

Assessment of Radiation Shielding Integrity and Structural Compliance in Computed Tomography Facilities in Delta State, Nigeria.

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DOI: <https://doi.org/10.51584/IJRIAS.2026.11080196>

Received: 24 August 2026; Accepted: 29 August 2026; Published: 28 September 2026

ABSTRACT

Computed tomography (CT) facilities are major contributors to medical radiation exposure, raising safety concerns for patients, staff, and the general public. Shielding design is critical, yet often applied uniformly without accounting for local workload or geometry. This study evaluated shielding efficiency in CT facilities across Delta State, Nigeria. A cross-sectional survey was conducted in six CT centers (two government, four private). Facility specifications, room dimensions, and workload data were recorded. Radiation exposure was measured at primary and secondary barriers using calibrated survey meters. Required shielding thickness was calculated using NCRP 49 methodology. Statistical analyses included descriptive statistics, ANOVA, Kruskal-wallis tests, and correlation matrices. Installed shielding (mean 2.738 mmPb) exceeded calculated requirements (mean 0.444 mmPb) by ~6.7 times, with average excess shielding of 2.294 mmPb. Shielding efficiency averaged 83.8% (range 62-95%) and positive skewness (3.113), indicating outlier exceedances. Material equivalence analysis revealed that 115.8 mm steel, or 127.9 mm glass equaled 1 mm lead. Strong correlations ($r > 0.97$) confirmed consistency across material equivalents, while higher design shielding strongly predicted overshielding ($r = 980$). Inter-facility comparisons showed significant differences in shielding efficiency and excess shielding ($p < 0.001$). CT facilities in Delta State demonstrate conservative overshielding, ensuring safety but reflecting inefficiencies in material use. Despite adequate protection, extreme dose outliers highlight the need for site-specific shielding assessments, continuous monitoring, and optimization in line with as low as reasonably achievable (ALARA) principles.

Keywords: Radiation shielding, dose optimization, computed tomography, patient safety, occupational exposure.

INTRODUCTION

Radiation is a fantastic medical tool that has significantly increases therapeutic and diagnostic capacities and give invaluable palliative care. It is divided into two primary categories: ionizing and non-ionizing radiation with known amplitude, frequency, and wave length (Dance *et al.*, 2014). Radiation shielding is important since ionizing radiation exposure might have detrimental effects that could affect the exposed individual as well as progeny and these effects could be somatic or genetic (Ovwasa *et al.*, 2023). In an attempt to reduce the potential hazards of biological damage linked to ionizing radiation, a number of advisory and regulatory bodies have been established at the national and international levels to control and offer guidelines for radiation protection reasons (Anizor *et al.*, 2021). Although many studies have evaluated radiation shielding in diagnostic radiology departments and CT facilities in various countries and parts of Nigeria, there is little published research specifically evaluating the radiation shielding integrity of CT facilities in Delta State, Nigeria. It is unique for this study since Delta State has a range of government, private, urban, and semi-urban CT facilities with different scanner ages, workloads, and shielding designs. Because of this variability, radiation shielding integrity under different operating conditions within the same state can be statistically compared. Instead of evaluating the actual effectiveness of installed shielding barriers through radiation measurements, most current research focus on

