Evaluation of Risk Assessment of Scattered Radiation in Selected Radiological Centers in Delta State, Nigeria

[1*]I.H. Hafsat, [2]G.O. Avwiri and [3]E.O. Agbalagba, [4]V.B Olaseni,
[1,2,4]Department of Physics, Federal University of Petroleum and Resources, [3]Department of Physics, University of Port Harcourt
[*]Corresponding Author: hafsatinuwa3@gmail.com| +2348038001377
Email: agbalagba.ezekiel@fupre.edu.ng
Email: gregory.avwiri@uniport.edu.ng
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Abstract
This study evaluated ambient scattered radiation levels and health risks at five diagnostic radiology facilities in Delta State, Nigeria. Dose rates were measured using a well calibrated Radiation Alert Monitor 200 (ICC=0.9997) in five functional zones per facility with five replicates per location. The dose rates in the X-ray room ranged from from 19.40 to 21.80 μSv/h and the annual effective dose equivalents were from 5.10 to 5.73 mSv/yr. X-ray rooms and console areas all exceeded the ICRP public limit of 1.0 mSv/yr, with Facility A having the highest console dose (4.76 mSv/yr) and 99.96% probability of exceeding occupational limits. In all 25 sampled sites, the excess lifetime cancer risk was higher than the global average of UNSCEAR (0.29×10^{-3}), from 27 to 57 times higher in console areas. The mean dose rate was lower in private facilities than in public hospitals, with the lowest mean dose rate recorded in Facility C (4.74 μSv/h). The required lead equivalent shielding upgrades range from 0.159 to 0.349 mm. The results demonstrate systematic violations of public exposure limits in different functional zones, particularly in public facilities, due to inadequate structural shielding. There is an urgent requirement to upgrade shielding, perform regular ambient monitoring and enforce mandatory personal dosimetry to address these preventable health risks.

Keywords: *Scattered radiation; diagnostic radiology; excess lifetime cancer risk; radiation shielding; occupational exposure*

1 Introduction

Diagnostic radiology is a non-invasive method for detecting disease based on the use of ionizing radiation, but it is associated with health risks due to the presence of scattered radiation (Krhovska et al., 2019; Najjar, 2023). The primary X-ray beam interacts with matter and generates scattered radiation mainly thru Compton scattering (Bjørkås et al., 2020; Qiao et al., 2021). It causes stochastic effects (carcinogenesis, heritable mutations) and deterministic effects (tissue reactions) (Ahmad et al., 2022). The International Commission on Radiological Protection (ICRP) highlights the safety measures of justification, optimisation, and dose limitation (Clement et al., 2021). The ALARA principle, which is aimed at keeping exposure "As Low As Reasonably Achievable" is a guiding principle for minimizing exposure (Bamidele et al., 2022; Ovwasa et al., 2023). But, many developing regions, including parts of Nigeria, struggle to enforce these safety measures due to outdated equipment, inadequate facility design, insufficient training, and weak regulatory systems

(Adewole et al., 2023). Radiological safety in Nigeria has been mainly focused on the patient dosimetry, equipment performance or localised machine leakage (Eyisi-Enuka et al., 2021; Ovwasa et al., 2023; Akande et al., 2023). Thus, the characterisation of the spatial distribution of ambient scatter radiation in the functional zones of the radiology departments in Delta State remains understudied. Such omissions are problematic given the region's increasing clinical throughput, ageing imaging infrastructure and inconsistent structural shielding. Scatter radiation routinely spreads outside the primary imaging suite, exposing radiography staff, patients and the public in adjacent uncontrolled areas such as waiting rooms and corridors to chronic, unmonitored exposure. Anecdotal evidence suggests potentially high environmental doses at some local facilities, due to inadequate shielding or suboptimal operating procedures. Strong empirical measurements are required, however, to accurately characterize these radiation fields.

2. Materials and Methods

2.1 Study Area and Design

This cross-sectional study was conducted in five diagnostic radiology facilities in Delta State, Nigeria (Latitude 5°00'-6°30'N, Longitude 5°00'-6°45'E). Facilities were selected purposely to represent public (n=2) and private (n=3) institutions that offer general radiography services.
Table 1 shows anonymized facility characteristics. Facilities A-B are public government hospitals and facilities C-E are private specialist hospitals.

