



Research Article

Evaluation of mAs Linearity, kVp Accuracy, and Reproducibility in Selected X-ray Diagnostic Facilities in Freetown

Saidu Kamara^{1, 2, *} ¹Faculty of Engineering, Ernest Bai Koroma University of Science and Technology, Magburaka, Sierra Leone²Nuclear Safety and Radiation Protection Authority, Ministry of Environment, Freetown, Sierra Leone

Abstract

Quality control in medical radiology is a process used by a regulatory authority to evaluate the performance of a diagnostic X-ray machine, including acceptable limits and the actions necessary to meet regulatory requirements. This study evaluates the radiation dose outputs of X-ray equipment in diagnostic medical hospitals by measuring mAs linearity, kVp accuracy, and reproducibility as quality control parameters to ensure that radiation doses administered to patients meet standard regulatory requirements. Radiation measuring instruments were used in this work to measure mAs, kVp accuracy, and reproducibility outputs for five (5) medical diagnostic X-ray machines. The detector was placed on the couch at a distance of 100 cm from the collimator to take measurements for each parameter under investigation. Dose rate measurements for each parameter were recorded one at a time. The mathematical equations for mAs linearity, kVp accuracy, and reproducibility were used to compute the linearity coefficient, percentage error, and coefficient of variation. The computed figures for mAs linearity for the five X-ray machines show that four (4) passed and one fell below the allowable limit. Data for kVp accuracy indicate that three of the machines are within the allowable limits and two (2) failed, while the calculated values for reproducibility show that only two (2) machines passed the tests. The study generates empirical quality control data rarely reported in X-ray diagnostic centers. It verifies the linearity coefficient, percentage kVp error, and the coefficient of variation with practical knowledge in radiology studies. Additionally, it provides a systematic mathematical approach to compute mAs linearity, kVp accuracy, and reproducibility for teaching radiology in non-diagnostic laboratory settings.

Keywords

kVp Accuracy, mAs Linearity, Quality Control, Radiology, Reproducibility, X-ray

1. Introduction

The global implementation of health services has improved rapidly, but much more remains to be addressed, especially the quality of services due to decentralization. Public health

and the quality of life of people will be improved by increasing the quality and efficiency of health services [1]. The quality assurance policy in healthcare services serves as a guide for implementing quality healthcare services [2]. Radiology is

*Correspondence: Saidu Kamara (ksaidu2013@gmail.com)

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a health service meant to support the quality of health. The ability and quality of service vary in both government and private radiological health facilities and have not fully met the standard regulatory requirements. Quality control tests are normally conducted so that radiological facilities meet the regulatory requirements [3-6]. A compliance test in a diagnostic health facility is carried out to make sure that X-ray machines meet radiation safety requirements and provide accurate information [3, 7-11]. Precise and accurate patient diagnosis is the main objective for any quality assurance program at the installation of a radiology facility [6, 12, 13] and comprehensively involves reducing radiation exposure, improving diagnostic images, and reducing costs.

Quality in diagnostic radiology is when the expected objectives or outputs are met and always align with new developments in professional knowledge [14-18]. The inputs, process, and output components must be highlighted/detailed in the quality assurance program. One of the quality assurance activities is quality control. Studies have reported the significance of quality control tests in diagnostic radiology to ensure accurate exposure parameters, production of quality images, and radiation protection of patients in line with acceptable international standards and the regulations of national regulatory bodies. The problems of quality control of diagnostic X-ray machines are common in developing countries such as Tanzania, Nigeria, Sierra Leone, etc according to various research evidence. The main objective of this research is to evaluate the reproducibility, kVp accuracy, and mAs linearity parameters in some X-ray diagnostic facilities in the capital city, Freetown, Sierra Leone. Reproducibility highlights the X-ray machine's consistency. It is used to check the consistency of the radiation output [19-22]. This is done by keeping the mA and time fixed and measuring the radiation output at various kV settings. kVp accuracy is the accelerating voltage. kVp stands for kilovoltage peak, and it is the maximum voltage difference between the cathode and the anode in an X-ray tube [23-25]. The electrons are accelerated by this voltage from the cathode to the anode, which controls the energy (quality) and the penetration of the resulting X-ray beam; no X-rays would be produced in the absence of this voltage. An increase in kVp increases the average energy of the photons. The number of photons produced is also determined by the kVp. The higher the kVp, the higher the number of photons produced. Increasing kVp increases the beam's quality and quantity, as well as the patient dose and receptor exposure [26-31]. The quality of the X-ray beam and exposure to the patient are affected by the peak potential of the X-ray generator. The tube potential is assessed to make sure that the resulting kVp is very close to the one set on the equipment by the operator of the X-ray equipment. A linearity test is conducted to verify the linearity of the radiation output with respect to changes in timer stations, while maintaining the mA station constant at a particular kV station [32-35]. The purpose of performing linearity tests is to monitor the patient dose and image quality [36, 37]. Variation in output intensity during diagnostic exposures can result in

