ORIGINAL ARTICLE

OPTIMIZATION OF RADIATION PROTECTION THROUGH QUALITY ASSURANCE IN SOME RADIO-DIAGNOSTIC FACILITIES IN KATSINA STATE, NIGERIA

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ABSTRACT

BACKGROUND: This study was motivated by the high incidence of cancer and the rapid growth of the radio-diagnostic industry in the Nigeria and globally. **OBJECTIVES:** To investigate the errors during quality control tests conducted on three x-ray units. **METHODS:** *kV$_p$ accuracy:* exposures were made on the RMI multifunction meter Model 240 starting from 50 kV$_p$ with increments of 10 kV$_p$. *kV$_p$ reproducibility:* five exposures were also made at 70 kV$_p$ and 20 mAs. *Filtration check:* three exposures were made on a universal survey meter (RADOS RDS 120) with different aluminium thickness placed on it. *mAs / exposure timer linearity:* three exposures were made on the universal survey meter at 70 kV$_p$ for each mAs selected. *mAs / exposure timer reciprocity:* three exposures were made on the universal survey meter at 80 kV$_p$ with three different combinations of mA and exposure time to yield 20 mAs. *Radiation out-put reproducibility:* five exposures were made on the universal survey meter using constant exposure factors. *Beam alignment:* exposure was made on an 18 x 24 cm x-ray film with four coins placed on either edge of the light field to make contact with each other. *Radiation leakage:* with the shutters tightly closed, the universal survey meter placed at 100cm from the x-ray tube was exposed at 125 kV$_p$ and 250 mAs. **RESULTS:** Shimadzu and DM-105N x-ray units failed kVp accuracy test with 05.06% and -8.58% error respectively. Also, the Siemens failed the mAs reciprocity with 0.36% error. However, the three x-ray machines passed the other remaining QC tests. **CONCLUSIONS:** The results obtained demonstrated an acceptable condition for all the x-ray machines.

Keywords: Optimization, x-ray, quality control (QC) tests.

Introduction

Scientific evidence has revealed cancer as one of the top causes of death in the world,[1,2,3,4] and among the many risk factors of getting cancer is radiation such as ultraviolet, x-rays and gamma rays.[5] Deaths from cancer are projected to continue rising by about 70% in 2030 which is estimated to 13.1 million deaths worldwide.[2] The National Council on Radiation Protection and Measurements NCRP[6] and International Commission on Radiological Protection ICRP-105[7] reported medical exposure as the major worldwide source of radiation exposure.

Furthermore, biological effects of radiation are classi-

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fied as deterministic and stochastic. Deterministic effects are effects induced after a certain radiation absorbed dose threshold is exceeded; Severity of deterministic effects depends on dose. While the stochastic effects are probabilistic effects which are not dependent on absorbed dose threshold; the severity of stochastic effects is independent of the absorbed dose.[8,9,10] Deterministic effects are not of major concern in diagnostic imaging, rather the stochastic effects; since low doses of radiation are involved in diagnostic imaging and the probability of cancer occurrence increases with a continuous accumulation of radiation dose over a period of time.[9,10,11]
Optimization of practice is one of the cardinal principles in radiation protection which ensures that while radiation is being used, the likelihood of getting exposed, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable (ALARA), with economic and societal factors taken into consideration.[12,13] ALARA in diagnostic imaging can be achieved through; quality assurance program, minimizing radiation exposure time, maximizing distance from the radiation source, reducing scattered radiation, use of shielding (such as lead apron and wall lead lining) and so on.[13,14]
However the radiation dose received; whether large or small, it is necessary that quality assurance program is implemented in radio-diagnostic facilities and the various quality control tests are conducted periodically as stipulated in the quality assurance program. This study evaluated the radiation safety condition of some conventional x-ray machines through quality control tests in order to ensure optimization of radiation protection.

Materials and Methods

Assessment 1(a): kVp Accuracy

Objective: To investigate the variation between the peak voltage (kVp) set on the control panel with that recorded by the RMI multifunction meter, that is the measured kVp.

