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Technical Note

First implementation of quality control procedures on selected X-ray machines in South of Benin

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Abstract

Introduction: The use of X-ray equipment for medical diagnostic radiography procedures has increased due to advances and complexity of radiological procedures. Achieving good image quality while keeping exposure of workers, public and patient exposure to an acceptable level has become a prerequisite for the radiology department in order to comply with best international practices. The aim of this study was to undertake quality control measurement of seven (7) diagnostic radiography equipment in the south of Benin, the first of its kind.

Material and methods: Multifunction detector (Piranha) and beam alignment test tool were used to perform quality control tests on seven (7) X-ray units. The method used as well as the interpretation of the results was based on the American Association of Physicists in Medicine (AAPM), United States Food and Drug Administration (FDA), Healing Arts Radiation Protection (HARP), Institute of Physics and Engineering in Medicine (IPEM), International Atomic Energy Agency (IAEA) and Canadian Safety code 35 (S.C 35) recommendations.

Results: The quality control results showed that all X-ray equipment investigated were within standard limits for accuracy of exposure time below 10 ms; reproducibility of kVp, exposure time and dose output; specific dose-kVp^2 linearity; and specific dose-mAs linearity. Five (5) out of seven (7) diagnostic X-ray machines passed quality control tests such as X-ray beam alignment, exposure time above 10 ms and kVp accuracy. One (1) X-ray machine failed the quality control test of beam filtration at 70 kVp and above.

Conclusions: The findings of this study have provided baseline data for other radiology departments to embark on similar QA/QC activities, and also explore options for optimization of patient dose. However, there is a need to extend the study to cover more diagnostic X-ray machines throughout the country. It is anticipated that this would ultimately assist in improving radiation protection and safety during medical diagnostic radiological procedures.

Keywords: quality control; diagnostic radiology; X-ray machines; Southern Benin.

Introduction

From the beginning of X-ray use, harmful effects were observed and continue to occur. This situation pushed practitioners to suggest radiation safety rules. International organizations such as the International Commission on Radiological Protection (ICRP), and, the International Atomic Energy Agency (IAEA), recommend that proper management systems that include quality assurance (QA) programme encompasses activities involving the use of ionizing radiation.[1] According to the World Health Organization (WHO), a QA programme in diagnostic radiology is an organized effort by the staff operating a facility to ensure that the diagnostic images produced are of sufficiently high quality so that they consistently provide adequate diagnostic information at the lowest possible cost and with the least possible exposure of the patient to radiation.[2] As part of QA, quality control (QC) intends to verify that structures, systems and components verify predetermined requirements.[3] The QC procedures are concerned directly with the equipment performance that can affect the patient dose and the quality of the radiographic image.[4] In the Benin Republic, X-ray machines

Authors' contribution:
A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

are in operation daily for diagnosis of medical conditions of patients in the public health as well as private health sector. Most of the X-ray equipment is not subjected to acceptance testing and the facilities are also not assessed since the regulatory body is yet to undertake regulatory inspections of the facilities. Due to the lack of QCs on the equipment, there is uncertainty about the performance of the equipment. For decades, the machines have only been repaired when there are mechanical and electrical defaults and QC after repair is not performed. The use of X-ray machines for radiography is good for a patient's diagnosis, but when not held in check, it could induce severe health effects to the radiographer/operators, patient and the general public. The adverse health effects associated with ionizing radiation do not allow it to be used without balancing between benefit and risk. The aim of this study was to undertake comprehensive quality control procedures on seven (7) X-ray machines in South of Benin, in order to provide data for the first time on the performance status of selected X-ray machines in the major hospitals surveyed.

Materials and Methods

Materials

Diagnostic radiology X-ray machines

Seven X-ray units, including four machines with a Screen Film (SF) system, two (2) Computed Radiography (CR) systems and one Digital Radiography (DR) system were utilized in this study. The specifications of the X-ray equipment are indicated in **Table 1**.