unnecessary dose to the patient due to repeats from poor-quality images [38]. While performing this test, the assumption is that every other factor, such as kVp and timer, is working accurately. It is important to perform QC tests on the kVp as well as the timer before completing the linearity test, as if there are variations in linearity, mAs may not be the culprit [39-42]. Inaccurate performance from the kVp meter and X-ray timer can also produce the same results. Keeping exposure time and kVp constant, radiation output is measured at different mA stations. Measurement for the mA loading station is to be repeated a number of times each to eliminate statistical errors. Radiation output readings of each mA loading station are averaged, and the coefficient of linearity (CoL) is evaluated from average mR/mAs or mGy/mAs [43].

The use of radiation in medical applications has rapidly increased over the years. One major public exposure to radiation is diagnostic X-ray examinations, and it is the largest man-made source of ionizing radiation in the world [44-48]. The most commonly used X-rays for medical imaging are X-ray radiography, computed tomography (CT), mammography, angiography, and fluoroscopy. Medical exposures can best be justified and optimized by adequately implementing Quality Control (QC) programs [49-51]. In Sierra Leone, Diagnostic X-ray radiography is the most commonly used ionizing radiation in medical facilities and has played a key role in diagnosing diseases, injuries, and in oncology (radiation therapy). The availability and utilization of X-ray equipment in both government and private health facilities are increasing globally. To prevent high doses, radiation leakage, and the damaging effects of radiation on the public and occupationally exposed workers (radiation workers), it is essential to maintain adequate quality control (QC) standards in X-ray examinations.

2. Materials and Methods

In general, the materials used in the process included a survey meter, personal radiation detectors (PRD), quality control kits (tape rule, PTW Diavolt kVp and dose meter, and cone), control console, and a collimator. Radiographic tests/measurements of three major quality control parameters (milliampere-seconds (mAs) linearity, kilovoltage peak (kVp) accuracy, and reproducibility) were carried out on five (5) X-ray machines in different diagnostic hospitals in Freetown. Measurements of the three sets of parameters were performed by placing the detector (kVp diavolt dose meter) on the couch at a distance of 100 cm (1m) from the collimator (source). Before making the exposures, the collimator shutters were fully closed, and the X-ray tube was pointed downward. The mAs and kVp values for the three different parameters (reproducibility, kVp accuracy, and mAs linearity) were selected for all X-ray equipment at the different medical facilities. The selected mAs and kVp reproducibility values are unique for four (4) of the X-ray machines, with one X-ray machine showing a variation in its selected mAs value relative to the others. X-ray kVp reproducibility tests require keeping kVp and mAs

exposure parameters fixed across consecutive measurements to assess output stability. For kVp-accuracy dose measurements, the set mAs was kept constant across various kVp values. A similar procedure was done for mAs linearity, where kVp was kept constant at different mAs. The dose measurements for the different parameters were recorded and tabulated for each X-ray equipment. The data obtained for each parameter were then computed and analyzed.

