

ORIGINAL RESEARCH ARTICLE

The imperative of quality control in Namibian diagnostic radiology: A standardized approach to medical physics dosimetry

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Abstract

The rapid expansion of diagnostic radiology services across Namibia's public and private sectors necessitates a robust, standardized framework for quality control (QC), which is part of a comprehensive quality assurance program to ensure patient safety and diagnostic accuracy. While ionizing radiation is a powerful diagnostic tool, its use carries inherent risks of stochastic and deterministic effects, making the meticulous management of radiation dose a critical public health concern. The current radiological landscape in Namibia is characterized by varying practices and a lack of unified QC protocols, which lead to significant inconsistencies in radiation dose delivery and suboptimal image quality. This paper proposes a comprehensive, pragmatic framework for QC designed to harmonize national practices. The methodology includes routine equipment performance testing focusing on kilovoltage peak (kVp) accuracy, kVp reproducibility, timer reproducibility, half-value layer, and tube output reproducibility. This framework is specifically tailored to address the unique logistical and resource challenges within Namibia's healthcare system, such as the geographical dispersion of facilities and limited specialized personnel. By implementing this standardized approach, Namibia can enhance patient protection through optimized radiation doses and significantly improve the reliability and clinical value of radiological examinations. Furthermore, the framework facilitates the transition from reactive maintenance to proactive quality assurance. This initiative represents a vital step toward strengthening the Namibian healthcare infrastructure, ensuring that diagnostic services align with international standards of radiation safety as set by the International Atomic Energy Agency. Ultimately, this framework fosters a sustainable culture of excellence in medical imaging for the benefit of all Namibian patients.

Keywords: Diagnostic radiology; Quality control; Medical physics; Dosimetry; Patient safety; Radiation dose

1. Introduction

The field of diagnostic radiology has undergone a profound transformation, driven by relentless advancements in instrumentation, equipment, and technology.¹ This evolution has fundamentally reshaped the requirements of effective quality assurance (QA) programs.¹ Indeed, the necessity of a rigorous QA program in diagnostic radiology is a global standard rooted in the International Commission on Radiological Protection principles.^{2,3} QA is not merely an optional best practice; it is a fundamental pillar of patient safety and optimal clinical performance.³

While conventional radiology remains a cornerstone diagnostic modality in Namibia, its widespread use for visualizing internal structures and diagnosing diseases also accounts for the largest portion of the population's exposure to artificial radiation.

The increasing complexity of modern digital radiography and fluoroscopy systems, therefore, necessitates a more sophisticated and systematic approach to ensuring consistent and reliable performance.⁴ Every use of radiation must be justified for every patient, meaning the individual or societal benefit must outweigh the detriment (risk of harm) it might cause. QA ensures that the equipment is functioning correctly to maximize the diagnostic yield, thereby justifying the patient's exposure. If equipment provides non-diagnostic images, the exposure is inherently unjustified.^{5,6}

In Namibia, the regulatory framework governing the use of radiation is established under the Atomic Energy and Radiation Protection Act, Act No. 5 of 2005 (GRN), and the Radiation Protection and Waste Disposal Regulations of 2011.^{7,8} Regulatory oversight is exercised by the National Radiation Protection Authority (NRPA).⁸ The NRPA fulfills the critical role of the national regulator, mandated to ensure compliance with radiation protection requirements and adherence to the law.⁸ Its core strength lies in establishing and enforcing the legal framework for radiation safety within diagnostic facilities through licensing, inspection, and enforcement of safety standards and basic equipment performance requirements.⁸

While this regulatory oversight effectively supports compliance with radiation protection obligations, there is scope, consistent with the optimization principle of General Safety Requirement (GSR Part 3), to further strengthen proactive engagement that promotes the optimization of equipment performance and patient dose in diagnostic radiology.⁸ In this context, regulatory inspections, while essential for legal compliance, are complementary to but cannot replace the continuous, in-house quality control (QC) measurements and calibration procedures that must

be implemented by a suitably qualified medical physicist.⁹

In accordance with the requirements of GSR Part 3, the medical physicist plays a key role in ensuring the optimization of protection and safety in medical exposure.⁹ This includes responsibility for the acceptance testing, commissioning, calibration, and ongoing QC of diagnostic imaging equipment, as well as the assessment and optimization of patient doses while maintaining diagnostic image quality.⁹⁻¹¹ The medical physicist provides expert advice on radiation dosimetry, equipment performance, and risk assessment, supports the establishment and implementation of QA programs, and contributes to the investigation and prevention of unintended or accidental medical exposures.⁹⁻¹¹ Through continuous involvement in clinical practice, the medical physicist ensures that radiation protection principles, particularly optimization, are effectively applied in routine diagnostic procedures in line with International Atomic Energy Agency (IAEA) GSR Part 3 requirements.⁹⁻¹⁴

