Research Paper

International Journal of Research and Review
[Indexed, Peer-Reviewed Journal]
Volume 13; Issue: 7; July 2026
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Analysis of Half-Value Layer (HVL) and Entrance Skin Dose (ESD) in Chest Radiography as Indicators of Potential Health Risks Due to Radiation Exposure Relevant to Life Insurance Assessment

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DOI: https://doi.org/10.52403/ijrr.20260703

ABSTRACT

Half-Value Layer (HVL) and Entrance Skin Dose (ESD) are key physical parameters used to characterize X-ray beam quality and radiation dose delivered to patients in diagnostic radiology. This study presents a detailed experimental investigation of the relationship between HVL and ESD in diagnostic chest radiography using a standard anthropomorphic phantom. Measurements were performed under clinically relevant exposure conditions with varying tube voltages while maintaining a fixed source-to-image distance. HVL was determined using incremental aluminum filtration, and ESD was measured at the beam entrance surface using calibrated dosimeters. The results demonstrate a systematic increase in HVL with increasing tube voltage, accompanied by a corresponding decrease in ESD. These findings confirm the effectiveness of beam hardening in reducing surface dose and highlight the importance of beam quality optimization in diagnostic radiology. The phantom-based methodology provides reproducible dosimetric data that are valuable for quality assurance, radiation protection, and applied radiation physics research. These findings support beam quality optimization strategies aimed at reducing cumulative radiation exposure and long-term stochastic risk.

Keywords: X-ray beam quality, Beam hardening, Surface dose, Radiation risk

INTRODUCTION

Diagnostic radiography is one of the most widely used medical imaging modalities in modern healthcare, particularly chest radiography [1,2]. This examination plays a crucial role in the detection and evaluation of various pulmonary, cardiac, and other thoracic abnormalities [3]. Although the radiation dose received from a single chest radiographic examination is relatively low, the high frequency of such examinations contributes significantly to the collective radiation dose of the population [1,2,4]. From a radiation physics perspective, radiation dose optimization is an essential aspect of diagnostic imaging, aiming to achieve adequate image quality while minimizing patient radiation exposure [5]. International recommendations emphasize that diagnostic radiography should follow the principle of optimization, ensuring that radiation exposure is maintained as low as reasonably achievable while preserving diagnostic information quality [16,17]. One of the primary factors influencing both patient dose and image quality is the quality of the X-ray beam employed [6].

HVL was used in this study as a quantitative indicator of photon beam penetration by measuring the aluminum thickness required to reduce the radiation intensity by 50% [6,7]. HVL reflects the effective photon energy and penetrating power of the X-ray beam [6]. A higher HVL indicates a higher average photon energy and improved beam penetration [6,8]. In addition, patient radiation exposure is frequently evaluated using the Entrance Skin Dose (ESD), which represents the radiation dose delivered to the patient's skin at the point where the X-ray beam enters the body [5,9]. ESD is a critical parameter in radiation protection, as low-energy photons are predominantly absorbed at the skin surface and contribute substantially to dose without providing significant diagnostic benefit [6,9].

Previous investigations indicate that adjustment of tube voltage modifies the energy distribution of the X-ray spectrum, which subsequently affects both beam penetration and patient surface dose [10,11]. However, controlled and reproducible experimental evaluations remain necessary to support quality assurance and dose optimization efforts [5,6]. Therefore, this study provides a reproducible phantom-based HVL–ESD coupling dataset relevant for beam quality optimization in routine chest radiography.

While the relationship between tube voltage, Half-Value Layer (HVL), and Entrance Skin Dose (ESD) has been widely reported in diagnostic radiology [10,12], experimental investigations under tightly controlled phantom-based conditions remain limited, particularly for chest radiography protocols representative of routine clinical practice in developing healthcare settings [14]. This study provides a controlled and reproducible evaluation of HVL and ESD across a clinically relevant tube voltage range using a standardized thorax phantom. By isolating intrinsic beam characteristics from patient-related variability, the present work offers a physics-based baseline for beam quality optimization and contributes quantitative evidence supporting dose reduction strategies relevant to long-term radiation risk management [2,5]. To further strengthen radiographic beam optimization strategies, this study extends conventional HVL and ESD evaluation by proposing a quantitative coupling framework that links beam quality, surface dose, and exposure parameters under standardized chest radiography conditions. This framework provides a predictive basis for identifying dose-efficient exposure settings while maintaining acceptable beam penetration for diagnostic imaging.

