

Development and Experimental Evaluation of a Modified Computational Model for Estimating Occupational Whole-Body Radiation Dose in the Conventional Diagnostic Radiography Unit of Federal Medical Center, Jalingo, Taraba State, Nigeria



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ABSTRACT

Personal dosimetry using thermoluminescent dosimeters (TLDs) can be constrained in resource-limited settings by equipment, processing, and logistical requirements, motivating the development of complementary computational approaches for occupational radiation-dose estimation. This study developed and experimentally evaluated a calibrated computational model for estimating personnel whole-body radiation dose in a conventional diagnostic radiography unit. The primary model incorporated tube potential (kVp), tube current–time product (mAs), source-to-personnel distance, occupancy factor, and a facility-specific calibration coefficient. We obtained six-month personnel dose measurements using chest-worn TLD badges from 15 radiography personnel at the Federal Medical Centre, Jalingo, Nigeria, and compared them with Monte Carlo estimates based on 10,000 simulations per participant. The TLD-measured doses ranged from 0.96 to 1.78 mSv, with a mean of 1.479 ± 0.216 mSv, whereas the corresponding Monte Carlo estimates ranged from 2.204 to 2.265 mSv, with a mean of 2.234 ± 0.017 mSv. The mean model–measurement difference was 0.755 mSv, indicating systematic overestimation by the computational model. Bland–Altman analysis gave 95% limits of agreement of 0.311 to 1.199 mSv, with 14 of 15 observations (93.3%) falling within these limits. One-at-a-time sensitivity analysis demonstrated that source-to-personnel distance and tube potential had the strongest analytical influence on model output because of their squared dependence in the dose equation, while mAs and occupancy factor exhibited first-order dependence. The findings indicate that the calibrated model reproduced the general magnitude of personnel whole-body dose but systematically overestimated the measured TLD values. The model may therefore be useful as a complementary screening and dose-estimation approach, but further calibration and independent validation using larger datasets and multiple radiography facilities are required before application to individual dose assessment.

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INTRODUCTION

Diagnostic X-ray imaging is essential to modern healthcare, supporting diagnosis, treatment planning, and patient management. However, its increasing use has also increased exposure to ionizing radiation among patients and healthcare personnel, making dose optimization and radiation protection important components of clinical practice (ICRP, 2023; Martin et al., 2024). International recommendations emphasize optimization of exposure through appropriate control of exposure time, distance, shielding, and adherence to the ALARA principle (ICRP,

2023; Martin et al., 2024). In Nigeria, however, effective occupational dose monitoring may be constrained by limitations in dosimetry infrastructure, quality assurance, and dose-management systems (Garba et al., 2024; Dambele et al., 2024).

Thermoluminescent dosimeters (TLDs) remain established tools for personal radiation monitoring because of their small size, dosimetric performance, and ability to provide cumulative dose measurements. Nevertheless, their routine use in resource-constrained settings may be limited by processing costs, access to

specialized readout facilities, and compliance with badge-wearing requirements (Vano et al., 2023). These limitations have stimulated interest in computational approaches that can complement personal dosimetry by relating measurable radiographic and workplace parameters to personnel dose.

In conventional diagnostic radiography, personnel dose is influenced by factors including tube potential (kVp), tube loading (mAs), source-to-personnel distance, occupancy, and individual characteristics. Distance is particularly important because radiation intensity decreases approximately according to the inverse-square relationship, whereas kVp and mAs influence X-ray output (Martin et al., 2024; Poludniowski & Evans, 2007). Computational models that incorporate these measurable parameters may therefore provide a practical means of estimating dose under routine working conditions.

Mohammed et al. (2025) proposed a computational framework for personnel radiation-dose estimation. The present study extends this approach by incorporating kVp, mAs, source-to-personnel distance, occupancy factor, and a facility-specific empirical calibration coefficient. The modified formulation is subsequently evaluated using Monte Carlo simulation to propagate variability in the model inputs and estimate personnel whole-body dose. Model performance is assessed by comparison with TLD measurements, while sensitivity analysis is used to examine the influence of individual parameters and Bland–Altman analysis to evaluate agreement between measured and model-estimated doses. Such an approach provides a means of assessing whether a calibrated computational model can complement conventional personal dosimetry in resource-constrained diagnostic radiography facilities.