Material: RMI multifunction meter Model 240

Procedure:
1. The RMI multifunction meter was placed on the x-ray table
2. Exposures were made on the RMI multifunction meter starting from 50 kVp with increments of 10 kVp.
3. The readings displayed on the light emitting diode (LED) of the RMI multifunction meter were recorded.
4. Three different exposures for each kVp set were made and average taken.
5. The SID/ FFD was maintained at 100 cm.

Performance assessment: Tolerance limit of five percent (5%) and the Variations between the kVp set and the beam quality displayed on the RMI multifunction meter was determined using the equation below;[15,16]

$$\%\ \text{error} = \frac{\text{measured value - set value}}{\text{set value}} \times 100\% \quad \text{— — —(1)}$$

Assessment 1(b): kVp Reproducibility
Objective: To investigate the consistency in the measured kVp with the set kVp.

Material: RMI multifunction meter Model 240
Procedure:
1. The RMI multifunction meter was placed on the x-ray table
2. Exposures were made on the RMI multifunction meter with the kVp set at 70 kVp and 20 mAs
3. The readings displayed on the LED of the RMI multifunction meter were recorded.
4. Five different exposures for the set kVp and mAs were made.
5. The SID/ FFD was maintained at 100 cm.

Performance assessment: Tolerance limit of two percent (2%) and the variations of the kVp was determined using the equation below;[17]

$$\text{kVp Reproducibility variance} = \frac{(\text{kVpmax - kVpmin})}{(\text{kVpmax + kVpmin})} \quad \text{— — -(2)}$$

Assessment 2: Filtration Check (HVL investigation)
Objective: To determine the half value layer (HVL). This is to ensure that low photon energies which contribute to excess dose are removed. This will ensure that the patient's skin dose is reduced.

Materials: Universal survey meter (RADOS RDS 120), various thickness of aluminium sheets ranging from 1 to 5 mm in increments of 1 mm, lead apron and Adhesive tape.

Procedure:
1. Universal survey meter was placed on the x-ray table on top of a lead apron (to prevent backscatter).
2. The Universal survey meter-to-tube distance was adjusted between 60 and 80 cm, because values from 30 to 100 cm show a variation of less than 4.1%.[18]
3. The Universal survey meter was placed within the adjusted field size of collimator.
4. Exposures were made with different aluminium thickness (starting from 1 mm) at 80 kVp and 50 mAs and the universal survey meter readings were recorded per exposure.
5. The different aluminium plates were placed between the collimator and the Universal survey meter.
6. The procedure was repeated while adding aluminium plates in an increment of 1 mm.
7. A graph of x-ray intensity (universal survey meter reading) versus absorber mass thickness was plotted.
8. The HVL was determined from the graph by tracing half of the maximum universal survey meter reading a line from this point on the Y axis to the curve and then another line from this point on the curve down to the X axis. The value on the X axis represented the HVL.

Performance assessment: The HVL should have a minimum value of 2.3mm at 80 kVp.[19]

Assessment 3(a): mAs/ exposure timer linearity
mAs Linearity refers that sequential increase in mAs should produce sequential increase in radiation exposure produced. But since q = it (mAs), therefore it is also a test for the exposure timer. Where i and t are current and exposure time, respectively.

Objective: To determine if the radiation exposure produced compliment the increase in mAs.

Materials: Universal survey meter (RADOS RDS 120), Lead apron

Procedure:
1. The universal survey meter was placed on the lead apron which was on the x-ray table.
2. Three exposures for each mAs selected were made at 100 cm FFD with the exposure factors set at 70 kVp and mAs of 5, 10. 20 and 40.
3. The universal survey meter reading from each exposure was recorded and then divided the set mAs to yield mR per mAs.
4. The minimum, maximum and average readings of the four exposures were determined.

Performance assessment: The linearity variance was calculated using the equation below. Linearity is adequate when the value is less than 10% (0.1).[15]

$$\text{Linearity variance} = \frac{\left(\frac{mR}{mAs}\right)\text{max} - \left(\frac{mR}{mAs}\right)\text{min}}{\left(\frac{mR}{mAs}\right)\text{average}} \div 2 \quad (3)$$

Assessment 3(b): mAs and exposure timer reciprocity
Reciprocity refers to the same mAs being selected but with different selections of mA and exposure time.[19]

Objective: To determine the radiation output accuracy at different combinations of mA and time to give rise to same mAs.

