Open Journal of Medical Imaging, 2025, 15(3), 192-205
https://www.scirp.org/journal/ojmi
ISSN Online: 2164-2796
ISSN Print: 2164-2788

Effect of Varying HVL Values on the Dose Output of Plain X-Ray Machines at a Fixed kV of 80, a Regulatory Perspective

Wellen Rukundo*, **Natharius Nimbashabira**, **Noah Deogratias Luwalira**

Atomic Energy Council, Kampala, Uganda
Email: *rukundowellen@gmail.com

How to cite this paper: Rukundo, W., Nimbashabira, N. and Luwalira, N.D. (2025) Effect of Varying HVL Values on the Dose Output of Plain X-Ray Machines at a Fixed kV of 80, a Regulatory Perspective. *Open Journal of Medical Imaging*, **15**, 192-205.
https://doi.org/10.4236/ojmi.2025.153017

Received: April 25, 2025
Accepted: September 22, 2025
Published: September 25, 2025

Abstract

Background: HVL in diagnostic X-ray machines is an important property for defining the penetration ability of an X-ray beam into the human body and, hence, the beam hardness. **Materials and Methods:** The study utilized the findings of the radiation safety inspections conducted between 2022 and 2023 to investigate the variation of the Half-value layer (HVL) with dose output, taking 64 X-ray machines based on a set criterion. **Results:** A total of 26 X-ray machines failed the HVL test, while 38 passed the HVL test. Of the 38 that passed the test, 14 had very high and extremely high HVLs and produced doses below the lower limit of the permissible range of 0.025 - 0.08 mGy/mAs. The corrective action for 26 machines that generally failed the HVL test was to minimize the filtration by removing the filter plates. However, this had to be done only after a conclusive investigation to check the accuracy of tube current (mA), timer (s), and tube potential (kVp) parameters. **Conclusion:** Therefore, the regulatory body recommends that HVL tests be part of the acceptance and commissioning tests for the new machines in Uganda and be done routinely for the machines in use, as specified in the quality control program for each X-ray machine.

Keywords

Filtration, Penetration Ability, Dose Output, Image Quality, Regulatory Limit

1. Introduction

HVL defines the quality of the beam and, hence, the penetrating ability. This is the most important property of X-ray radiation for medical imaging equipment, which varies for different energies determined by the tube potential (kV). Penetration ability is determined by several factors, which include the thickness of the target object, photon energy, and atomic density, as discussed in detail by [1] (Sprawls, 2001). For each photon traveling a distance (d) before being absorbed, the distance is inversely proportional to the amount of radiation attenuated (μ). Therefore, HVL is given in Equation (1) below;

$$\text{HVL} = 0.693 * \text{range} = 0.693 * 1/u \tag{1}$$

For diagnostic X-ray machines, this is one of the most important quality control (QC) tests to be assessed in a quality assurance (QA) program [2]-[4] (Amoako & Owusu, 2018; Gallini *et al.*, 1995; IAEA, 2023). Note that the primary role of QC tests is to evaluate the compliance of the product with the set standards and requirements of a regulatory body [4] (IAEA, 2023). The HVL factor also determines a component of beam hardness, which in turn can be used to determine the shielding requirement of a facility and the amount of soft radiation in a beam. The soft X-ray beam is an important component of the X-ray spectrum, as it offers a higher contrast for improved image quality [5] (Huda & Abrahams, 2015). However, it has the effect of increasing the patient dose (unjustified dose) and increasing the scatter associated with a noisy image [1] (Sprawls, 2001). Therefore, in practice, the diagnostic techniques should optimally minimize the dose to the patient while ensuring a better image quality for satisfying the purpose of the exposure. The little literature about this concept shows that increasing HVL reduces the dose output, while keeping other associated exposure factors constant [4] [6]-[8] (Behrman & Yasuda, 1998; IAEA, 2023; McBroome *et al.*, 2021a; Poletti, 1994). For example, a study by [6] (Behrman & Yasuda, 1998) showed that increasing the HVL from 1.5 to 4.0 mm Al at a fixed kVp reduced the effective dose to 17% for the case of a constant exit dose, and 25% for a constant film density with a "400 speed" rare-earth screen-film system. However, some of our findings contradicted the above relationship.

We note that filtration and HVL terms are used concurrently. As discussed by [1] (Sprawls, 2001), adequate filtration enables the selective absorption of lower-energy photons. This shifts the effective energy of the X-ray beam and hence the shape of the X-ray spectrum. Therefore, increasing filtration increases the beam penetration ability, which is defined as HVL. We, therefore, set the filtration requirements using the minimum acceptable limit of HVL thickness adopted from the European Union Acceptability criteria of Medical Radiological Equipment used in Diagnostic Radiology, Nuclear Medicine, and Radiotherapy, Radiation Protection No. 162 [9] (Faulkner *et al.*, 2012). A more penetrating X-ray beam gives a patient entrance dose that is nearly equal to the dose at the image receptor position, hence a minimal dose absorption by the patient.

