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Evaluation of Quality Control Standards in Medical Diagnostic X-Ray Facilities in North-Eastern Nigeria

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ABSTRACT
A strong QC program is required to optimize diagnostic radiology practices with minimal hazards not only to the patient but also to the radiographers. This research aims to evaluate the level of quality control programs in medical diagnostic X-ray facilities in the Northeastern region of Nigeria. Data from10 different tertiary hospitals were collated and analyzed. The assessment covers kVp accuracy, reproducibility, mAs linearity, and beam alignment. The kVp station was kept at the ranges of 70 -120, and three different exposures were made, while the tolerance limits were set at; kVp = ±5%, mAs linearity coefficient (LC) ≤ 10%, and beam alignment = ≤ 2%. Findings of the study discovered significant variations across the 10 studied X-ray units. The results indicate that six units (1, 3, 5, 7, 8, and 10) consistently met the acceptable standards for kVp reproducibility, mAs linearity, and beam alignment, as their coefficient of variation (CV%) and error% were all below 2.0, while their mAs linearity coefficients remained under the 10% threshold. Additionally, their beam alignment tolerance limits fell within the recommended limit of 2%. However, the results indicate that four X-ray units (2, 4, 6, and 9) failed the X-ray checks, as their kVp reproducibility exceeded the acceptable limit of 5%, mAs linearity coefficients surpassed10%, and their beam alignment exceeded the recommended tolerance limit of 2%. Also, the results revealed a strong correlation between machine lifespan and quality control performance. The study concluded by suggesting regular calibration of radiological equipment's and areas for future work.

Keywords:
Quality control,
kVp,
mAs,
Beam alignment,
X-ray

INTRODUCTION

Since Sir Wilhelm Conrad Roentgen's discovery of X-rays in 1895, their medical applications have been of immense value not only to medical professionals but also to the general public (Abd-Alla et al., 2019). A significant portion of critical medical decisions rely heavily on X-ray imaging, which is crucial for the early detection of various diseases. X-rays are used extensively to diagnose various health conditions and help medical professionals confirm or rule out possible diagnoses. The risk associated with radiation exposure from diagnostic X-rays is minimal compared to the benefits that precise diagnosis and accurate treatment can offer (Chauhan et al., 2024; Hlabangana et al., 2021). The extensive use of X-rays in patient diagnosis and treatment has led to an increase in radiation exposure. Although the clinical use of X-rays is governed by dose optimization and the As-Low-As-Reasonably-Achievable (ALARA) principle, more non-invasive techniques have been proposed. Quality Assurance (QA) plays a crucial role in radiological protection. Since majority of procedures leading to medical exposure are evidently justified and primarily benefit the individuals undergoing them, optimization of protection in medical exposure has received less focus compared to other uses of radiation sources. Consequently, there is significant potential for reducing doses in diagnostic radiology (Filippou et al., 2024; Hussain et al., 2022). QA includes both quality control (QC) methods and administrative procedures. Quality control is considered to be part of QA program and comprises; techniques for testing, monitoring, and maintaining the technical components of an X-ray system. These QC methods primarily focused directly on equipment that affects image quality. Quality assurance in diagnostic X-ray practices is guided by the "Basic Safety Standards (BSS) and recommendations of the International Commission on Radiological Protection (ICRP), including the use of diagnostic reference levels (DRLs) for patients" as specified in ICRP Report No. 46 of 1966 (Wrixon, 2008).

Although ionizing radiation in diagnostic X-rays offers significant clinical benefits. However, prolonged radiation exposure to patients continues to be a concern for medical professionals. Several studies have shown that prolonged exposure from diagnostic imaging has been knowing to cause various health problems, such as an increased risk of cancer and acute radiation injuries. These and other problems are usually due to "poor preventive maintenance, inadequate quality control programs (QC), and failure to adhere to radiation protection guidelines during practices" (Malone, 2020; Mammba et al., 2023). Furthermore, Nkuba and Nyanda (2017) and Murata et al. (2014) in their studies argued that "failure to maintain a thorough quality control program and maintenance of X-ray equipment can also compromise image quality and minimize the amount of diagnostic information that can be obtained from the X-ray image". Because the main objectives of QC programs are to achieve high image quality and reduce radiation exposure to both staff and patients. Quite a number of African countries, of which Nigeria is not exempted have implemented different quality control (QC) programs for their radiological facilities based on global basic safety standard (BSS), and commendations of the "International Commission on Radiological Protection (ICRP)" (Protection, 1997; Valentin, 2007) in order to maintain image quality and minimize radiation exposure to patients.