radiation exposure to patients, quality assurance, or shielding design calculations. Furthermore, many previous studies provide descriptive findings without performing extensive statistical analysis to assess shielding efficiency across different CT facilities or identify factors influencing shielding efficacy. However, there is insufficient local data to assess whether Delta State's current CT facilities comply with national and international radiation protection laws. Additionally, differences in CT scanner age, workload, room layout, shielding materials, and maintenance practices between facilities have not been adequately investigated by statistical methods. Because of this, regulatory agencies and medical experts have limited information at their disposal to support evidence-based decisions intended to improve radiation safety in the region. However, radiation dose evaluations from medical imaging tests are important in helping doctors diagnose patients correctly and provide important insights into human health (Abdullahi *et al.*, 2020). Europe, North America, and some regions of Asia account for the majority of published research on CT radiation shielding (Akpochafor *et al.*, 2018). There aren't many studies from Nigeria, especially Delta State. By offering information from a growing healthcare environment, this study broadens the body of knowledge worldwide. Any planned CT facility's main objective is to keep the local population from being exposed to radiation levels over the current regulatory limits, which are 1 mSv/yr for the general public and 5 mSv/yr for occupational exposure. Radiography rooms must be adequately protected to reduce the absorbed dose to employees, patients, and the general public (Sadril., 2013). Radiography facility shielding standards are provided by the National Council on Radiation Protection and Measurements (NCRP) guidelines, which provide the basis for radiographic CT room design and shielding in most countries. Both primary and secondary radiation sources, such as scatter and leakage radiation, need to be protected in a diagnostic CT room (Akpochafor *et al.*, 2018). Due to changes in workload and the replacement of CT machines, the primary and secondary shielding thickness must be periodically reevaluated. It is essential to apply the ALARA (as low as reasonably achievable) approach to keep radiation exposure substantially below these limits, despite dose constraints. The ALARA concept must be applied in all radiation-related activities. This includes the design, construction, and operation of existing and future facilities. A few studies have evaluated main and secondary barriers with differing suggestions in order to develop parameters that will help determine the thickness of materials necessary for a particular CT room depending on its location, radiography workload, use factor, and occupancy factor. By giving information on the level of radiation shielding provided at different CT facilities in Delta State, Nigeria, this study improves the safety of workers, patients, and the general public. Additionally, it enhances the department's standing and provides recommendations for how to make these facilities' shielding better. The somatic and genetic risks associated with radiation exposure and absorbed dose to patients during CT scan examinations have recently been a greater concern for medical physicists (Abdullahi *et al.*, 2020). Compared to other ionizing radiation-using imaging methods like plain radiography, the radiation dose that a patient receives from CT is larger (Ikubor *et al.*, 2022). Since its initial usage in diagnostic radiology in the 1970s, CT scanners have grown in popularity all over the world due to their substantial and life-saving clinical benefits (Chiaghanam *et al.*, 2023). Even though there aren't many CT scans among those radiography investigations, CT applications make up a sizable amount of medical radiation exposure, which has given rise to radiologic concerns like cancer risk because of the increased effective dose (ED) connected with its use (Buhari *et al.*, 2024). The high dose from CT has been associated with disastrous outcomes globally, in addition to increasing the potential for deterministic and stochastic effects (Adejoh *et al.*, 2018). When compared to conventional radiography or mammography, CT's high scan parameters result in higher radiation exposures (Martin *et al.*, 2024). Consequently, increasing use of CT facilities raises radiation doses to the public and personnel, supporting ongoing efforts to lower doses (Akpochafor *et al.*, 2018). Godfrey Newbold Hounsfield introduced CT in 1972 as a medical imaging technique that uses x-rays and calculated algorithms to produce incredibly detailed cross-sectional images of the body. There may be random or predictable dangers related to CT procedures. CT creates a cross-sectional image by removing superimposed features that are frequently discovered during imaging using conventional radiography. However, since there is no longer any dispersion, two tissues with the same density may be easily separated from each other (Ekpo *et al.*, 2018). Optimizing patient care while maintaining a reasonable degree of image quality is necessary to minimize or eliminate these effects (Akpochafor *et al.*, 2018).

MATERIALS AND METHODS

Description of the study area

Study Area. The study used a prospective cross-sectional design with the goal of evaluating the structural shields currently in place at the chosen CT facilities and calculating the necessary thickness for each barrier using the NCRP 49 methodology based on occupancy areas, workload, and distance. Delta State's CT facilities were the study's target demographic. The technique of purposive sampling was applied. The research used a sample size of six CT facilities that satisfied the inclusion requirements of having a working CT unit, radiation shielding installed, and CT machine availability. The Ethical and Research Committee of the Six CT centers authorized the study's conduct and the authorities of the CT facilities where it was carried out granted permission.

Table 1: Description of the studied facilities.