MATERIALS AND METHODS

Development of the Modified Radiation Dose Estimation Model

The modified empirical radiation dose-estimation model was developed from the computational framework proposed by Mohammed et al. (2025), with explicit incorporation of the principal radiographic exposure and geometric parameters relevant to personnel radiation exposure in conventional diagnostic radiography. The geometric component of the model was based on the inverse-square relationship, according to which radiation fluence rate decreases approximately with the square of the distance from a point source under idealized geometric conditions (Bushberg et al., 2021; Martin & Sutton, 2022):

$$I = \frac{k}{d^2} \quad (1)$$

where (I) is the radiation fluence rate or irradiance, (d) is the distance from the radiation source, and (k) is a

proportionality constant representing source- and geometry-dependent factors.

Radiant power incident per unit area may be expressed as

$$I = \frac{P}{A} = \frac{E}{A \cdot t} \quad (2)$$

where (P) is radiant power (W), (E) is radiant energy (J), (A) is the exposed area (m^2), and (t) is exposure time (s) (Bushberg et al., 2021).

The inverse-square relationship provides the geometric basis for describing the reduction in radiation fluence with increasing source-to-object distance. However, the dose received by personnel also depends on radiation energy, beam quality, attenuation, exposure geometry, scattering conditions, and other factors (Bushberg et al., 2021; Martin & Sutton, 2022).

Absorbed dose (D) is defined as the mean energy imparted by ionizing radiation per unit mass of irradiated material and is expressed in gray (Gy), where $1 \text{ Gy} = 1 \text{ J kg}^{-1}$ (ICRU, 2020; Bushberg et al., 2021):

$$D = \frac{E}{m} \quad (3)$$

where (E) is the energy imparted to the irradiated material (J) and (m) is its mass (kg).

The relationships in Eqs. (1) – (3) provide the conceptual and geometric basis for the empirical dose-estimation framework proposed by Mohammed et al. (2025) presented in Eq. (4).

$$D = k \frac{At}{m d^2} \quad (4)$$

To adapt this framework to conventional diagnostic radiography, the source-output component was expressed in terms of the principal radiographic exposure parameters, namely tube potential and tube current-time product.

Under approximately constant filtration and other controlled equipment conditions, X-ray tube output increases approximately with the square of tube potential and approximately linearly with tube current-time product (Seeram, 2024). Accordingly, the exposure-dependent component was represented empirically as

$$E \propto (kVp)^2 \times (mAs) \quad (5)$$

where (kVp) is tube potential and (mAs) is tube current-time product.

The facility-specific proportionality terms, including equipment output characteristics and other experimental factors not explicitly represented in the model, were incorporated into a calibration coefficient (C). Thus, the exposure-dependent component was expressed as

$$E = C(kVp)^2 \times (mAs) \quad (6)$$

The occupancy factor (T) was incorporated to represent the fraction of the relevant working period during which personnel were present within the radiation environment (NCRP, 2004). Combining the exposure-dependent component with the inverse-square relationship and occupancy factor gives the final empirical dose-estimation model:

$$D = C(kVp)^2(mAs) \frac{T}{d^2} \quad (7)$$

where (D) is the estimated occupational whole-body dose (mSv), (C) is the facility-specific calibration coefficient, (kVp) is tube potential (kV), (mAs) is tube current-time product (mAs), (T) is the dimensionless occupancy factor, and (d) is the source-to-personnel distance (m).

BMI was initially considered during model development as a possible anthropometric parameter. Although relationships between body mass and body dimensions may be expressed mathematically in terms of BMI, such relationships do not establish a validated physical relationship between BMI and occupational radiation dose received by radiography personnel. In particular, deriving an inverse BMI term from anthropometric relationships would require additional assumptions that are not directly supported by the radiation-transport conditions investigated in this study.