Procedure:
1. A lead apron was placed on the x-ray table.
2. Universal survey meter (RADOS RDS 120) was placed on the lead apron.
3. Three exposures for each mAs selected were made at 80 kVp and 20 mAs, the set kVp remained constant while three different combinations of mA and exposure time were set to yield 20 mAs.
4. The universal survey meter readings were recorded and the universal survey meter was reset after each exposure.
5. The FFD was maintained at 100 cm.
6. The universal survey meter readings displayed from each exposure were then divided the set mAs to yield mR per mAs.
7. The minimum, maximum and average readings of the five exposures were determined.

Performance assessment: The reciprocity variance was calculated using the equation below.
The reciprocity variance should be less than 0.1 (10%).[15]

$$\text{Reciprocity variance} = \frac{\left(\frac{mR}{mAs}\right)\max - \left(\frac{mR}{mAs}\right)\min}{\left(\frac{mR}{mAs}\right)\text{average}} \div 2 \quad (4)$$

Assessment 4: Radiation Output Reproducibility

Objective: To investigate the x-ray machine out-put production consistency.

Materials: Universal survey meter (RADOS RDS 120) and Lead apron.

Procedure:

1. A lead apron was placed on top of an x-ray table.
2. Universal survey meter was placed on the lead apron.
3. The central ray of the x-ray beam was centred to the Universal survey meter at an FFD of 100 cm.
4. A series of five exposures to the universal survey meter were done using the same machine parameters of 80 kVp, 100 mA and 100 ms set at same dimensions.
5. After each exposure before another one was made, the previous reading was recorded and then the universal survey meter reset for a fresh exposure.

Performance criteria: The equation below was used to obtain the reproducibility variance. The reproducibility variance should be less than 0.05 (or 5%).[15]

$$\text{Reproducibility variance} = \frac{(mRmax - mRmin)}{(mRmax + mRmin)} \quad (5)$$

Assessment 5: Beam Alignment Test

Objective: To assure that the light field accurately defines the x- ray field.

Materials: nine coins, measuring tape and loaded x-ray cassette

Procedure:

1. A loaded cassette was placed on the x-ray table at SID/FFD of 100 cm.
2. The light field size was adjusted to be smaller than the film (18 x 24 cm or 24 x 30 cm).
3. Four coins were placed on the inside edge of the light field at the centre of each dimension, and the other four on the outside edge in contact with the inner coins.
4. A ninth coin was placed in the light field towards the cathode end of the x-ray tube to demonstrate on the image the direction of the misalignment.
5. X-ray exposure was made using low exposures (example 65 kVp, 4 mAs) and x-ray film was developed.
6. The distances between the light (where the coins touch) and x-ray fields for all coin locations were measured.

Performance assessment: The light and x-ray field misalignment does not exceed 2% of 100cm in either the length or the width of the film.[20]

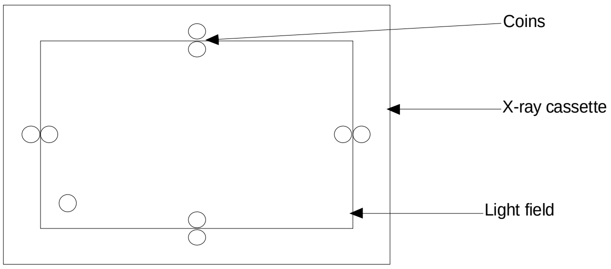

Figure 1: Nine Penny Test

Assessment 6: Radiation Leakage

Objective: To determine the level of radiation leakage from the x-ray tube as this leakage radiation will increase the patient and staff doses, respectively.

Materials: Meter rule and a Universal survey meter (RADOS RDS 120).

Procedure:

1. The collimator shutter of the x-ray tube was completely closed and the x-ray tube turned vertically downward position.
2. A universal survey meter was placed at 100 cm from the x-ray tube and at 4 different sides of the tube to measure leakage radiation.
3. Five exposures were made using 125 kVp and 250 mAs.
4. The universal survey meter readings for each of the different positions of the universal survey meter were recorded.
5. The average of the five readings was determined.