However, a significant and critical gap persists; there is no formal, routine QC program, and diagnostic medical physicists are not regularly assigned to radiology departments to develop and execute QA protocols.^{6,9-11,13-15} The absence of such a program and a medical physicist in diagnostic radiology facilities increases the risk of unnecessarily high radiation doses to patients and staff, and may compromise image quality, which can hinder accurate and timely diagnosis.^{11,13-16} To address this crucial gap, the implementation of a tailored QC program is paramount for medical physics practices in Namibian diagnostic settings. This paper aims to highlight the urgent need for a structured QC program and provide a practical guide for its implementation, ultimately advocating for the pivotal role of the medical physicist in ensuring the safety and optimization of radiological equipment.¹⁶⁻¹⁸

1.1. Quality assurance

Quality assurance is a planned and systematic set of actions intended to provide confidence that a facility, equipment, procedure, or service consistently meets specified requirements for radiation protection, safety, and clinical effectiveness.^{5,12-14,17,19}

Quality assurance encompasses organizational arrangements, policies, procedures, documentation, training, and audits that ensure radiation practices are conducted in compliance with regulatory requirements and international safety standards, including the principles of justification and optimization as set out in GSR Part 3.^{2,8,12,13,20-22}

Quality control is the set of operational techniques and activities used to fulfill the requirements for quality.^{1,13}

QC is the technical measurement and testing of the equipment itself. It involves measuring parameters such as kilovoltage peak (kVp), dose linearity, half-value layer (HVL), and image display monitor performance. QC is the core responsibility of the diagnostic medical physicist.^{1,5,9-11,13,15,21,23}

The current challenge in Namibia is the absence of the hands-on QC component, which prevents the effective realization of the broader QA goals.

The most significant operational gap is the lack of dedicated, in-house diagnostic medical physics services:

- (i) Equipment drift: X-ray tube output, kVp accuracy, and beam filtration are known to change over time (drift) due to wear and tear. Without routine QC, these changes go unnoticed until a catastrophic failure or, more critically, until patient dose becomes unnecessarily high.^{3,15,22,24-28} For example, a drift in the kVp setting might require the technologist to increase the mAs, that is, the tube current–time product, to achieve adequate image density, resulting in a higher patient dose for the same diagnostic outcome.^{15,27,28}
- (ii) Image quality compromise: Failures in detector calibration, monitor luminance, or automatic exposure control mean that images may appear grainy, lack contrast, or fail to visualize subtle pathology, leading to:
 - (a) Missed or delayed diagnosis: The primary risk to the patient.
 - (b) Repeat examinations: Non-diagnostic images necessitate repeat exposures, directly violating the as low as reasonably achievable (ALARA) principle and increasing radiation risk. This is the focus of the American Association of Physicists in Medicine (AAPM) TG-305 on reject analysis.^{6,18}
- (iii) Technology lag: Modern digital radiography and computed radiography systems, fluoroscopy, and interventional systems (e.g., C-arms) are highly complex. They rely on sophisticated software algorithms that must be periodically validated. Only a medical physicist is qualified to perform this validation, linking image processing parameters to dose metrics.^{9-11,22,25,27}

The medical physicist is the only professional qualified to establish and execute this program, bridging the gap between physics, technology, and clinical medicine.^{9-11,22,25,27} Their responsibilities include:

- (i) Instrumentation and measurement: Possessing the specialized knowledge and calibrated equipment to perform accurate measurements (e.g., dosimeters, kVp meters, image performance phantoms).

- (ii) Protocol development: Tailoring international guidelines (AAPM, IAEA) to the specific equipment and clinical needs of the hospital.^{2,10,12,13,17,21,29}
- (iii) Consultation and optimization: Working with radiologists and radiographers to establish optimal imaging techniques (technique charts) and to investigate failed QC tests, providing corrective actions.^{3,9-11,13,17,25}
- (iv) Acceptance testing: Before any new equipment is used on patients, the medical physicist must perform acceptance testing to verify that the vendor's specifications are met. This is the first and most critical step in QC.^{1-3,5,6,9-11,13-16,26,28}

