL	8	110	4	15	8.41	0.55 ± 0.03
FL	9	116	4	15	9.63	0.63 ± 0.01
FL	10	120	4	15	10.59	0.51 ± 0.06
CI	1	61	146	7.5	24.0	3.86 ± 0.02
CI	2	66	371	7.5	91.2	3.53 ± 0.10
CI	3	70	588	7.5	202.3	2.79 ± 0.09
CI	4	74	799	7.5	365.3	2.89 ± 0.05
CI	5	78	964	7.5	550.7	2.62 ± 0.04
CI	6	84	903	7.5	648	2.07 ± 0.01
CI	7	89	851	7.5	718.7	1.96 ± 0.01
CI	8	93	810	7.5	782.7	1.82 ± 0.04
CI	9	98	770	7.5	842.7	1.96 ± 0.01
CI	10	103	737	7.5	901.3	1.12 ± 0.04

Table 2. Tube potential (kV_p), tube current (mA), ESAK at 63 cm from the focus and SNR, for fluoroscopy low-dose (FL) and cine (CI) modes and all the PMMA thicknesses used in the experiment, FOV 25 cm.

Acquisition mode	Absorber (cm PMMA)	Tube potential (kV_p)	Tube current (mA)	Frame rate (pulses s^{-1})	ESAK (μGy fr^{-1})	SNR
FL	12	71	3.2	15	1.42	1.45 ± 0.03
FL	16	77	4.4	15	2.94	1.16 ± 0.01
FL	20	83	5.6	15	5.48	0.87 ± 0.03
FL	24	97	4.9	15	9.03	0.48 ± 0.01
FL	28	113	4.2	15	14.83	0.29 ± 0.04
CI	12	61	151	7.5	37.3	3.77 ± 0.04
CI	16	64	277	7.5	88.6	3.42 ± 0.05
CI	20	67	433	7.5	183.2	2.94 ± 0.05
CI	24	71	642	7.5	338.2	2.48 ± 0.03
CI	28	76	862	7.5	600	2.08 ± 0.03

per frame during fluoroscopy runs (Tables 1 and 2). Cardiologists should consider the use of archiving fluoroscopy runs instead of cine runs whenever in a procedure a high image quality is not required. The save in dose per frame results in factors ranging from 30 to 40 (see Figure 4 and Table 2) for the different PMMA thicknesses used during the experiment. Due to the different quality of the X-ray beams for cine and fluoroscopy modes, the Cu thickness required to drive the generator to similar kilovolts as the one set for PMMA resulted in the following values (cine and fluoroscopy, respectively): 12 cm of PMMA (1 and 1.5 mm Cu), 20 PMMA (2.5 and 3.5 mm Cu) and 28 cm PMMA (4.5 and 8.5 mm Cu). According to Rassow *et al.*[13] this PMMA range (from 12 to 28 cm) should be equivalent to patient chest thicknesses from 18 to 42 cm. Different systems may have different settings in dose per frame and this could be one of the factors leading to the large variation in patient dose found in recent European surveys[14]. These setting differences justify the need to perform the dosimetric and image quality characterisation suggested in this paper during the commissioning of the cardiac X-ray systems.

Figures 5 and 6 prove that the AEC curve used by the X-ray system for the protocol evaluated enables one to maintain a reasonable SNR during the full