Multifunction meter (Piranha)

The multifunction meter is a solid-state detector designed to detect mostly X-ray radiation (**Figure 1**). The black Piranha used in the present study has a serial number is CB2-11020219. It was used to measure simultaneously, the kilovoltage peak, exposure time, half value layer (HVL) and dose output of each X-ray machine. The OCEAN Software associated with the detector allows the selection of the simultaneous measurement.[5] The detector is suitable for the measurement because of its specification as indicated in **Table 2**.[6]

Collimator and beam alignment test tool

The test tool allows the performance of both QC for light field and X-ray field congruence and central beam perpendicularity with the image receptor. The test tool consists of a flat plate (20 cm × 25 cm) made of brass and contains a rectangular outline and marking etched. The main component of the beam alignment tool is the sixteen centimeter high acrylic cylinder. Each end of the cylinder holds one steel ball. The superimposition of the steel ball determines the alignment of central X-ray beam. The test tool also includes a leveler for checking whether patient couch top is horizontally levelled (**Figure 2**).[7]

Figure 1: Black Piranha Detector

Table 1. X-ray equipment specifications

Hospitals	Tube Manufacturer & Country	Tube serial number	Manufacture date	X-ray system(*)	Range	
					kVp	mAs
H-1	SIEMENS, Germany	579502	Not readable	SF	40-125	0.5-800
H-2	SHIMADZU, Japan	75178	November 2007	CR	40-150	0.5-800
H-3	COMET ROHRE, Germany	348482	Not readable	SF	40-125	0.1-400
H-4	Varian	-	-	SF	40-125	1-500
H-5	PERLONG, China	820017131	June 2017	DR	40-130	0.4-360
H-6	BMI, Italy	12799	January 2007	CR	40-150	0.5-630
H-7	DMS APELEM, France	71k061	June 2010	SF	40-150	0.4-1000

**SF - Screen Film, CR - Computed Radiography, DR - Digital Radiography (DR)*

Table 2. Specifications of Piranha detector

Measurement	Kilovoltage peak	Exposure time	Half value layer	Dose output
Range	35 - 160 kVp	0.1 ms – 2000 s	0.72 – 13 mm Al	0.1 nGy – 1.5 kGy

Other materials

A tape measure with a minimum count of 0.1 cm was used in the present study. It was used in focus to table top distance (FTD) checking. Based on the type of X-ray system, CR plate, X-ray film and cassette were used for light field and X-ray field alignment tests. The CR plate or cassette chosen was the one available that could contain the alignment test tool. For the screen-film system, the film used was processed manually in two radiology departments and automatically in one Centre. For CR and DR systems, the obtained image of the test tool set was printed on radiographic film.

Methods

The methods used for each quality control test were based on recommendations of Safety Code S.C 35[8] American Association of Physicist in Medicine (AAPM), [9,10] United States Food and Drug Administration (FDA),[11] Institute of Physics and Engineering in Medicine (IPEM),[12] and Healing Arts Radiation Protection Act (H.A.R.P).[13] The methods are described in detail in the following sections

Setting up the materials and general procedure for measurement

Set up for kVp, exposure time, HVL and dose measurement

The Black Piranha was connected to the computer and the Ocean software was started to select parameters to be measured. X-ray machine was warmed up with three exposure parameters [(50 kVp, 50 mA, 100 ms); (50 kVp, 100 mA, 200 ms); (70 kVp, 100 mA, 200 ms)] and with 5 minutes interval between exposures. A schematic diagram for the set up for kVp, exposure time, HVL and dose measurements is illustrated in **Figure 3**.

Set up for collimator and beam alignment

The collimator of the X-ray machine was set at 0° to face the patient table in such a way that X-ray source assembly was centred over the table. The focus to table top distance (FTD) was set at 100 cm and it was verified using a tape measure. The X-ray field was collimated where possible to cover the sensitive area of the detector, in order to achieve conditions of narrow beam geometry. The detector was placed in the center of the X-ray field. The patient table was levelled to verify its horizontality and the X-ray tube was centred to the table so that the central beam was perpendicular to the table. A loaded cassette or CR plate was placed on the table in the center of the light field. FTD was kept at 100 cm. The congruency tool was placed on the cassette in the center of the light field and the perpendicularity tool was in the center of the congruency tool. Collimator shutters were adjusted so that the edges of the rectangular field coincided with the rectangular outline of the congruency tool. A schematic diagram for the set up for collimator and beam alignment measurement is illustrated in **Figure 4**.