Code	Facility						
	Equipment Name	Model	Serial Number	Company	Year Of Manufacture	Max Kvp	
A	General Electric	Revolution Acts	42051bg3	Wipro General Electric Healthcare Pvt. Ltd, bangalore, india	June 2018	140	
B	General Electric	Bright Speed	Bs1c8017ct	General Electric YokogaWa medical systems, china	August 2017	140	
C	Toshiba	Asteion	1aa0822651	Toshiba Medical System Corpration, Japan	June 2015	140	
D	Siemens	Somatom Gonow	11101885	Siemens Healthcare, Germany	November 2021	.140	
E	Neusoft	Neuviz 128	N12812100595	Neusoft Medical System Co. Ltd, china	December 2021	140	
F	General Electric	Revolution Acts	60744bg0	General Electric Healthcare Pvt. Ltd, Bangalore, india.	October 2019	140	

Measurement of radiation

The main equipment used are:

CT Scanners, digital laser tape and radiation survey meter.

METHODS

This study used six CT centers in Delta State, two of which were owned by the government and four of which were commercial facilities. A thorough radiation protection safety inspection were performed upon the arrival on the CT scan facilities under investigation, a comprehensive radiation protection safety inspection was carried

out. A calibrated digital survey meter was used to assess the primary and secondary barriers of the CT room under study utilizing a data collecting checklist that included machine specifications, CT room size, number of patients, maximum Kvp, and unshielded air kerma. During the patient examination, the survey meter was placed in various parts of the CT room and exposed to unshielded air kerma. To assess scatter radiation, the radiation meter was also placed at several locations, such as the control console, neighboring walls, and entrance door. The NCRP 49 approach was utilized to determine the barrier thickness, taking into account the protective barriers and shields that were already in place at each facility. The number of active CT facilities in Delta State that satisfied the study's inclusion requirements and authorized data collection determined the study's sample size. The six facilities—referred to as centers A, B, C, D, E, and F—were specified in a workbook. Since each of the six centers has an operating manual, each machine's specifications were written down from the CT machine's body. Using laser tape, the dimensions of the six CT facilities were measured at the following points: Barrier 1 (wall right to the CT gantry), Barrier 2 (wall left to the CT gantry), Barrier 3 (wall rear to the CT gantry), Barrier 4 (wall anterior of the CT gantry), Barrier 5 (CT console), Barrier 6 (CT room entrance door), and Barrier 7 (CT console door). The mean workload for facilities and the thickness of the barriers were calculated using descriptive statistics. To ensure consistency and comparability of radiation measurements across all CT facilities participated in this work, survey meter results were standardized using a single measuring technique. Throughout the experiment, the same calibrated survey meter was used to prevent variances caused by instrument variability. Calibration was verified in compliance with the manufacturer's specifications prior to data collection. Measurements were taken in the control room, entrance door, adjacent occupied areas, and outside the shielding barriers of each facility. To measure the distance between the walls of the several barriers and the CT isocenter, the survey meter was positioned in different places across the CT room. Many readings were taken at each measurement location, and the mean results were calculated. After all radiation measurements were recorded in the same unit and statistically evaluated, the independent sample t-test was used to compare the radiation shielding performance of CT facilities in Delta State, Nigeria.