1.2. Need for optimization under the ALARA principle

Radiation dose should be maintained in accordance with the ALARA principle, taking into account economic and social factors. QC protocols are the practical tools used to achieve ALARA.^{1,2,13,17,24,29} By regularly testing and calibrating X-ray systems, medical physicists ensure that the minimum dose required to produce an image of acceptable diagnostic quality is delivered.^{6,9-11,13,15,30,31} Undetected equipment drift (e.g., changes in beam filtration or kVp accuracy) can lead to excessive patient dose without regulatory action, making routine QC indispensable.^{5,24} The optimization principle is paramount in diagnostic radiology, often leading to the more specific concept of keeping radiation exposure as low as diagnostically acceptable, indication-oriented, and patient-specific, which ensures that dose reduction does not compromise the image's diagnostic value.^{13,16,27,30}

While primarily applied to occupational exposure and the public, the general ethos of dose limitation guides the necessity of preventing equipment failure that could lead to accidental overexposure.^{7,24}

1.3. Production of radiation in diagnostic radiology

Conventional diagnostic radiology is based on the controlled production and use of X-rays to generate images of internal anatomical structures for clinical diagnosis.²⁵ X-rays are a form of ionizing electromagnetic radiation produced when high-energy electrons interact with matter, a process that is deliberately controlled in medical imaging to balance diagnostic benefit against radiation.²⁵ Owing to its accessibility, diagnostic value, and wide availability, conventional radiology remains the most frequently used imaging modality and is therefore the dominant contributor to population exposure from medical sources of ionizing radiation.

The generation of X-rays takes place within an evacuated X-ray tube, which consists primarily of a cathode and an anode enclosed in a protective housing.^{1,22-24} The cathode

comprises a tungsten filament that is heated by an electric current, resulting in thermionic emission of electrons. These electrons are focused toward the anode by a focusing cup and accelerated across a high potential difference, typically in the range of 40–150 kVp for diagnostic radiology.^{1,22-24} The anode, commonly made of tungsten and often rotating to dissipate heat, serves as the target where electrons rapidly decelerate, converting kinetic energy into X-ray photons and heat.^{1,22-24}

X-ray production at the anode occurs through two fundamental physical mechanisms, namely Bremsstrahlung radiation and characteristic radiation.^{1,22-25} Bremsstrahlung radiation, which forms the continuous energy spectrum, is used predominantly in diagnostic imaging.^{1,22-24} It is generated when high-speed electrons are decelerated or deflected by the electric field of the atomic nuclei in the target material.^{1,22-25} The resulting X-ray photons have a range of energies up to a maximum equal to the applied kVp. Characteristic radiation occurs when an incident electron ejects an inner-shell electron from the target atom, after which an electron from a higher energy shell fills the vacancy and emits a photon with energy characteristic of the target material.^{1,22-24}

The quantity and quality of the X-ray beam are controlled by the exposure parameters selected by the operator.¹³ The tube current and exposure time (measured in mAs) determine the number of electrons striking the anode and therefore the number of photons produced, while the kVp controls the maximum photon energy and

penetrating power of the beam.²⁵ Beam modification is further achieved through inherent and added filtration, which removes low-energy photons that contribute to patient dose without improving image quality, and through collimation, which restricts the beam to the region of clinical interest, reducing unnecessary irradiation of surrounding tissues.²⁷ The schematic diagram of a diagnostic X-ray tube is illustrated in Figure 1.^{1,22,25}

After leaving the X-ray tube, the beam passes through the patient, where differential attenuation occurs due to variations in tissue composition, thickness, and atomic number. These attenuation differences form the basis of image contrast at the detector.^{1,22,25} From a radiation protection perspective, the production and application of X-rays in diagnostic radiology constitute a planned medical exposure, requiring adherence to the principles of justification and optimization.^{13,24} The International Atomic Energy Agency emphasizes that X-ray production parameters must be appropriately selected, monitored, and optimized through QA and QC programs, with the involvement of a qualified medical physicist, to ensure that patient doses are kept as low as reasonably achievable while maintaining diagnostic image quality.^{6,9-11,13,24} This requirement is further embedded in Regulation 33 of the Radiation Protection and Waste Disposal Regulations.⁷

2. Materials and methods

This section describes the equipment and instrumentation used in the study, as well as the methodological approach