Figure 2: Collimator and beam alignment test tool

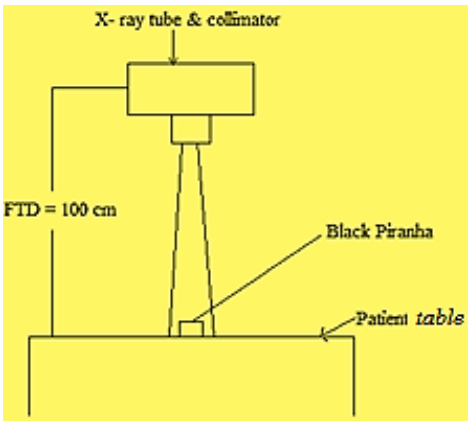


Figure 3. Set up for kVp, exposure time, HVL and dose measurement

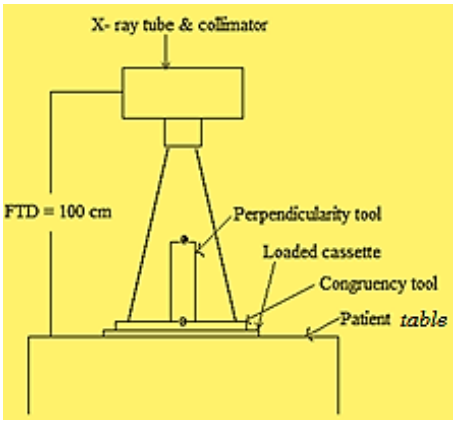


Figure 4. Set up for collimator and beam alignment

Accuracy of kilovoltage peak and exposure time

Accuracy of kilovoltage peak was performed on all the seven (7) diagnostic X-ray machines involved in the present study. The radiographic parameter mAs, was kept at a constant value (20 mAs), and clinically used kilovoltage peak accuracy was investigated. The value of kVp tested ranged from 50 to 120 kVp. For each kVp value, three measurements were recorded. The focus size was the frequently used one for the radiographic procedures at the radiology department.

Exposure time accuracy was conducted on six (6) diagnostic X-ray machines. The QC test takes account of two (2) intervals of exposure time, exposure time below 10 ms and exposure time above 10 ms. For each interval, three values of exposure times were selected and each of them was measured three (3) times. Measurements were done at a constant and most commonly used kVp.

The accuracy of the measured values was calculated by using **Equation 1**:

$$E = \left|\frac{\overline{Xm} - Xs}{Xs}\right| \times 100\% \qquad \text{Eq. } 1^{[14]}$$

where E is the error on kVp or exposure time selected, $\overline{Xm}$ is the mean of the three measurements and Xs is the selected kVp value.

Reproducibility of kilovoltage peak, exposure time and dose output

At the frequently used focal size, ten consecutive exposures were made with the Black Piranha at constant mAs and kVp. The most commonly used kVp was the one used for the reproducibility test. Kilovoltage peak, dose output and exposure time reproducibility were all tested on the seven (7) X-ray units. For the Unit at radiology department H-5 it was not possible to select exposure time. But at the constant parameter setting exposure time was measured and its reproducibility was checked. At H-4 exposure was displayed by the X-ray unit after each exposure. 122 ms was the exposure time used at this radiology department to perform the reproducibility test. The coefficient of variation of the ten measurements of each reproducibility test was calculated using **Equation 2**:

$$CV_x = \frac{SD_x}{\bar{x}} = \sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{n}\left(\frac{x_i}{\bar{x}} - 1\right)^2\right]} \qquad \text{Eq. } 2^{[14]}$$

where CV_x is coefficient of variation, $\bar{x}$ is the mean value of measurement, SD_x is the standard deviation, n is the total number of measurements, x_i is the i^{th} measurement and x is time or kVp or dose output.