Table 1: Characteristics of Study Facilities

Code	Type	Location	Bed Capacity	Equipment Status
A	Public	Ughelli	80-120	Aging, variable maintenance
B	Public	Warri	100-150	Aging, variable maintenance
C	Private	Warri	40-60	Modern, well-maintained
D	Private	Warri	30-50	Modern, well-maintained
E	Private	Warri	20-40	Modern, well-maintained

2.2 Sampling and Measurement Protocol

Five functional zones were selected within each facility: X-ray room (XR), console area (CA), entrance doorway (ED), waiting area (WA), and generator house (GH). Table 2 presents the GPS coordinates for all locations. Measurements were performed using a calibrated Radiation Alert® Monitor 200 (SE International, USA), a Geiger-Müller counter with energy response of 40 keV to 3.0 MeV and detection range of 0.001 to 200 µSv/h (factory calibrated, traceable to national standards). The detector was placed at one metre height (torso level). Five successive readings were taken at one-minute intervals. GPS coordinates were collected using a handheld receiver (accuracy ±3 m) (Kennedy, 2002). Protocol followed UNSCEAR (2008) recommendations.

2.3 Dosimetric Calculations and Statistical Analysis

For dosimetric evaluation, the following parameters were calculated

(1) Annual Effective Dose Equivalent (AEDE) was calculated as (UNSCEAR, 2000; ICRP, 2007):

$$AEDE\ (mSv/yr) = \bar{D}(\mu Sv/h) \times 8760 \times OF \times 0.001 \quad (1)$$

$\bar{D}$ is the mean absorbed dose rate, OF is the occupancy factor which is dimensionless.
Occupancy factors (OF) were applied as: X-ray room 0.03, console area 0.30, waiting area 0.15, entrance doorway 0.08, generator house 0.04 (NCRP, 2004).

(2) Excess Lifetime Cancer Risk (ELCR) was calculated as (ICRP, 2007):

$$ELCR = AEDE\ (Sv/yr) \times 70 \times 0.05 \quad (2)$$

Organ-Specific Equivalent Doses used ICRP Publication 103 tissue weighting factors (wT) (ICRP, 2007):

$$H_T = AEDE \times w_T \quad (3)$$

where H_T is the equivalent dose to organ T, and w_T is the tissue weighting factor for that organ (ICRP, 2007; Harrison et al., 2021).

(3) Shielding Effectiveness was calculated as (NCRP, 2004):

$$SE\ (\%) = (1 - D_{out}/D_{in}) \times 100 \quad (4)$$

where D_{in} is the dose rate inside the X-ray room, and D_{out} is the dose rate outside the X-ray room at the location of interest (NCRP, 2004).

(4) Required Lead Thickness used the exponential attenuation equation (NCRP, 2004):

$$t = (1/\mu) \times ln(D_0/D) \quad (5)$$

where t is the required lead thickness in mm, μ is the linear attenuation coefficient for lead at diagnostic X-ray energies (5.0 mm^{-1} at 100 keV), D_0 is the current dose rate, and D is the desired dose rate (NCRP, 2004).

(5) The Lifetime Attributable Risk (LAR) was estimated using age-specific risk coefficients from the BEIR VII Phase 2 report (BEIR VII, 2006; NRC, 2006). The LAR represents the additional lifetime risk of cancer from radiation exposure and was calculated as:

$$LAR(\%) = AEDE \times \alpha \times 100 \quad (6)$$

where α is the age-specific risk coefficient per sievert. For a 30-year-old radiographer, the coefficients are 0.14 per Sv for males and 0.19 per Sv for females (BEIR VII, 2006; NRC, 2006). Collective Effective Dose and Excess Cancers followed ICRP (2007) and UNSCEAR (2008) methodologies. Years of Life Lost (YLL) used ICRP Publication 26 assumption of 15 years lost per fatal cancer (ICRP, 1977).

Data were analyzed using IBM SPSS Statistics v26 and Microsoft Excel. Reliability was assessed using intraclass correlation coefficients. Distributional assumptions were tested using Shapiro-Wilk and Levene's tests. Two-way ANOVA examined facility and location effects; multiple linear regression predicted AEDE; linear mixed-effects models accounted for nested observations. Uncertainty was propagated via Monte Carlo simulation (10,000 iterations) incorporating uncertainties in occupancy factors and risk coefficients (±20%) and measured dose rates (±15%). Effect sizes used partial η^2 and Cohen's d. Significance level: $\alpha = 0.05$.

3. Results

3.1 Descriptive Statistics and Reliability

Reliability of measurement was excellent for the 25 sampled locations (ICC = 0.9997; 95% CI: 0.99 to 1.00). Normality was confirmed in 25 of 25 strata (Shapiro Wilk); homogeneity of variance was verified in all groups (Levene's test, $p > 0.05$). Figure 1 shows the spatial variation in dose rates across locations.

