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Average Glandular Dose (AGD) and Radiation Dose Optimization in Screen-Film and Digital X-ray Mammography

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Abstract: We determined the average glandular dose (AGD) from the craniocaudally (CC) and mediolateral oblique (MLO) views of 496 breasts (247 women) at eight clinics in Sudan. The incident air kerma from the X-ray tube output values and the typical patient-specific breast exposure factors were measured. The AGD values were inferred from the measured incident air kerma and breast-specific dose-conversion coefficients. The AGD per CC and MLO projection and per woman ranged from 0.56 to 2.89 mGy (average: 1.36), 0.48 to 2.08 mGy (average: 1.19), and 2.08 to 9.94 mGy (average: 5.10). The proposed national diagnostic reference levels (mGy) for digital mammography are 1.8 and 1.6 mGy for CC and MLO projection, respectively. Establishing the proposed diagnostic reference levels is an essential step in ensuring patient protection from radiation and will help promote dose optimization for X-ray mammography at the national level and beyond. These results provide important baseline data that can be used to formulate national diagnostic reference levels.

Keywords: X-ray mammography; radiation dose; incident air kerma; diagnostic reference levels (DRLs); compressed breast thickness (CBT); radiation protection

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1. Introduction

Breast cancer is the fifth most significant cause of cancer-related deaths worldwide and is a significant health concern among women [1,2]. The early diagnosis and treatment of breast cancer are crucial for reducing mortality [3,4]. Mammography screening can reduce breast cancer mortality by 15–20% [5]. Thus, X-ray mammography is the optimal choice for the screening and diagnosis of breast cancer.

During X-ray mammography, the glandular tissue in the breast receives a significant dose of absorbed radiation. In 2007, the International Commission on Radiological Protection (ICRP) almost doubled the previously identified breast tissue weighting factor based on epidemiological studies, showing an increase in fetal breast cancer following exposure to ionizing radiation [6,7]. Therefore, the breast is among the most radiosensitive organs in the body, along with the colon and bone mirrors.

In diagnostic radiology, organizations such as ICRP emphasize setting and using diagnostic reference levels [6–10]. As defined by the ICRP, DRLs are a type of investigation level used as a tool to help determine radiation dose optimization [8]. Significant variations in dose levels highlight the need for DRL benchmarking in clinical practice. There was also a need to identify hospitals that performed below average inpatient radiation exposure, thus necessitating optimization measures. The development of this concept has motivated

several authors worldwide to propose DRLs in diagnostic and interventional radiology, including mammography [11–16]. Significant improvements in patient doses have been reported due to the establishment and implementation of DRLs [17].

In 2017, the Sudan government passed an act [18] that established the Sudanese Nuclear & Radiological Regulatory Authority (SNRRA) as an independent body that oversees all activities related to the peaceful applications of nuclear radiation. The SNRRA mandate comprises guidelines, DRLs in medical imaging, and dose constraints for different exposure scenarios. Several dose surveys have been conducted in diagnostic radiology for optimization [19–22]. Despite these efforts, mammography was left behind, mainly because there are few mammography units across the country, which is a source of concern. As of 2018, there were only 12 units across the country, serving 35 million people. Given the lack of mammography-related radiation dose data available from Sudan and Africa at large, it is not surprising that this is the first nationwide survey to be conducted in Sudan.

Through the present study, we aimed to determine the average glandular dose (AGD) of radiation to promote dose optimization and acquire baseline data that will eventually help set national DRLs (NDRLs) for future dose optimization.

2. Materials and Methods

We estimated the AGD of 247 women who underwent mammographic X-ray examinations at eight clinics in Sudan. The women underwent symptomatic and screening mammography. The different types of equipment investigated included direct digital radiography (DR), computed radiography, and screen-film (SF) radiography. Table 1 lists information regarding the studied mammography equipment. For dose assessment in digital mammography devices, patient exposure parameters were retrospectively extracted from the Digital Imaging and Communications in Medicine header. In the SF devices, the required data were registered in special forms by a technologist during the examination. Our institutional ethic committee approved this study. Due to the retrospective nature of the data collection, the requirement for individual patient consent was waived for this study. The workload for the mammography system ranged from 10 to 20 patients per week.

Table 1. Mammography equipment information.