The primary objective was to develop a practical computational model for estimating personnel whole-body radiation dose from measurable radiographic exposure and workplace geometric parameters. The final model was therefore restricted to tube potential, tube current-time product, source-to-personnel distance, and occupancy factor, which have direct and established relevance to X-ray output, exposure duration, and radiation-field geometry.

Consequently, BMI was excluded from the final model and from subsequent dose calculations, Monte Carlo simulations, and sensitivity analysis. This decision avoids imposing an unsupported functional relationship between body habitus and occupational radiation dose and ensures that the model parameters have a clear physical or operational basis within the study framework.

Dimensional Consistency and Calibration of the Developed Computational Model

Dimensional consistency was assessed to ensure that the variables in Eq. (7) were used consistently with their defined measurement units. Because the model is empirically calibrated, the numerical value and composite units of the calibration coefficient (C) depend on the units assigned to the model variables.

For the present study, the variables were expressed as follows:

- i. (D): mSv
- ii. (kVp): kV
- iii. (mAs): mAs
- iv. (T): dimensionless
- v. (d): m

Rearranging Eq. (7), the calibration coefficient is given by

$$C = \frac{Dd^2}{(kVp)^2(mAs)T} \quad (8)$$

Substituting the dimensions of the respective variables:

$$[C] = \frac{(mSv)(m^2)}{(kV)^2(mAs)}$$

which may be expressed as

$$[C] = mSv \ m^2 \ kV^{-2} \ mAs^{-1}$$

Thus, (C) carries the composite units required to yield dose in mSv when the model variables are expressed in the specified practical units. The numerical value of (C) is therefore specific to the selected unit system and calibration conditions and should not be interpreted as a universal physical constant.

The facility-specific calibration coefficient was determined using the experimentally measured mean TLD dose together with the corresponding mean values of tube potential, tube current-time product, source-to-personnel distance, and occupancy factor. BMI was not used in the calculation of (C). The resulting calibration coefficient was subsequently held constant throughout the Monte Carlo simulation.

Dimensional consistency establishes only that the model is internally consistent with the selected measurement units; it does not by itself demonstrate predictive accuracy or physical validity. Model performance was therefore evaluated independently by comparing the model-estimated personnel doses with the corresponding TLD measurements using statistical agreement analysis.

Sensitivity Analysis of the Model Parameters

A one-at-a-time (OAT) sensitivity analysis was performed to assess the influence of (kVp), (mAs), occupancy factor (T), and source-to-personnel distance (d) on predicted personnel dose. Each parameter was varied by $\pm 10\%$ and $\pm 20\%$ from its baseline value while the others were held constant. The normalized sensitivity coefficient was calculated as

$$S_i = \frac{\Delta D / D_o}{\Delta x_i / x_{i,o}} \quad (9)$$

where (D_o) and ($x_{i,o}$) are the baseline dose and parameter value, respectively, and (ΔD) and (Δx_i) are their corresponding changes.

$$\text{For } D = C(kVp)^2(mAs) \frac{T}{d^2}$$

The analytical sensitivity coefficients are (+2), (+1), (+1), and (-2) for (kVp), (mAs), (T), and (d), respectively. The calibration coefficient (C) was held constant after calibration. These analytical relationships were used to support interpretation of the OAT results. The magnitude of the dose variation produced by each parameter was used to assess its relative influence on the model output. The results were presented using a tornado diagram. The sensitivity analysis was conducted in accordance with established approaches for evaluating parameter influence in computational models (Pianosi et al., 2016; Saltelli et al., 2021).

Measurement of Occupational Whole-Body Dose Using TLD Badges

Personnel radiation doses were monitored over six months using coded, chest-worn TLD badges. The dosimeters were processed at Ahmadu Bello University,

Zaria, to determine accumulated doses, which were compared with computational estimates. The TLD results served as the experimental reference data for model calibration and evaluation. However, incomplete

compliance with TLD-wearing procedures among some personnel was identified as a potential source of dose under-recording and uncertainty in the comparison between measured and modeled doses.