The mean dose rates, AEDE and ELCR by facility and location are shown in Table 2. The highest exposure was found in the X-ray rooms (19.40 to 21.80 μSv/h; AEDE: 5.10 to 5.73 mSv/yr), followed by the console areas (0.84 to 1.81 μSv/h; AEDE: 2.21 to 4.76 mSv/yr) and the waiting zones (0.64 to 1.75 μSv/h; AEDE: 0.84 to 2.30 mSv/yr). The generator houses had the lowest levels (AEDE: 0.34 to 0.69 mSv/yr).

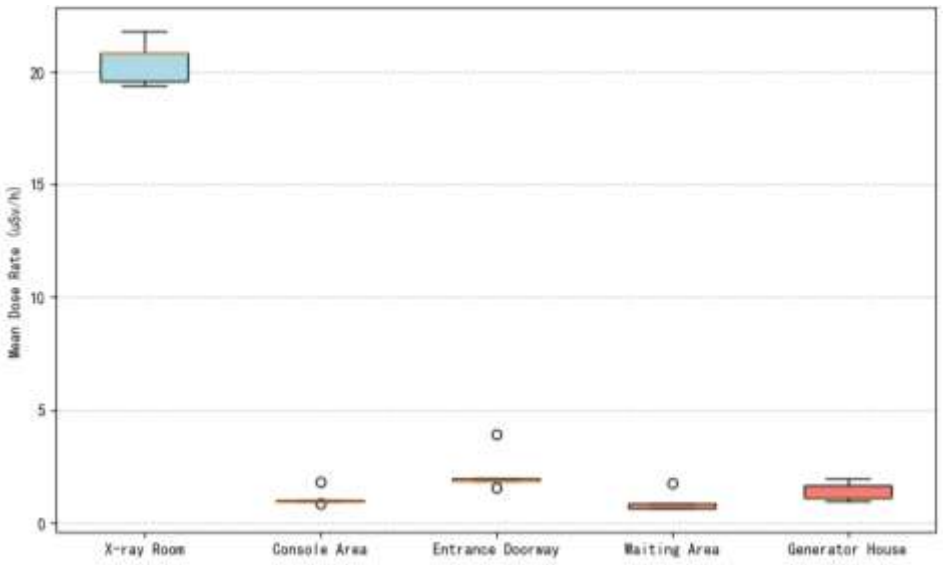

Figure 1: Distribution of Scattered Dose Rates Across Location Types

Table 2: Mean Dose Rates, Annual Effective Dose Equivalents, and Excess Lifetime Cancer Risks

Facility	Location	Mean ± SD Dose Rates (μSv/h)	AEDE (mSv/yr)	ELCR ($\times 10^{-3}$)
Facility A	X-ray Room	21.80 ± 0.24	5.73	20.06
	Console Area	1.81 ± 0.02	4.76	16.66
	Entrance Doorway	3.95 ± 0.02	2.77	9.70
	Waiting Area	1.75 ± 0.03	2.30	8.05
	Generator House	1.97 ± 0.02	0.69	2.42
Facility B	X-ray Room	20.84 ± 0.30	5.48	19.18
	Console Area	1.02 ± 0.10	2.68	9.38
	Entrance Doorway	1.86 ± 0.01	1.30	4.55
	Waiting Area	0.85 ± 0.03	1.12	3.92
	Generator House	1.13 ± 0.02	0.40	1.40
Facility C	X-ray Room	19.58 ± 0.32	5.15	18.03
	Console Area	0.96 ± 0.02	2.52	8.82
	Entrance Doorway	1.55 ± 0.03	1.09	3.82
	Waiting Area	0.65 ± 0.03	0.85	2.98
	Generator House	0.98 ± 0.02	0.34	1.19
Facility D	X-ray Room	20.86 ± 0.30	5.48	19.18
	Console Area	0.96 ± 0.02	2.52	8.82
	Entrance Doorway	1.85 ± 0.02	1.30	4.55
	Waiting Area	0.76 ± 0.03	1.00	3.50
	Generator House	1.17 ± 0.02	0.41	1.44
Facility E	X-ray Room	19.40 ± 0.31	5.10	17.85
	Console Area	0.84 ± 0.03	2.21	7.74
	Entrance Doorway	1.95 ± 0.03	1.37	4.80
	Waiting Area	0.64 ± 0.03	0.84	2.94
	Generator House	1.68 ± 0.02	0.59	2.07

3.2 Annual Effective Dose Equivalents and Regulatory Compliance

All five facilities exceeded the ICRP public dose limit of 1.0 mSv/yr in the X-ray rooms and console areas. X-ray room AEDE (5.1 0to 5.73 mSv/yr) represented 5- to 6-fold exceedances; console AEDE (2.21–4.76 mSv/yr) represented 2.2- to 4.8-fold exceedances. The maximum console AEDE was found in Facility A (4.76 mSv/yr), about one-fourth of the occupational limit (20 mSv/yr). Four facilities exceeded the public limit at entrance doorways (1.09 to 2.77 mSv/yr) and facilities A and B exceeded the limit in waiting areas (1.12 and 2.30 mSv/yr, respectively). Only the generator houses were consistently below the public limit with values ranging from 0.34-0.69 mSv/yr. Figure 2 compares AEDE across facilities.