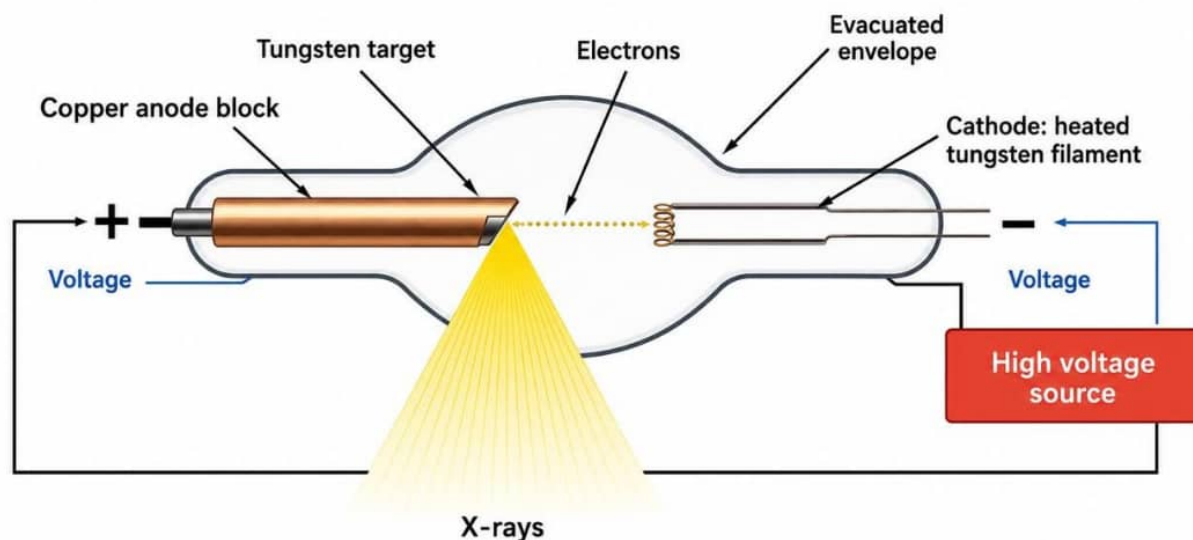


Figure 1. Schematic diagram of a diagnostic X-ray tube outlining the cathode, anode, and vacuum enclosure components

applied to evaluate the performance of diagnostic imaging systems. Section 2.1 outlines the radiation measurement devices and imaging equipment included in the investigation, while the methods subsection details the measurement procedures, exposure conditions, and data analysis techniques employed to ensure accurate, reproducible, and standardized assessment of equipment performance in accordance with accepted diagnostic radiology QC practices.

2.1. Materials

The study utilized a range of calibrated radiation measurement and imaging equipment to support accurate data acquisition and analysis. Measurements were performed using non-invasive solid-state detectors to ensure accuracy without interfering with routine clinical operation. These included RaySafe solid-state detectors (Billdal, Sweden) and PTW solid-state detectors (Freiburg, Germany), both of which are widely used for diagnostic radiology dosimetry and QC. The performance of two diagnostic X-ray machines and two fluoroscopy units was assessed under routine clinical operating conditions.

2.2. Methodology

This study was conducted in four diagnostic radiology facilities in Windhoek, Namibia. The facilities were chosen according to the daily workload on the equipment. [Table 1](#) provides the details of the machines used in the study.

Two of the facilities had conventional X-ray units (BuckyDiagnos and Radiography 7300 C) manufactured by Philips (the Netherlands) with installation years of 2009 and 2018, respectively, representing equipment of different technological generations. The other two fluoroscopy X-ray units (Luminos dRF Max and Luminos Agile Max) manufactured by Siemens (Germany) were installed in 2009 and 2020, allowing comparison of performance characteristics between older and more recently installed fluoroscopic systems under routine clinical conditions.

Table 1. Details of the X-ray machines

Machine number	Type	Manufacturer	Year installed
1	Conventional X-ray unit	Philips	2009
2	Conventional X-ray unit	Philips	2018
3	Fluoroscopy X-ray unit	Siemens	2009
4	Fluoroscopy X-ray unit	Siemens	2020

To evaluate the conformity of these X-ray and fluoroscopic machines in line with international standards, QC tests indicated in [Table 2](#) were performed. The quality tests were carried out in accordance with internationally recognized guidelines, including the AAPM Report No. 74 and the Establishment of a Quality Control Program in X-Ray Imaging in Africa (RAF 6/053) document, respectively.^{13,17,23,29,30,32} The measuring devices were placed on the examination table, and a source-to-surface distance (SSD) of 100 cm was maintained for all measurements.