2.1. Mathematical Equations

Below are the three quality control parameters and their mathematical expressions used to compute the collected data:

2.1.1. mAs Linearity

The coefficient of linearity (CoL) is evaluated from average mR/mAs or mGy/mAs as follows:

$$mAs \text{ Linearity} = \frac{maxDose - minDose}{maxDose + minDose}$$

Tolerance: Coefficient of timer linearity $\leq \pm 0.1$ or 10%

2.1.2. kVp Accuracy

$$Percentage \text{ kVp error} = \frac{kVp_{measured} - kVp_{set}}{kVp_{set}} \times 100\%$$

The allowed standard kVp limit = ± 5

2.2.3. Reproducibility

The average (X) of mR/mAs or mGy/mAs is calculated. The consistency at each kV setting is determined by calculating the coefficient of variation.

$$Coefficient \text{ of Variation (CV)} = \frac{Standard \text{ Deviation } (\sigma)}{Mean (\bar{x})} \times 100\%$$

$$Standard \text{ Deviation } (\sigma) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

The standard reproducibility limit for a diagnostic X-ray machine = $\pm 5\%$

The table below provides key information to describe the characteristics of the five X-ray machines:

Table 1. Characteristics of X-ray machines.

No	Manufacturer	Model	Serial No	Date of manufacture/ Installation	Max voltage	Permanent filtration
1	X-ray Tube					
	Toshiba Electron Tubes and Devices Co., Ltd.	E7843X	11G485	N/A	150 kVp	1.3 Al/75
	Collimator					
2	GE HUALUN MEDICAL SYSTEMS Co. Ltd	5189248	81622HL	December, 2011	N/A	N/A
	X-ray Tube					
	Nanjing Perlove Medical Equipment Co. Ltd	HD052-30-50/125	1111132	2014	125kV	2.5 mm Al
3	Collimator					
	Nanjing Perlove Medical Equipment Co. Ltd	N/A	1016	N/A		1.5 mm Al
	X-ray Tube					
4	IMD Generators s.r.l	E-100R HF XR03 C	11/14-12346	December, 2012	80 kVp	1.8 mm Al
	Collimator					
	Ralco s.r.l	R105	1500471	January, 2015	N/A	2 mm Al/75
4	X-ray Tube					
	SMAM arl	MX 4000Dual	021036	April, 2002	125	3.5 mm Al
	Collimator					

No	Manufacturer	Model	Serial No	Date of manufacture/ Installation	Max voltage	Permanent filtration
5	Ralco X-ray Tube	R221/A	026/123	March, 2008		2 mm Al
	Nanjing Perlove Medical Equipment Co. Ltd	N/A	A1411138	December, 2014	110 kV	2.5 mm Al
	Collimator Nanjing Perlove Medical Equipment Co. Ltd	X-101A	1401199	December, 2014	N/A	1.2 mm Al

3. Results and Discussions

3.1. Results

3.1.1. mAs Linearity Tests

Table 2. mAs linearity measurements for X-ray 1.

Set mAs	Set kVp	Dose (μGy)	Convert μGy to mGy ($\frac{\mu\text{Gy}}{1000}$)	$\frac{\text{mGy}}{\text{mAs}}$
5	80	194.75	$\frac{194.75}{1000} = 0.19475$	$\frac{0.19475}{5} = 0.03895$
10	80	374.3	$\frac{374.3}{1000} = 0.3743$	$\frac{0.3743}{10} = 0.03743$
40	80	1311	$\frac{1311}{1000} = 1.311$	$\frac{1.311}{40} = 0.032775$
60	80	1984.2	$\frac{1984.2}{1000} = 1.9842$	$\frac{1.9842}{60} = 0.03307$

$$mAs \text{ Linearity} = \frac{\text{maxDose} - \text{minDose}}{\text{maxDose} + \text{minDose}} = \frac{0.03895 - 0.032775}{0.03895 + 0.032775} = 0.08609 \approx 0.086$$

Table 3. mAs linearity measurements for X-ray 2.