Table 1: Six-month Radiographic Workload and Exposure Data

S/N	Observations	Recorded Magnitude
1	Mean tube potential applied (kVp)	87.745 Kv
2	Tube potential range (kVp)	65 to 100 Kv
3	Total tube current-time product (mAs)	18,301.20 mAs
4	Mean tube current-time product (mAs)	6.054 mAs
5	Tube current-time product range (mAs)	0.5 to 26.0 mAs
6	Total number of X-ray examinations	3023

The recorded exposure parameters were used to define the input ranges for the computational simulation.

Calibration of the Computational Model

Before the Monte Carlo simulation, the model was calibrated using the mean TLD dose and corresponding mean exposure parameters. The facility-specific calibration coefficient was calculated using Eq. (8) and held constant throughout the simulation.

Monte Carlo Simulation Procedure

Python-based Monte Carlo simulation was performed to propagate the variability of the model input parameters and estimate personnel whole-body radiation dose. For each of the 15 radiography personnel, 10,000 independent simulations were performed, giving a total of 150,000 simulated dose estimates. The model inputs were randomly sampled from uniform distributions over the observed ranges in the study: tube potential (kVp), 65–100 kV; tube current–time product (mAs), 0.5–26.0 mAs; source-to-personnel distance, 3–5 m; occupancy factor, 0.5–1.0; and a constant calibration coefficient, 0.00049. Thus, each value within the specified range had

an equal probability of being selected during the simulation. The sampled values were substituted into the final dose model (Eq. 7) for each iteration. A fixed random seed of 42 was used to ensure reproducibility of the simulation results. The resulting simulated dose distributions were summarized using the minimum, maximum, mean, and standard deviation for each participant. Because the same observed parameter ranges were used for all personnel, the simulation was designed to characterize stochastic variability across the facility exposure space rather than reconstruct individual workers' exact exposure histories.

RESULTS AND DISCUSSION

The analytical elasticity coefficients are +2, +1, +1, and –2 for kVp, mAs, T, and d, respectively. The coefficients reported in Table 2 represent the normalized numerical OAT sensitivity calculated over the specified perturbation range and therefore may differ slightly from the analytical exponents.

Table 2: One-at-a-Time Sensitivity Analysis of the Modified Radiation Dose Estimation Model

Parameter	Normalized OAT Sensitivity Coefficient	Absolute Sensitivity	Relative Sensitivity (%)
kVp	2.1000	2.1000	35.99
Distance	-1.7355	1.7355	29.74
mAs	1.0000	1.0000	17.14
T	1.0000	1.0000	17.14