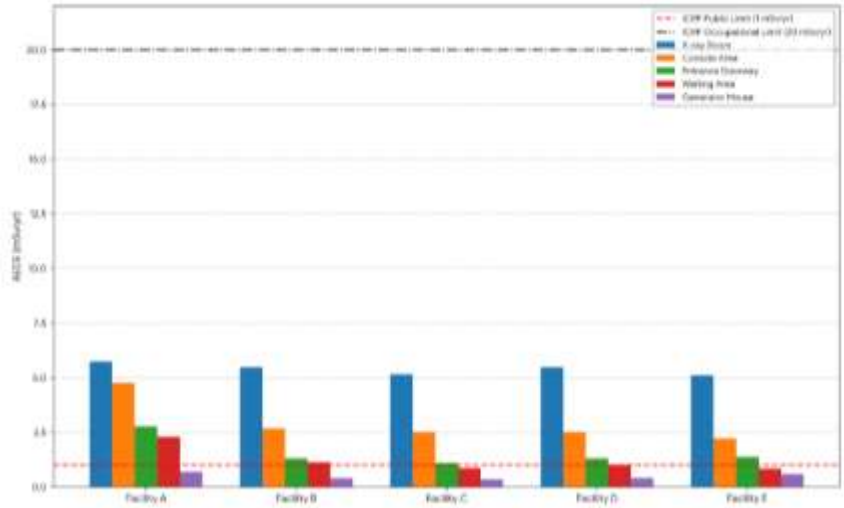

Figure 2: Comparison of Mean Annual Effective Dose Equivalent across Facilities with ICRP Public Limit

All 25 sampling locations were above the UNSCEAR global average ELCR of 0.29×10^{-3}. The risk in X-ray rooms was 62 to 69 times higher with value ranging from 17.85 to 20.06×10^{-3}, in console areas 27–57 times higher ranging from 7.74 to 16.66×10^{-3} and in waiting zones 10 to 28 times higher ranging from 2.94-8.05×10^{-3}. The ELCR of 16.66×10^{-3} at the Facility A console is a 1.67 % lifetime increased cancer risk to a worker over a 30-year career.

3.3 Organ-Specific Equivalent Doses

Table 3 presents estimated doses to the three most radiosensitive organs (ICRP, 2007). Across all locations, X-ray room exposures consistently exceeded those recorded at the console. Lung/breast doses ranged from 0.612 to 0.688 mSv/yr in X-ray rooms compared with 0.265 to 0.571 mSv/yr at the console; gonad doses ranged from 0.408 to 0.458 versus 0.177 to 0.381 mSv/yr; and thyroid doses ranged from 0.204 to 0.229 versus 0.088 to 0.190 mSv/yr. At Facility A, console-area organ doses reached 46–83% of the ICRP public dose limit.

Table 3: Organ-Specific Equivalent Doses (mSv/yr) by Facility and Location

Organ	w_T	Facility	X-ray Room	Console Area	Entrance	Waiting Area	Generator
Lung/Breast	0.12	Facility A	0.688	0.571	0.332	0.276	0.083
		Facility B	0.658	0.322	0.156	0.134	0.048
		Facility C	0.618	0.302	0.131	0.102	0.041
		Facility D	0.658	0.302	0.156	0.120	0.049

		Facility E	0.612	0.265	0.164	0.101	0.071
Gonads	0.08	Facility A	0.458	0.381	0.222	0.184	0.055
		Facility B	0.438	0.214	0.104	0.090	0.032
		Facility C	0.412	0.202	0.087	0.068	0.027
		Facility D	0.438	0.202	0.104	0.080	0.033
		Facility E	0.408	0.177	0.110	0.067	0.047
Thyroid	0.04	Facility A	0.229	0.190	0.111	0.092	0.028
		Facility B	0.219	0.107	0.052	0.045	0.016
		Facility C	0.206	0.101	0.044	0.034	0.014
		Facility D	0.219	0.101	0.052	0.040	0.016
		Facility E	0.204	0.088	0.055	0.034	0.024

3.4 Lifetime Attributable Risk

Lifetime attributable risk (LAR) estimates for 30-year-old console radiographers ranged from 0.031% to 0.067% for males and 0.042% to 0.090% for females (Table 4). The maximum additional lifetime cancer risk was observed among female staff at Facility A (0.090%, or 1 in 1,105), more than double the estimate for female personnel at Facility E (0.042%, or 1 in 2,381).