The measured parameters were then compared against the relevant acceptable limits stipulated in these guidelines.^{2,6,12,13,20,21,27,32}

The performance of diagnostic X-ray equipment was evaluated using a set of standardized QC test parameters selected for their direct relevance to radiation protection and image quality.^{13,31}

Kilovoltage peak accuracy was performed to verify that the actual tube potential corresponded with the selected value. This is because deviations in kVp directly influence beam penetration, image contrast, and patient dose.^{13,31,32}

Dose and timer reproducibility tests were conducted to confirm that repeated exposures under identical exposure settings produced consistent radiation output. Reliable reproducibility is essential for maintaining predictable patient doses and ensuring compliance with the ALARA principle, as variability may indicate instability in tube output or exposure timing mechanisms.

Dose linearity testing was also performed to verify that radiation output increased proportionally with changes in tube current–time product (measured in mAs). Failure to meet linearity criteria can result in unpredictable patient doses and compromised image quality.

The HVL was measured to assess beam quality and adequacy of filtration. HVL testing ensures that low-energy, non-diagnostic photons are effectively removed from the beam, thereby minimizing unnecessary patient exposure while maintaining diagnostic effectiveness.

These QC tests are generally recommended to be conducted annually.

2.3. Statistical analysis

Statistical analysis of the collected data was performed to quantify system performance and variability. Descriptive statistics, including the mean and standard deviation, were calculated for HVL, kVp, dose, and timer. The coefficient of variation (CoV) was calculated to evaluate the precision and repeatability of these measurements. Dose linearity was assessed by examining the relationship between

tube current–time product (mAs) and measured dose output. All statistical computations were conducted using Microsoft Excel software (Microsoft Corporation, USA).

3. Results and discussion

3.1. kVp, dose, and timer reproducibility

This section presents the findings obtained from the QC measurements performed on the diagnostic X-ray and fluoroscopy systems included in the study. The results are analyzed in relation to established acceptance criteria and international radiation protection standards, with particular emphasis on equipment performance and radiation dose consistency. The discussion interprets these findings in the context of optimization principles and highlights their relevance to routine clinical practice.

Tables 3–6 present the results of kVp, dose, and timer reproducibility testing for Machines 1–4, respectively.

For Machine 1, the measured kVp averaged 69.3 kVp against a set value of 70 kVp, indicating a small deviation of less than 1%. The dose output remained consistent at 1.240 mGy with negligible variability across repeated exposures. The CoV values were below 1%, confirming excellent reproducibility.

Machine 2 also showed stable performance, maintaining an average kVp of 70.5 kVp, with reproducible dose (1.02 mGy) and timer values (0.04 s), all demonstrating zero variation. Machine 3 had an average measured kVp of 70.3 kVp, a dose of 0.67 mGy, and a timer value of 0.22 s, with CoV values ranging from 0.12% to 0.39%. Machine 4 had an average measured kVp of 70.5 kVp, a dose of 0.938 mGy, and a timer value of 0.34 s, with negligible variability.

Table 2. Quality control tests performed

Test parameter	Frequency (recommendation)	Relevance
kVp accuracy	Annual	Directly affects patient dose and image contrast. Test the actual kVp output against the selected value using a non-invasive meter.
Dose and timer reproducibility	Annual	Ensures that repeat exposures using the same settings yield a consistent radiation output. Failure violates the ALARA principle.
Dose linearity	Annual	Ensures that dose output increases linearly with increasing mAs (tube current-time product). Failure can lead to an unpredictable patient dose.
HVL	Annual	Measures the beam quality and filtration. Low HVL means more low-energy (non-diagnostic) X-rays reach the patient, increasing the dose.

Abbreviations: ALARA: As low as reasonably achievable; HVL: Half-value layer; kVp: Kilovoltage peak; mAs: Milliampere-seconds.

Table 3. kVp, dose, and timer reproducibility for Machine 1

Parameter	SET kV (adult protocol)	Measured kV	Measured dose (mGy)	Measured time (s)
Measurement 1	70.0	69.00	1.240	0.080
Measurement 2	70.0	69.50	1.240	0.080
Measurement 3	70.0	69.50	1.240	0.080
Measurement 4	70.0	69.50	1.240	0.080
Measurement 5	70.0	69.00	1.240	0.080
Mean		69.30	1.240	0.08
SD		0.27	0.00	0.00
CoV: (<5%)		0.40	0.00	0.00
Manufacturer CoV/Max CoV		5.00	5.00	5.00
Pass/fail criteria		Pass	Pass	Pass

Note: Test conditions: 70 kVp, 20 mAs, and 100 cm SSD.

Abbreviations: CoV: Coefficient of variation; kVp: Kilovoltage peak; SD: Standard deviation; SSD: Source-to-surface distance.