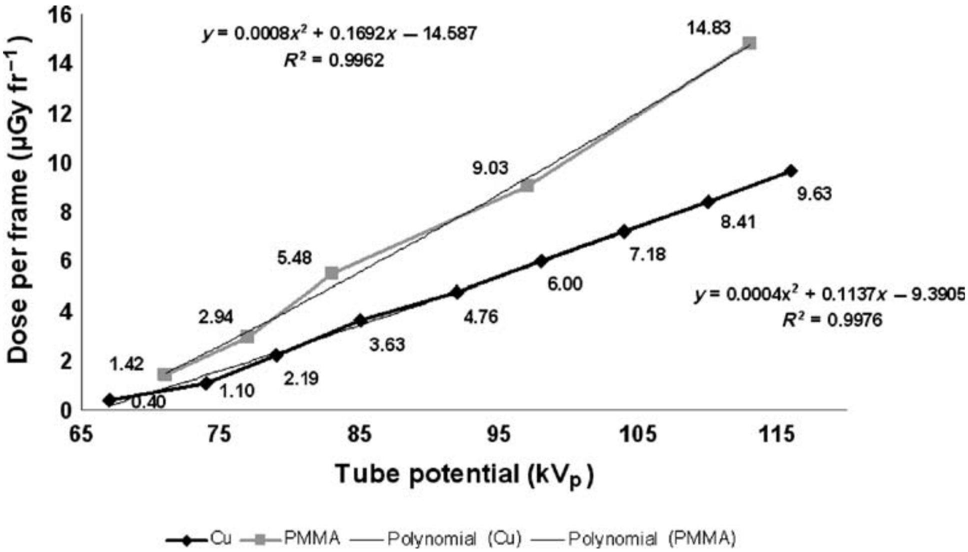

Figure 3. ESAK (for PMMA) and IAK (for Cu) per frame in fluoroscopy low-dose mode (indicated as dose per frame) for different Cu and PMMA thicknesses measured at 63 cm from the focus (table and mattress on the X-ray beam). FOV 25 cm.

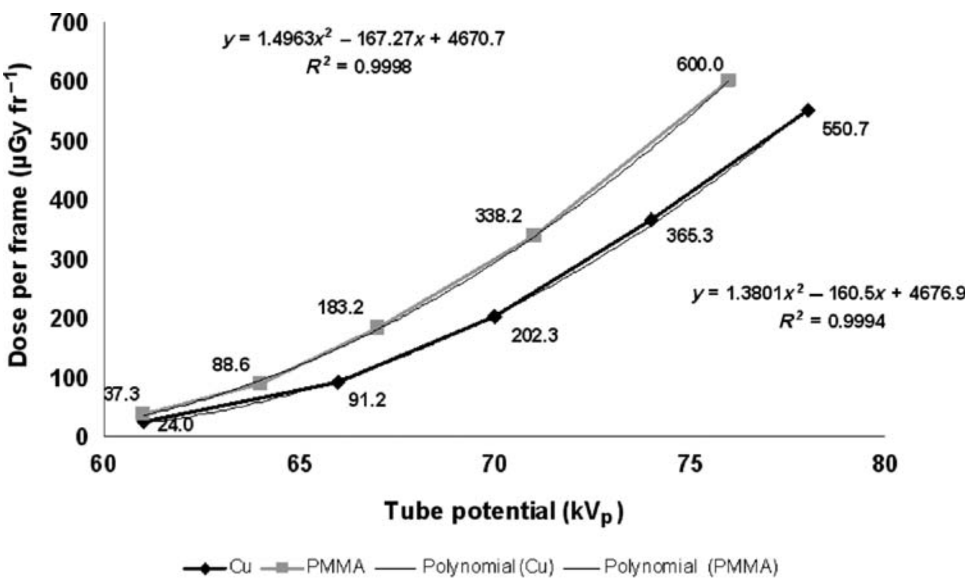

Figure 4. ESAK (for PMMA) and IAK (for Cu) per frame in cine dose mode (indicated as dose per frame) for different Cu and PMMA thicknesses measured at 63 cm from the focus (table and mattress on the X-ray beam). FOV 25 cm.

range of the thicknesses used (and adjusted kilovolts). The SNR values decreased by 71–67 % when the thickness of absorber moves from 1 to 10 mm of Cu and decreased by 80–45 % when the thickness of absorber moves from 12 to 28 cm of PMMA for fluoroscopy and cine modes, respectively. Note that the images in fluoroscopy mode maintain an SNR that is around 40 % (absorber of Cu) and 30 % (absorber of PMMA) of the values measured in cine. These results in SNR reinforce the recommendation to use and archive fluoroscopy runs instead of cine runs whenever a lower SNR can be accepted.