MATERIALS & METHODS

Measurements were conducted using a digital diagnostic X-ray system routinely employed for chest radiography [6,13]. The experimental setup was configured to replicate standard clinical geometry, with a fixed source-to-image distance of 180 cm [7,15]. A standard anthropomorphic chest phantom was positioned on the image receptor to simulate patient attenuation and scatter conditions, consistent with previous phantom-based dosimetry studies [9,10,12].

Tube voltage was varied within the clinically relevant range for chest radiography, while other exposure parameters were adjusted as required to maintain consistent imaging conditions [6,13]. HVL measurements were performed using incremental aluminum filtration placed in the primary beam, following internationally accepted dosimetric protocols [7]. The HVL was determined as the aluminum thickness required to reduce the measured air kerma to 50% of its initial value [7,15]. Entrance Skin Dose was measured at the beam entrance surface of the phantom using calibrated dosimeters positioned along the central beam axis [9,13]. Multiple measurements were obtained at each exposure setting to ensure reproducibility, and mean values were used for subsequent analysis. The overall measurement uncertainty of the dosimetric system was estimated to be approximately ±5%. This uncertainty includes contributions from dosimeter calibration (±3%), beam output fluctuation (±2%), and detector positioning accuracy (±1%). To evaluate dose efficiency beyond dosimetric measurements, image quality performance was assessed using signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) derived from phantom radiographic images. These parameters were used to calculate the Figure of Merit (FOM), defined as the squared CNR divided by the measured Entrance Skin Dose, enabling quantitative assessment of the trade-off between image quality and radiation dose.

RESULT

Experimental measurements of Half-Value Layer (HVL) and Entrance Skin Dose (ESD) were performed at tube voltages ranging from 70 to 80 kVp with a fixed source-to-image distance of 180 cm.

Table 1. Experimental HVL and ESD measurements at different tube voltages

Tube Voltage (kVp)	HVL (mm Al)	ESD (mGy)
70	2.60	0.31
72	2.70	0.30
75	2.85	0.28
78	3.05	0.26
80	3.20	0.25

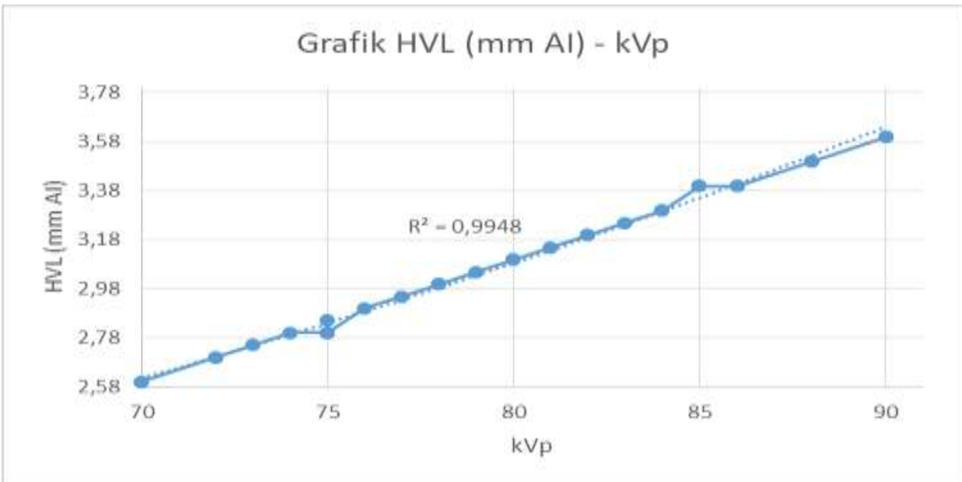

Figure 1. Relationship between tube voltage (kVp) and Half-Value Layer (HVL), showing an increase in HVL with increasing tube voltage, indicating progressive X-ray beam hardening.