RESULTS AND DISCUSSION

Results

From Table 2, shows the important shielding variables' descriptive statistics. The descriptive statistics show a number of noteworthy trends. With a coefficient of variation of 108.08% and a positive skewness of 1.915, unshielded kerma shows remarkable variability, suggesting that a subset of barriers gets abnormally high exposure. The installed design shielding ranges from 0.00 to 5.00 mmPb, averaging 2.738 mmPb, while the required shielding (RadShield) ranges from 0.00 to 1.13 mmPb, with a mean of 0.444 mmPb. The installed shielding surpasses the computed needs by around 6.7 times, according to the mean RadShield-to-design ratio of 0.15. Additionally, annual dose rates (ADR) exhibit extreme positive skewness (3.113) and great variability (CV = 97.82%) with a kurtosis of 10.656, indicating the presence of outlier exceedances. The average excess shielding is 2.294 mmPb, and the average shielding efficiency for all barriers is 83.8%, with a range of 62% to 95%. The shielding efficiency for each facility is shown in Table 4. The percentage of radiation that placed barriers attenuate is measured by shielding efficiency. The average efficiency for all barriers is 83.8%, meaning that shielding lowers exposure by about 84% when compared to unshielded situations. A standard deviation of 8.08% indicates moderate variability, with values ranging from 62.4% to 94.8%. The three barriers exceeding dosage limits and the absence of barriers categorized as "insufficient" seem to be at odds, indicating that the metric is based on installed versus necessary thickness rather than observed performance. Table 5 presents the material shielding equivalency ratios are shown in Figure 1, demonstrates the material equivalency analysis by contrasting several materials with lead in order to get the necessary shielding performance. For shielding design, the equivalency ratios provide useful advice. To attain the same attenuation as 1 mm of lead, an average of 115.8 mm of concrete, 306.6 mm of gypsum, 8.1 mm of steel, or 127.9 mm of glass are required. These connections are stable, as seen by the low standard deviations for steel (1.31) and concrete (12.49). These ratios enable designers to choose the best materials depending on factors including cost, available space, and construction issues. The statistical study confirms that the facilities cannot be considered similar for shielding purposes by revealing highly significant disparities ($p < 0.01$) across the majority of shielding characteristics. Significant differences in the amount of overshielding between facilities are highlighted by the greatest F-value (20.65) for excess shielding. The significant Kruskal-Wallis result for ADR ($p = 0.043$) shows that outlier exceedances

produce substantial changes in the dose distribution, while the ANOVA findings for ADR are not significant ($p = 0.491$), indicating that installed shielding generally equalizes doses across barriers. The RadShield-to-design ratio's non-significant finding ($p = 0.057$) shows that overshielding relative to calculated requirements is generally constant across sites. The association analysis between important shielding and dosage factors is shown in Table 7, and Figure 2, displays the heatmap of the correlation matrix. Shielding efficiency and the RadShield-to-design ratio show high negative connections (blue), while material-related factors show strong positive correlations (red). Deterministic linkages are demonstrated by perfect correlations between Occupancy Factor and Design Goal ($r = 1.00$) and between DR and ADR ($r = 1.00$). RadShield-to-design Ratio and Efficiency have a virtually perfect negative correlation ($r = -0.999$), which validates their mathematical reliance. All material equivalents have nearly perfect correlations ($r > 0.97$), indicating that the material equivalency connections are consistent throughout the sample. Higher design shielding immediately leads to larger overshielding, as evidenced by the strong link between Design mmPb and Excess Shielding ($r = 0.980$).

Table 2: Descriptive Statistics of Key Shielding Variables

Variable	Mean	Std. Dev.	Variance	Min	Q1	Median	Q3	Max	Range	CV (%)	Skewness	Kurtosis
Distance(m)	3.169	1.033	1.068	1.50	2.00	3.10	4.00	5.30	3.80	32.60	0.142	-1.202
Occupancy Factor	0.589	0.378	0.143	0.25	0.25	0.25	1.00	1.00	0.75	64.11	0.199	-2.061
Design Goal (mSv/yr)	0.056	0.040	0.002	0.02	0.02	0.02	0.10	0.10	0.08	71.72	0.199	-2.061
Unshielded Kerma(mGy/wk)	1.213	1.311	1.719	0.00	0.32	0.91	1.34	5.95	5.95	108.08	1.915	3.786
RadShield(mmPb)	0.444	0.288	0.083	0.00	0.21	0.45	0.58	1.13	1.13	64.78	0.491	-0.382
Design (mmPb)	2.738	1.211	1.466	0.00	2.50	2.50	2.50	5.00	5.00	44.22	0.274	1.389
Ratio RadShield to Design	0.150	0.088	0.008	0.00	0.08	0.15	0.21	0.37	0.37	58.35	0.381	0.007
MmPb	0.466	0.364	0.133	0.00	0.20	0.45	0.58	1.98	1.98	78.20	1.889	6.214
MmConcrete	48.78	27.41	751.29	0.00	26.55	52.22	63.38	105.36	105.36	56.19	0.118	-0.669
MmGypsum	142.23	102.41	10488.08	0.00	62.92	140.90	182.26	427.53	427.53	72.01	0.855	0.410
MmSteel	3.95	3.03	9.16	0.00	1.33	3.79	5.40	10.70	10.70	76.57	0.635	-0.579
MmGlass	53.97	30.43	926.12	0.00	29.29	58.02	70.57	118.41	118.41	56.38	0.122	-0.663
ADR (mSv/yr)	0.780	0.763	0.581	0.32	0.40	0.53	0.66	4.20	3.88	97.82	3.113	10.656
DR (uSv/h)	0.390	0.381	0.145	0.16	0.20	0.27	0.33	2.10	1.94	97.82	3.113	10.656
Shielding Efficiency	0.838	0.081	0.007	0.62	0.79	0.82	0.91	0.95	0.32	9.63	-0.705	0.322
Excess Shielding	2.294	1.032	1.066	0.00	1.96	2.20	2.33	4.47	4.47	44.99	0.254	1.200
Dose Percent of Limit	51.97	77.44	5997.15	6.8	12.0	36.0	53.5	420.0	413.2	149.01	3.640	14.432