Clinic	Make/Model	Country of Origin	Modality	Target/Filter	AEC	Year of Installation	Institution Type
SF mammography							
M3	Philips	The Netherlands	Kodak Mini R2 cassette/Mini R2 2000 screen	Mo/Mo	No	2007	Private
M4	Lilyum/Metaltronica	Italy	Kodak Mini R2 cassette/Mini R2 2190 screen	Mo/Mo	No	2010	Private
Digital mammography (CR & DR)							
M1	Giotto	Italy	CR/Fuji IP	Mo/Mo	No	2010	Government
M2	GE	USA	DR/FP	Rh/Rh, Mo/Rh, Mo/Mo	AEC	2012	Government
M5	SIEMENS/Mammomat C/	Germany	CR/Fuji IP cassette type CC	Mo-Rh	No	2012	Private
M6	Lilyum/Metaltronica	Italy	CR/Fuji IP cassette type CH	Mo-Mo	AEC	2014	Private
M7	Philips	The Netherlands	CR	Mo/Mo	AEC	2014	Government
M8	Neusoft/NM-GA	China	DR/amorphous selenium FP	Ag-Rh	AEC	2016	Government

In mammography, the radiation dose is determined in terms of AGD, the recommended dosimetric quantitative value of interest for radiation risk assessments in mammography (NCRP 1987, 1996) [23]. For each breast, the AGD was estimated for two views: the craniocaudal (CC; head to foot) and mediolateral oblique (MLO; from the middle of the chest out to the side of the body with the X-ray tube placed at an angle) views.

In each of the CC and MLO views of the breast, the following parameters were recorded: compressed breast thickness (CBT), target and filtration material, tube peak kilovoltage (kVp), and exposure current–time product (mAs). Other machine parameters, such as the beam half-value layer (HVL) and radiation output, were measured. The study included only women over 30 years of age with breast thickness between 20 and 80 mm.

2.1. Half-Value Layer (HVL)

The beam quality of the mammography device was measured using a Piranha multimeter (RTI Electronics). This multimeter measures the HVL in mammography with a single exposure using multiple diode detectors inside the detector. We measured the HVL for each target/filter combination, as listed in Table 1.

2.2. Determination of the Average Glandular Dose (AGD)

The AGD is the mean absorbed dose in the glandular tissue of the breast. The AGD is derived from measurements of the incident air kerma (K_i) and applying conversion coefficients that depend on the radiation beam quality (HVL) determined by the anode/filter materials, breast thickness, and composition [24,25]. The AGD was estimated from K_i in a three-step process:

First, the normalized X-ray tube output, $Y(d,kV)$, was obtained from the incident air kerma free in air (K_a) measured at a certain focus-to-detector distance (FDD) with the breast compression plate in position using a calibrated dose rate meter type Piranha (RTI; Ballad, Sweden). The normalized X-ray tube output, $Y(d,kV)$, was determined according to Equation (1).

$$Y(d,kV) = K_a(d,kV)/mAs \quad (1)$$

where $K_a(d,kV)$ is the air kerma measured using a range of the tube voltage and exposure time current product (mAs), denoted as value conditions encountered in mammography examinations for a particular mammography unit. A calibration curve of Y (d,kV) versus kV values was obtained and fitted using a power function [26,27].

Next, K_i was determined from the X-ray tube output—$Y(d)$—corresponding to the specific kV value used during mammography and corrected for the focal spot-to-skin distance, FSD, and mAs according to Equation (2):

$$K_i = Y(d,kV)\cdot mAs\cdot\left(\frac{FDD}{FSD}\right)^2 \quad (2)$$

FSD was estimated from the focus-to-film detector (FFD) as $d_{FSD} = FFD - CBT$. The AGD is then estimated from the measured K_i values using conversion coefficients according to Equation (3):

$$AGD = C_{D_{G50},K_i}.C_{D_{Gg},D_{G50}}.S.K_i \quad (3)$$

where C_{D_{G50},K_i} is the coefficient to convert measured K_i to AGD for a breast with 50% granularity, $C_{D_{Gg},D_{G50}}$ converts AGD for a breast with 50% glandularity to that for breast glandularity (g) of the same thickness. The S correction factor represents the selected target/filter combination [26,27]. The values of these conversion coefficients are tabulated as a function of the beam quality (HVL) for compressed breast thicknesses and compositions but also for a reference phantom in the relevant International Atomic Energy Agency (IAEA) and International Commission on Radiation Units and Measurements (ICRU) publications [26,27].