Set mAs	Set kVp	Dose (μGy)	Convert μGy to mGy ($\frac{\mu\text{Gy}}{1000}$)	$\frac{\text{mGy}}{\text{mAs}}$
5	80	267.0	$\frac{267.0}{1000} = 0.267$	$\frac{0.267}{5} = 0.0534$
10	80	569.4	$\frac{569.4}{1000} = 0.5699$	$\frac{0.5699}{10} = 0.0569$
20	80	1197.5	$\frac{1197.5}{1000} = 1.1975$	$\frac{1.1975}{20} = 0.0599$
32	80	1932.5	$\frac{1932.5}{1000} = 1.932$	$\frac{1.932}{32} = 0.0604$
40	80	2458.5	$\frac{2458.5}{1000} = 2.459$	$\frac{2.459}{40} = 0.0615$

$$mAs \text{ Linearity} = \frac{\text{maxDose} - \text{minDose}}{\text{maxDose} + \text{minDose}} = \frac{0.0615 - 0.0534}{0.0615 + 0.0534} = \frac{0.0081}{0.1149} = 0.07049 \approx 0.071$$

Table 4. mAs linearity measurements for X-ray 3.

Set mAs	Set kVp	Dose (μGy)	Convert μGy to mGy ($\frac{\mu Gy}{1000}$)	$\frac{mGy}{mAs}$
5	80	244.2	$\frac{245.2}{1000} = 0.2452$	$\frac{0.2452}{5} = 0.04904$
10	80	460.2	$\frac{460.2}{1000} = 0.46017$	$\frac{0.46017}{10} = 0.04602$
20	80	933.7	$\frac{933.7}{1000} = 0.9337$	$\frac{0.9337}{20} = 0.04669$
32	80	1507.7	$\frac{1507.7}{1000} = 1.5077$	$\frac{1.5077}{32} = 0.04712$

$$mAs \text{ Linearity} = \frac{\max Dose - \min Dose}{\max Dose + \min Dose} = \frac{0.0490 - 0.0460}{0.0490 + 0.0460} = \frac{0.0030}{0.0950} = 0.03158 \approx 0.032$$

Table 5. mAs linearity measurements for X-ray 4.

Set mAs	Set kVp	Dose (μGy)	Convert μGy to mGy ($\frac{\mu Gy}{1000}$)	$\frac{mGy}{mAs}$
5	80	321.93	$\frac{321.93}{1000} = 0.32193$	$\frac{0.32193}{5} = 0.0644$
10	80	626.6	$\frac{626.6}{1000} = 0.6266$	$\frac{0.6266}{10} = 0.0627$
20	80	1206	$\frac{1206}{1000} = 1.206$	$\frac{1.206}{20} = 0.0603$
32	80	2094	$\frac{2094}{1000} = 2.094$	$\frac{2.094}{32} = 0.0654$

$$mAs \text{ Linearity} = \frac{\max Dose - \min Dose}{\max Dose + \min Dose} = \frac{0.0654 - 0.0603}{0.0654 + 0.0603} = \frac{0.0051}{0.1257} = 0.04057 \approx 0.041$$

Table 6. mAs linearity measurements for X-ray 5.

Set mAs	Set kVp	Dose (μGy)	Convert μGy to mGy ($\frac{\mu Gy}{1000}$)	$\frac{mGy}{mAs}$
12	100	462.8	$\frac{462.8}{1000} = 0.4628$	$\frac{0.4628}{12} = 0.038557$
16	100	758	$\frac{758}{1000} = 0.758$	$\frac{0.758}{16} = 0.047375$
20	100	781.1	$\frac{781.1}{1000} = 0.7811$	$\frac{0.7811}{20} = 0.039055$
25	100	711.1	$\frac{711.1}{1000} = 0.7111$	$\frac{0.7111}{25} = 0.02844$

$$mAs \text{ Linearity} = \frac{\max Dose - \min Dose}{\max Dose + \min Dose} = \frac{0.039055 - 0.02844}{0.039055 + 0.02844} = \frac{0.0106}{0.0675} = 0.15727 \approx 0.157$$

3.1.2. kVp accuracy Tests

Table 7. kVp accuracy measurements for X-ray 1.