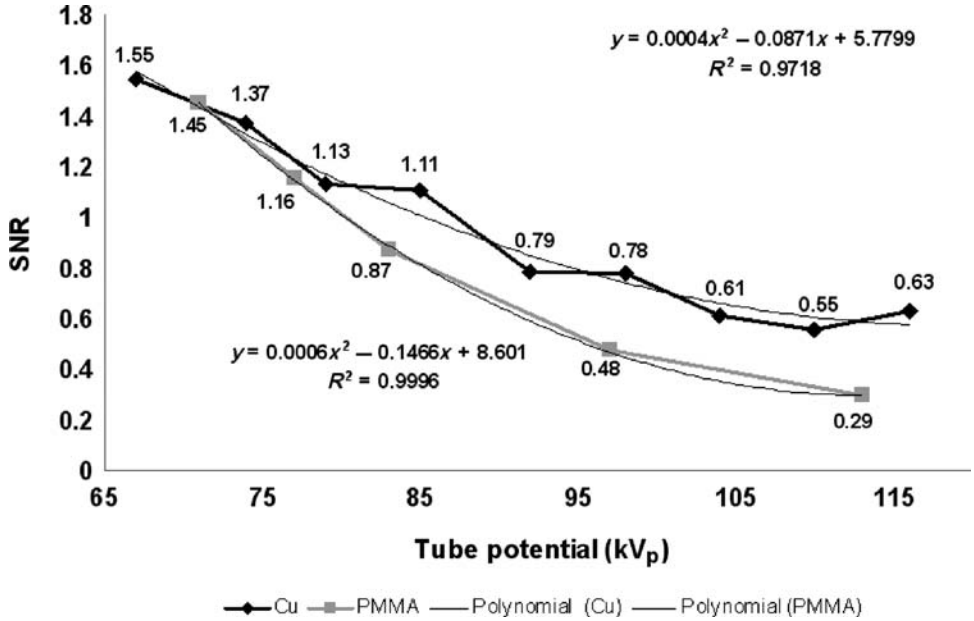

Figure 5. SNR for different kilovolt values set by the X-ray system for fluoroscopy low mode when Cu absorber and PMMA plate thicknesses move from 1 to 9 mm and 12 to 28 cm, respectively. FOV 25 cm.

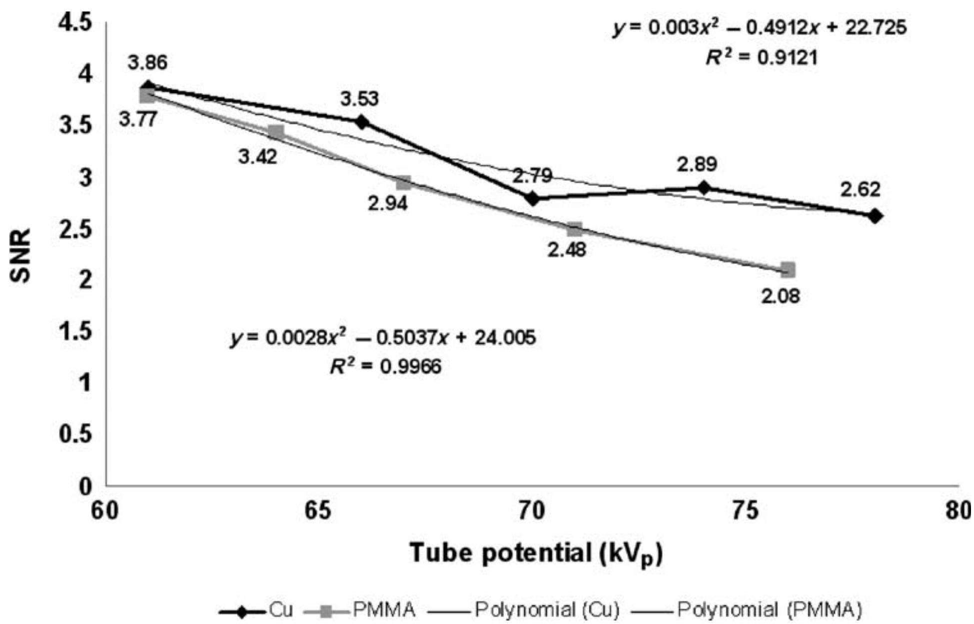

Figure 6. SNR for different kilovolt values set by the X-ray system for cine mode when Cu absorber and PMMA plate thicknesses move from 1 to 9 mm and 12 to 28 cm, respectively. FOV 25 cm.

The methodology described here includes a numerical analysis of the images archived during the acceptance or commissioning tests and when compared with the typical dosimetric results offers additional added value and two important benefits: first, it helps confirm the appropriate setting of the