Table 4: Lifetime Attributable Risk (LAR) for Console Area Radiographers (%)

Facility	Gender	Age 20	Age 30	Age 40	Age 50	Age 60
Facility A	Male	0.081	0.067	0.057	0.048	0.033
	Female	0.105	0.090	0.076	0.062	0.043
Facility B	Male	0.046	0.038	0.032	0.027	0.019
	Female	0.059	0.051	0.043	0.035	0.024
Facility C	Male	0.043	0.035	0.030	0.025	0.018
	Female	0.055	0.048	0.040	0.033	0.023
Facility D	Male	0.043	0.035	0.030	0.025	0.018
	Female	0.055	0.048	0.040	0.033	0.023
Facility E	Male	0.038	0.031	0.027	0.022	0.016
	Female	0.049	0.042	0.035	0.029	0.020

3.5 Collective Effective Dose and Excess Cancers

The total effective dose for all facilities was 0.07345 person-Sv/yr and the occupational burden for Facility A was 32.4% (Table 5). For a typical career of 30 years, the estimated cohort of 42 radiography staff is expected to develop 13.44 excess cases of cancer. Facility-specific estimates show the highest burden at Facility A (5.00 cases), followed by Facility B (2.81), Facilities C and D (2.12 each), and Facility E (1.39).

Table 5: Collective Effective Dose and Expected Excess Cancers

Facility	AEDE (Sv/yr)	Console Staff Count	Collective Dose (person-Sv/yr)	Excess Cancers (30 years)
Facility A	0.00476	5	0.02380	5.00
Facility B	0.00268	5	0.01340	2.81
Facility C	0.00252	5	0.01260	2.12
Facility D	0.00252	5	0.01260	2.12
Facility E	0.00221	5	0.01105	1.39
Total		25	0.07345	13.44

3.6 Shielding Effectiveness and Required Upgrades

X-ray room to console area shielding ranged from 91.7% (Facility A) to 95.7% (Facility E) (Table 6). Four facilities were rated "Excellent" (≥95%) and one was rated "Good" (91.7%). Shielding on the entrance doorways ranged from "Fair" (81.9% at Facility A; 89.9% at Facility E) to "Good" (91.1-92.1% at other facilities).

Table 7: Shielding Effectiveness and Required Lead Thickness

Facility	Location	Shielding Effectiveness (%)	Rating	Required Lead (mm)
Facility A	Console	91.7	Good	0.312
	Entrance	81.9	Fair	0.204
Facility B	Console	95.1	Excellent	0.197
	Entrance	91.1	Good	0.052
Facility C	Console	95.1	Excellent	0.185
	Entrance	92.1	Good	0.017
Facility D	Console	95.4	Excellent	0.185
	Entrance	91.1	Good	0.052
Facility E	Console	95.7	Excellent	0.159
	Entrance	89.9	Fair	0.063

The required lead thickness to attain ICRP public limit of 1.0 mSv/yr ranged from 0.326-0.349 mm for X-ray rooms, 0.159-0.312 mm for console areas, and 0.017-0.204 mm for entrance doorways (Table 7). All facilities need to have shielding upgrades, with Facility A requiring the most extensive.

3.7 Monte Carlo Uncertainty Analysis

Monte Carlo simulations (10,000 iterations) showed that the X-ray rooms at Facility A had a 99.96% probability of exceeding the ICRP occupational limit of 20 mSv/yr (Table 7). Probability of exceeding the public limit of 1.0 mSv/yr for console areas at all facilities was 99.1-100%. Facility A's waiting areas had a 19.8 % probability of exceeding the public limit.

Table 7: Monte Carlo Uncertainty Analysis (10,000 iterations)

Facility	Location	Point Estimate (mSv/yr)	Median (mSv/yr)	95% UI	P(>1.0)	P(>20.0)
Facility A	X-ray Room	43.60	40.69	28.29-53.58	1.000	0.9996
	Console	3.63	3.39	2.35-4.46	1.000	0.000
	Entrance	1.98	1.97	1.35-2.67	0.999	0.000
	Waiting	0.87	0.87	0.59-1.18	0.198	0.000
Facility B	X-ray Room	41.68	38.90	27.04-51.23	1.000	0.9996
	Console	2.04	1.90	1.32-2.51	0.999	0.000
Facility C	X-ray Room	39.16	36.55	25.41-48.13	1.000	0.998
	Console	1.91	1.78	1.24-2.35	0.998	0.000
Facility D	X-ray Room	41.72	38.93	27.07-51.27	1.000	0.9996
	Console	1.93	1.80	1.25-2.37	0.998	0.000
Facility E	X-ray Room	38.80	36.21	25.17-47.69	1.000	0.998
	Console	1.69	1.58	1.10-2.07	0.991	0.000