Set mAs	Set kVp	Max. kVp measured	% kVp error = $\frac{kVp_{measured} - kVp_{set}}{kVp_{set}} \times 100\%$
8	50	60.5	$\%kVp \text{ error} = \frac{60.5 - 50}{50} \times 100\% = 21.00\%$

Set mAs	Set kVp	Max. kVp measured	% <i>kVp</i> error = $\frac{kVp_{measured} - kVp_{set}}{kVp_{set}} \times 100\%$
8	60	68.3	% <i>kVp</i> error = $\frac{68.3-60}{60} \times 100\% = 13.00\%$
8	90	93.0	% <i>kVp</i> error = $\frac{60.5-50}{50} \times 100\% = 3.33\%$
8	100	102.7	% <i>kVp</i> error = $\frac{60.5-50}{50} \times 100\% = 2.70\%$
kVp accuracy =			$\frac{21.00+13.83+3.33+2.70}{4} = 10.21 \approx 10\%$

Table 8. *kVp* accuracy measurements for X-ray 2.

Set mAs	Set kVp	Max. kVp measured	% <i>kVp</i> error = $\frac{kVp_{measured} - kVp_{set}}{kVp_{set}} \times 100\%$
8	50	55.55	% <i>kVp</i> error = $\frac{55.55-50}{50} \times 100\% = 11.10\%$
8	60	67.00	% <i>kVp</i> error = $\frac{67.0-60}{60} \times 100\% = 11.60\%$
8	70	79.30	% <i>kVp</i> error = $\frac{79.3-70}{70} \times 100\% = 13.28\%$
8	80	81.80	% <i>kVp</i> error = $\frac{81.8-80}{80} \times 100\% = 2.25\%$
8	90	91.95	% <i>kVp</i> error = $\frac{91.95-90}{90} \times 100\% = 2.17\%$
Average kVp error =			$\frac{11.10+11.60+13.28+2.25+2.17}{5} = 8.08 \approx 8\%$

Table 9. *kVp* accuracy measurements for X-ray 3.

Set mAs	Set kVp	Max. kVp measured	% <i>kVp</i> error = $\frac{kVp_{measured} - kVp_{set}}{kVp_{set}} \times 100\%$
8	60	63.23	% <i>kVp</i> error = $\frac{63.23-60}{60} \times 100\% = 5.38\%$
8	70	75.94	% <i>kVp</i> error = $\frac{75.94-70}{70} \times 100\% = 8.49\%$
8	80	87.38	% <i>kVp</i> error = $\frac{87.38-80}{80} \times 100\% = 9.22\%$
8	90	88.37	% <i>kVp</i> error = $\frac{88.37-90}{90} \times 100\% = 1.81\%$
8	100	98.37	% <i>kVp</i> error = $\frac{98.37-100}{100} \times 100\% = 1.63\%$
Average kVp error =			$\frac{5.38+8.49+9.22+1.81+1.63}{5} = 5.306 \approx 5\%$

Table 10. *kVp* accuracy measurements for X-ray 4.

Set mAs	Set kVp	Max. kVp measured	% <i>kVp</i> error = $\frac{kVp_{measured} - kVp_{set}}{kVp_{set}} \times 100\%$
8	60	60.67	% <i>kVp</i> error = $\frac{60.67-60}{60} \times 100\% = 1.12\%$
8	70	71.60	% <i>kVp</i> error = $\frac{71.6-70}{70} \times 100\% = 2.29\%$

Set mAs	Set kVp	Max. kVp measured	% <i>kVp error</i> = $\frac{kVp_{measured} - kVp_{set}}{kVp_{set}} \times 100\%$
8	80	83.30	% <i>kVp error</i> = $\frac{83.3-80}{80} \times 100\% = 4 \cdot 13\%$
8	90	90.23	% <i>kVp error</i> = $\frac{90.23-90}{90} \times 100\% = 0 \cdot 65\%$
8	100	100.47	% <i>kVp error</i> = $\frac{100.47-100}{100} \times 100\% = 0 \cdot 47\%$
Average kVp error =			$\frac{1.12+2.29+4.13+0.65+0.47}{5} = 1.65 \approx 1.7\%$

Table 11. *kVp accuracy measurements for X-ray 5.*

Set mAs	Set kVp	Max. kVp measured	% <i>kVp error</i> = $\frac{kVp_{measured} - kVp_{set}}{kVp_{set}} \times 100\%$
12	70	69.8	% <i>kVp error</i> = $\frac{69.8-70}{70} \times 100\% = -0 \cdot 28\%$
12	80	79.5	% <i>kVp error</i> = $\frac{79.5-80}{80} \times 100\% = -0 \cdot 01\%$
12	90	89.7	% <i>kVp error</i> = $\frac{89.7-90}{90} \times 100\% = -0 \cdot 33\%$
12	100	99.8	% <i>kVp error</i> = $\frac{99.8-100}{100} \times 100\% = -0 \cdot 20\%$
kVp accuracy =			$\frac{(-0.28)+(-0.01)+(-0.33)+(-0.20)}{4} = -0.21 \approx -0.2\%$