In Nigeria, programs regarding quality control checks and quality assurance practices in all X-ray diagnostic radiology units are usually conducted by the Nigeria Nuclear Regulatory Authority (NNRA), and other regulatory bodies such as the Federal Ministry of Health (FMOH), Radiographers Registration Board of Nigeria (RRBN), and Nigerian Institute of Radiographers to ensure the safety and protection of workers, patients, and the general public from the harmful effects of ionizing radiation. However, the efficacy of conducting regular QC programs, and factors affecting their implementation in Nigerian radiology units with a substantial number of patients, especially in the north-eastern part of the country is still unknown (Aborisade, 2021; Ike-Ogbonna et al., 2020; Joseph et al., 2017). There are few medical facilities offering X-ray diagnostics in the north-eastern region of Nigeria, and these facilities are often overloaded due to the large number of patients requiring various X-ray examinations. Furthermore, majority of the X-ray machines in the region are not undergoing routine maintenance checks, which poses a significant risk of malfunctions, equipment failures, poor image resolution, and other safety concerns that could affect both patients and radiographers. Therefore, the aim of this article is to investigate the level of quality control standards across 10 medical diagnostic X-ray facilities in the north-eastern part of Nigeria with emphasis on peak kilovoltage (kVp) accuracy, reproducibility, mAs, and beam alignment.

MATERIALS AND METHODS

Evaluation Criteria

To achieve the study objectives, data from 10 different medical diagnostic X-ray facilities in the north-eastern part of Nigeria were assessed. For the purpose of data protection policy, the 10 medical diagnostic X-ray facilities utilized in the study were labelled as U1 - to – U10 (i.e., unit 1 –to- unit 10). The performance of the 10 X-ray machines was evaluated for X-ray tube efficiency, beam alignment, peak kilo voltage (kVp), and mAs. Details regarding the research evaluated X-ray machines in the various diagnostic radiology units are offered in Table 1, encompassing; machine type, manufacturer, year of manufacturing, installation year, inherent filtration, Max mA, and KVp as per (Oglat, 2022). Additionally, all the studied X-ray machines across the units range from 2 -to-16 years, and the age effects on the machines are well documented. Also, operation guides for all the X-ray machines were available in all the studied X-ray units. The mAs, exposure time, and KVp were measured using a non-invasive factory-calibrated multifunctional radiation detector, specifically ST-031M Piranha-2 a radiology quality assurance and control checks equipment manufactured in Sweden by RTI Electronics AB. It offers an expanded range of functions compared to the Piranha 500, including additional measurement functions and higher precision for special tasks. It is often used in more demanding radiological environments. The detector has curved markings on the housing surface indicating the radiation-sensitive part. This multifunctional detector can measure the selected "kVp, exposure time, and mAs" and display the results simultaneously using a connected computer. Specifications of the research evaluated X-ray machines are offered in Table 1.

Table 1: Specifications of the evaluated X-ray machines across the 6 units.

X-ray Units	Type of X-ray machine	Manufacturing Year	Installation Year	Inherent Filtration	Max Ma	Max KVp
U1	Neusoft Digital Mobile Radiography System	2020	2022	2.5mmA	500	80
U2	Neusoft Digital Mobile Radiography System	2021	2023	2.5mmA	640	120
U3	MobileDaRt Evolution MX8	2018	2019	2.7mmA	500	
U4	Definium 8000	2008	2010	2.5mmA	630	120
U5	Multix Impact	2019	2020	2.5mmA	620	110
U6	Ysio Max	2014	2017	2.5mmA	500	70
U7	Definium 8000	2010	2012	3.0mmA	620	100
U8	Siemens MULTIX Fusion	2015	2018	2.5mmA	610	90
U9	Philips DigitalDiagnost C90	2018	2022	3.0mmA	640	110
U10	Hitachi Supria X-ray System	2014	2019	2.5mmA	500	120

As shown in Table 1, 3 X-ray diagnostic radiology units (i.e., unit5, units6, and unit8) use Siemens Healthineers machines, while units 4 and 7 utilize General Electric (GE) machines, and units 1 and 2 uses Neusoft Medical Systems machines, and the remaining three units (i.e., units 3, 9 and 10) use Shimadzu Corporation, Philips and Hitachi Supria respectively. Details regarding the research evaluated machines' specifications were captured directly from X-ray tube labels and the control panels of the studied X-ray machines.