3. Results

The results are presented for AGD resulting from the CC and MLO views in one breast and the total dose per woman for 247 patients who underwent X-ray mammography at eight clinics in Sudan.

Table 2 shows the mammographic exposure settings and breast compression thicknesses used in these examinations. The average kV and mAs values used across the hospitals ranged from 26 to 34 (average: 30) and 15 to 66 (average: 39), respectively. The mean CBTs for the CC and MLO projections ranged from 30 to 49 mm (average: 38 mm) and 33 to 55 mm (average: 43 mm), respectively. All X-ray sets used the manual mode with the beam quality selected by the technician.

Table 2. Median and range of exposure settings and breast compression thickness.

		Age (y)	kV	mAs	FSD	CBT (mm)		AEC
						CC	MLO	
M1	Mean ± σ	**	32	45	59 ± 2	33 ± 11	46 ± 15	Fixed
	Range	**	**	**	(55–61)	(24–87)	(27–80)	
M2	Mean ± σ	**	29 ± 1	55 ± 11	55 ± 1	47 ± 10	52 ± 11	AEC
	Range	**	(26–31)	(34–99)	(53–58)	(24–63)	(27–72)	
M3	Mean ± σ	**	34 ± 1	40 ± 5	54 ± 1	36 ± 8	43 ± 10	Fixed
	Range	**	(32–35)	(32–50)	(52–56)	(25–50)	(25–65)	
M4	Mean ± σ	**	32 ± 2	31 ± 6	60 ± 1	36 ± 7	33 ± 6	Manual
	Range	**	(28–35)	(25–40)	(58–61)	(25–50)	(25–50)	
M5	Mean ± σ	43 ± 7	28 ± 3	15 ± 2	56 ± 1	40 ± 12	47 ± 13	Manual
	Range	(30–60)	(22–32)	(12–18)	(53–59)	(20–70)	(25–70)	
M6	Mean ± σ	50 ± 10	26 ± 1.0	25 ± 1.0	62 ± 1.0	30 ± 9	33 ± 9	Fixed
	Range	(32–65)	(24–27)	(20–25)	(60–63)	(20–50)	(21–51)	
M7	Mean ± σ	48 ± 14	33 ± 1	32.0 ± 0.0	61	42 ± 2.0	42 ± 1	Fixed
	Range	(30–73)	(32–35)	**	**	(39–44)	(39–44)	
M8	Mean ± σ	50 ± 11	29 ± 1	57 ± 12	56 ± 1	39 ± 10	42 ± 9	AEC
	Range	(34–81)	(27–32)	(35–84)	(54–58)	(20–64)	(25–64)	
Average		48	30	39	58	38	43	

** indicate missing data

Table 3 presents the measured average kerma in air and the calculated AGD for two views and 247 female patients for each mammography system based on the measurement of eight mammography devices. Figure 1 shows the boxplot distributions of the average glandular dose per view (AGD) (Figure 1a—CC view; Figure 1b—MLO view). The AGD values ranged from 0.56 to 2.89 mGy (average: 1.43 mGy) per CC view, 0.0.48 to 2.08 mGy (average: 1.22 mGy) per MLO view, and 1.04 to 4.97 mGy (average: mGy) per woman.

Table 3. Median values for the air kerma, HVL, and the calculated average MGD per view and per woman for each mammography system.