3.1.3. Reproducibility Tests

Table 12. *Reproducibility measurements for X-ray 1.*

Set mAs	Set kVp (<i>x</i>)	Exposure measurements obtained		<i>x</i> - <i>x</i> ₁	(<i>x</i> - <i>x</i> ₁) ²
		max kVp	Max. Mean kVp (<i>x</i> ₁)		
8	70	77.0	77.0	-7	49
8	70	76.0	76.1	-6	36
8	70	77.0	77.1	-7	49
8	70	77.8	77.9	-7.8	60.84
			$\sum x_1 = 307.8$	$\sum (x_i - x_1)^2 = 194.84$	

$$\text{Standard Deviation } (\sigma) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - x_1)^2} = \sqrt{\frac{1}{4-1} (194.84)} = 8.05$$

$$\text{Mean } (\bar{x}) = \frac{\sum x_1}{n} = \frac{307.8}{4} = 76.95$$

$$\text{Coefficient of Variation} = \frac{S.D. (\sigma)}{\text{Mean } (\bar{x})} \times 100\% = \frac{8.05}{76.95} \times 100\% = 10\%$$

Table 13. Reproducibility measurements for X-ray 2.

Set mAs	Set kVp (x)	Exposure measurements obtained		$x - x_1$	$(x - x_1)^2$
		max kVp	Max. Mean kVp (x_1)		
9	70	77.1	76.1	-6.1	37.21
9	70	76.0	76.0	-6.0	36.00
9	70	77.0	77.0	-7.0	49.00
9	70	77.8	77.8	-7.8	60.84
9	70	77.8	77.8	-7.8	60.84
			$\Sigma x_1 = 384.73$	$\Sigma(x - x_1)^2 = 243.89$	

$$\text{Standard Deviation } (\sigma) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - x_1)^2} = \sqrt{\frac{1}{5-1} (194.84)} = 7.80$$

$$\text{Mean } (\bar{x}) = \frac{\Sigma x_1}{n} = \frac{384.73}{5} = 76.95$$

$$C V = \frac{S D (\sigma)}{\text{Mean } (\bar{x})} \times 100\% = \frac{7.80}{76.95} \times 100\% = 0.10 \times 100\% = 10\%$$

Table 14. Reproducibility measurements for X-ray 3.

Set mAs	Set kVp (x)	Exposure measurements obtained		$x - x_1$	$(x - x_1)^2$
		max kVp	Max. Mean kVp (x_1)		
8	70	79.3	79.3	-9.3	86.49
8	70	74.7	74.7	-4.7	22.09
8	70	75.0	75.0	-5.0	25.00
8	70	75.5	75.5	-5.5	30.25
8	70	75.2	75.2	-5.2	27.04
			$\Sigma \bar{x}_1 = 379.7$	$\Sigma(x - x_1)^2 = 190.87$	

$$\text{Standard Deviation } (\sigma) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - x_1)^2} = \sqrt{\frac{1}{5-1} (190.87)} = 6.91$$

$$\text{Mean } (\bar{x}) = \frac{\Sigma x_1}{n} = \frac{379.7}{5} = 75.94$$

$$C V = \frac{S D (\sigma)}{\text{Mean } (\bar{x})} \times 100\% = \frac{6.91}{75.94} \times 100\% = 0.090 \times 100\% = 9\%$$

Table 15. Reproducibility measurements for X-ray 4.