Deviation of each measurement from the mean measurement was also calculated based on **Equation 3**:

$$E = \left|\frac{x_i}{\bar{x}} - 1\right| \times 100\% \qquad \text{Eq. } 3^{[14]}$$

X-ray beam filtration

The half-value layer (HVL) was measured by direct reading for all seven (7) X-ray units. The tube current and exposure time product were kept constant. Kilovoltage peak was varied in increments of 10 from 40 to 90 kVp. For each kVp value the half value layer was recorded three (3) times. The mean of the three (3) measurements was the HVL at the specific kVp.

Specific dose-kVp^2 linearity

The mAs was kept constant. The kVp was varied from 40 to 90 with increments of 10. The dose output and kVp were recorded. The specific dose expressed in mGy/mAs variation as a function of the measured kVp has been analyse under discussion session

Specific dose-mAs linearity

The kilovoltage peak (kVp) commonly used was kept constant and mAs values were varied. Dose output was recorded for each mAs value and specific dose output (D'_i) was calculated by dividing the dose output value by the corresponding mAs value. To check for linearity, the linearity coefficient (LC) was calculated using **Equation 4** below for two consecutive mAs values.

$$LC = \frac{|D'_i - D'_{i+1}|}{|D'_i + D'_{i+1}|} \qquad \text{Eq. } 4^{[14]}$$

where D'_i is the i^{th} specific dose, D'_{i+1} is the $i+1^{th}$ specific dose.

Beam alignment

At each radiology department, the exposure factors for extremity radiographic projection were used to expose the collimator and beam alignment test tool. Beam alignment was performed in all the seven hospitals that participated in the survey.

Results and Discussion

Accuracy of kilovoltage peak

The results obtained in assessing the kilovoltage peak accuracy in the seven radiology departments are illustrated in **Figure 5**. It emerged that H-1; H-2; H-3; H-6 and H-7 successfully passed the QC test. For those five X-ray machines the percentage error on the selected kVp was below the 5% limit recommended by AAPM.[10] When efficiently used they would produce the desired good image quality required for an X-ray examination. In H-5, as the kVp increased the deviation also increased and the inaccuracy was mainly observed at high kVp values above 70 kVp. Concerning the X-ray unit at H-4, all the commonly used kVp values were inaccurate. For those two machines, radiographic image contrast may be affected because the selected kVp was not the expected kVp that was measured.

Accuracy of exposure time below 10 ms

Accuracy of exposure time below 10 ms was investigated for six (6) X-ray units including the X-ray unit at H-4 where exposure time selection was not possible, as illustrated in **Figure 6**. In this

radiology department the control console indicated the exposure time at the end of exposure. The measurement done with the Piranha multifunction meter was compared with the exposure time display on the X-ray unit control console. The six (6) X-ray units, measurements of exposure time below 10 ms, were within the required limit set by Safety Code S.C 35 (10% +1 ms).[8] Four out of six X-ray units were accurate according to the AAPM standard limit (**Figure 7**).[10] Two (2) X-ray units (H-3 and H-4) present inaccuracy for some selected exposure time below 10 ms. As exposure time is one of the operational principles of radiation protection, radiographers should be confident in the selected exposure time for radiation protection purposes and to avoid blurred images in some examinations such as chest radiography.