The adequacy of filtration in diagnostic X-ray machines benefits both the patient and radiation workers with regard to radiation protection through dose minimization to the patient, minimization of scatter radiation to the patient and workers, and beam hardening that improves image quality [7] (McBroome *et al.*, 2021b). By the design of X-ray machines, the inherent filtration of about 0.5 - 1 mm Al is contributed by the X-ray tube and collimator housing [10]-[12] (International Atomic Energy Agency (IAEA), 2014; International Commission on Radiological Protection (ICRP), 1982; Lacerda *et al*., 2007). The added filtration is composed of additional filters, which are commonly aluminum and, in rare cases, copper. These should give at least a minimum of total filtration of about 2.5 mm Al for X-ray machines operating around 70 kVp [10] (International Atomic Energy Agency (IAEA), 2014). According to [2] (Amoako & Owusu, 2018), the HVL of the X-ray machines ideally should not change over a machine's lifetime, and hence, this makes it one of the MUST parameters for testing at commissioning. Any later deviation from the commissioning results indicates the inadequacy of filtration. For regulatory purposes, specific requirements of filtration are set following country-specific regulations, guidance, and standards. Other countries, however, have adopted international standards recommended by the IAEA and the ICRP, as well as those of any other international organization. The Atomic Energy Council (AEC) of Uganda, mandated with regulating the peaceful application of ionizing radiation, adopted the European standards of filtration requirements for plain radiography X-ray machines [9] (Faulkner *et al*., 2012). Refer to **Table 1**, which shows the minimum HVL recommended limits for common set kVs used in this study, extracted from the European standards of filtration requirements.

Table 1. A table of HVL minimum recommended limits for each kV commonly used for this study.

X-ray Tube Voltage (kV)	Minimum Permissible First HVL (mmAl)
50	1.8
60	2.2
70	2.5
80	2.9
90	3.2
100	3.6

Regulatory inspections carried out in Uganda on the performance of X-ray machines have established that some of the X-ray machines had HVL values less than the recommended regulatory limits. Factors that have been taken into consideration include radiation field size, focus filter focus distance (FFD), and X-ray beam geometry. Other researchers have noted that these factors contribute to uncertainties during such measurements [12]-[14] (Farr, 1955; Lacerda *et al*., 2007; Trout *et al*., 1960). Therefore, this study intends to determine the extent of correlation between HVL and dose output in plain X-ray machines in Uganda. The study further intends to determine the appropriate regulatory actions for the X-ray machines that fail the comply with the regulatory established limits of HVL and dose output.

2. Materials and Methods

The detector was placed on a couch and exposed at different kV settings ranging from 50 to 90 for each X-ray machine. An exposure at a value of 80 kV was included in the range since it has a known standardized recommended dose output. The reference values for FFD and mAs were set to 1m and 20 mAs, respectively. For each measurement, at least 3 exposures were taken, and an average was calculated. A quality control kit manufactured by Unfors Ray Safe AB, Model: 8252010-6, S/N: 272907, which had been calibrated on August 11, 2021, was used to perform the measurements. This is a solid-state detector with essentially p-n junction diodes that create electron-hole pairs in the depletion region, creating an electric field that drives electrons and holes apart to produce a current pulse that can be quantified as a proportion of the deposited energy [15] (Ahmed, 2015). This makes these detectors ideal for dynamically changing measurements of kVp, dose rate, and HVL over a diagnostic X-ray energy range of 30 - 150 kV [16] (RaySafe, 2018). The accurate HVL measurements are enabled by the built-in filtration and calibration algorithms that require no manual correction. This measurement may be influenced by the X-ray beam composition, detector geometry, positioning, and beam quality. The data was collected from the routine inspection reports done by the Atomic Energy Council in 2022. The study considered plain X-ray machines with a fixed and mobile orientation that passed the kV accuracy test but had failed the HVL/beam quality test, the normalized dose output test, or both. A machine was considered to have passed the kV accuracy test once the percentage errors at all set kVs were ±10% of the set kV. A machine was considered to have failed the HVL test once the average measured HVL values at any of the selected kVs were below the minimum recommended thickness [9] (Faulkner *et al.*, 2012). A machine failed the normalized dose output test once the values dose at 80 kV was outside the recommended permissible range of 0.025 - 0.08 mGy/mAs at reference values. All the X-ray machines selected from the above criteria were classified into groups defined by different HVL ranges, as shown in **Table 2**.

Table 2. A table showing the HVL description for different ranges.

Ranges of HVL deviation from the recommended HVL limit of 2.9 mm Al at 80 kV	Description
HVL < 2.9	Fail
2.9 < HVL ≤ 3.1	Moderate
3.1< HVL ≤ 3.6	High
3.6 < HVL ≤ 4.0	Very high
HVL > 4.0	Extreme high

3. Results and Discussion

From the criteria in **Table 2**, 64 X-ray machines were selected, of which 36 had a fixed orientation (fixed X-ray machines) and 28 had a mobile orientation. Out of the 64 machines, 26 failed the HVL test, while 38 failed the normalized dose output test. A detailed analysis of each classification and discussion is in the next subsections.