Set mAs	Set kVp (x)	Exposure measurements obtained		$x - x_1$	$(x - x_1)^2$
		max kVp	Max. Mean kVp (x_1)		
8	70	72.1	72.1	-2.1	4.41

Set mAs	Set kVp (x)	Exposure measurements obtained		$x - x_1$	$(x - x_1)^2$
		max kVp	Max. Mean kVp (x_1)		
8	70	71.3	71.3	-1.3	1.69
8	70	71.4	71.4	-1.4	1.96
$\sum x_1 = 214.8$				$\sum (x_i - x_1)^2 = 8.06$	

$$\text{Standard Deviation } (\sigma) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - x_1)^2} = \sqrt{\frac{1}{3-1} (8.06)} = 2.01$$

$$\text{Mean } (\bar{x}) = \frac{\sum x_1}{n} = \frac{214.8}{3} = 71.6$$

$$C V = \frac{S D (\sigma)}{\text{Mean } (\bar{x})} \times 100\% = \frac{2.01}{71.6} \times 100\% = 0.028 \times 100\% = 2.8\%$$

Table 16. Reproducibility measurements for X-ray 5.

Set mAs	Set kVp (x)	Exposure measurements obtained		$x - x_1$	$(x - x_1)^2$
		max kVp	Max. Mean kVp (x_1)		
8	70	71.4	70.7	-0.7	0.49
8	70	71.4	70.7	-0.7	0.49
8	70	71.4	69.1	0.9	0.81
8	70	71.2	69.8	0.2	0.04
8	70	71.3	69.1	0.9	0.81
$\sum x_1 = 349.4$				$\sum (x_i - x_1)^2 = 2.64$	

$$\text{Standard Deviation } (\sigma) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - x_1)^2} = \sqrt{\frac{1}{5-1} (2.64)} = 0.81$$

$$\text{Mean } (\bar{x}) = \frac{\sum x_1}{n} = \frac{349.4}{5} = 69.88$$

$$C V = \frac{S D (\sigma)}{\text{Mean } (\bar{x})} \times 100\% = \frac{0.81}{69.88} \times 100\% = 0.012 \times 100\% = 1.2\%$$

Summary data table

Table 17. Summary data table.

QC Parameters	Acceptable limits	1	2	3	4	5
mAs Linearity	$\leq \pm 0.1$ or 10%	0.086	0.071	0.032	0.041	0.157
kVp Accuracy	$\leq \pm 5\%$	10	8	5	1.7	0.2
Reproducibility	$\leq \pm 5\%$	10	10	9	2.8	1.2

3.2. Discussion

Three quality control tests were carried out on five (5) X-ray machines in selected diagnostic medical hospitals in Freetown. Before the tests, a radiation survey was carried out around the X-ray installation at various locations, such as the door, console, patient waiting area, and lead barrier, to ensure the safe protection of workers, the general public, and the environment. The calculated figures obtained for mAs linearity are 0.086, 0.071, 0.032, 0.041, and 0.2. The allowable limit is $\leq \pm 0.1$ or 10%, which indicates that four (4) X-ray machines passed and one (1) failed the mAs linearity test. The kVp accuracy results are 10%, 8%, 5%, 1.7%, and 0.2%. The acceptable limit for kVp accuracy is $\leq \pm 5$. This means that three (3) machines passed the accuracy test and two (2) failed. Further, the computed kVp reproducibility results for all machines are 10%, 10%, 9%, 2.8%, and 1.2%. The allowable limit is $\leq \pm 5$, indicating that only two of the X-ray machines passed the reproducibility test. Quality assurance in a diagnostic radiological facility ensures that exposure parameters are calibrated, that the X-ray machine's functional performance is adequate, and that radiation safety is maintained within the X-ray room. This is normally done to obtain the optimal diagnostic data at the lowest risk to the patient. Routine checks are carried out to ensure that the values of the radiation output by the X-ray equipment are within the allowable limit specified by the regulatory authority. Quality assurance tests are performed at regular intervals (once a year) and at major repairs of the X-ray machine, and should be done by a qualified service engineer, diagnostic medical physicist, or a well-trained QC technologist at a facility approved by the regulatory body. The failure of some machines is due to extremely high kVp, which increases the penetration of the beam and affects the image contrast, while a lower kVp leads to inadequate beam penetration and increased image noise. Incorrect kVp leads to inappropriate patient exposure and possibly repeat examinations. Reproducibility shows the highest failure rate because it is sensitive to instability in the X-ray machine. This could be due to such factors as machine age, inadequate maintenance culture, or calibration. Equipment age may be associated with deterioration of generator components, X-ray tubes, exposure-control systems, and electrical components. Inadequate preventive maintenance may accelerate such deterioration. Research conducted on medical X-ray machines in Tanzania revealed that 85.71% and 71.43% passed the reproducibility and mAs linearity tests, respectively. A report from Nigeria indicated that out of the ten (10) X-ray equipment evaluated for kVp accuracy, reproducibility, mAs linearity, and beam alignment tests, six (6) were within the acceptable limits and four (4) failed the quality control parameters. However, there is no evidence of published work that specifically highlights the quality control test on diagnostic X-rays in Freetown, Sierra Leone, that focuses on measuring the kVp accuracy, mAs linearity, and reproducibility. The significance of evaluating the five facilities is based on them serving as a baseline assessment or evidence