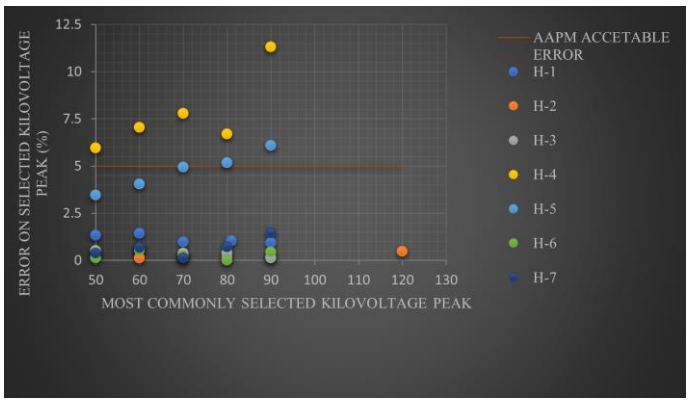


Figure 5: Kilovoltage peak accuracy

Accuracy of exposure time above 10 ms

The percentage deviation of exposure time in the different diagnostic radiology departments showed that four (4) out of the six (6) X-ray units investigated passed the quality control test of exposure time accuracy. The four X-ray unit errors on selected exposure time were all below standard limits recommended by international bodies, such as AAPM (5%),[10] HARP (10%),[13] (**Figure 7**). Two (2) X-ray units failed the QC test. X-ray unit at H-4 accuracy tests revealed that the exposure time displayed by the control console was far different from the measured one. Further investigation is required to improve the X-ray beam quantity.

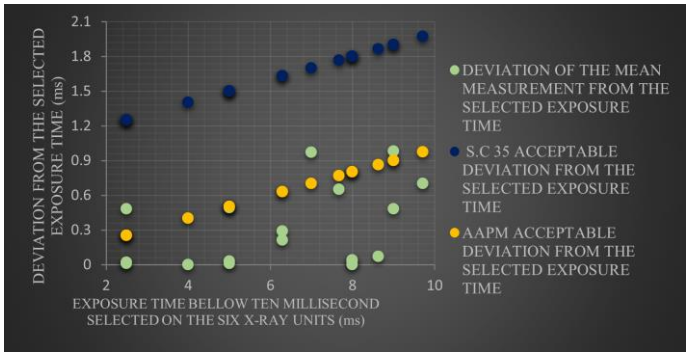


Figure 6: Accuracy of exposure time below 10 ms

Reproducibility of kilovoltage peak, exposure time and dose output

For all X-ray units involved in the present study, kilovoltage peak, exposure time and dose output coefficient of variation were within the standard limit specified by AAPM (5%),[10] as shown in **Table 3**. The average deviation of each measurement from the mean measurement ranged from 0.06 to 1.36% for the kilovoltage peak. For exposure time the maximum deviation of each measurement from the mean measurement value was 0.36%. The deviation between the mean dose output calculated and each measured dose output ranged from 0.03 to 1.36%.

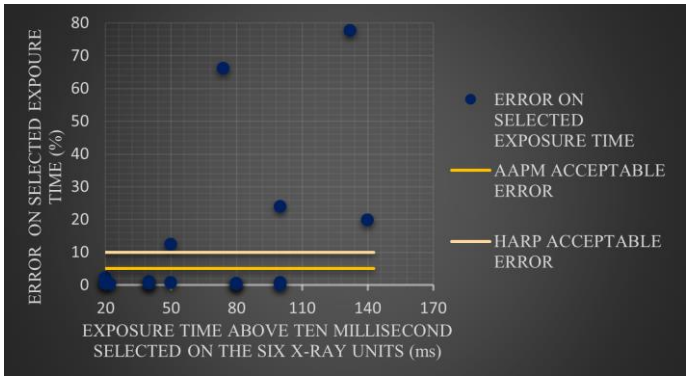


Figure 7: Accuracy of exposure time above 10 ms

Table 3. Reproducibility of exposure time, kilovoltage peak and dose output

Hospitals	Reproducibility							
	Time (ms)			kVp			Dose output (mGy)	
	Set	Measured mean	CV (%)	Set	Measured mean	CV (%)	Measured mean	CV (%)
H-1	100	124.06	0.18	60	58.94	0.15	0.70	0.15
H-2	100	99.88	0.01	80	79,78	0.40	0.79	0.43
H-3	100	99.58	0.26	80	79,64	0.07	1.28	0.12
H-4	122	142.88	0.34	80	73.44	1.60	1.14	1.5
H-5	n/a	84.62	0.31	80	75,62	0.72	0.60	0.52
H-6	100	100.23	0.24	80	80.70	0.47	0.89	0.04
H-7	100	99.83	0.16	80	80.07	0.07	0.97	0.06

n/a = exposure time could not be selected

Deviation of each measurement from the mean measurement was within the limit recommended by S.C 35 (15%),[8] and HARP (20%).[13] All the X-ray units passed the reproducibility tests. The implication is that the kVp, exposure time and dose output could be repeated without any major deviation outside the tolerance limits.