Table 3: Facility-Specific Shielding Efficiency Metrics

Facility	Efficiency (Mean $\pm$ SD)	Min	Max	Excess Shielding (Mean $\pm$ SD) mmPb
A	0.891 $\pm$ 0.070	0.788	0.948	2.23 $\pm$ 0.18
B	0.836 $\pm$ 0.043	0.774	0.894	4.18 $\pm$ 0.21
C	0.821 $\pm$ 0.060	0.752	0.896	1.76 $\pm$ 0.79
D	0.724 $\pm$ 0.080	0.624	0.800	1.55 $\pm$ 0.71
E	0.890 $\pm$ 0.046	0.824	0.924	2.23 $\pm$ 0.11
F	0.850 $\pm$ 0.071	0.768	0.920	1.82 $\pm$ 0.82

Table 4: Material Shielding Equivalence Ratios

Material	Mean Thickness (mm)	Equ. Ratio (mm material / mmPb)	Std. Dev.
Concrete	48.78 ± 27.41	115.82	12.49
Gypsum	142.23 ± 102.41	306.58	66.13
Steel	3.95 ± 3.03	8.12	1.31
Glass	53.97 ± 30.43	127.93	24.35

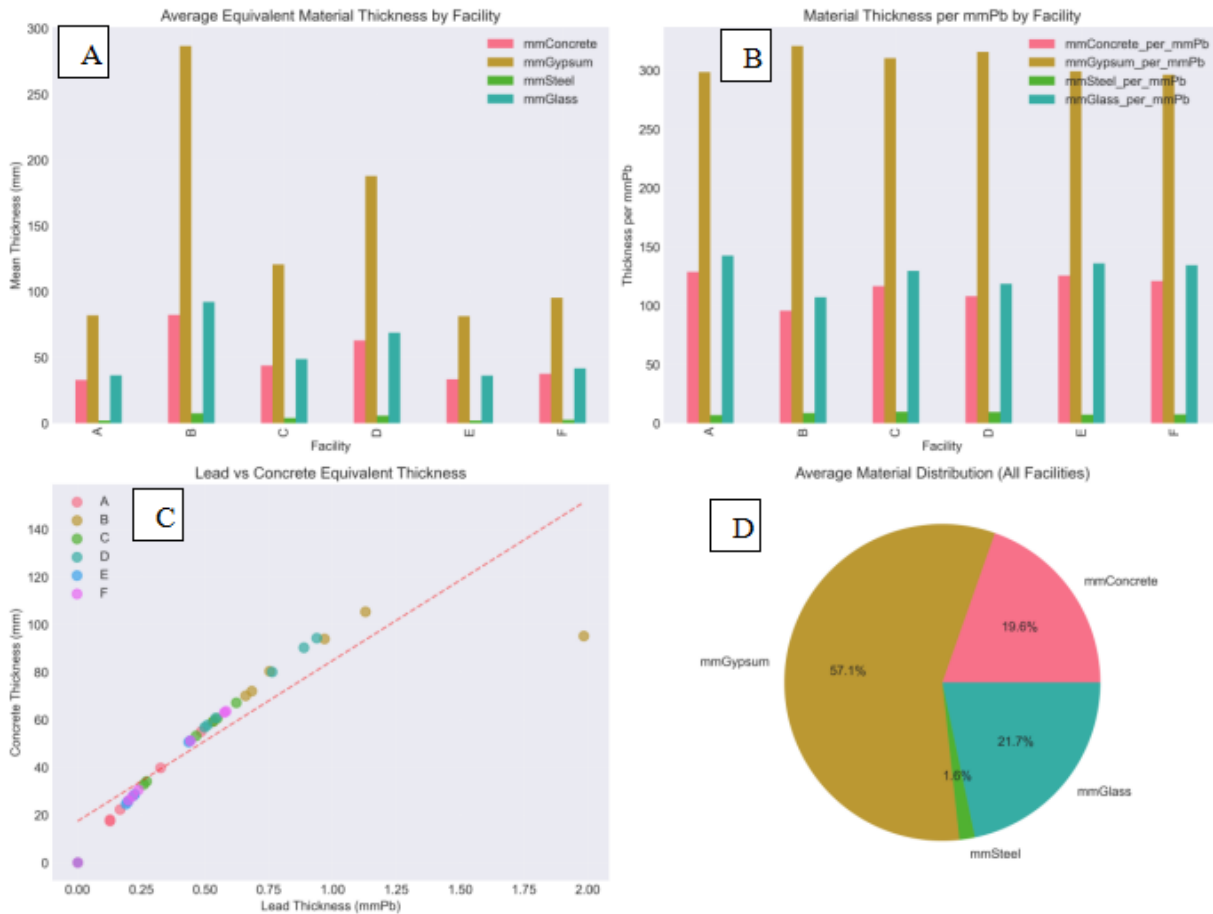


Figure 1. Material equivalence analysis. (A) Average equivalent material thickness by facility; (B) Material thickness per mmPb by facility; (C) Lead versus concrete equivalent thickness scatter plot with trend line; (D) Average material distribution across all facilities.

Table 5. Inter-facility statistical comparisons of shielding parameters