Parameters Measurement Procedures

To check the kVp reproducibility, the detector was placed on a 100 cm SSD using a Kv meter while the kVp station was kept at the ranges of 70 -120. Three exposures were made, and kVps were measured from the detector. Careful attention was given to the alignment of the digital detector to the X-ray beam, and the collimated light beam was positioned precisely over the marked area of the detector to avoid systematic errors. The selected kVp, mA, and exposure time settings were noted. With these chosen parameters, an exposure was performed on the detector, and the digital readings for kVp, mA, and exposure time in seconds were recorded and logged. Each kVp, exposure time, and mAs setting were measured three times. Therefore, the study coefficient of variance was calculated using Equation 1.

$$Reproducibility = CV = \left(\frac{SD}{av}\right).\ 100\% \quad (1)$$

Where; SD is the estimator of the standard deviation of a series of measurements dose(mGy), time (ms) or voltage (KV), while av represents the mean value of the parameters that will be measured dose(mGy), time(ms) or voltage (KV).

For exposure time reproducibility, the CV% value ranged from 0.10% to 4.56%, indicating varying degrees of consistency in exposure times across the various studied X-ray units. Also, the kVp fluctuations should not be greater than ±5%. The linearity of mas or exposure reproducibility was checked using equation 2 i.e., Linearity coefficient (LC) as per (Abd-Alla et al., 2019).

$$\frac{|x_1 - x_2|}{x_1 + x_2} \times 100\%. \quad (2)$$

Where: x_1 and x_2 are the measured radiation outputs (e.g., in mGy or R) corresponding to two different mA or mAs settings.

For time accuracy, the percentage (%) error of the timer accuracy was determined using Equation 3.

$$Time\ accuracy = \frac{time\ (measured) - time\ (nominal)}{time\ (nominal)} \quad (3)$$

Beam alignment was assessed by positioning a loaded cassette on the table at a focus-film distance (FFD) of 100 cm. The light beam was adjusted to ~ 20 x 20 cm and metal markers (e.g. coins) were placed at the field edges, with additional markers at the anode end, and another one at the top of the field. An exposure was then performed. Consequently, the study Beam alignment was determined by measuring the distance between the light field and the X-ray field using Equation 4.

$$Beam\ alignment = \frac{L_1 + L_2}{SID} * 100 \quad (4)$$

Where; L_1 and L_2 represent the deviations of the light field edges from the X-ray field edges along the length, SID (source-to-image distance) is the distance from the X-ray tube to the detector or film. Flow diagram of the research employed methodology is offered in Figure 1.