Table 4. kVp, dose, and timer reproducibility for Machine 2

Parameter	SET kV (adult protocol)	Measured kV	Measured dose (mGy)	Measured time (s)
Measurement 1	70.0	70.50	1.02	0.038
Measurement 2	70.0	70.50	1.02	0.038
Measurement 3	70.0	70.50	1.02	0.038
Measurement 4	70.0	70.50	1.02	0.038
Measurement 5	70.0	70.50	1.02	0.038
Mean		70.50	1.02	0.04
SD		0.00	0.00	0.00
CoV: (<5%)		0.00	0.00	0.00
Manufacturer CoV/Max CoV		5.00	5.00	5.00
Pass/fail criteria		Pass	Pass	Pass

Note: Test conditions: 70 kVp, 20 mAs, and 100 cm SSD.

Abbreviations: CoV: Coefficient of variation; kVp: Kilovoltage peak; SD: Standard deviation; SSD: Source-to-surface distance.

Table 5. kVp, dose, and timer reproducibility for Machine 3

Parameter	SET kV (adult protocol)	Measured kV	Measured dose (mGy)	Measured time (s)
Measurement 1	70.0	70.50	0.673	0.220
Measurement 2	70.0	70.50	0.672	0.221
Measurement 3	70.0	70.50	0.672	0.221
Measurement 4	70.0	70.00	0.671	0.220
Measurement 5	70.0	70.00	0.67	0.221
Mean		70.30	0.67	0.22
SD		0.27	0.00	0.00
CoV: (<5%)		0.39	0.12	0.25
Manufacturer CoV/Max CoV		5.00	5.00	5.00
Pass/fail criteria		Pass	Pass	Pass

Note: Test conditions: 70 kVp, 20 mAs, and 100 cm SSD.

Abbreviations: CoV: Coefficient of variation; kVp: Kilovoltage peak; SD: Standard deviation; SSD: Source-to-surface distance.

Overall, all reproducibility assessments show that the machines are functioning reliably, with all measurements falling within manufacturer tolerance levels and meeting the QA acceptance criteria.

3.2. Dose linearity

The dose–linearity results of the machines are presented in [Table 7](#) and illustrated in [Figure 2](#).

The dose linearity evaluation demonstrated that all four machines exhibit good proportionality between dose and mAs, with consistent dose-per-mAs ratios across the tested ranges.

Machine 1 produced the highest radiation output, increasing from 0.624 mGy at 10 mAs to 2.460 mGy at 40 mAs, with a stable dose-per-mAs ratio of 0.062–0.061, indicating excellent linearity.

Machine 2 followed closely, with dose values ranging from 0.514–2.010 mGy and a consistent ratio of 0.051–0.050, confirming reliable output proportionality.

Machine 3 produced the lowest output (0.335–1.340 mGy) but maintained a steady dose-per-mAs ratio of 0.033–0.034, demonstrating linearity despite lower magnitude.

Machine 4 showed intermediate performance,

Table 6. kVp, dose, and timer reproducibility for Machine 4

Parameter	SET kV (adult protocol)	Measured kV	Measured dose (mGy)	Measured time (s)
Measurement 1	70.0	70.50	0.937	0.340
Measurement 2	70.0	70.50	0.939	0.340
Measurement 3	70.0	70.50	0.937	0.340
Measurement 4	70.0	70.50	0.939	0.340
Measurement 5	70.0	70.50	0.937	0.340
Mean		70.50	0.938	0.34
SD		0.00	0.00	0.00
CoV: (<5%)		0.00	0.12	0.00
Manufacturer CoV/Max CoV		5.00	5.00	5.00
Pass/fail criteria		Pass	Pass	Pass

Note: Test conditions: 70 kVp, 20 mAs, and 100 cm SSD.

Abbreviations: CoV: Coefficient of variation; kVp: Kilovoltage peak; SD: Standard deviation; SSD: Source-to-surface distance.

Table 7. Dose linearity data Machines 1–4

mAs	Machine 1 dose (mGy)	Machine 2 dose (mGy)	Machine 3 dose (mGy)	Machine 4 dose (mGy)
10	0.624	0.514	0.335	0.471
16	0.990	0.816	0.536	0.751
20	1.240	1.010	0.671	0.937
32	1.970	1.620	1.080	1.160
40	2.460	2.010	1.340	1.500

Note: Machine settings: 70 kVp and 100 cm SSD.

Abbreviations: kVp: Kilovoltage peak; SSD: Source-to-surface distance.

increasing 0.471–1.500 mGy, with a stable ratio of 0.047–0.046, respectively.