that can support the development of quality control programs, maintenance planning, regulatory control, and a national X-ray diagnostic survey in the future.

Accuracy evaluates whether the measured output corresponds to the selected value, whereas reproducibility evaluates whether the equipment can repeatedly produce essentially the same output under identical exposure conditions. A failure in kVp reproducibility causes a variation in radiation output and appearance of the image, which may lead to repeat examinations. Poor kVp reproducibility is an indication that identical console settings may produce different X-ray tube voltages on repeated exposures. Poor mAs linearity shows that changes in mAs do not lead to proportional changes in radiation output, hence reducing the prediction of patient dose and image receptor exposure. Failure of quality control parameters leads to non-diagnostic images that require exposure to be repeated, causing additional patient radiation exposure. This also increases the workload of radiologists and radiographers. A consistent quality control failure indicates a deterioration of the X-ray machine, which requires preventive or corrective maintenance.

Unprecedentedly, this research provides a baseline assessment of the performance of quality control parameters of selected diagnostic X-ray machines in Freetown, Sierra Leone, where there is currently no empirical evidence of published work on the quality control performance of X-ray machines. The evaluation of mAs linearity, kVp accuracy, and reproducibility provides initial evidence on the functional performance of diagnostic X-ray equipment, which can be used as a baseline to compare future quality control assessments of medical diagnostic facilities. According to the findings, the failure of quality control parameters of some X-rays affects or has implications on patient dose, image quality, and equipment maintenance. This work is, however, limited to only five selected diagnostic facilities in Freetown, focusing only on three selected parameters, and did not assess other significant quality control parameters such as half-value layer, radiation output, exposure-time accuracy, beam alignment, collimation, image quality and patient entrance-surface dose.

4. Conclusion

Quality control tests were carried out on five (5) different X-ray equipment in selected diagnostic hospitals in Freetown. Three parameters (mAs Linearity, kVp accuracy, and reproducibility) were evaluated to determine whether the radiation dose to patients meets the standard regulatory requirement. The computed figures show that four results for the mAs linearity test are within the tolerance level. Three values for kVp accuracy passed, while two are below the limits. For reproducibility, two X-ray machines passed the test, and three failed. Inconsistency in radiation output may lead to high radiation exposure and poor or degraded image quality. Corrective actions are required for all X-ray machines, with special

emphasis on equipment with extremely inadequate/default reproducibility results. Future work will capture a good number of diagnostic X-ray facilities in Freetown and other parts of the country to establish a national baseline for the operational performance of X-ray equipment in Sierra Leone. Further studies should also incorporate additional quality-control parameters such as exposure-time accuracy, half-value layer, beam alignment, collimation, image-quality assessment, etc. The establishment of a national database for diagnostic X-ray QC results would also support regulatory monitoring, preventive maintenance, and evidence-based radiation protection programs.

Abbreviations

PRD	Personal Radiation Detector
mAs	Milliampere seconds
kVp	Kilovoltage
CoL	Coefficient of Linearity
mR	Milliroentgen
SD (σ)	Standard Deviation
CV	Coefficient of Variation
μ Gy	Microgray
mGy	Milligray

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Author Contributions

Saidu Kamara: Conceptualization, Data curation, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing

Conflicts of Interest

The author declares no conflicts of interest.

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