Variable	ANOVA (F)	p-value	Significant	Kruskal-Wallis H	KW p-value	KW Significant
Unshielded Kerma (mGy wk)	7.80	<0.001	Yes	18.74	0.002	Yes
RadShield (mmPb)	7.10	<0.001	Yes	19.52	0.002	Yes
mmPb	6.26	<0.001	Yes	19.67	0.001	Yes
Shielding Efficiency	6.18	<0.001	Yes	17.14	0.004	Yes

Excess Shielding	20.65	<0.001	Yes	28.48	<0.001	Yes
Ratio RadShield to Design	2.39	0.057	No	10.06	0.074	No
ADR (mSvyr)	0.90	0.491	No	11.46	0.043	Yes

Table 6: Correlation Analysis between Key Shielding and Dose Variables

Variable 1	Variable 2	Pearson r	Spearman ρ	Strength
Occupancy Factor	Design Goal (mSv/yr)	1.000	1.000	Perfect
DR (uSv/h)	ADR (mSv/yr)	1.000	1.000	Perfect
Ratio RadShield to Design	Shielding Efficiency	-0.999	-0.999	Perfect
mm Concrete	mmGlass	0.999	0.994	Very Strong
RadShield (mmPb)	mmConcrete	0.994	0.999	Very Strong
RadShield (mmPb)	mmGlass	0.994	0.995	Very Strong
RadShield (mmPb)	mmGypsum	0.993	0.993	Very Strong
Design (mmPb)	Excess Shielding	0.980	0.744	Very Strong
mmGypsum	mmGlass	0.978	0.990	Very Strong
mmConcrete	mmGypsum	0.977	0.992	Very Strong