3.1. Machines that Failed the HVL Test

Figure 1 shows the X-ray machines that failed the HVL test at 80 kV with their corresponding dose output. Out of the 26 machines, 14 had a mobile orientation while 12 were fixed. About 54% of the 26 machines produced dose output within an optimal range of 0.025 mGy/mAs - 0.080 mGy/mAs. An implication of the failure of the HVL test is that the HVL of the machine at any selected kV was below the recommended regulatory limit, indicating inadequate filtration of the damaging soft X-rays. Since the patient receives an optimal dose even at HVLs below the recommended limit, the appropriate action to be recommended for such machines is complicated. With a little modification to Edmond's equation [8] (Poletti, 1994), an inverse relationship exists between HVL and dose as shown in Equation (2). Noting that the kV accuracy test has passed, the facility may consider adding additional filters of either aluminum or copper material to normalize the HVL. However, this may lower the patient's dose and contrast, which affects the planned purpose of the imaging. For most machines, the variation of X-ray tube potential results in the variation of the filtration automatically [8] (Poletti, 1994).

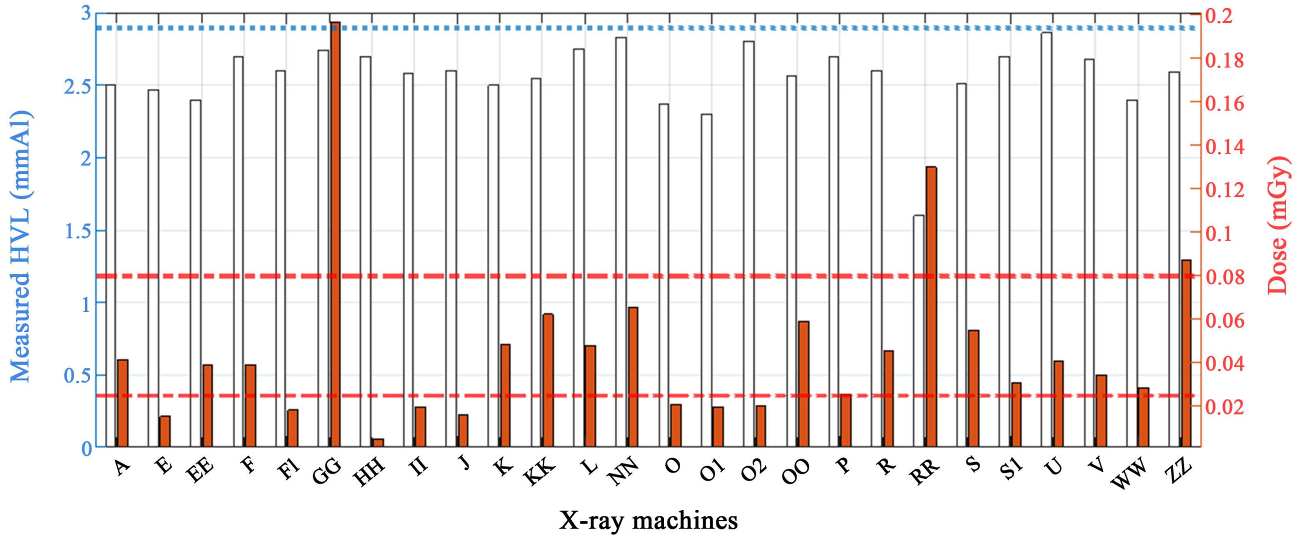

Figure 1. A bar graph showing the variation of HVL (unshaded bars) with dose output (shaded bars) for different X-ray machines that failed the HVL test. Note that this is considered at only 80 kV, as shown in Table 1.

$$\text{Dose} = \frac{\text{kV}^n * \text{mAs}}{\text{FFD}}\left(\frac{1}{\text{HVL}} + 0.114\right) \tag{2}$$

A total of 7 X-ray machines (~31%) of the 26 machines produced doses below the lower limit of 0.025 mGy/mAs. This is rather more complicated because we would expect a high dose because of the less filtration of the X-ray beam. In this case, the patients are likely to receive very low doses, and hence, the purpose of the diagnosis may not be achieved. This may result in cases of repeated exposures, and or misdiagnosis, and hence patients may receive unjustified doses. As already discussed, the HVL reduces beam intensity and increases the average beam energy, which is controlled by the tube potential/kVp variation [1] (Sprawls, 2001). This does not affect the number of photons in the spectrum that contribute to the dose, which is controlled by the mA/tube current modulation as shown in Equation (2). Therefore, while HVL may affect the dose output, the dose does not affect HVL.