Performance assessment: The leakage radiation at 100 cm should be 0.1 Rh^{-1} when tube is operated at maximum tube current and potential.[21,22]

Results

kVp Station	Measured kVp						
	RMI multi function meter readings			Mean	SD(σ)	Error(%)	Tolerance (%)[15,16]
60	64.60	62.80	62.60	63.33	1.10	+ 05.56	< ±05.00
70	72.20	72.20	71.90	72.10	0.17	+ 03.00	< ±05.00
80	82.70	82.90	82.90	82.83	0.11	+ 03.54	< ±05.00
90	95.00	94.90	95.30	95.07	0.21	+ 05.63	< ±05.00
100	107.50	107.00	108.20	107.57	0.60	+ 07.56	< ±05.00
Mean kVp variation or error (%)						+ 05.06	

Table 1A: kVp accuracy on Shimadzu x-ray machine in facility I. This shows a maximum variation of +7 % at 100 kVp but the x-ray shows an acceptable level of kVp accuracy with mean variation of about +3.5%

kVp Station	Measured kVp							
	RMI multifunction meter readings					Mean	SD(σ)	Error(%)
70.00	72.20	72.20	71.90	71.70	71.90	71.98	0.22	0.003
Acceptable Variation or Error (%)[17]								< ±02.00

Table 1B: kVp reproducibility on Shimadzu x-ray machine. This shows a reproducibility variation of 0.003 which is below the acceptable variation of 2%. Therefore, the machine has passed the test.

kVp Station	Measured kVp						
	RMI multi function meter readings			Mean	SD(σ)	Error(%)	Tolerance (%)[15,16]
60	64.50	64.70	64.80	64.67	0.15	+07.78	< ±05.00
70	71.60	70.60	71.00	71.07	0.50	+01.52	< ±05.00
80	80.50	80.20	79.60	80.10	0.46	+00.13	< ±05.00
90	88.30	88.10	89.80	88.73	0.93	-01.41	< ±05.00
100	101.40	100.30	100.30	100.30	0.64	+00.67	< ±05.00
Mean kVp variation or error (%)						+01.74	

Table 2A: kVp accuracy on Siemens x-ray machine in facility I. This shows a maximum variation at 60 kVp and minimum variation at 100 kVp. Therefore, mean variation is within acceptable limits.

kVp Station	Measured kVp							
	RMI multifunction meter readings					Mean	SD(σ)	Error(%)
70.00	71.60	70.60	71.00	71.60	71.70	71.30	0.48	0.012
Acceptable Variation or Error (%)[17]								< ±02.00

Table 2B: kVp reproducibility on Siemens x-ray machine. This shows that the variation is within acceptable limits.

kVp Station	Measured kVp						
	RMI multi function meter readings			Mean	SD(σ)	Error(%)	Tolerance (%)[15,16]
60	61.90	62.70	63.20	62.60	0.54	+04.33	< ±05.00
70	65.50	65.00	65.20	65.23	0.21	- 06.81	< ±05.00
80	72.00	71.40	71.70	71.70	0.24	- 10.38	< ±05.00
90	78.50	77.90	78.70	78.37	0.34	- 12.93	< ±05.00
100	82.70	83.00	83.00	83.00	0.14	- 17.10	< ±05.00
Mean kVp variation or error (%)						- 08.58	

Table 3A: kVp accuracy on DM- 105N x-ray machine in facility II. This shows a maximum kVp variation of 17 at 100 and least variation at 60 kVp.

kVp Station	Measured kVp							
	RMI multifunction meter readings					Mean	SD(σ)	Error(%)
70.00	65.50	65.00	65.20	65.30	64.90	65.18	0.24	0.005
Acceptable Error or Tolerance (%)[17]								< ±02.00

Table 3B: kVp reproducibility on DM- 105N x-ray machine. This shows that the x-ray machine has passed the kVp reproducibility test.