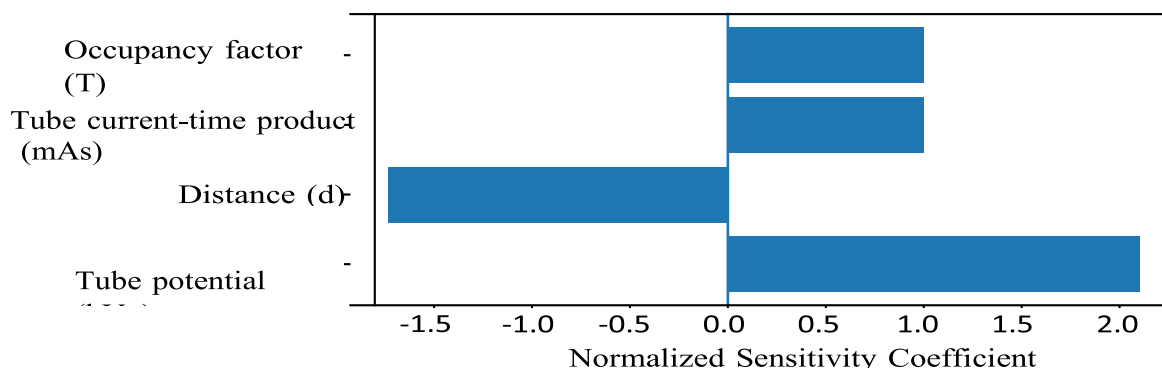


Figure 1: Tornado Chart of Model Parameters Sensitivity Analysis

Table 3: Personnel Dose Levels Measured with TLDs

SN	Radiation Personnel	TLD Whole-body Dose Levels (mSv)
1	R001	1.44
2	R002	1.58
3	R003	1.46
4	R004	1.42
5	R005	1.34
6	R006	0.96
7	R007	1.56
8	R008	1.30
9	R009	1.68
10	R010	1.34
11	R011	1.76
12	R012	1.74
13	R013	1.78
14	R014	1.38
15	R015	1.44

Table 4: Simulated Whole-body Dose using Monte Carlo Method

Personnel	Minimum (mSv)	Maximum (mSv)	Mean dose (mSv)	Standard Dev. (mSv)
R001	0.038	10.894	2.240	1.661
R002	0.032	12.320	2.230	1.677
R003	0.039	11.823	2.253	1.714
R004	0.038	11.636	2.229	1.694
R005	0.035	11.019	2.225	1.673
R006	0.032	12.101	2.265	1.701
R.007	0.031	12.223	2.235	1.682
R008	0.034	11.894	2.240	1.676
R009	0.049	11.690	2.217	1.673
R010	0.041	11.976	2.260	1.699
R011	0.034	12.153	2.242	1.709
R012	0.030	12.517	2.204	1.668
R013	0.038	12.092	2.218	1.654

Personnel	Minimum (mSv)	Maximum (mSv)	Mean dose (mSv)	Standard Dev. (mSv)
R014	0.035	11.364	2.215	1.663
R015	0.033	12.853	2.233	1.679

Table 5: Comparison of Monte Carlo Simulation and TLD-Measured Whole-body Doses

S/N	Radiation Personnel	TLD whole-body dose (mSv)	Simulated whole-body dose (mSv)
1	R001	1.44	2.240
2	R002	1.58	2.230
3	R003	1.46	2.253
4	R004	1.42	2.229
5	R005	1.34	2.225
6	R006	0.96	2.265
7	R007	1.56	2.235
8	R008	1.30	2.240
9	R009	1.68	2.217
10	R010	1.34	2.260
11	R011	1.76	2.242
12	R012	1.74	2.204
13	R013	1.78	2.218
14	R014	1.38	2.215
15	R015	1.44	2.233

Table 6: Bland-Altman Assessment of Agreement Between TLD and Monte Carlo Results

Personnel	TLD Dose (mSv)	Monte Carlo Dose (mSv)	Mean Dose (mSv)	Difference (mSv)	Within 95 LoA
R001	1.44	2.240	1.840	0.800	TRUE
R002	1.58	2.230	1.905	0.650	TRUE
R003	1.46	2.253	1.857	0.793	TRUE
R004	1.42	2.229	1.825	0.809	TRUE
R005	1.34	2.225	1.783	0.885	TRUE
R006	0.96	2.265	1.613	1.305	FALSE
R007	1.56	2.235	1.898	0.675	TRUE
R008	1.3	2.240	1.770	0.940	TRUE
R009	1.68	2.217	1.949	0.537	TRUE
R010	1.34	2.260	1.800	0.920	TRUE

R011	1.76	2.242	2.001	0.482	TRUE
R012	1.74	2.204	1.972	0.464	TRUE
R013	1.78	2.218	1.999	0.438	TRUE
R014	1.38	2.215	1.798	0.835	TRUE
R015	1.44	2.233	1.8365	0.793	TRUE