Three X-ray machines (GG, RR & ZZ) produced doses greater than the upper limit of the optimal dose range, which subjects the patients to higher doses. Therefore, we recommend immediate action on such machines not to be used for medical exposures till the appropriate action is taken to correct the dose. The X-ray machine RR had the lowest HVL at each kV compared to other machines, though all the machines had HVLs less than the regulatory limit at each kV. The HVL dose relationship for the 3 machines does not comply with Equation (2), otherwise, RR should have the greatest dose. This is because other factors contribute to the dose specific to generator type, manufacturer, and age. Machines that have different manufacturers of the collimator, X-ray tube, and generator tend to fail the kV output, and hence HVL, due to mismatched tube-generator characteristics [4] [17] [18] (AAPM, 2002; European Commission: Directorate-General for Research and Innovation, 1996; IAEA, 2023). Additionally, the old X-ray machines require frequent calibration services to maintain compliance with the regulatory standards of dose and HVL. Past studies have shown that 1- and 2-pulse waveforms yield softer X-ray spectra associated with increased doses to the patient [10] (International Atomic Energy Agency (IAEA), 2014). Some of these isolated cases of inconsistencies in machine performance that affect the HVL dose relationship have been identified during our routine inspections, though they lack the detailed documentation for further assessment. This study, therefore, identifies the knowledge and literature gap to be addressed in subsequent research works.

For all the above three cases, the immediate recommendation is to add additional filter plates of aluminum or copper to increase the HVL thickness. However, this should be done after an adequate investigation that checks the accuracy of the tube current and timer for machines with different mA and timer consoles. We note from Equation (2) that the tube current has a direct impact on dose output. Other than the accuracy of the tube output, other tests, for example, reproducibility and power quality, also define the quality of kVp [19] [20] (Godfrey *et al.*, 2015; Hjouj *et al.*, 2022). In this study, all 26 machines had good kV reproducibility, shown by a coefficient of variation of less than 10% at each kV setting. However, we could not assess the power quality of each machine, which was a limitation of the study. Therefore, as we conclude in this case, the type of orientation of the X-ray machine may not necessarily affect the performance standard of

HVL. However, from the general observation during routine inspections, the failure rate of the HVL test was higher in mobile than in fixed X-ray machines. This might be due to;

a) Old-aged mobile X-ray machines manufactured before 2012 with low HVL compared to the regulatory standards [4] [9] [20] (Faulkner *et al*., 2012; Hjouj *et al*., 2022; IAEA, 2023).

b) Mobile X-ray machines are meant to be used for emergencies, but not for general radiography, which results in overloading and hence faster deterioration of their performance [21] [22] (Kartika & Savitri, 2020; Nevada Division of Public and Behavioral Health (DPBH), 2023).

Most of these types of machines were imported into the country even before the establishment of regulatory standards. We also note that the current trend of machines being imported into the country generally has high HVL standards for adequate filtration.

3.2. Machines that Passed the HVL Test but Failed the Dose Output Test

From **Table 2**, it's noted that all machines that had HVL above 2.9 mmAl at 80 kV passed the HVL test. The number of X-ray machines in each class was 5, 19, 10, and 4 for moderate, high, very high, and extreme high, respectively. **Figure 2** shows the X-ray machines for the different classifications above the regulatory limit and their variation of measured dose output.

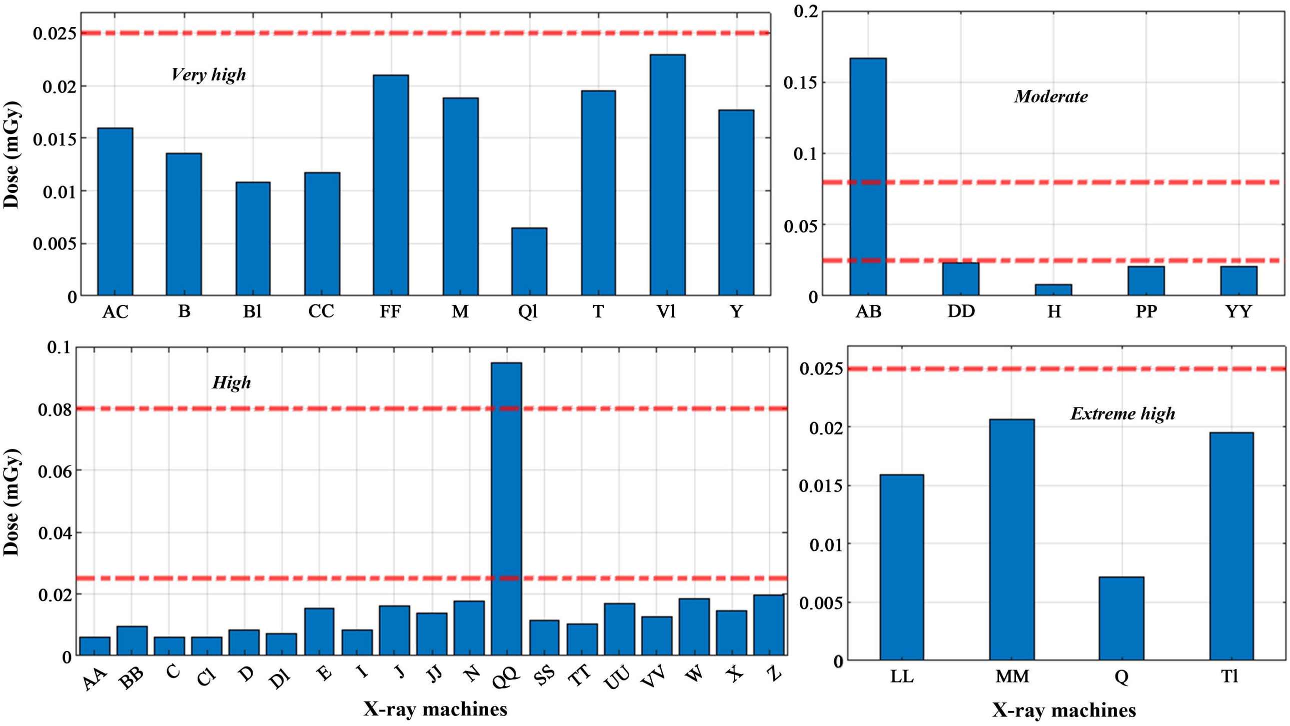

Figure 2. A subplot of bar graphs showing the variation of dose for X-ray machines in different HVL classifications above the recommended 2.9 mmAl at 80 kV.