These results comply with international standards. The AAPM guidelines recommend that the dose-per-mAs CoV should not exceed 10%, and the International Electrotechnical Commission (IEC) 60601-2-54 standard requires consistent air kerma output across loading conditions. All machines meet these criteria, demonstrating acceptable performance.^{6,12,13,16,20}

Similarly, these findings are consistent with the literature. Sy *et al.*²⁶ also observed predictable increases in dose with mAs in diagnostic X-ray equipment. Figure 2 shows the measured dose relative to mAs for each machine included in the study.

The minor differences in absolute output (e.g., lower output in Machine 3) are typical of variations in tube aging, generator design, or calibration differences and

do not indicate malfunction, provided proportionality is maintained, which the results of the study confirm.

3.3. Half-value layer

The results of the HVL values of the machines are indicated in Table 8. The HVL range is between 3.0 and 3.7 mm Al, which is a narrow spread, suggesting that all four machines are reasonably consistent in beam quality.

Table 8. HVL results for Machines 1–4

Machine	HVL mmAl
1	3.7
2	3.0
3	3.4
4	3.0

Abbreviations: Al: Aluminum; HVL: Half-value layer.

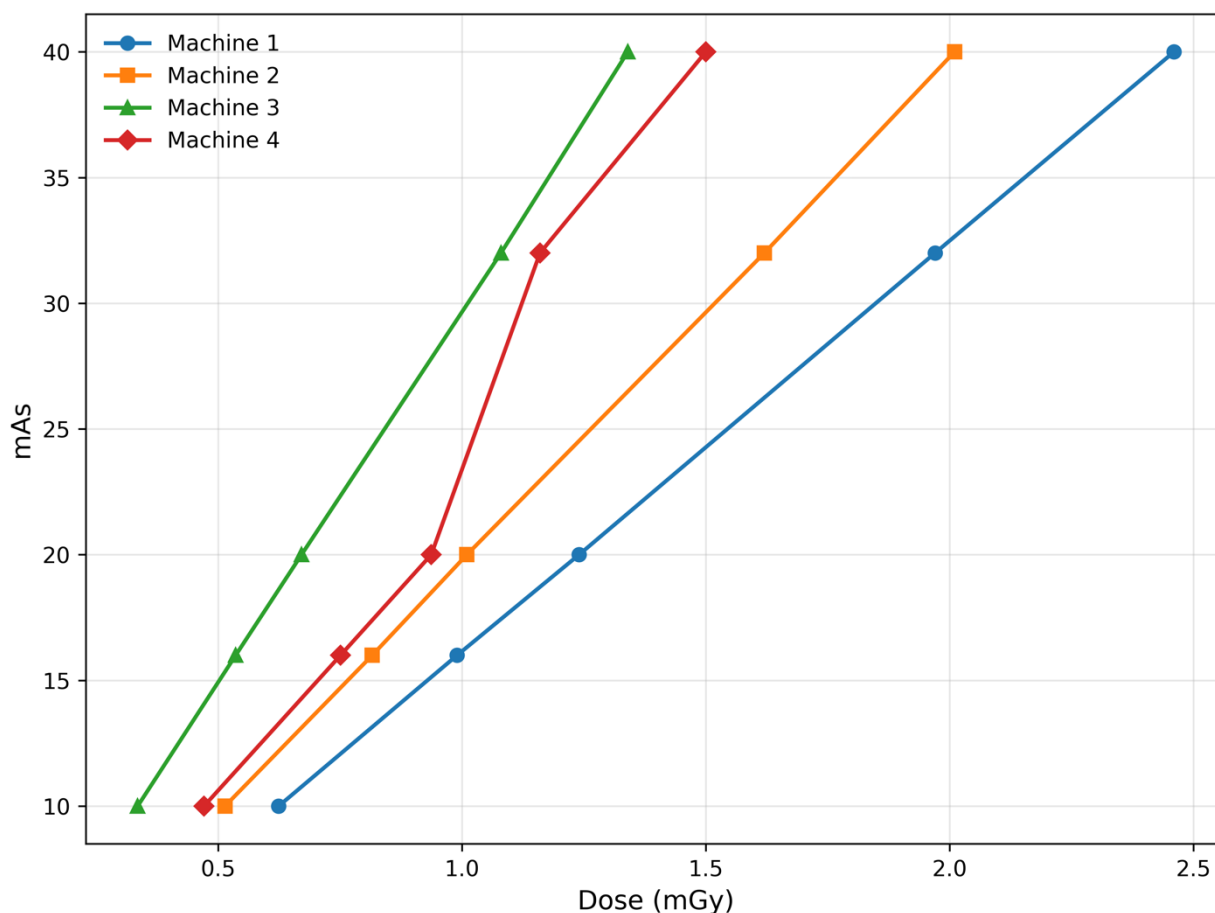


Figure 2. Dose output as a function of tube current–time product (mAs) for Machines 1–4

Machine 1 shows the highest HVL (3.7 mm Al), indicating a slightly harder (more penetrating) beam compared to the others. Machines 2 and 4 have the lowest HVL (3.0 mm Al), implying a relatively softer beam. Machine 3 is intermediate (3.4 mm Al).