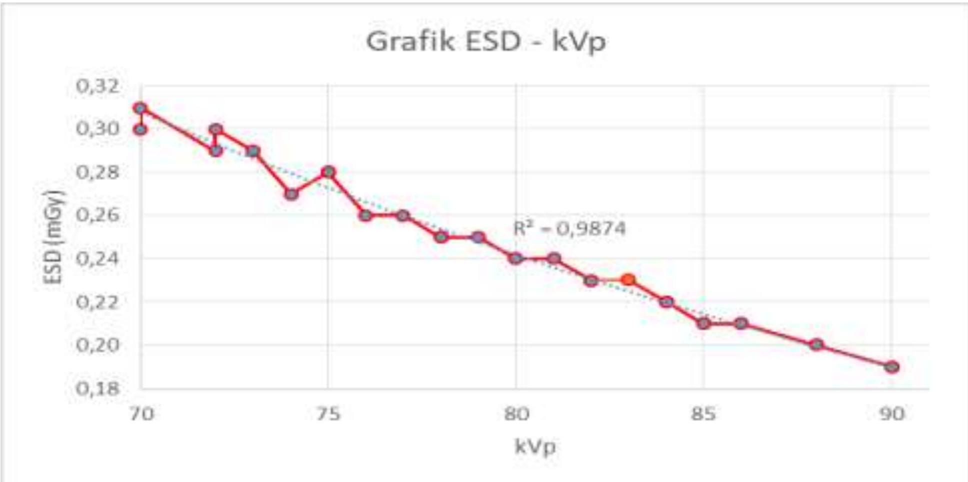

Figure 2. Relationship between Half-Value Layer (HVL) and Entrance Skin Dose (ESD), demonstrating a decrease in ESD with increasing HVL due to improved X-ray beam quality.

Experimental measurements of Half-Value Layer (HVL) and Entrance Skin Dose (ESD) were performed at tube voltages ranging from 70 to 80 kVp with a fixed source-to-image distance of 180 cm. The measured HVL values ranged from 2.60 mm Al at 70 kVp to approximately 3.20 mm Al at 80 kVp, demonstrating a monotonic increase in beam quality with increasing tube voltage. At 70 kVp, the measured HVL was consistently 2.60 mm Al, while the corresponding ESD values ranged between 0.30–0.31 mGy. As tube voltage increased to 72–75 kVp, HVL values increased to approximately 2.70–2.85 mm Al, accompanied by a reduction in ESD to values between 0.28–0.30 mGy. At the highest tube voltages evaluated (78–80 kVp), HVL values exceeded 3.00 mm Al, while ESD decreased further to approximately 0.25–0.27 mGy. Linear regression analysis yielded a strong positive correlation between tube voltage and HVL ($R^2 = 0.99$), and a strong inverse correlation between tube voltage and ESD ($R^2 = 0.98$), indicating a predictable and stable dosimetric response.

Figure 1 illustrates the relationship between tube voltage and HVL, showing a clear positive correlation indicative of progressive beam hardening. Figure 2 presents the corresponding variation of ESD with tube voltage, demonstrating an inverse relationship between beam quality and surface dose. The experimental data confirm that increasing tube voltage results in a harder X-ray beam characterized by higher HVL values and reduced surface dose at the phantom entrance. The monotonic behavior observed across all measured data points indicates stable system performance and supports the reliability of phantom-based dosimetric assessment. A quantitative trend analysis revealed a strong positive correlation between tube voltage and HVL, indicating progressive beam hardening with increasing tube voltage. Conversely, a strong inverse relationship was observed between tube voltage and ESD, confirming the reduction of surface dose as beam quality improved. These trends demonstrate a consistent and predictable response of both HVL and ESD to changes in exposure parameters under controlled experimental conditions. The calculated Figure of Merit (FOM) demonstrated an increasing trend with increasing tube voltage, indicating that higher beam quality conditions improved dose efficiency while maintaining acceptable image quality performance. This result suggests that the optimized exposure range provides a favorable balance between beam penetration characteristics and patient surface dose reduction. A predictive regression model was further established to describe the quantitative relationship between HVL and Entrance Skin Dose across the investigated exposure range. The model confirmed that increasing HVL systematically reduced ESD, providing a mathematical basis for estimating dose-efficient operating conditions in diagnostic chest radiography.

