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QUALITY CONTROL OF EQUIPMENT USED IN DIGITAL AND INTERVENTIONAL RADIOLOGY

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Digital and interventional radiology are increasingly important areas of radiology. Quality control (QC) of such equipment is of particular importance to avoid unnecessary high doses and to help to achieve good image quality. Within the DIMOND III project, equipment requirements and specifications for digital and interventional radiology have been formulated. A protocol for QC tests has been drafted based on various national and international recommendations. Tests are included for various parts of the imaging chain, i.e. X-ray tube and generator, X-ray tube control system, laser printer and display station, and image quality and patient dose. Preliminary tolerance levels have been set for the various tests, after initial measurements. To check the suitability of QC tests and stated tolerance levels, measurements were made at the University Hospital Gasthuisberg in Leuven for equipment used for paediatric radiology and a unit used for chest examinations. The results of the various tests are reported.

INTRODUCTION

Digital and interventional radiology are increasingly important areas of radiology. In interventional radiology patient doses can be high especially at local areas of, for example, skin. Deterministic effects have been reported for patients, mainly local skin damage, but cases of deterministic effect, have also been reported for medical staff performing interventional radiology. In general in digital radiology, observable overexposure is no longer noticeable as a result of the large dynamic range of digital image receptors. Therefore, quality control (QC) of equipment used in digital and interventional radiology is of particular importance to avoid unnecessary high doses and to help to achieve good image quality.

Within the European Commission (EC) research and technology development project DIMOND III, equipment requirements and specifications for digital and interventional radiology have been formulated[(1)]. The equipment requirements and specifications are of various types, including ergonomic, dosimetric and image quality aspects. Specific requirements are related to the type of procedure. The latter requirements are available for equipment used in cardiac interventions.

In addition, a protocol for QC tests of digital and interventional radiology equipment has been drafted based on various national and international recommendations[(2)]. Tests are available for various parts of the imaging chain, i.e. X-ray tube and generator, X-ray tube control system, display station and hard copy device, and image quality and patient dose. Preliminary tolerance levels have been set for the various tests, based upon initial experience with various types of equipment at a local hospital.

The present measurements were conducted to check the suitability of the QC tests and the stated tolerance levels for various types of digital equipment at the University Hospital Gasthuisberg in Leuven for equipment used for paediatric radiology and for equipment used for chest examinations. In the present contribution, the QC tests are summarised including the equipment used. The QC measurements and results are presented for various parts of the QC protocol. The results were then compared with the preliminary requirements and finally conclusions were drawn.

SUMMARY OF QC TESTS GIVEN IN THE DIMOND III PROTOCOL

X-ray tube and generator

X-ray tube output is the single most important parameter to quantify radiation yield. X-ray tube output is generally characterised by the air kerma free-in-air at 1 m distance from the focus per unit of tube-current exposure-time product and commonly given in units of Gy $(\text{mA s})^{-1}$. For measurement of air kerma, a R100 solid-state detector connected to a PMX III multimeter (RTI Electronics AB, Mölndal, Sweden) was used. X-ray tube output is measured at the tube voltage and filter combinations used in practice for radiology. The consistency of X-ray tube output with tube current (mA) or tube-current exposure–time product (mA s) is measured for the range of mA or mA s values used in practice.

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The accuracy of the peak tube voltage (kV) is important, since kV determines the maximum photon energy in the generated X-ray spectrum. Together with the shape of the kV (dependent on the generator type), anode material, anode angle and total filtration (materials and thickness) it determines the radiation quality. The radiation quality (e.g. specified by a combination of peak kV, first half value layer (HVL) and second HVL, determines the attenuation and scatter characteristics of the X-ray beam used. Both the kV and the HVL were measured using the PMX III unit.

In film-screen radiography, the use of the automatic exposure control (AEC) unit should provide constant average optical density independent of patient or phantom thickness and of tube voltage filtration combination. The AEC unit for digital radiography and fluoroscopy should provide approximately constant air kerma or air kerma rate values at the entrance of the image receptor entrance plane, respectively, independent of patient or polymethyl methacrylate (PMMA) phantom thickness. The characteristics of the AEC unit should match the spectral sensitivity of the digital image receptor.