All four machines demonstrated acceptable and consistent HVL values, falling within the range of 3.0 to 3.7 mm Al. While there is a 0.7 mm Al variation between the softest and hardest beams, this remains within typical QC expectations. Many protocols, including those from the AAPM, IAEA, and IEC, consider variations of ± 0.3 to ± 0.5 mm Al reasonable, depending on clinical technique charts and equipment design.

Machines 2 and 4 may warrant routine verification to ensure filtration and calibration alignment, while Machine 1 appears to produce a slightly harder beam, though still within acceptable limits.

According to IAEA Basic Safety Standards and IEC equipment requirements, the minimum HVL for a 70 kVp beam is 2.5 mm Al. All measured HVL values comfortably exceed this threshold, indicating adequate filtration and good beam quality. This is essential for patient safety, as proper filtration reduces unnecessary low-energy radiation while maintaining diagnostic image quality.^{13,19,27}

These results of the study also align with published studies. The study by Ireland *et al.*¹⁶ reported HVL values between 2.8–3.6 mm Al for diagnostic units operating at comparable kVp settings. The AAPM TG-150 report (2024) similarly identifies HVL values around 3.0 mm Al as typical for 70 kVp settings.^{6,21}

Thus, the measured HVL values confirm that all machines tested are producing appropriately filtered beams and performing within internationally accepted standards.

4. Conclusion and recommendations

The QC tests conducted on the equipment in the four radiology departments demonstrated that all the machines met the acceptability criteria outlined by the AAPM, IAEA, and RAF 6/053 for the parameters assessed. The measurements for linearity, reproducibility of kVp and output, and HVL were found to be reliable and accurate, showing that even with a high daily workload and the age of the equipment, they were still performing within an acceptable range. This positive outcome is likely attributed to effective after-sales services provided by the manufacturers and the diligence of local biomedical engineers who perform maintenance.

However, the identified deficiencies, particularly the variations in tube voltage on the four machines, underscore the vital importance of a formalized, routine QC program.

Based on the findings of this research, we recommend the following:

- (i) **Establish a formal QC program:** The Namibian health system, in collaboration with the NRPA, should establish a mandatory and systematic QC program for all diagnostic imaging facilities. Create a comprehensive, itemized inventory of all radiation-producing equipment, including its age, make, model, last major service date, and current operational status. A qualified diagnostic medical physicist must be assigned primary responsibility for the program to develop, implement, and oversee these QA protocols.^{3,9-11,13,18}
- (ii) **Provide a practical protocol:** By establishing a national Acceptance Criteria for Namibian diagnostic equipment. This is going to be achieved by adopting internationally recognized tolerances.^{2,5,6,13,14,18,21,29} For example, AAPM TG-150 [2024]⁶ recommends that kVp accuracy should be within $\pm 5\%$ of the indicated value. The protocol and methods detailed in this paper should be adopted as a national standard for QC procedures for conventional radiology and fluoroscopy equipment.
- (iii) **Mandatory corrective action:** A system should be implemented to ensure that deficiencies identified during QC tests are addressed promptly by biomedical engineers, with documented evidence of corrective action and re-testing. Implement a rigorous system for recording all test results, maintenance actions, and corrective actions taken. This documentation is crucial for NRPA compliance and trend analysis.
- (iv) **Academic collaboration:** Partnerships with established academic institutions across the globe can

provide peer review of local protocols, co-development of training modules, and joint research on optimizing imaging techniques for the local institutions. This also addresses the lack of formal medical physics residency or training programs.

- (v) **Clinical collaboration:** Encouraging routine interaction between the medical physicist and the diagnostic team (radiographers and radiologists to foster a Culture of Safety and Quality. Radiographers, who perform daily QC, are the front line; the medical physicist provides the technical expertise and oversight.¹³

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Conflict of interest

The authors declare no conflict of interest.

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Not applicable.

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Not applicable.

Availability of data

All data generated or analyzed during this study are included in this published article. Additional datasets are available from the corresponding author upon reasonable request.

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