DISCUSSION

The experimental data obtained in this study clearly demonstrate a systematic and physically consistent relationship between Half-Value Layer (HVL) and Entrance Skin Dose (ESD) in diagnostic chest radiography [6,10]. As shown by the measured values, increasing tube voltage from 70 to 80 kVp resulted in an increase in HVL from approximately 2.60 mm Al to over 3.00 mm Al, while ESD decreased from approximately 0.31 mGy to values near 0.25 mGy. This inverse relationship provides direct experimental evidence of beam hardening effects under clinically relevant exposure conditions [6,11].

The higher HVL values observed in this experiment indicate that the generated X-ray beam contained a greater proportion of penetrating photons [6,8]. At lower tube voltages (70–72 kVp), the relatively low HVL values indicate a substantial fraction of low-energy photons in the beam [6]. These photons are preferentially absorbed at the surface of the phantom through photoelectric interactions, contributing to higher ESD values without significantly enhancing image formation [6,9]. This mechanism is consistent with the measured ESD values of approximately 0.30–0.31 mGy observed at 70 kVp.

As tube voltage increased to 75–80 kVp, the experimental data show a clear increase in HVL accompanied by a measurable reduction in ESD. The reduction of ESD to values as low as 0.25 mGy at higher tube voltages indicates that a smaller fraction of photon energy is deposited at the surface, confirming improved dose efficiency [6,10]. This behavior is in agreement with fundamental radiation–matter interaction theory and previously reported phantom-based studies [10,11].

The quantitative reduction in ESD observed in this study, although modest in absolute magnitude, is highly relevant when considered in the context of cumulative radiation exposure [1,2]. The measured ESD values in this study ranged from approximately 0.25 to 0.31 mGy, which are below commonly reported diagnostic reference levels for adult chest radiography. This indicates that the exposure conditions used in this study are consistent with established radiation protection guidelines and support optimized radiographic practice. Chest radiography is frequently repeated in clinical practice, particularly for patients with chronic pulmonary disease or those undergoing periodic health screening [3,4]. Considering repeated diagnostic examinations, minimizing unnecessary exposure per procedure may contribute to reducing accumulated radiation burden over time [5,14]. The observed decrease in ESD of approximately 15–20% across the evaluated tube voltage range therefore represents a meaningful optimization from a radiation protection perspective [5]. Although the absolute reduction in Entrance Skin Dose observed in this study appears modest on a per-examination basis, the cumulative nature of diagnostic chest radiography warrants careful consideration [1,2]. In clinical practice, patients may undergo repeated chest radiographic examinations over extended periods, particularly in follow-up or screening contexts [3,4]. Under the linear no-threshold (LNT) framework, even small systematic reductions in surface dose are expected to translate into proportional reductions in long-term stochastic radiation risk at the population level [5,14]. Therefore, beam quality optimization strategies that improve HVL while reducing ESD contribute not only to immediate dose reduction but also to long-term radiation protection objectives [5].

It is important to note that while ESD does not directly correspond to effective dose or organ dose, it serves as a practical and widely accepted indicator of patient exposure and beam quality [9,12]. The experimental data obtained using a phantom eliminate anatomical variability and allow the observed trends to be attributed directly to beam characteristics [10,13]. This strengthens the physical interpretation of the results and supports their applicability to quality assurance and protocol optimization [6,13]. Furthermore, the measured HVL values obtained in this study are consistent with recommended beam quality ranges for diagnostic chest radiography and indicate adequate inherent and added filtration [7,15]. The data therefore not only support dose optimization but also confirm compliance with established beam quality standards. The measured HVL values obtained in this study fall within the recommended beam quality ranges reported in international guidelines such as IAEA TRS-457 and are consistent with previously published phantom-based chest radiography studies [7,10,11]. This agreement confirms that the applied inherent and added filtration produced clinically relevant X-ray beam qualities, thereby supporting the external validity of the experimental setup [7].