Finally, the focal spot size is important with respect to resolution in the image, especially in the case of magnification techniques. The focal spot dimensions have been determined using a star pattern. In an image of a star pattern, the diameters (d) are determined where the 'rays' of the pattern disappear through blurring (starting from the outside of the pattern). Commonly, these diameters are determined in the cathode–anode direction (C–A: d_{C-A}) and perpendicular to the C–A direction ($d_{\perp C-A}$). The magnification factor (M) is calculated as the ratio of the star pattern diameter in the image and the diameter of the real star pattern. When ω is the angle (radians) of divergence of the 'rays' of the pattern, the focal spot diameter (F) follows:

$$F = \frac{\omega d}{M - 1}. \quad (1)$$

X-ray tube control system

Limitation of the size of the X-ray field is one of the most important measures in radiology, which decreases patient dose and improves image quality. For this purpose, light fields are commonly used in imaging which visualise the field on the patient. Ideally, the X-ray field should coincide with the light field. In addition, the X-ray field should coincide with the monitor field and, if applicable, the hard copy.

In interventional radiology, it is essential to limit the dose to skin, to avoid the induction of deterministic effects. Relatively high dose rates may occur, when the distance between the focus of the X-ray tube and the skin is small. Therefore, it is recommended to use a minimum distance of 30 cm between X-ray tube focus and skin.

Display station and hard copy device

Test patterns can be used to test the appropriate functioning of display stations (monitors) and hard copy devices. A suitable software test pattern generator has been designed by the US Society of Motion Picture and Television Engineers (SMPTE) including requirements for the visibility of various elements of the test pattern[3].

Image quality

Image quality and patient dose are the two most essential aspects of medical imaging using X rays. In the present study, three approaches were used for assessment of image quality, i.e. the use of a special phantom for assessment of overall image quality, a contrast-detail (CD) phantom and the determination of high-contrast limiting resolution.

A suitable phantom for assessment of both low-contrast and high-contrast resolution and spatial resolution has been developed by the Pehamed Company[4]. In addition, the DIGRAD phantom allowed the determination of the dynamic range and the homogeneity of the exposure. According to the manufacturer, the phantom can be applied to acceptance and constancy testing.

The performance of a complete imaging system may be quantified by psychophysical measurements using contrast-detail detectability[5]. The CD phantom developed at Nijmegen University Hospital[6] was used. Images of the CD phantom were assessed by a human observer and the image quality figure (IQF) and the image quality parameter K[7] were determined. Both parameters decrease with increasing image quality.

The high-contrast limiting resolution of an imaging system can be used as a parameter, rather simply to determine, which indicates the system's resolution. The spatial frequency of the group were the sinusoidal or block shaped patterns can be visually detected is taken as the limiting resolution. In the present study, the DIGRAD phantom is used to determine the limiting resolution. For computed radiography, a value has been proposed for the limiting resolution[5].

Patient dose

Concerning assessment of patient dose the entrance air kerma was measured for various thicknesses of PMMA phantoms. In addition, the air kerma incident on the image receptor entrance plane was measured. Both measurements were made using the R100 detector connected to the PMX III. The R100

detector does not measure the contribution of backscatter radiation, since the detector is backed by a lead absorber.

RESULTS AND DISCUSSION

Two X-ray units were used for the measurements: a digital system employing an image intensifier for fluoroscopy and imaging for paediatric radiology (1997) and a digital chest radiography system using a flat panel detector (2002). In addition to the PMX III and the phantoms already presented, a MacBeth 931 densitometer (Kollmorgen Company, Newburg, New York, USA) was used to measure film density and a luminance meter (MAVOlux 5032B meter; Gossen, Nürnberg, Germany) was employed to measure the luminance of the display station.