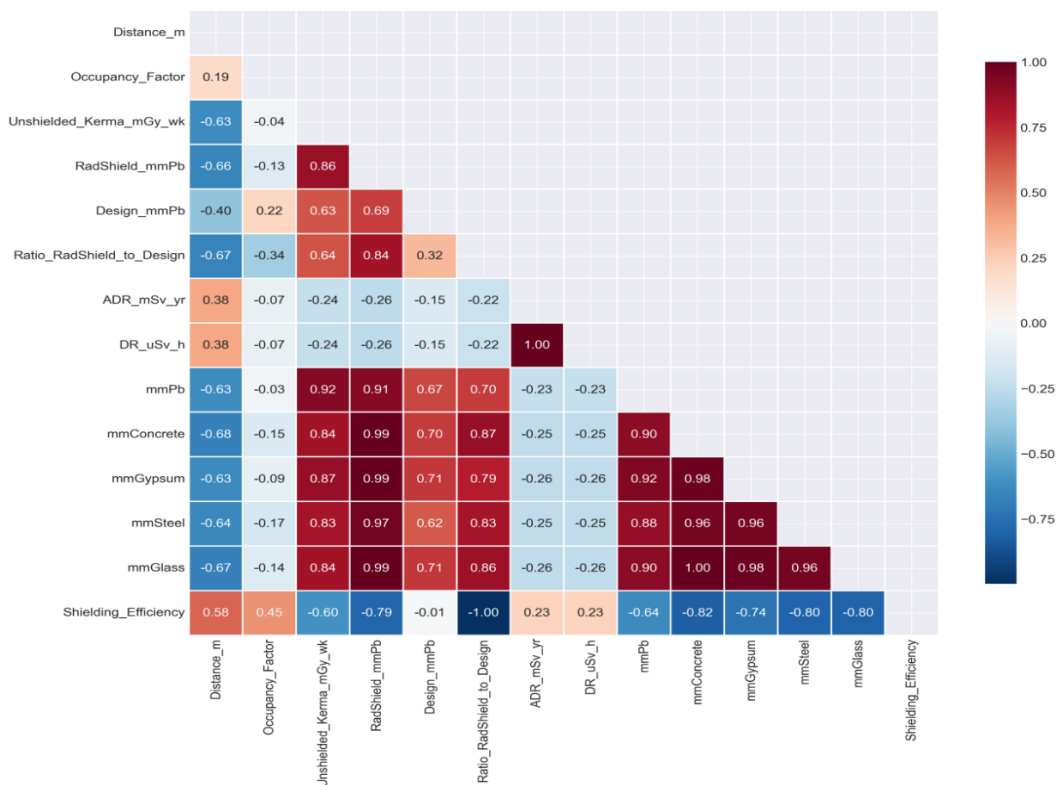


Figure 2. Correlation matrix of key radiation shielding parameters. Color intensity indicates correlation strength (red: positive, blue: negative). All material thickness variables show strong positive intercorrelations ($r > 0.95$).