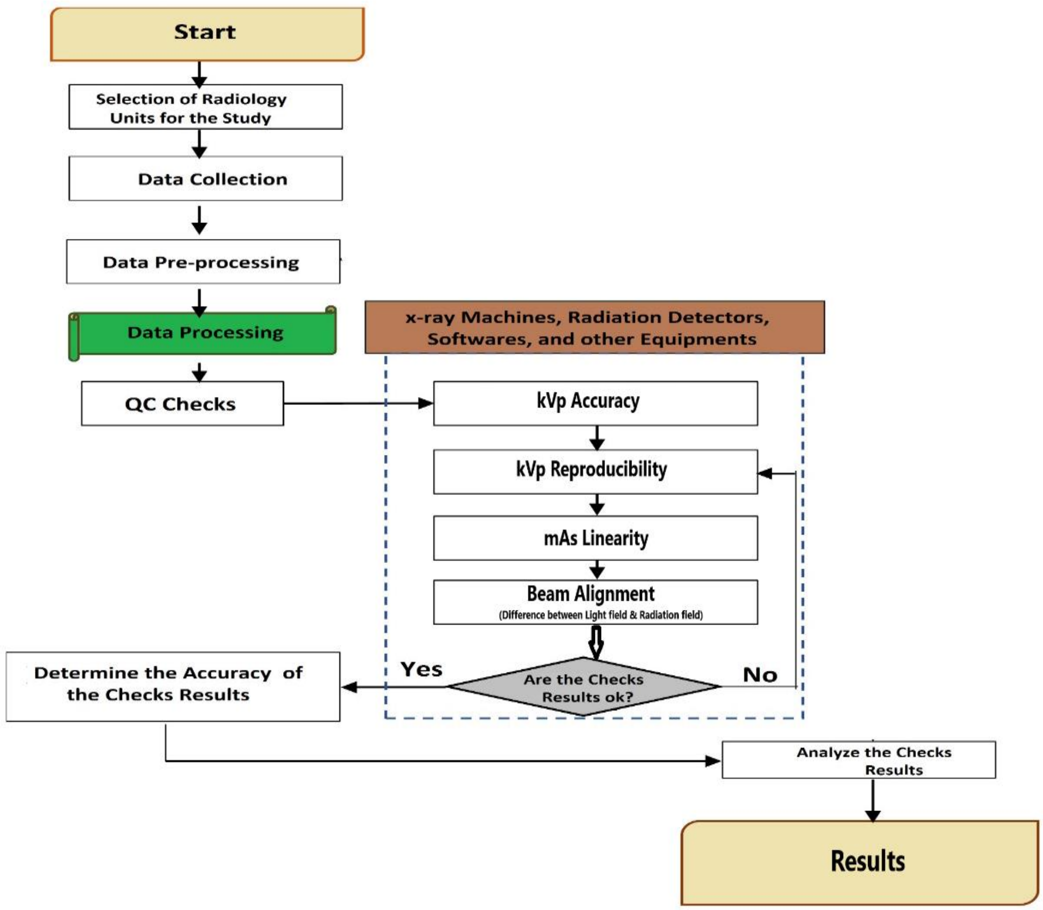

Figure 1: Flow diagram of the study employed methodology

RESULTS AND DISCUSSION

kVp precision results

For this research, the mAs were held constant, the tolerance limit was set at ±5%, and exposures were performed at six different kVp settings (i.e., 70, 80, 90, 100, 110, and 120), as per (Sauter et al., 2020). As shown in Table 2, the kVp error% results clearly show that the accuracy level for 6 of the studied X-ray machines (i.e., units 1, 3, 5, 7, 8, and 10) were all less than 2%, thus considered to have an excellent accuracy that is within the tolerance level. However, 4 of the studied X-ray machines (i.e., units 2, 4, 6, and 9) fall outside the tolerance level as their kVp error% were all greater than 5%. Table 2 depicts the research kVp accuracy results

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Table 2: Accuracy of the kVp measurement across the 10 X-ray units

X-ray Unit	Set kVp 1	Measured kVp 1	Set kVp 2	Measured kVp 2	Set kVp 3	Measured kVp 3	kVp Error% (Mean)
1	70	71.1	90	91.4	110	111.5	1.63
2	70	73.6	100	94.2	120	115.3	5.13
3	70	71.2	90	91.6	110	111.9	1.76
4	70	73.8	100	94.6	120	115.8	5.41
5	70	71.4	90	91.9	110	112.3	1.94
6	70	73.7	100	94.5	120	115.5	5.26
7	70	70.9	90	91.2	110	111.4	1.33
8	70	71.2	80	91.5	110	111.8	1.73
9	70	73.6	100	94.3	120	115.2	5.17
10	70	71.4	90	91.8	110	112.2	1.93

kVp reproducibility results

For kVp reproducibility, the CV% (coefficient of variation) measures the consistency of the kVp output using various exposures with the same settings. Lower CV values indicate better reproducibility and more consistent performance, while higher CV values indicate poor reproducibility. As shown in Table 3, six of the X-ray units (Units 1, 3, 5, 7, 8, and 10) has excellent kVp reproducibility results as their CV% values were all <2.0. whereas the CV% values for units 2, 4, 6, and 9 exceed the acceptable reproducibility limit of 5%. Hence, requires recalibration and other maintenance activities in order to ensure accurate and consistent performance. The research kVp reproducibility CV% results for all the 10 X-ray units are presented in Table 3.