X-ray tube and generator

X-ray tube output of both units is presented in Figure 1. The values are quite similar, but for the chest unit, a larger range of tube voltages is shown. It should be noted that the filtrations, i.e. 2.0 mm Al + 0.2 mm Cu for the paediatric unit and 2.5 mm Al for the chest X-ray unit are quite similar. The consistency of X-ray tube output with mA s has been measured for a range of mA s values and is presented in Figure 2. For the chest X-ray unit

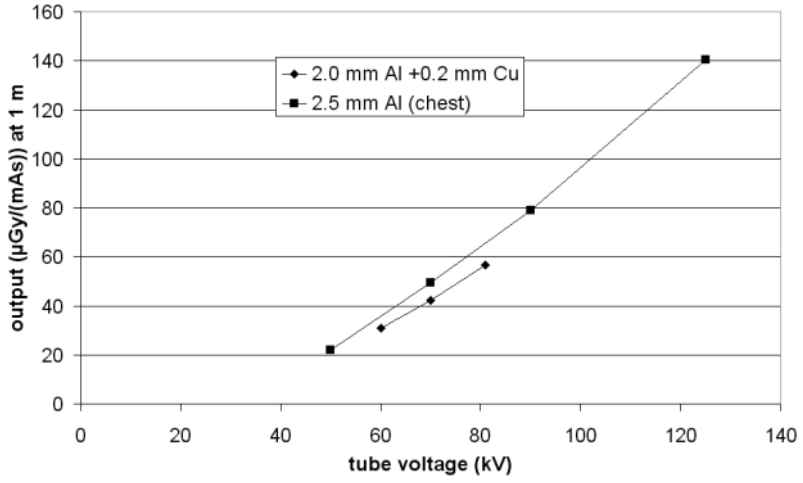

Figure 1. X-ray tube output as a function of kV for two X-ray units.

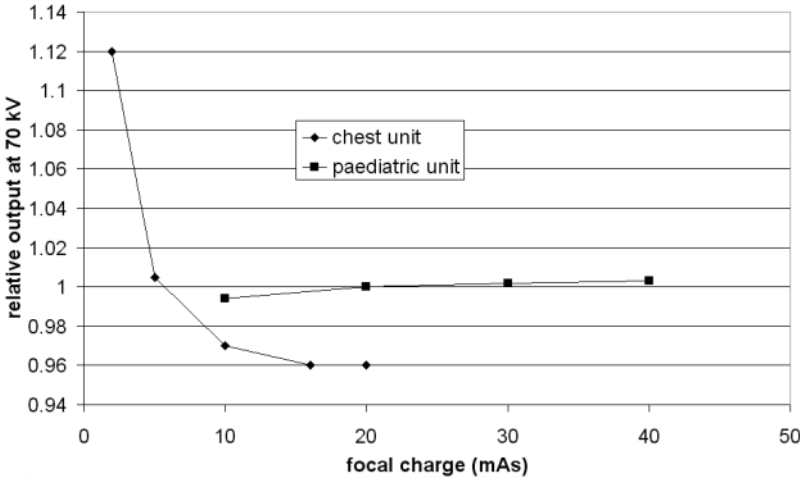

Figure 2. X-ray tube output consistency as a function of mA s for two X-ray units.

a considerable deviation in X-ray tube output is observed at a small mA s value of 2 mA s compared with the average output value for mA s values in the range of 2–20 mA s. The requirement for X-ray tube output consistency was set at ±5%. Except for the lowest mA s value at the chest X-ray unit, the units comply with the requirement. For the paediatric unit, the requirement is very easily met.

The tube voltage accuracy at a number of tube voltages at the two X-ray units is shown in Table 1. The maximum deviation observed is 1.9%, which is considerably smaller than the requirement of ±5%. Measurements of the radiation quality in terms of the first HVL made with the PMX III are shown in Table 2 for the two X-ray units. According to International Electrotechnical Commission (IEC)[8], the requirements for HVL in the case of interventional radiology are 1.8, 2.5 and 4.5 mm Al at tube voltages of 50, 70 and 125 kV, respectively. It is concluded that these requirements are met. For the paediatric unit it is concluded that the use of copper is very effective to increase the HVL. A tube voltage of 125 kV is probably most realistic in chest radiography. The HVL at a tube voltage is rather small compared with the average value of 7.4 mm Al found in a recent survey of PA chest radiography in The Netherlands[9].