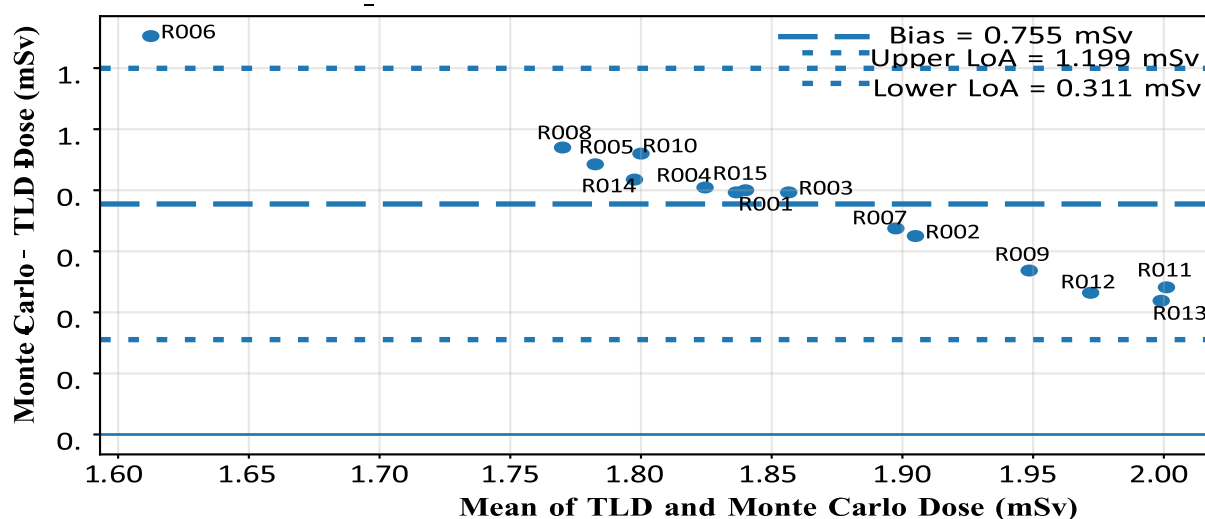


Figure 2: Bland–Altman analysis

Discussion

The present study developed and evaluated a calibrated computational model for estimating personnel whole-body radiation dose in a conventional diagnostic radiography unit. The revised model was deliberately formulated using the principal radiographic exposure and geometric variables including tube potential, tube current–time product, occupancy factor, and source-to-personnel distance, while the sensitivity analysis demonstrated that the model output was strongly dependent on the exposure and geometric parameters. The analytical form of the model gives second-order dependence on tube potential and source-to-personnel distance and first-order dependence on tube loading and occupancy. This explains why changes in tube potential and distance can produce substantial changes in the predicted dose. The OAT results further showed that the practical magnitude of the effect depends on the range over which each parameter is varied. These findings emphasize the importance of accurately recording exposure factors and source-to-personnel distance when applying a simplified computational model to workplace dose estimation.

The TLD measurements showed personnel doses ranging from 0.96 to 1.78 mSv, with a mean of 1.479 ± 0.216 mSv. The variation among personnel indicates that radiation exposure was not uniform within the radiography workforce. Such differences may arise from variations in workload, positioning, time spent near the radiation source, working practices, and the extent to which personnel remained within the radiation field

during examinations. Because the measurements represent actual cumulative personnel monitoring, they provide an important reference against which the computational estimates can be evaluated.

The Monte Carlo simulations produced personnel-specific mean dose estimates ranging from 2.204 to 2.265 mSv, with an overall mean of 2.234 ± 0.017 mSv. These estimates were consistently higher than the corresponding TLD measurements. The mean difference of 0.755 mSv therefore indicates a systematic positive bias in the computational estimates. The relatively small variation in the personnel-specific simulated means, compared with the much wider within-person simulation standard deviations, reflects the stochastic nature of the sampling procedure and the use of common exposure ranges across participants.