Generally, all the machines exhibited a phenomenon in Equation (2), except X-ray machines AB in the moderate class and QQ in the high class. It's observable that as the HVL values increased from moderate to extremely high, the dose continuously lowered below the lower limit of the optimal dose range of 0.025 mGy/mAs. The high HVL values imply that there is excessive filtration of the X-ray spectrum, which may lower the dose to the patient. This is important for dose minimization to the patient; however, this may affect the optimal dose required to achieve the purpose of imaging for proper diagnosis. It's noted during the inspections that some machines with HVL values above the recommended limit, similar to this case, produced doses within the recommended optimal range. The excessive filtration greatly reduces the low-energy photons, which significantly reduces the contrast. At low photon energies, the absorption properties of body tissues vary [23] [24] (Kadri & Alfuraih, 2019; Sandell & Zhu, 2011). Therefore, the reduction in contrast may only be perceived at very high values of HVLs greater than the recommended regulatory values [8] (Poletti, 1994).

For these cases, we recommend checking for removable additional filters to minimize the filtration. However, this should be done after an adequate investigation, including checking the geometry setup and the accuracy of the tube's current output [4] (IAEA, 2023). For the modern trend of X-ray machines, the inverse relationship between dose and HVL may not directly apply. We can observe this from the recent modifications in the traditional Edmond's equation, refer to [25] [26] (Kothan & Tungjai, 2011; Simo *et al*., 2021) for details. This is because of the improved technologies of image processing that ensure a better quality image even at minimal doses like digital radiography systems [27]-[29] (Lee *et al*., 2020; Ou *et al*., 2021; Singh, 2023).

In a follow-up exercise on the previous inspection findings for the machines AB and QQ, we established the following: 1) the fixed X-ray machine AB, manufactured in 2013, had no past inspection history, and 2) the mobile X-ray machine QQ, manufactured in 1991, had been inspected about four times. **Table 3** shows a summary of its performance results at set parameters of 80 kV, 20 mAs, and FFD of 100 cm.

Table 3. A table showing the summary of performance results for X-ray machine QQ at set parameters of 80 kV, 20 mAs, and FFD of 100 cm.

Year of Inspection	Measured kV	Measured HVL (mm Al)	Dose (mGy)
2018	84.7	3.0	0.0621
2019	77.8	3.4	0.0589
2021	77.7	3.3	0.0947
2022	80.3	3.5	0.0602

We noticed the variation of the results of performance parameters during different inspection visits, despite no actions of machine repair or calibration were recorded. We established that the facility had resorted to operating the machine using a generator since there was an unstable power supply. Previous studies[30] [31] (Ngounou *et al*., 2015; Zhang *et al*., 2011) have noted that the low stability of the power supply can affect the performance of the X-ray machine. Therefore, it's recommended to maintain a high power supply for any operating X-ray equipment to ensure the production of stable and constant X-rays with enough penetrating power. The cases of power instability have been reported to affect mostly mobile X-ray machines, which use battery charging systems for power supply. Therefore, we always recommend assessing performance parameters for such machines when the batteries are fully charged.

4. HVL Dose Relationship with the Other Performance Parameters of the X-Ray Machine

4.1. HVL Dose Relationship

The graphical representation in **Figure 3** above shows the inverse relationship between HVL and dose, though the equation of the linear relationship of the above graphs may not estimate the accurate dose. A detailed statistical analysis using Excel is shown in **Table 4**.