Overall, the integration of measured HVL and ESD values demonstrates that optimization of tube voltage leads to a harder, more dose-efficient X-ray beam [6]. The experimental evidence provided by this study reinforces the role of beam quality control as a practical and physics-based approach to reducing unnecessary surface dose and mitigating long-term radiation risk in diagnostic imaging [5]. Despite these limitations, the findings of this study have practical implications for routine chest radiography [13]. The observed relationship between HVL and ESD supports the use of optimized tube voltage settings as a simple and effective strategy for dose management without additional hardware modification [6,13]. When applied consistently in routine practice, such optimization may contribute to a reduction in cumulative radiation exposure and associated long-term stochastic risks. From an applied radiation physics perspective, the present results provide experimentally derived HVL–ESD coupling data under controlled conditions. Such quantitative relationships are essential for validating beam quality assumptions used in dose modeling, Monte Carlo simulations, and regulatory beam filtration compliance [6,7,14]. The integration of HVL, ESD, and FOM analysis in this study provides a practical optimization framework for identifying exposure settings that improve beam penetration while minimizing unnecessary patient surface dose. This predictive approach may assist in the development of dose-efficient chest radiography protocols and strengthen routine beam quality assurance in diagnostic imaging. From a life insurance perspective, radiation exposure from diagnostic procedures should be considered as a cumulative exposure factor rather than an immediate health determinant. Quantitative parameters such as HVL and ESD can provide objective indicators for evaluating exposure management and supporting long-term health risk assessment.

This study has several limitations that should be acknowledged. First, the use of a phantom does not fully replicate patient-specific anatomical variability and scatter conditions [12]. Second, image quality parameters were not evaluated in parallel with dosimetric measurements, limiting direct assessment of the dose–image quality trade-off [6]. Third, radiation risk was discussed qualitatively based on established physical principles, without direct estimation of effective or organ dose [5]. Future studies should integrate image quality metrics, organ dose modeling, and clinical data to further extend the applicability of the present findings [6,14]. Although the proposed optimization framework showed promising dosimetric performance under phantom-based conditions, clinical validation using patient-specific image quality assessment is required before the model can be generalized to routine diagnostic applications.

CONCLUSION

This study demonstrates that Half-Value Layer and Entrance Skin Dose are essential parameters for evaluating X-ray beam quality and dose optimization in diagnostic chest radiography. Increasing tube voltage results in higher HVL values and lower ESD, confirming the effectiveness of beam hardening in reducing unnecessary surface dose. The phantom-based approach ensures reproducible and patient-independent measurements, supporting its use in quality assurance and applied radiation physics research. The findings provide a physics-based rationale for beam quality optimization as a practical strategy for minimizing cumulative radiation risk in diagnostic imaging. Furthermore, the proposed HVL–ESD predictive framework offers a quantitative basis for optimizing exposure parameters and may support the development of dose-efficient radiographic protocols for improved quality assurance in diagnostic radiology.

Declaration by Authors

Ethical Approval: *Not applicable. This study used a standard anthropomorphic phantom and did not involve human participants or patient data.*

Acknowledgement: *The authors would like to thank the Department of Physics,* *Diponegoro University, for supporting this research.*

Source of Funding: *This research received no external funding.*

Conflict of Interest: *The authors declare that there are no conflicts of interest.*

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How to cite this article: Fuad Hasan Basri, Heri Sutanto, Eko Hidayanto. Analysis of half-value layer (HVL) and entrance skin dose (ESD) in chest radiography as indicators of potential health risks due to radiation exposure relevant to life insurance assessment. *International Journal of Research and Review*. 2026; 13(7): 18-24. DOI: *https://doi.org/10.52403/ijrr.20260703*

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