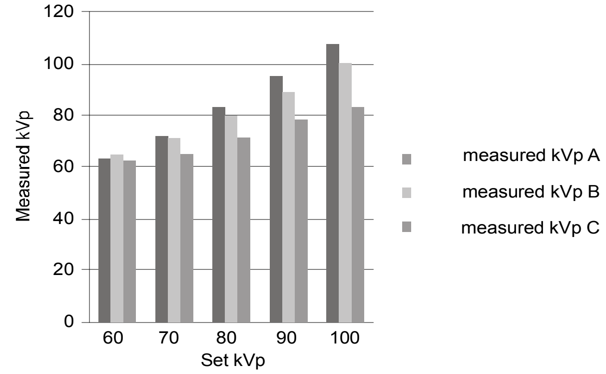

Figure 2: kVp variations compared for the different x-ray machines A - C. kVp affects the penetration of the x-rays. Variations at lower kVps would result in decreased x-ray penetration thereby increasing patient dose. Higher kVp variations would result in increased x-ray penetration thereby decreasing patient dose. However, this effect may affect the image quality leading to repeat exposure and indirectly increasing patient radiation dose.

Thickness of Aluminium (mm)	Mean universal survey meter readings (R/min)		
	(A) Shimadzu	(B) Siemens	(C) DM- 105N
01.00	0.324	0.533	0.154
02.00	0.257	0.445	0.127
03.00	0.205	0.388	0.102
04.00	0.169	0.334	0.083
05.00	0.150	0.299	-

Table 4: Filtration values for HVL estimation. This shows the various measurements at different thickness of aluminium. The measurements are plotted against the several thickness of aluminium. The universal survey meter (RADOS RDS 120) did register any reading for DM-105N at 5mm aluminium thickness.

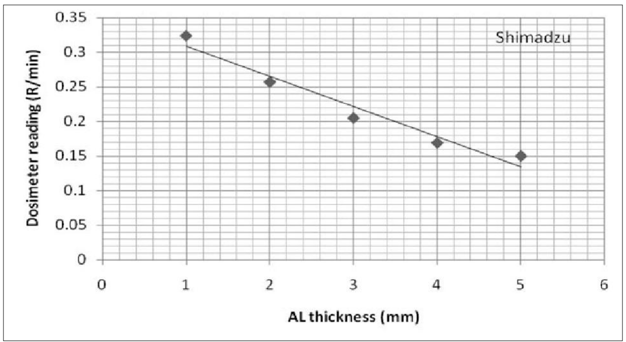

Figure 3: HVL graph for Shimadzu (x-ray unit A) and this shows a HVL of about 4.4 mm at 80 kVp. The HVL should have a minimum of 2.3 mm Aluminium thickness at 80 kVp.[19]

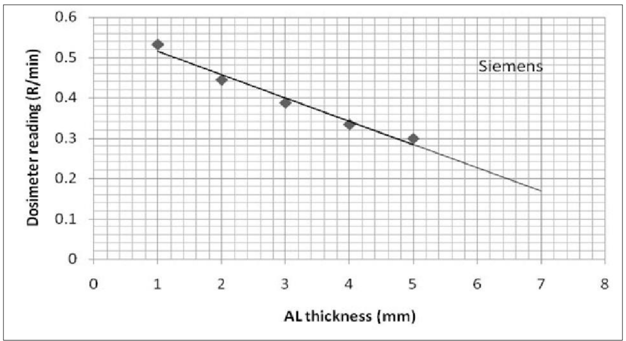

Figure 4: HVL graph for Siemens (x-ray unit B). This shows a HVL of about 5 mm at 80 kVp. The HVL should have a minimum of 2.3 mm Aluminium thickness at 80 kVp.[19]