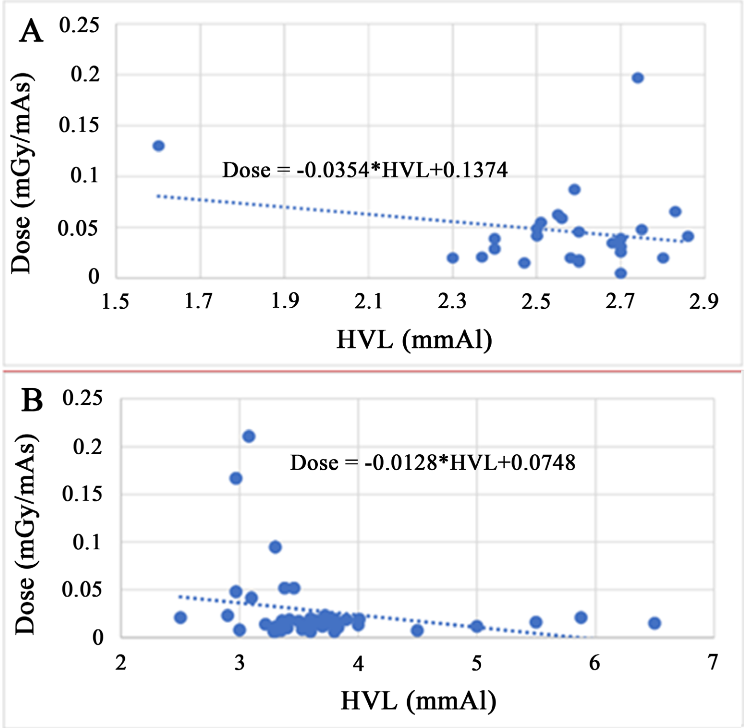

Figure 3. The figure shows the HVL dose relationship for the different groups of X-ray machines. A is a group of machines that failed the HVL, while B is a group of machines that passed the HVL test.

The correlation coefficient (multiple R) tends to zero rather than 1 for both A and B machines, implying a weak correlation between HVL and dose for the two cases. However, the dose HVL relationship is explained better by group B machines that passed the HVL test, shown by the higher F-statistic value compared to group A machines. A negative HVL coefficient for both cases confirms the discussion in the above section that an increase in HVL decreases the dose, which is in line with the previous studies [8] [24] [28] [32] (Ofori *et al.*, 2016; Ou *et al.*, 2021; Poletti, 1994; Simo *et al.*, 2021). The degree of impact of HVL on dose can be defined by the P-value. The statistical results from **Table 4** show that the P-value was >0.05 for both cases, implying that HVL had less influence on the dose. Based on these statistical results, we can conclude that dose does not solely depend on HVL, but rather several factors, as referred to in Equation (2) [8] (Poletti, 1994).

Table 4. A table showing the results of the regression analysis for the two cases of groups of X-ray machines (A & B).

Parameter	Graph A	Graph B
Multiple R	0.214	0.245
R Square	0.046	0.060
Standard Error	0.040	0.040
F Statistic	1.152	2.55
HVL Coefficient	−0.035	−0.013
P-value	0.294	0.118

4.2. HVL Relationship with kV Output

Despite the discrepancies in the HVLs discussed in the results and discussion, HVL and kV output follow a normal variation of the linear relationship with HVL increasing with tube potential (kV) [8] [32]-[34] (Ofori *et al.*, 2016; Patel, 1992; Poletti, 1994; Procter, 1973). During our routine inspections, we found out that most machines that failed the kV accuracy test also failed the HVL test. Consequently, the calibration of kV automatically affected the HVL values. Also, [33] (Patel, 1992) noted that the linear relationship of kV and HVL tends to diminish

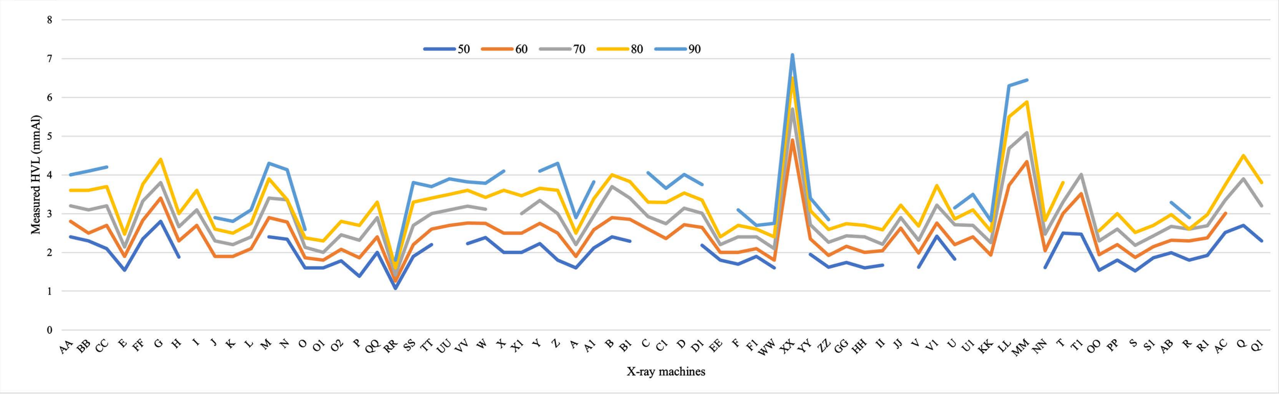

Figure 4. The figure shows the variation of HVL at different set kVs for X-ray machines.

at high kV values. This was not observed in our study due to a limited range of kV values that were selected. But this is also attributed to the fact that most facilities in Uganda use kV ranges from 50 - 90 kV for justified medical exposures.

5. Conclusions

In conclusion, any action for correcting the HVL of an X-ray machine should not be done in isolation from other machine parameters, like tube potential, current parameters, and dose output. From this assessment, we conclude that the HVL test is the most important performance parameter to be evaluated on a routine basis for optimization of machine performance in compliance with the regulatory standards. From the study, we suggest protocols to maintain the standard HVL values for adequate filtration as follows:

a) Operators/ machine owners need to establish baseline values of HVL at commissioning, which should comply with the regulatory limits.

b) Routine HVL measurements done according to the established facility quality control program.

c) Maintenance of records associated with HVL and dose measurements for follow-up and review.