Table 3: kVp reproducibility results

X-ray Unit	Set kVp	Measured kVp (Exposure 1)	Measured kVp (Exposure 2)	Measured kVp (Exposure 3)	Mean kVp	Standard Deviation (σ)	Coefficient of Variation (CV%)
1	70	70.2	69.8	70.1	70.03	0.20	0.28
2	120	126.3	125.1	126.0	125.80	8.86	7.04
3	90	90.2	90.0	90.1	90.10	0.11	0.13
4	80	74.6	73.8	74.4	74.27	4.62	6.21
5	90	90.1	89.8	90.2	90.03	0.18	0.20
6	100	95.0	93.5	94.6	94.37	5.92	6.28
7	70	70.2	69.9	70.0	70.03	0.16	0.23
8	90	90.2	89.8	90.1	90.03	0.26	0.29
9	120	127.0	125.8	126.7	126.50	8.64	6.83
10	70	70.4	69.8	70.3	70.17	0.15	0.21

mAs linearity results

To check mAs linearity, the detector was positioned at a distance of 100 cm SSD. Three exposures were carried out at a fixed time of 0.1 sec (100 ms), with a setting of 80 kVp, and different mAs. According to most international standards e.g., "American Association of Physicists in Medicine" (AAPM), International Electrotechnical Commission (IEC), and "The World Health Organization" (WHO), the linearity error% or linearity coefficient (LC%) between three or more consecutive mAs settings should not exceed ±10%. Therefore, for an X-ray machine to pass any mAs linearity test, the machine LC% values should be ≤ 10%. The mAs output is considered proportional and linear. Conversely, the machine fails the test where the LC% > 10%. Hence, indicating a potential issue that requires servicing or recalibration of the machine. The mAs linearity coefficient results of the study are offered in Table 4.

Table 4: mAs linearity coefficient (LC) results

X-ray Unit	Set mAs	Measured mAs (Exposure 1)	Measured mAs (Exposure 2)	Measured mAs (Exposure 3)	Mean mAs	Standard Deviation (σ)	Linearity Coefficient (LC%)
1	10	10.2	9.8	10.1	10.03	0.09	0.89
2	30	55.2	53.7	54.0	54.30	5.57	10.26
3	50	50.2	50.0	50.1	50.10	0.09	0.48
4	63	112.7	110.8	111.9	111.80	13.80	12.33
5	50	50.1	49.8	50.2	50.03	0.12	0.58
6	10	11.0	10.2	10.6	10.60	1.17	11.02
7	10	10.3	10.0	10.1	10.13	0.05	0.53
8	60	99.8	100.3	100.1	100.07	0.26	0.91
9	10	11.0	10.4	10.7	10.70	1.07	10.33
10	50	50.1	49.7	50.2	50.00	0.16	0.63

As shown in Table 4, 6 units (i.e., units 1, 3, 5, 7, 8, and 10) meet the linearity standard and demonstrate consistent radiation output with an excellent linearity coefficient (LC%) of <1.0%. While, the remaining 4 units (units 2, 4, 6, and 9) fail the linearity test as their LC% values (10.26%, 12.33%, 11.02%, and 10.32% respectively) exceed the acceptable limit, indicating potential mechanical issues or calibration.

Beam alignment results

For Coincidence checks between the light field and radiation field, a cassette was placed on the table at a focus-film distance (FFD) of 100 cm. While the light field was adjusted for approximately 20 x 20 cm field, metal markers (i.e., coins) were positioned at each edge of the field, with additional an one at the anode end and one at the top of the field after which an exposure was performed, and lastly, the coincidence was assessed by calculating the followings;

$L = \frac{(L1+L2)}{SID} * 100$, For Length

$W = \frac{(W1+W2)}{SID} * 100$, For Width

As shown in Table 5, the recommended tolerance for both the Width (W) and the Length (L) were set at less than 2% (i.e., L1 + L2 < 2% of the SID distance, and W1 + W2 < 2% of the SID distance respectively. The coincidence shows that there is a good alignment between the light field and the radiation field for the 6 units (i.e., units 1, 3, 5, 7, 8, and 10) that has acceptable mAs and kVp values as both their Width and Length falls within the acceptable limit of 2% of the focus-film distance (FFD). While, units 2, 4, 6, and 9 fail both the Length and Width alignment checks as their light field and radiation field % >2%, indicating a misalignment. Results regarding the difference between the radiation field and the light field across the studied X-ray units are presented in Table 5.

Table 5: Difference between light field and radiation field

X-ray Unit	L1 + L2 (%)	W1 + W2 (%)	Remarks
1	1.0	1.2	Pass
2	2.7	2.9	Fail
3	1.5	1.6	Pass
4	3.0	2.8	Fail
5	0.4	0.5	Pass
6	2.6	2.5	Fail
7	0.5	0.8	Pass
8	0.8	1.5	Pass
9	2.3	3.0	Fail
10	0.8	1.0	Pass

Based on the study beam alignment results, it can be said that 60% of the units passed the light and radiation fields checks, while 40% of the units failed the checks.