X-ray beam filtration

According to FDA[11] and IAEA [15], HVL which determines beam quality should not be below a specific minimum value for a given kVp. From **Figure 8**, all average HVL measured at kVp ranging from 40 to 90, for the seven diagnostic X-ray units were above the FDA minimum required value except at H-4 where the mean HVL was below the minimum acceptable HVL for 80 and 90 kVp. Beam quality is affected in this radiology department for those kVp selected. In the six hospitals that passed successfully the QC test, patient entrance surface dose from X-ray machines would mainly depend on operator errors for a specific examination because soft X-rays are efficiently removed from the beam spectrum before they reach the patient.

Specific dose-kVp^2 linearity

The kVp squared versus specific dose showed that all seven diagnostic X-ray units reported a very high correlation with a linear trendline (**Figure 9**). The square of correlation coefficient (R^2) when taken at two decimal places, was equal to 1 for all diagnostic radiology X-ray units. This means that variation of specific dose with kVp square was linear for all kVp selected between 40 and 90 kVp. Specific dose from each X-ray unit could be expressed as a linear function of the kVp^2.

Specific Dose-mAs linearity

Linearity coefficients obtained by keeping kVp constant and varying mAs, were less than 0.1 as indicated in **Table 4**. The seven X-ray units in the diagnostic radiology departments passed the specific dose-mAs linearity test. This means that for the screen film system the same density could be achieved if the mAs are kept constant.

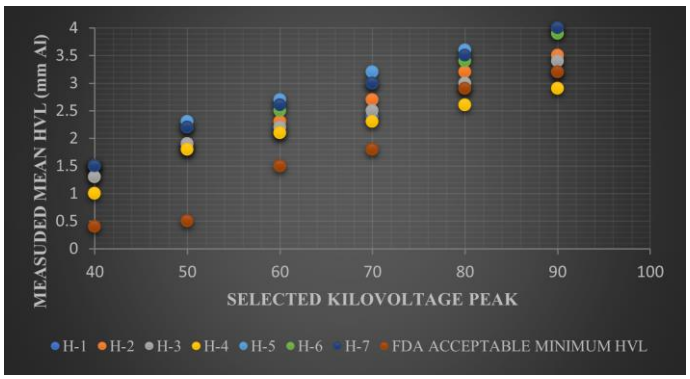


Figure 8: Half-value layer variation with kVp

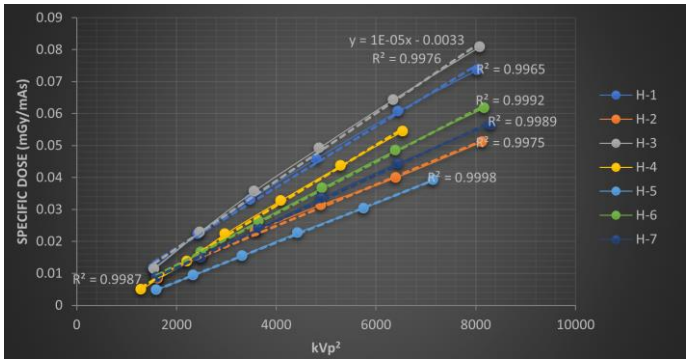


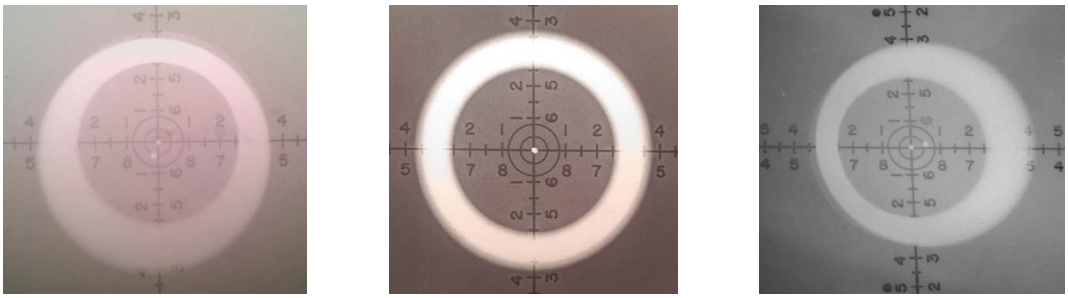
Figure 9: Correlation of the specific dose versus kVp2 with a linear trendline.