The fact that this parameter does not change over time makes it one of the most important quality control tests that assures the regulatory body of acceptable machine standards at the time of commissioning. The experimental measurement requires a very narrow beam geometry [3] (Gallini *et al.*, 1995), and can be affected by back and side scatter [35] (Sekimoto & Katoh, 2016), which makes such conditions difficult to achieve in practice. However, from the results, the detector was able to achieve an acceptable standard HVL measurement. In summary, the inverse relationship between HVL and dose for plain X-ray machines is limited by other dose contributing factors, most importantly, tube current. While HVL is a factor of kV that defines the penetrating ability and hence quality of the beam, dose is a factor of tube current, defined by the number of photons/X-rays produced and hence beam quantity. Therefore, to generate appropriate actions for the X-ray machines that fail to comply with HVL and dose output standards, the accuracy of the tube potential (kV) and tube current (mA) should be checked, respectively. The study recommends a further analysis while considering image quality with variation in HVL and dose to ensure an optimized machine performance that serves the imaging purpose adequately.

Ethical Statement

This article does not contain any studies with human participants or animals performed by any of the authors.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Sprawls, P. (2001) The Physical Principles of Medical Imaging. 2nd Edition, Wiley.

[2] Amoako, G. and Owusu, I. (2018) Assessment of Some Selected Conventional Diagnostic X-Ray Facilities at Cape-Coast in the Central Region of Ghana. *Austin Journal of Radiology*, **2**, 1-4.

[3] Gallini, R.E., Belletti, S., Berna, V., Giugni, U. and Prandelli, G. (1995) A Simple Test for X Ray Tube Filtration. *Radiation Protection Dosimetry*, **57**, 253-256. https://doi.org/10.1093/oxfordjournals.rpd.a082536

[4] IAEA (2023) Handbook of Basic Quality Control Tests for Diagnostic Radiology (IAEA Human Health Series No. 47) (Issue 47). https://www.iaea.org/publications/14890/handbook-of-basic-quality-control-tests-for-diagnostic-radiology

[5] Huda, W. and Abrahams, R.B. (2015) Radiographic Techniques, Contrast, and Noise in X-Ray Imaging. *American Journal of Roentgenology*, **204**, W126-W131. https://doi.org/10.2214/ajr.14.13116

[6] Behrman, R.H. and Yasuda, G. (1998) Effective Dose in Diagnostic Radiology as a Function of X-Ray Beam Filtration for a Constant Exit Dose and Constant Film Density. *Medical Physics*, **25**, 780-790. https://doi.org/10.1118/1.598260

[7] McBroome, M., Chase, J., Farmer, D. and Mourant, N. (2021) The Use of Filtration in Diagnostic X-Ray Imaging. 2021 Undergraduate Research Showcase.

[8] Poletti, J.L. (1994) Factors Affecting Patient Dose in Diagnostic Radiology.

[9] Faulkner, K., Christofides, S., Lillicrap, S., Horton, P. and Malone, J. (2012) Criteria for Acceptability of Medical Radiological Equipment used in Diagnostic Radiology, Nuclear Medicine and Radiotherapy. Radiation Protection No. 162 (Issue May).

[10] International Atomic Energy Agency (IAEA) (2014) Diagnostic Radiology Physics: A Handbook for Teachers and Students.

[11] International Commission on Radiological Protection (ICRP) (1982) Protection of the Patient in Diagnostic Radiology. A Report of Committee 3 of the International Commission on Radiological Protection. *Annals of the ICRP*, **9**, 1-82.

[12] Lacerda, M.A.D.S., Silva, T.A., Da Oliveira, A.H., De, Da Silva, T.A. and De Oliveira, A.H. (2007) The Methodology for Evaluating Half-Value Layer and Its Influence on the Diagnostic Radiology. *Radiologia Brasileira*, **40**, 331-336.

[13] Farr, R.F. (1955) The Specification of Roentgen Ray Output and Quality. *Acta Radiologica*, **43**, 152-160. https://doi.org/10.3109/00016925509172758

[14] Trout, E.D., Kelley, J.P. and Lucas, A.C. (1960) Determination of Half-Value Layer. *The American Journal of Roentgenology, Radium Therapy, and Nuclear Medicine*, **84**, 729-740.

[15] Ahmed, S.N. (2015) Solid-State Detectors. In: *Physics and Engineering of Radiation Detection*, Elsevier, 259-329. https://doi.org/10.1016/b978-0-12-801363-2.00005-x

[16] RaySafe (2018) RaySafe X2 User Manual. https://www.flukebiomedical.com/sites/default/files/resources/5001083-raysafe_x2-manual-en-7.pdf

[17] AAPM (2002) AAPM Report No. 74: Quality Control in Diagnostic Radiology. https://www.aapm.org/pubs/reports/detail.asp?docid=73

[18] European Commission: Directorate-General for Research and Innovation (1996) European Guidelines on Quality Criteria for Diagnostic Radiographic Images. Publications Office.