The use of the AEC did not result in a constant image receptor entrance dose as measured with the PMX III (Table 3). For the paediatric X-ray unit and for phantom thickness of 5–12 cm PMMA a maximum dose difference of 30% was found. For the chest X-ray unit the difference was 18% for phantom thicknesses of 10–20 cm.

Table 1. Tube voltage accuracy measured at two X-ray units.

Tube voltage set (kV)	Tube voltage measured (kV)	Deviation (%)	Unit
60	60.9 ± 0.1	1.5	Paediatric unit
81	82.5 ± 0.1	1.9	Paediatric unit
50	50.6 ± 0.1	1.2	Chest X-ray unit
81	82.3 ± 0.1	1.6	Chest X-ray unit
125	125.9 ± 0.1	0.7	Chest X-ray unit

Table 2. Measurement of the first HVL at two X-ray units.

Tube voltage set (kV)	Filtration (mm)	First HVL (mm Al)	Unit
70	2 Al + 0.2 Cu	4.9	Paediatric unit
80	2 Al	2.8	Paediatric unit
50	2.5 Al	2.1	Chest X-ray unit
70	2.5 Al	2.9	Chest X-ray unit
125	2.5 Al	5.0	Chest X-ray unit

The focal spot size measured for the paediatric X-ray unit was 1.28 mm in both the C–A and perpendicular (⊥C–A) directions. For the chest X-ray unit, the results are given in Table 4. It is concluded that both stated focal spot sizes fulfil the IEC requirements[10], both for the large and focal spot size.

X-ray tube control system

Alignment between light field, X-ray beam, image on the monitor and image on hard copy has been investigated. The results are presented in Tables 5 and 6. The requirements are formulated as not exceeding ±2% of the focus-to-image receptor distance (FID), which means a difference of ±2 cm for the paediatric X-ray unit and ±3 cm for the chest X-ray unit. It should be noted that the QC requirements are met, but it should also be stressed that part of the images are not visible on the monitor. For imaging on hard copies the situation seems to be better.

Display station and hard copy device

The display station (Sony monitor PVM-20NSE colour video monitor) was adjusted to a contrast

Table 3. Dose at the image receptor for various phantom thicknesses at two X-ray units.

Phantom thickness (cm PMMA)	Image receptor entrance dose (μGy)	Relative dose	Unit
5	945.2	0.88	Paediatric unit[a]
8	1050	0.98	Paediatric unit[a]
12	1221	1.14	Paediatric unit[a]
10	5.14	1.07	Chest X-ray unit[b]
15	4.90	1.02	Chest X-ray unit[b]
20	4.38	0.91	Chest X-ray unit[b]

[a]The paediatric unit was operated at a tube voltage of 55 kV and a field size of 30.1 × 30.7 at the image receptor
[b]The chest X-ray unit was operated at a tube voltage of 125 kV and a field size of 43 × 43 at the image receptor

Table 4. Stated focal spot size, measured focal spot size and requirements[10] for the chest X-ray unit.

Nominal focal spot size	Measured		Requirement	
	d_{C-A} (mm)	$d_{\perp C-A}$ (mm)	d_{C-A} (mm)	$d_{\perp C-A}$ (mm)
0.6	0.76	0.82	0.60–0.90	0.90–1.3
1.0	0.86	0.98	1.0–1.4	1.4–2.0

Table 5. Alignment between light field and field on the display station (monitor) for fluoroscopy and imaging.

Correspondence of light field vs. image on monitor (fluoroscopy)			
Top: +0.25 cm	Bottom: +0.5 cm	Left: 0.25 cm	Right: +1.0 cm
Correspondence of light field vs. image on monitor (imaging)			
Top: +1.0 cm	Bottom: +0.75 cm	Left: 0.0 cm	Right: +0.75 cm
Correspondence of light field vs. image on film (imaging)			
Top: −1.0 cm	Bottom: −0.5 cm	Left: −0.75 cm	Right: −0.5 cm

Alignment between light field and field on radiographic film. Data for paediatric radiology X-ray unit. '+' value indicates that the image on the monitor is smaller than the corresponding X-ray field. '−' value indicates that the image on the hard copy is larger than the corresponding X-ray field

Table 6. Alignment between light field and field on the display station (monitor) for imaging.