3.8 Statistical Modeling

The two-way ANOVA indicated that 84.3% of the variance in dose rates was explained by location (partial η^2=0.843, F(4,100)=668.89, p<0.001), 3.4% was explained by facility (partial η^2=0.034, F(4,100)=4.72, p=0.002), and the interaction effect was significant (partial η^2=0.022, F(16,100)=3.31, p<0.001). Multiple linear regression explained 99.8% of the variance in AEDE (R^2=0.998, F(8,16)=1017.5, p<0.001). The X-ray room was the most significant predictor (β=0.973, p<0.001) that increased AEDE by 19.376 mSv/yr. Only Facility A had a significant positive effect (β=0.057, p<0.001) with an increase in AEDE of 1.137 mSv/yr. These findings were confirmed by linear mixed-effects modelling (log-likelihood=19.58, group variance=0.1765).

4 Discussion

4.1 Spatial Distribution and Facility Design

The measured dose rates in the X-ray room (19.40-21.80 µSv/h) were significantly higher than the regional natural background (0.08-0.20 µSv/h) (Avwiri et al., 2021; Ukerun-Akpesiri et al., 2023). The high dose rates were attributed to the primary beam scatter and the operation of the equipment (Seeram & Brennan, 2016). The 12% variation between facilities suggests that equipment age and maintenance schedules and building design are major factors influencing ambient radiation profiles (Ovwasa et al., 2023). Console dose rates (0.84-1.81 µSv/h) were 6 to 14 times background, consistent with reports from neighbouring Port Harcourt (Orlunta & Sokari, 2023). The difference of 115% between Facility A (1.81 µSv/h) and Facility E (0.84 µSv/h) shows a large difference in shielding. The private facilities consistently measured lower console doses than the public hospitals, confirming observations that private institutions often have access to newer equipment and better maintenance (Ukerun-Akpesiri et al., 2023). There were concerns with the entrance door levels (1.55–3.95 µSv/h); the Facility A level (3.95 µSv/h) was more than double that of other locations indicating inadequate door shielding or maze configuration (NCRP, 2004). This was further verified by the shielding effectiveness analysis, where the entrance of Facility A received a “Fair” (81.9% attenuation) rating. Waiting area doses (0.64 to 1.75 µSv/h) were 5 to 13 times background. Facility A exceeded the ICRP public limit, signaling significant radiation migration to uncontrolled areas. However, it was shown that scatter to imaging rooms could be effectively limited using optimised design for Facilities C and E (Omogunloye et al., 2021).

4.2 Dosimetric Compliance and the ALARA Principle

All five facilities exceeded the ICRP public dose limit in the X-ray rooms and console areas, which are areas commonly occupied by non-monitored individuals (Harrison et al., 2021). Console AEDE (2.21-4.76 mSv/yr) is a concern because of radiographer’s long occupancy. Even the lowest console AEDE (2.21 mSv/yr at Facility E) exceeded the NCRP design goal of 1.0 mSv/yr for controlled areas (NCRP, 2004), suggesting that current shielding paradigms may be inadequate for low- and middle-income country (LMIC) settings. ELCRs exceeding UNSCEAR averages by 27 to 69 times are important stochastic risks. Facility A’s console ELCR (16.66×10^{-3}) is associated with a 1.67% incremental cancer risk over a 30-year career (~1 in 60 probability), in agreement with Orduvwe et al. (2023). LAR estimates for 30-year-old radiographers (0.042 to 0.090%) are well above the ICRP acceptable risk range (10^{-3} to 10^{-6}) and agree with Onu et al. (2024). The total collective dose (0.07345 person-Sv/yr) and 13.44 projected excess cancers represent a significant preventable occupational health burden.

4.3 Performance of Public Versus Private Facilities

Public hospitals (A, B) performed consistently worse compared to private facilities (C, D, E). The mean dose rate (6.26 µSv/h) of Facility A was 32% higher than that of Facility C (4.74 µSv/h) with a corresponding 63% higher mean ELCR. This discrepancy indicates that the main determinants of radiation protection outcomes are resource allocation and infrastructure investment. Private facilities showed that good radiation safety is achievable with modern, well-maintained equipment, optimised structural shielding and rigorous quality assurance. Public hospitals are confronted with ageing infrastructure, limited maintenance budgets, high patient throughput and limited training resources (Adewole et al., 2023). Future funding should focus on structural shielding upgrades and preventive maintenance in public facilities.