[19] Godfrey, L.D., Adeyemo, D.J. and Sadiq, U. (2015) Radiological kVp Accuracy, Reproducibility and Consistence Assessment of Some Hospitals in Zaria Environs of Kaduna State, Nigeria. *Scholars Research Library Archives of Applied Science Research*, **7**, 27-31.

[20] Hjouj, M., Budeiri, D., Rajabi, A., Abu Khalaf, S. and Jghama, D. (2022) Assessment of Peak Voltage Accuracy and Reproducibility of Conventional X-Radiography Units in Palestine. *Proceedings of the* 2022 5*th International Conference on Digital Medicine and Image Processing*, Kyoto, 10-13 November 2022, 50-57. https://doi.org/10.1145/3576938.3576947

[21] Kartika, T. and Savitri, L. (2020) Radiation Safety Assessment on The Use of Portable X-Ray for General Radiography. Case Study: Portable X-Ray of X-Manufacture. 2020 *Annual Nuclear Safety Seminar* (*SKN*), Jakarta, 26 October 2020, 123-128. https://inis.iaea.org/records/fzkg3-h8j47

[22] Nevada Division of Public and Behavioral Health (DPBH) (2023) Use Limitations for Portable and Mobile X-Ray Machines. https://nvose.org/use-limitations-for-portable-and-mobile-x-ray-machines/

[23] Kadri, O. and Alfuraih, A. (2019) Photon Energy Absorption and Exposure Buildup Factors for Deep Penetration in Human Tissues. *Nuclear Science and Techniques*, **30**, Article No. 176. https://doi.org/10.1007/s41365-019-0701-4

[24] Sandell, J.L. and Zhu, T.C. (2011) A Review of *In- Vivo* Optical Properties of Human Tissues and Its Impact on PDT. *Journal of Biophotonics*, **4**, 773-787. https://doi.org/10.1002/jbio.201100062

[25] Kothan, (2011) An Estimation of X-Radiation Output Using Mathematic Model. *American Journal of Applied Sciences*, **8**, 923-926. https://doi.org/10.3844/ajassp.2011.923.926

[26] Simo, C.R.T., Samba, O.N., Talla, P.K. and Fai, L.C. (2021) Radiation Dose from Three-Phase X-Ray Machines: A Comparison between Different Models. *International Journal of Radiation Research*, **19**, 559-567. https://doi.org/10.52547/ijrr.19.3.559

[27] Lee, W., Lee, S., Chong, S., Lee, K., Lee, J., Choi, J.C., *et al*. (2020) Radiation Dose Reduction and Improvement of Image Quality in Digital Chest Radiography by New Spatial Noise Reduction Algorithm. *PLOS ONE*, **15**, e0228609. https://doi.org/10.1371/journal.pone.0228609

[28] Ou, X., Chen, X., Xu, X., Xie, L., Chen, X., Hong, Z., *et al*. (2021) Recent Development in X-Ray Imaging Technology: Future and Challenges. *Research*, **2021**, Article 9892152. https://doi.org/10.34133/2021/9892152

[29] Singh, N. (2023) What Are the Emerging Trends and Future Developments in X-Ray Technology, and How Will They Impact Medical Diagnostics and Treatment? Website Article.

[30] Ngounou, G.M., Gonin, M., Gachet, N. and Crettenand, N. (2015) Holistic Approach to Sufficient, Reliable, and Efficient Electricity Supply in Hospitals of Developing Countries: Cameroon Case Study. In: *Sustainable Access to Energy in the Global South*, Springer, 59-77. https://doi.org/10.1007/978-3-319-20209-9_6

[31] Zhang, S.J., Zhao, X.Y., Zeng, X.P., Peng, C.L., Guo, X.M. and Shi, L. (2011) The Power-Supply of X-Ray Machine Adopting PID Control and High-Frequency Inverter Technology.

[32] Ofori, E.K., Ofori-Manteaw, B.B., Gawugah, J.N.K. and Nathan, J.A. (2016) Relationship between Patient Anatomical Thickness and Radiographic Exposure Factors for Selected Radiologic Examinations. *Journal of Health*, *Medicine and Nursing*, **23**, 150-

162. https://iiste.org/Journals/index.php/JHMN/article/view/29048

[33] Patel, J.R. (1992) Kilovoltage Peak and Half Value Layer Relationships of a Dental X-Ray Machine. *Indian Journal of Dental Research*: *Official Publication of Indian Society for Dental Research*, **3**, 31-35.

[34] Procter, N.M. (1973) A Method of Checking Filtration and Kilovoltage on Diagnostic X-Ray Tubes. *The British Journal of Radiology*, **46**, 525-528. https://doi.org/10.1259/0007-1285-46-547-525

[35] Sekimoto, M. and Katoh, Y. (2016) Derivation of Total Filtration Thickness for Diagnostic X-Ray Source Assembly. *Physics in Medicine and Biology*, **61**, 6011-6024. https://doi.org/10.1088/0031-9155/61/16/6011