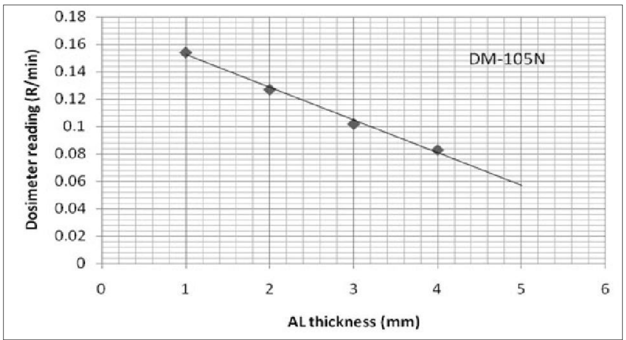

Figure 5: HVL graph for DM-105N (x-ray unit C). This shows that a HVL value of about 4 mm at 80 kVp. The HVL should have a minimum of 2.3 mm Aluminium thickness at 80 kVp.[19]

mAs Linearity of Shimadzu X-ray Machine					
	Exposure (mR)				
Exposure Factors	1st	2nd	3rd	Mean	mR/mAs
200mA,20mAs,70kVp	0.111	0.110	0.110	0.110	0.0055
400mA,40mAs,70kVp	0.224	0.225	0.224	0.224	0.0056
Linearity Variance or Error (%): 0.0045					
Acceptable Error[15] (%): < 0.1 (10%)					

Table 5: mAs /timer linearity for Shimadzu. This shows a that the variations are within acceptable limits.

mAs Linearity of Siemens X-ray Machine					
	Exposure (mR)				
Exposure Factors	1st	2nd	3rd	Mean	mR/mAs
80mA,40mAs,70kVp	0.0034	0.0035	0.0035	0.0035	0.141
160mA,80mAs,70kVp	0.0026	0.0025	0.0026	0.0026	0.210
Linearity Variance or Error (%): 0.074					
Acceptable Error15 (%): < 0.1 (10%)					

Table 6: mAs linearity for Siemens. This shows that the mAs linearity is within acceptable limits.

mAs Reciprocity of Shimadzu X-ray Machine					
	Exposure (mR)				
Exposure Factors	1st	2nd	3rd	Mean	mR/mAs
160mA,125ms,80kVp	0.146	0.145	0.145	0.145	0.00725
200mA,100ms,80kVp	0.137	0.137	0.136	0.137	0.00685
400mA,50ms,80kVp	0.147	0.147	0.147	0.147	0.00735
Reciprocity Variance or Error (%): 0.0166					
Acceptable Error[15] (%): < 0.1 (10%)					

Table 7: mAs reciprocity of Shimadzu X-ray Machine

mAs Reciprocity of Siemens X-ray Machine					
	Exposure (mR)				
Exposure Factors	1st	2nd	3rd	Mean	mR/mAs
20mA,0.70ms,80kVp	0.010	0.009	0.011	0.010	0.0007
40mA,0.33ms,80kVp	0.091	0.090	0.090	0.090	0.0064
80mA, 0.18ms,80kVp	0.298	0.300	0.300	0.300	0.0214
Reciprocity Variance or Error (%): 0.36					
Acceptable Error[15] (%): < 0.1 (10%)					

Table 8: mAs Reciprocity of Siemens X-ray Machine

Universal Survey Meter Reading (R/min)				
	Shimadzu	Siemens	DM-105N	Exposure Factors
	0.140	0.155	0.038	kVp: 80
	0.139	0.144	0.038	mA: 100
	0.141	0.155	0.037	Time(s): 0.2
	0.140	0.149	0.037	mAs: 20
	0.140	0.152	0.037	
Variance or Error (%):	0.007	0.037	0.013	
Acceptable Error15: <0.05 (5%)				

Table 9: Radiation Output Reproducibility Test; Universal survey meter (RADOS RDS 120) reading at constant kVp and mAs. This shows that all the three x-ray machines have a radiation output reproducibility values within the acceptable limits. The Siemens shows higher variation of 0.037 followed by DM-105N with 0.013.

Misalignment			
	Length (cm)	Width (cm)	Direction
SHIMADZU	0.1	0.4	Away from the Cathode (-)
SIEMENS	0.6	0.1	Towards the Cathode (-)
DM-105N	0.3	0.5	Away from the Cathode (-)
Acceptable misalignment: < 2cm (2% of 100cm) in Length and Width[20]			

Table 10: This shows misalignment of light field and the radiation emitted. All the three x-ray machines passed the test as the misalignment is within the acceptable limits in both length and width of the radiation field.