Correspondence of light field vs. image on monitor (imaging)			
Top: +1.0 cm	Bottom: +0.25 cm	Left: +0.5 cm	Right: +0.25 cm
Correspondence of light field vs. image on film (imaging)			
Top: −1.0 cm	Bottom: −0.25 cm	Left: 0.0 cm	Right: 0.0 cm

Alignment between light field and field on radiographic film. Data for chest radiography unit. '+' value indicates that the image on the monitor is smaller than the corresponding X-ray field. '−' value indicates that the image on the hard copy is larger than the corresponding X-ray field

of 75 and a brightness of 25. In the image of the SMPTE pattern the 5% contrast was visible in the 0% background, the same holds for the 95% in the 100% background. Only the two pixel test pattern was not observed for the horizontal orientation.

For the hard copy device (Agfa laser printer Drystar 2000), the test was similar, i.e. imaging of the SMPTE test pattern. The results were that 5% contrast was not visible in the 0% background, but the 95% was visible in the 100% background.

Image quality

Imaging of the DIGRAD phantom and assessment of the images led to the conclusion for the paediatric unit, that the phantom added to a PMMA phantom of 6 cm thickness, showed an image in which all seven step wedges were visible and four of the low-contrast objects. Imaging of the DIGRAD phantom and assessment of the images led to the conclusion for the chest X-ray unit, that the phantom added to a PMMA phantom of 10 cm thickness, showed an image in which all seven step wedges were visible and six of the low-contrast objects. Both radiographic images fulfil the requirements stated by the manufacturer, i.e. all seven step wedges should be visible and at least three of the low-contrast objects.

The results from the exposures of the CD phantom were expressed in terms of IQF and K. The values of IQF were 64.6 for the paediatric irradiation and 42.6 for the chest examination. For the image quality parameter K the results were 4.04 and 2.7, respectively. Results on both image quality parameters are not available for paediatric radiology.

Table 7. Incident air kerma at the PMMA phantom entrance plane for various phantom thicknesses at two X-ray units.

Phantom thickness (cm PMMA)	Incident air kerma (mGy)	Unit
5	2.05 ± 0.01	Paediatric unit[a]
8	3.95 ± 0.05	Paediatric unit[a]
12	9.61 ± 0.04	Paediatric unit[a]
10	0.0292 ± 0.0001	Chest X-ray unit[b]
15	0.0606 ± 0.0001	Chest X-ray unit[b]
20	0.1439 ± 0.0004	Chest X-ray unit[b]

[(a)]The paediatric unit was operated at a tube voltage of 55 kV and a field size of 30.7 × 30.7 at the image receptor
[(b)]The chest X-ray unit was operated at a tube voltage of 125 kV and a field size of 40.5 × 40.5 at the image receptor

However for chest radiography, data are available from a relatively recent survey[9]. In this survey an average IQF value of 46 and an average value of K of 2.7 was derived. This may be interpreted that the image quality achieved by the chest X-ray unit is close to the average value obtained in the recent chest radiology survey, organised in The Netherlands.

Patient dose

Incident air kerma values for PMMA phantoms of various thicknesses are shown in Table 7. Entrance air kerma values are high for the paediatric examinations compared with the reference values,

e.g. 1.5 mGy for skull, and low and compared to the values for PA chest radiography, i.e. 0.3 mGy. High and low entrance dose values could have been expected on the basis of the air kerma at the entrance of the image receptors (Table 3).

CONCLUSIONS

X-ray tube voltage and generator requirements are generally fulfilled, except for X-ray tube output at low mA s values. The use of an AEC unit for different phantom thicknesses for various types of examinations does not yield constant image receptor entrance dose.

The requirements for the correspondence of the X-ray field and the light field, as well as those for the display station and the hard copy device, are fulfilled. However, the image on the monitor is smaller than the corresponding X-ray field. The X-ray field is completely visualised on the hard copy.

The image quality assessed by the various methods indicates that the results for the paediatric unit are worse than for the chest X-ray unit. For the chest X-ray unit image quality is similar to the results obtained in a recent survey of PA chest radiography in The Netherlands[9]. Doses at the paediatric X-ray unit are relatively high and at the chest X-ray unit relatively low.

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