DISCUSSION

The descriptive statistics in Table 2, highlights several important patterns in the dataset. A tiny number of barriers have disproportionately high exposure, as indicated by the unshielded kerma values' very high coefficient of variation (108.08%) and positive skewness (1.915). Because it reveals certain obstacles that should be given priority in shielding design and quality assurance initiatives, this is clinically significant. Other Nigerian research have found comparable patterns of variability, for example, (Akpochafor *et al.* 2019) revealed significant inter-facility variations, with coefficients of variation surpassing 50% for numerous CT dosage measurements. Comparing Nigeria's CT facilities with those in other countries reveals both advancements and room for development. The discrepancy between installed design shielding and computed RadShield requirements is another noteworthy trend. The actual design shielding was significantly thicker, ranging from 2.5 to 5.0 mmPb, although RadShield values varied from 0.00 to 1.13 mmPb (Table 2). This "one-size-fits-all" approach to design ignores aspects unique to each facility, like workload, scanning procedures, and room shape. The disparity highlights the value of site-specific shielding evaluations as opposed to depending on general guidelines, a suggestion also stressed by (NCRP 2004) and supported by the findings of (Nkansah *et al.* 2013) in Ghana. The exposure variability is further demonstrated by the distribution of annual dose rates (ADR), which has a coefficient of variation of 97.82%, skewness of 3.113, and high kurtosis of 10.656 (Table 2). The distribution's strong skewness and "fat-tailed" characteristics suggest that infrequent but severe dose exceedances happen more frequently than would be predicted in a normal distribution. These anomalies have significant ramifications for risk assessment since they imply that, despite their rarity, sporadic extreme exceedances provide significant health hazards and have to be addressed with focused mitigation. This aligns with the observations of (Martin *et al.* 2024), who emphasized that, despite their rarity, severe outliers in dosage distributions need special consideration since they may affect safety. CT facilities cannot be regarded as similar when it comes to shielding design, as demonstrated by the extremely significant inter-facility disparities ($p < 0.01$) across most shielding factors in Table 6, ANOVA results. In practical terms, this means that it might not be sufficient to apply uniform standards to all facilities; instead, each facility needs a customized evaluation that takes into account its unique conditions, geometry, workload, and equipment. This strategy is in line with ICRP Publication 103 (ICRP, 2007), which emphasizes that local factors should be taken into account while optimizing rather than depending just on prescriptive universal criteria. The biggest F-value for excess shielding 20.65, emphasizes how much overshielding varies throughout facilities. For instance, Facility B had a severe mean excess of 4.18 mmPb (Table 4), but other facilities showed more mild overshielding. A similar pattern of variation in design conservatism was reported by (Rimi *et al.* 2023) in Katsina, where shielding thickness varied by factors of 2-3 between facilities with similar equipment and workloads. It's interesting to note that the ANOVA for annual dose rates (ADR) was non-significant ($p = 0.491$), indicating that installed shielding generally equalizes doses across facilities despite underlying differences in source terms. However, The Kruskal-Wallis test for ADR was significant ($p = 0.043$), suggesting that parametric analyzes fail to identify substantial changes in dose distributions caused by extreme outliers such localized dosage exceedances. As stressed by (Perezgonzalez *et al.*, 2019), this emphasizes the significance of non-parametric approaches for evaluating data with extreme values to make sure that uncommon but crucial events are not missed. The near-perfect correlations between all material equivalents ($r > 0.97$), which show that the relationships between materials like concrete, gypsum, steel, and glass are extremely consistent across all facilities, are more intriguing. This demonstrates that material performance may be accurately predicted when installation is done correctly and supports the validity of published equivalency factors in practical shielding design. According to (Barbhuiya *et al.*, 2025), who pointed out that variations in concrete qualities frequently generated some ambiguity in equivalency estimates, the consistency shown in this investigation is considerably higher. Lastly, a substantial connection ($r = 0.980$) between excess shielding and design mmPb indicates that higher design thicknesses inevitably result in more overshielding. This emphasizes how design decisions affect the amount of overshielding and how crucial it is to base shielding standards on data and calculations rather than arbitrary caution. This study has safety and economic implications since, after the proper standards are met, over-shielding increases building costs, structural requirements, and inefficient use of hospital resources rather than providing additional radiation protection. However, outlier dose exceedances may indicate inadequate shielding or equipment-related issues

that could increase public and employee radiation exposure. Therefore, statistical evaluation of shielding integrity helps identify facilities that require optimization, ensuring radiation safety and cost-effective CT facility design.

CONCLUSION

The study thoroughly evaluated the radiation shielding integrity of CT facilities in Delta State, Nigeria, using cutting-edge machine learning techniques to apply predictive models and classical shielding calculations. However, Logistic Regression properly identified all exceedances and achieved perfect classification of "Safe" versus "At-Risk" barriers. This suggests that straightforward, data-driven screening methods are capable of accurately identifying obstacles that call for focused assessment. Concrete, gypsum, steel, and glass derived equivalency ratios were quite similar across sites ($r > 0.97$), confirming the application of published equivalency factors in shielding design and material selection choices.

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