Radiation Leakage	
	Universal Survey Meter Reading(R/min)
DM-105N	0.004
SHIMADZU	0.001
SIEMENS	0.002
Acceptable Leakage[21,22]	< 0.1 R/h

Table 11: Radiation leakage test; this shows that the radiation leakages from all the x-ray machines are below the maximum acceptable value of < 0.1 at100cm. But DM-105N shows the value followed by the Siemens.

Discussion

kVp accuracy and reproducibility: (Tab. 1A) is a table of kVp accuracy of machine A (Shimadzu). It shows that the machine presented with greater ripple (error) than expected at 60, 90 and 100 kVps. This implies that the subject exposed with this machine would receive a dose higher than expected as the dose is exponential to the kVp.[23] The kVp error would also affect the image quality[16] which may necessitate the need for a repeat exposure, invariably increasing the patient radiation dose. However, the machine passed the kVp reproducibility test as shown in (Tab.1B).

Furthermore, as shown in (Tab. 2A), the Siemens machine in room B shows a promising result with an error only at 60 kVp. The kVp accuracy check conducted showed that DM-105N (in facility 2) presented with a ripple greater than the acceptable value (as shown in Tab. 3A). Therefore, the x-ray machines B presented with acceptable kVp ripple while machine A and C failed the test. This error may affect the image quality resulting to either overexposed or underexposed image which may lead to repeat exposure thereby leading to increased patient dose. Nevertheless, all three x-ray machines in the study showed acceptable kVp reproducibility (see Tab. 1B, 2B and 3B).

Filtration and half value layer HVL: It is important that x-rays produced are filtered in order to remove the soft x-rays, because if such soft x-rays are not removed, their energy would be deposited on the skin and other organs on their way thereby increasing the potential radiation risks to such tissues and organs of the body. Half value layer test is the test conducted to check if the x-rays are adequately filtered or not. (Fig. 6, 7 and 8) showed that all the x-ray machines adequately filter their x-rays as they presented with HVL values greater than the minimum value of 2.3 mm of aluminum thickness at 80 kVp.[19] Therefore, the higher the HVL above the minimum, the lower the radiation dose received.

mAs linearity and reciprocity check was performed on the two x-ray machines in facility (1), but not on the DM-105N (in facility 2). This was because the DM-105N gave little room for manipulation of exposure factors. Furthermore, the Siemens machine (in room B) failed the mAs reciprocity test as shown in (Tab.8). This means that for same choice of mAs, there is no certainty that the tube output would be similar. This would lead to more repeat exposure thereby increasing the risk for stochastic effect of radiation.[24]

Radiation out-put reproducibility: All the three machines passed the radiation out-put reproducibility tests (see Tab. 9). This implies that for a particular selection of exposure factors, if such factors are chosen in the future, similar exposure would result. Therefore, if the exposure factors used are recorded, in the future, such factors could still be used by the operator of the x-ray. This would invariably reduce repeat exposure for the patient thereby reducing the radiation dose received.

Beam misalignment test: This test was performed to check if the radiation beam by the x-ray machine is delineated by the light beam. All the three x-ray machines presented with acceptable misalignments of less than 2 cm (see table 10), that is 2 percent of the FFD. Beam misalignment may be as a result of dislodgement of the mirror in the light beam diaphragm; which may result in cut off of an anatomical area of interest or over collimation in order to include the needed anatomical area thereby including some unneeded anatomical area. Consequently, this may lead to repeat radiation exposure when there is cut off of anatomical area of interest; leading to more dose load on the patient. In a situation where more anatomical area is included in order to image the needed anatomical area; more scatter radiation would be generated which would degrade the radiographic image quality.[25]

This study has revealed that x-ray machines A, B and C passed the total QC tests with 87.5%, 87.5% and 62.5% respectively. Conducting a periodic QC tests would reveal the fault in an x-ray machine thereby requiring the attention of a service engineer. Therefore, knowing the working condition of the x-ray machine is very vital to ensuring that there are no unnecessary repeat exposures of radiographic procedures which invariably would increase the patient and staff radiation dose. Furthermore, conducting a quality assurance program is prime in ensuring the radiation safety of patient and staff.

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