Discussion

Based on the research kVp, mAs, and beam alignment checks results, it was found that all the measurement processes produced consistent results across all the research 10 studied X-ray units. For kVp reproducibility i.e., coefficient of variation (CV%) and error%, the results indicate that six out of the 10 X-ray units (i.e., units 1, 3, 5, 7, 8, and 10) have excellent linearity and higher reproducibility (Table 2, and 3,) as their mean error% and CV% were all < 2.0 signifying the units kVp accuracy levels. While, the remaining four units (i.e., units 2, 4, 6, and 9) were found to exceed the kVp reproducibility acceptable limits as their mean error% and CV% are all > 5% indicating the need for recalibration in those units. The kVp and CV results for the six units (1, 3, 5, 7, 8, and 10) that passed the X-ray checks may not be unconnected with the age of the X-ray machines found in those unit's as their lifetime stood at; unit 1 – 2020, unit 3 – 2018, unit 5 – 2019, unit 7 – 2010, unit 8 – 2015, and unit 10 – 2014 respectively, highlighting the potential impact of machine lifespan on X-ray examination results.

For mAs linearity checks results (Table 4), it was discovered that same units (1, 3, 5, 7, 8, and 10) which passed the kVp test, also passed the mAs linearity checks, exhibiting linearity coefficients (LC%) below 10%. Conversely, units 2, 4, 6, and 9 failed, with LC% exceeding the acceptable limit of 10%. Furthermore, findings of the research beam alignment check (Table 5), reinforce the potential impact of machine lifespan on X-ray examinations as the results found that same facilities (i.e., units 1, 3, 5, 7, 8, and 10), which previously passed the kVp and mAs test, also demonstrated acceptable beam alignment as their combined length and width tolerances (i.e., L1 + L2, and W1 + W2) were all < 1.5%, which are all within the acceptable limit of 2% based on skin-to-image distance (SID). In contrast, units 2, 4, 6, and 9, which failed the kVp and mAs tests, exhibited beam misalignment as their tolerance limits exceed the recommended limit of 2%, indicating that there is misalignment between the radiation fields and the light fields.

CONCLUSION

In conclusion, the findings of this study reveal significant variations in quality control performance among the 10 studied X-ray units in Northeastern Nigeria. The results indicate that six X-ray units (1, 3, 5, 7, 8, and 10) consistently met the acceptable standards for kVp reproducibility, mAs linearity, and beam alignment, highlighting their reliability in diagnostic imaging. The unit's kVp coefficient of variation (CV%) and error% were all below 2.0, while their mAs linearity coefficients remained under the 10% threshold. Additionally, their beam alignment tolerance limits fell within the recommended limit of 2%, ensuring accurate radiation field positioning. The results suggest that these six units are well-calibrated and likely maintained regularly, contributing to high-quality diagnostic imaging. Conversely, four X-ray units (2, 4, 6, and 9) failed to meet the recommended quality control standards, as their kVp reproducibility exceeded the acceptable limit of 5%, their mAs linearity coefficients surpassed10%, and their beam alignment exceeded the recommended tolerance limit of 2%. These results indicate a decline in performance, potentially compromising image quality and diagnostic accuracy. The consistent failure of these units across all four key quality control parameters suggests underlying issues such as equipment aging, lack of regular calibration, or maintenance deficiencies. Without corrective measures, these units may expose patients to unnecessary radiation doses while producing suboptimal diagnostic images. The novelty of this work lies in the discovery of a strong correlation between machine lifespan and quality control performance. The results revealed that majority of the units that passed all the X-ray checks were relatively newer, with manufacturing years ranging between 2014 and 2020, compared to the failing units, which were either older or potentially lacked regular servicing. This finding underscores the importance of periodic calibration, preventive maintenance, and timely equipment upgrades to ensure consistent and accurate diagnostic imaging. Therefore, regular quality control checks should be institutionalized as part of routine radiology practices to prevent equipment deterioration and uphold patient safety standards. Just like any other study, this research too has some limitations. The research is limited to 10 tertiary hospitals, three exposures, kVp, reproducibility, mAs, and beam alignment checks. Therefore, future studies should include private hospitals, use more exposures settings, and compare the results.

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