4.4 Shielding Effectiveness and Infrastructure Deficiencies

Shielding attenuation from X-ray rooms to console areas was nominally high (91.7-95.7%), but residual dose rates resulted in AEDE values that exceeded public limits by 1.2-4.8 times. This paradox suggests that the current design criteria may be inherently inadequate, even when large percentage reduction factors are used. Omojola et al. (2020) reported similar findings in Asaba, where >95% shielding effectiveness was achieved only with stringent operational monitoring. Attenuation through the entrance doorway was significantly reduced (81.9-92.1%) confirming that these are still critical leakage pathways (NCRP, 2004). The “Fair” rating (81.9%) of facility A is in agreement with Ofotokun and Umuze (2024) who noted poor door shielding as a common weakness in Delta State radiology centers. The required lead equivalency (0.159-0.349 mm Pb) is much lower than NCRP recommended 0.8 mm Pb for secondary barriers and IAEA (2012) minimum 0.5-1.0 mm Pb. The requirement for upgrades at even better-performing facilities suggests that the international shielding standards may need to be recalibrated for the conditions of tropical LMICs or that more conservative design safety factors should be used.

4.5 Statistical Predictors and Implications

Two-way ANOVA confirmed that spatial location was the main determinant of radiation exposure (84.3% variance). X-ray room proximity increased AEDE by 19.376 mSv/year. Facility A had an additional contribution of 1.137 mSv/yr compared to Facility D, showing a specific localised shielding deficiency which requires immediate resolution. Linear mixed-effects modelling confirmed facility-level differences (group variance=0.1765) were much smaller than residual variance (0.0194), suggesting targeted location-specific interventions, particularly console stations and entrance doorways, would achieve greater safety dividends than whole-facility renovations.

5 Conclusion

This study demonstrates that scattered radiation in diagnostic radiology facilities in Delta State, Nigeria, presents severe stochastic health risks, systematically exceeding international safety limits in both controlled and uncontrolled zones. The significant difference between public and private institutions showed that old infrastructure and lack of maintenance are the principal determinants of radiation protection failure.

Furthermore, a nominal shielding attenuation was inadequate to ensure regulatory compliance, with console stations and entrance thresholds representing a persistent leakage path requiring urgent remediation. We therefore recommend for immediate structural shielding upgrades, routine ambient dose surveillance, mandatory personal dosimetry and targeted capital investment in public imaging infrastructure. Additionally, the implementation of rigorous radiation safety measures in

this area is not simply a regulatory requirement but a critical public health necessity and a step toward the achievement of global sustainable development goals, offering essential evidence to inform policy changes in similar low-resource healthcare environments.

References

Adewole, M., Ige, T. A., Irurhe, N., Adewole, P., Akpochafor, M., Ibitoye, A., & Adeneye, S. (2023). Status of Magnetic Resonance Imaging Systems and Quality Control Programs in Nigeria. MedRxiv, 2023-06.

Ahmad, D., Almatari, M., Tumayhi, M., Alanazi, W., Shrefan, M., Agealy, W., & Alghamdi, M. (2022). Occupational Exposure of Scatter Radiation and Proper Protective Methods. Journal of Healthcare Science, 2(11), 443-448.

Akande, I. O., Vincent, U. E., Olowookere, C. J., Akomolafe, I. R., & Martins, G. (2023). Scatter radiation dose assessment in selected areas at a radiology department in a teaching hospital in South Western, Nigeria. African Journal of Medical and Health Sciences, 23(5), 61-69

Avwiri, G. O., Ebeniro, J. O., & Oladapo, O. O. (2021). Natural radioactivity and radiological hazards in soil samples from oil producing communities in Delta State, Nigeria. International Journal of Radiation Research, 19(3), 567-578.

Bamidele, L., Olowookere, C.J., Olatunji, K.O. & Martins, G. (2022). Evaluation of radiation doses delivered to patients during conventional pelvis radiographic imaging in selected Nigerian hospitals. Journal of Bioscience and Biotechnology Discovery. 7(1), 1-4

BEIR VII Phase 2. (2006). Health risks from exposure to low levels of ionizing radiation. National Research Council. National Academies Press.