The Monte Carlo simulations produced relatively similar participant-specific mean doses (2.204–2.265 mSv), despite wider variability in the corresponding TLD-measured doses (0.96–1.78 mSv). This pattern is attributable to the use of the same observed parameter ranges and uniform sampling distributions for all participants. Consequently, the simulations primarily characterize stochastic variability within the overall study exposure space rather than reproduce each individual's exact exposure history. The relatively large within-participant standard deviations (approximately 1.65–1.71 mSv) and the wide minimum–maximum ranges reflect the variability generated by random sampling across these input ranges. This limitation indicates that the present model does not fully capture

worker-specific differences in workload, positioning, distance, and occupancy. Future simulations should incorporate participant-specific exposure distributions and measured workload data to improve individual dose discrimination.

The Bland–Altman analysis provides additional information about the agreement between the two approaches. The mean bias was 0.755 mSv, with 95% limits of agreement of approximately 0.311 to 1.199 mSv. Fourteen of the 15 paired observations (93.3%) were within these limits. However, the high proportion of observations within the limits should not be interpreted as evidence that the methods are interchangeable. The persistent positive bias demonstrates that the computational model systematically predicted higher doses than the TLD measurements. The results therefore support the use of the model as a complementary estimation or screening approach rather than as a direct substitute for personal dosimetry.

Several factors may explain the observed positive bias. First, the Monte Carlo procedure sampled tube potential, tube loading, distance, and occupancy from predefined ranges. Consequently, the simulation can generate combinations of exposure conditions that do not necessarily correspond to the exact workload and workplace positioning experienced by an individual worker during the monitoring period. Second, the model is an empirical representation of a complex radiation-exposure process and does not explicitly account for all factors affecting personnel dose, including detailed room geometry, patient scatter, shielding configuration, beam orientation, workload distribution, and individual working practices. Third, incomplete compliance with TLD-wearing procedures by some personnel may have resulted in under-recording of their actual occupational exposure. These factors should be considered when interpreting the difference between the two approaches. The results also demonstrate the importance of calibration. The facility-specific calibration coefficient allows the model to incorporate characteristics of the X-ray equipment and the local measurement conditions that are not explicitly represented by the simplified equation. However, calibration against the same dataset used for evaluation can reduce the independence of model validation. Consequently, the present results should be regarded as an initial experimental validation rather than definitive evidence of general predictive performance. Independent validation using personnel from other monitoring periods and radiography facilities would provide a stronger assessment of model generalizability. BMI was intentionally excluded from the physical dose equation to avoid imposing an unsupported inverse or direct dose–BMI relationship on the model. Although previous observational research has identified BMI as a statistically significant factor associated with occupational dose (Alemayehu et al. 2023), such an

association does not establish BMI as a physical determinant of scattered radiation exposure. The present dataset is also small, with only 15 personnel, and therefore provides limited statistical power for assessing anthropometric associations.

Therefore, the model reproduced the general order of magnitude of the measured personnel dose but showed systematic overestimation. Its principal value is therefore not as a replacement for personal dosimetry but as a complementary computational framework that can provide dose estimates when relevant exposure and workplace parameters are available. Further refinement should incorporate independently measured workload, worker-specific positioning and occupancy information, improved representation of workplace geometry, and independent validation datasets.

CONCLUSION

A calibrated computational model was developed to estimate personnel whole-body radiation dose using tube potential, mAs, occupancy factor, and source-to-personnel distance. TLD measurements averaged 1.479 ± 0.216 mSv, compared with a Monte Carlo mean of 2.234 ± 0.017 mSv, indicating a mean overestimation of 0.755 mSv. Bland–Altman analysis showed 95% limits of agreement of 0.311–1.199 mSv, with 93.3% of observations within the limits. Sensitivity analysis identified source-to-personnel distance and tube potential as influential model parameters, emphasizing the importance of accurate exposure and geometric data. The model may provide a useful complementary approach for personnel dose screening where routine dosimetry is limited; however, its systematic positive bias prevents its use as a replacement for established personal dosimetry. Larger datasets, multiple monitoring periods, and independent facility-based validation are recommended to assess its generalizability.

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