Table 4. Range of linearity coefficient

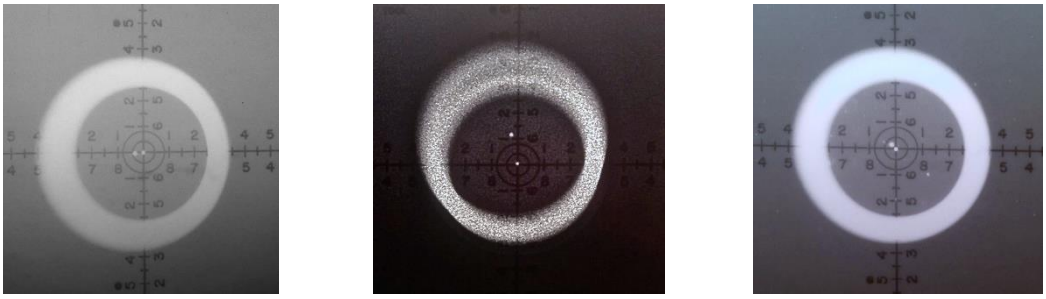
Hospitals	Range of mAs	Range of LC (%)
H-1	2.50 – 40.00	0.06 – 0.25
H-2	5.00 – 25.00	0.08 – 1.25
H-3	2.50 – 28.00	0.08 – 0.71
H-4	2.50 – 28.00	0.10 – 2.90
H-5	2.50 – 25.00	0.16 – 5.28
H-6	2.50 – 25.00	0.00 – 1.15
H-7	2.50 – 25.00	0.00 – 0.90

X-ray beam alignment

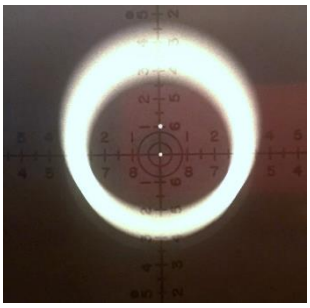
The findings of the beam alignment quality control test of the seven X-ray units are illustrated in **Figure 10**. It emerged that five (5) out of seven (7) of the diagnostic radiography equipment could be considered in the acceptable range of misalignment of 1.5°. The best beam alignment among the seven (7) units was obtained at the main public hospital (H-2) which had the highest workload. Two (2) X-ray units (H-5 and H-7) were out of acceptable range of misalignment. There was therefore the need to repair the collimator in order to fix the problem. However, there may be some challenges of re-assessment after the repairs due to the non-availability of a QC kit. Staff at those two (2) hospitals may have to continue to work with the image distortion due to misalignment. The highest misalignment was observed with the digital X-ray unit. This may be caused by the fact that the leveller indicated some inclination of the image receptor.



H-1 H-2 H-3



H-4 H-5 H-6



H-7

Figure 10. X-ray beam misalignment degree

Conclusion

The present study investigated seven diagnostic radiography X-ray machines in the South of Benin, to check compliance of some important quality control parameters that have implications for patient dose and comparison with international standard requirements. From the results obtained it was clear that such a study should be repeated and extended to cover more diagnostic X-ray machines throughout the country. The findings of this study would serve as a baseline data for other radiology departments to embark on similar QA/QC activities, and also explore options for optimization of patient dose. This would ultimately assist in improving radiation protection and safety during medical diagnostic radiological procedures. To ensure that machines perform satisfactorily in service, the Ministry of Health should embark on projects to acquire quality control kits, recruit medical physicists and recognize their profession.

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