Bjørkås, L. W., Blø, S., Rekdal, M. K., & Rusandu, A. (2020). Quality of radiation protection aprons and quality control routines at different diagnostic imaging modalities. Radiography Open. 6(1),1-11

Eyisi-Enuka, C. E., Nzotta, C. C., Robinson, E. D., Omojola, A. D., Adejoh, T., & Agboje, A. A. 2021). Determination of scatter radiation to the breast during lumbosacral x-ray examination using thermoluminescence dosimeter. Medical Science and Discovery, 8(5), 315-321.

Harrison, J. D., Balonov, M., Bochud, F., Martin, C., Menzel, H. G., Ortiz-Lopez, P. & Wakeford, R. (2021). ICRP publication 147: use of dose quantities in radiological protection. Annals of the ICRP, 50(1), 9-82.

International Commission on Radiological Protection (ICRP). (1977). Recommendations of the ICRP (ICRP Publication 26). Annals of the ICRP, 1(3).

International Commission on Radiological Protection (ICRP). (2007). The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Annals of the ICRP, 37(2-4).

Kennedy, M. (2002). The Global Positioning System and GIS: An Introduction (2nd ed.). Taylor and Francis.

Krhovska, P., Minarik, J., Pika, T., Bacovsky, J., & Proskova, J. (2019). Comparison of Radiodiagnostic Methods (Conventional Radiography, Low-Dose Computed Tomography and Magnetic Resonance Imaging) With Selected Markers of Bone Metabolism and Bone Marrow Microenvironment. Clinical Lymphoma, Myeloma and Leukemia, 19(10), e191.

Najjar, R. (2023). Radiology's ionising radiation paradox: weighing the indispensable against the detrimental in medical imaging. Cureus, 15(7).

National Council on Radiation Protection and Measurements (NCRP). (2004). Structural Shielding Design for Medical X-Ray Imaging Facilities. NCRP Report No. 147. Bethesda, MD: NCRP.

National Research Council (NRC). (2006). Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2. The National Academies Press. (Note: The foundational text for ERR, EAR, and LAR models).

Ofotokun, J. E., & and Umuze, W. (2024). Qualitative and Quantitative Dosimetric Evaluation of Diagnostic Radiology in Selected Health Insitutions and Hospitals in Delta State: Implications of Patients'exposure to Radiations and Actualization of Health Care Delivery Targets in Delta State. Innovative Journal of Science (ISSN: 2714-3309), 7(7), 47-59.

Omogunloye, O. Y., Adepoju, A. T., & Kururimam, P. (2021). Assessment of radiation risk from background radiation exposures in selected hospitals within Makurdi Metropolis, North-Central, Nigeria. European Journal of Applied Physics, 3(4), 43-47.

Omojola, A. D., Omojola, F. R., Akpochafor, M. O., & Adeneye, S. O. (2020). Shielding assessment in two computed tomography facilities in South-South Nigeria: How safe are the personnel and general public from ionizing radiation? The ASEAN Journal of Radiology, 21(2), 5-27.

Onu, C. P., & Nzotta, C. C. (2024). Scatter radiation levels in X-ray rooms during chest radiography. Applied Radiation and Isotopes, 212, 111472.

Orduvwe, T. A., Agbalagba, E. O., & Avwiri, G. O. (2023). Evaluation of radiological hazard indices of occupational health workers in some selected radiographical centre in Warri City Delta State, Nigeria. 43. Annual Conference of the Nigeria Institute of Physics, Awka (Nigeria).

Orlunta, A. N., & Sokari, S. A. (2023). Evaluation of Excess Lifetime Cancer Risk in Some Selected X-Ray Diagnostic Centers in Port Harcourt, Rivers State, Nigeria. Asian J. Adv. Res. Rep, 17(4), 26-33.

Ovwasa, H., Aiwuyo, H. O., Unuigbe, E., Rajora, N., & Okoye, O. (2023). Epidemiology trend of chronic kidney disease in a Semi-Urban tertiary hospital in Sub-Saharan Africa. Cureus, 15(3).

Qiao, C. K., Wei, J. W., & Chen, L. (2021). An overview of the compton scattering calculation. Crystals, 11(5), 525.

Seeram, E., & Brennan, P. C. (2016). Radiation protection in diagnostic X-ray imaging. Jones & Bartlett Publishers.

Ukerun-Akpesiri, A. A., Akpolile, A. F., Agbajor, G. K., & Mokobia, C. E. (2023). An Assessment of Integrity of Radiation Shielding in X-Ray Radiographic Facilities in Warri Metropolis. FUDMA Journal of Sciences, 7(5), 1-8.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). (2008). Sources and Effects of Ionizing Radiation. UNSCEAR 2008 Report to the General Assembly. New York: United Nations.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). (2000). Sources and Effects of Ionizing Radiation. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. New York: United Nations.