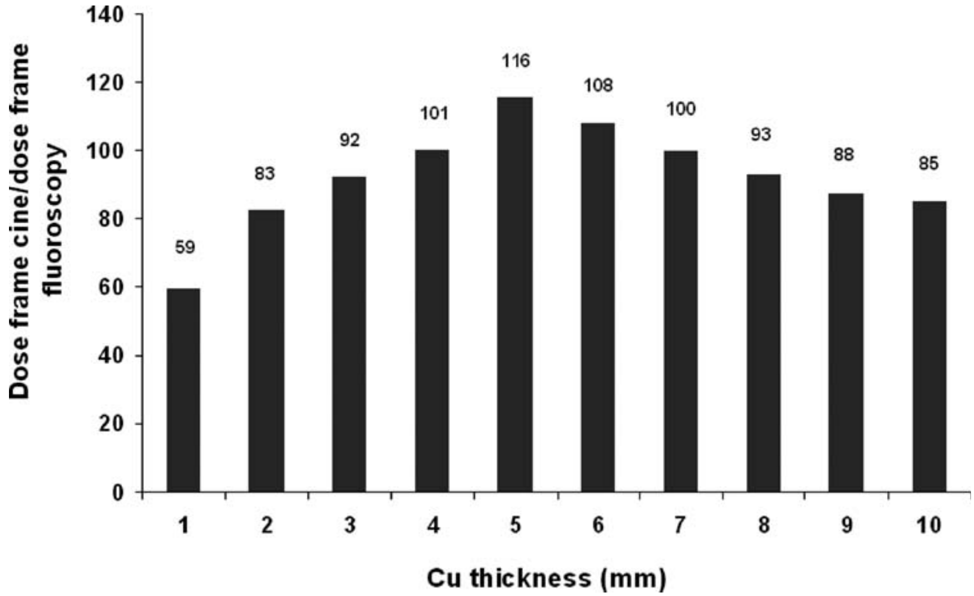

Figure 7. Ratio between IAK per frame for cine and fluoroscopy (low modes) for the different thicknesses of Cu used as absorbers.

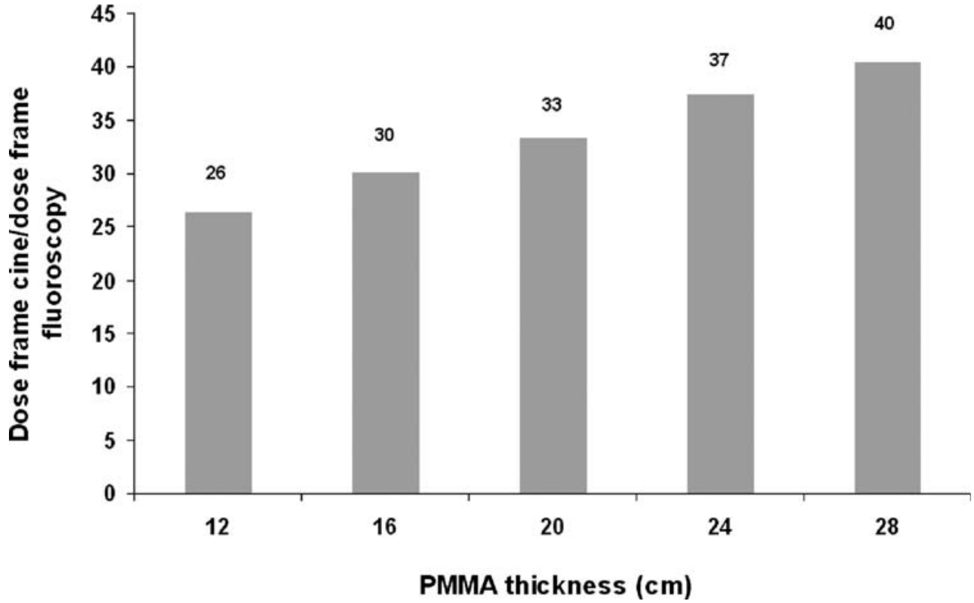

Figure 8. Ratio between ESAK per frame for cine and fluoroscopy (low modes) for the different thicknesses of PMMA used as absorber.

X-ray systems for some operation modes (e.g. if the increase in dose per frame is balanced by an improvement in image quality when comparing: (a) cine versus fluoroscopy modes and (b) different absorber thicknesses); second, it gives orientation on the increases in patient doses and the degradation of image quality (SNR), when patient thickness in the X-ray beam increases.

Figure 7 shows a peak in the ratio between IAK per frame for cine and fluoroscopy (low mode) for 5 mm of Cu due to a change in the AEC curve at this thickness. Note that the milliamperes for cine mode (Table 1) increases with Cu thickness until 5 mm (from 146 to 964 mA) starting a decrease from 5 to 10 mm of Cu (from 964 to 737 mA). This peak is not present when PMMA is used as absorber and ESAK ratios per frame are considered (Figure 8).

CONCLUSIONS

The analysis of dose per frame values and image quality (SNR) for X-ray systems operating with different AEC curves and added filtration options enables one to verify the appropriate setting during the commissioning process (e.g. increases in entrance doses that would not induce a concomitant benefit for image quality) and to obtain relevant information to help cardiologists in the management of patient doses by knowing the dose increase factors and image quality changes when increasing patient thickness or using different C-arm projections.

The use of the image of a semi transparent ionisation chamber to evaluate the degradation of SNR when increasing the absorber thickness (and higher kilovolt values) could prove a useful added value during these dose measurements.

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