Unit	N (Women)	HVL (mm Aleq)	Ki (mGy)	MGD (mGy) per Projection		MGD (mGy) per Woman
				CC	MLO	
SF mammography						
M4	22	0.47	2.95 ± 1.02	0.98 ± 0.26	1.01 ± 0.29	3.98 ± 1.10
M3	29	0.42	7.74 ± 1.2	2.45 ± 0.49	2.02 ± 0.48	8.94 ± 1.94
Mean ± σ (SF)			5.35 ± 3.39	1.72 ± 1.04	1.52±0.77	6.46 ± 3.51
Digital mammography (CR & DR)						
M1	29	0.38	8.0 ± 0.40	2.89 ± 0.82	2.08 ± 0.88	9.94 ± 3.4
M2	27	0.42	5.0 ± 1.16	1.10 ± 0.24	1.13 ± 0.26	4.46 ± 1.00
M5	30	0.41	2.02 ± 0.70	0.56 ± 0.21	0.48 ± 0.16	2.08 ± 0.74
M6	30	0.36	3.19 ± 0.47	1.02 ± 0.21	0.91 ± 0.18	3.86 ± 0.78
M7	30	0.39	5.07 ± 0.39	1.13 ± 0.09	1.13 ± 0.09	4.52 ± 0.36
M8	50	0.36	3.46 ± 1.10	0.75 ± 0.21	0.76 ± 0.22	3.02 ± 0.86
Mean ± σ (DR/CR)			4.46 ± 2.09	1.24 ± 0.84	1.08 ± 0.55	4.65 ± 2.75
75 percentile (DR/CR)			5.05	1.12	1.13	4.51
Mean ± σ (Combined SF & DR/CR)			4.86 ± 2.22	1.36 ± 0.84	1.19 ± 0.57	5.10 ± 2.81

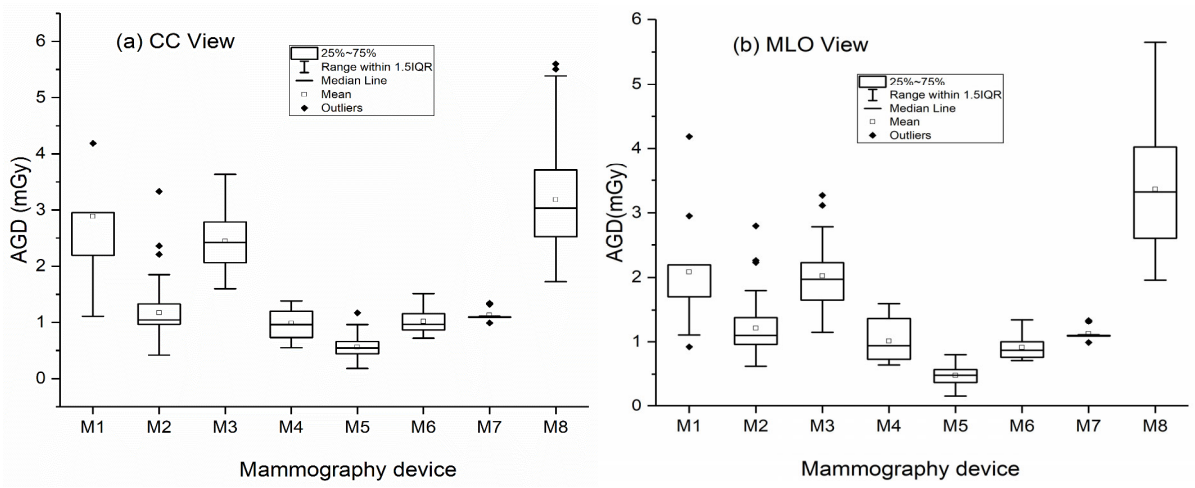


Figure 1. Boxplot distributions of the average glandular dose per view (AGD).

In addition to the CC view in the M1 hospital, the presented AGD values were within the established UK DRLs of 2.5 mGy.

4. Discussion

4.1. Factors Affecting AGD in Mammography

The AGD depends on several parameters, including exposure factors (kVp and mAs), beam quality (HVL), target filter/filter combination, breast composition, and breast thickness. In this study, mammography devices operate in the auto-mode, where the compressed breast thickness determines the kV and filter selection (for devices with more than one target filter combination). The required tube current exposure time was determined either via pre-exposure settings for manual systems (SF and CR) or by automatic exposure control (AEC) in digital mammography devices M2 and M8 (Table 2).

Variations in AGD is primarily caused by differences in mAs due to differences in CBT among women. It is essential to control both parameters in mammography because the AGD values increase with mAs and CBT. Automatic exposure control in mammography adjusts mAs values based on the patient's characteristics (CBT), thereby reducing the AGD.

Figure 2 shows a correlation between AGD and mAs in DR mammography devices that use AEC features. M2 and M8 show a correlation coefficient (R) of 0.54 and 0.84,

respectively, whereas Figure 3 shows a correlation between AGD and mAs mammography devices that use manual exposure factor selection; M4 and M5 show a correlation coefficient (R) of 0.75 and 0.31, respectively. Manual exposure factors should be determined using a technical chart to avoid further dose complications. Figures 2 and 3.

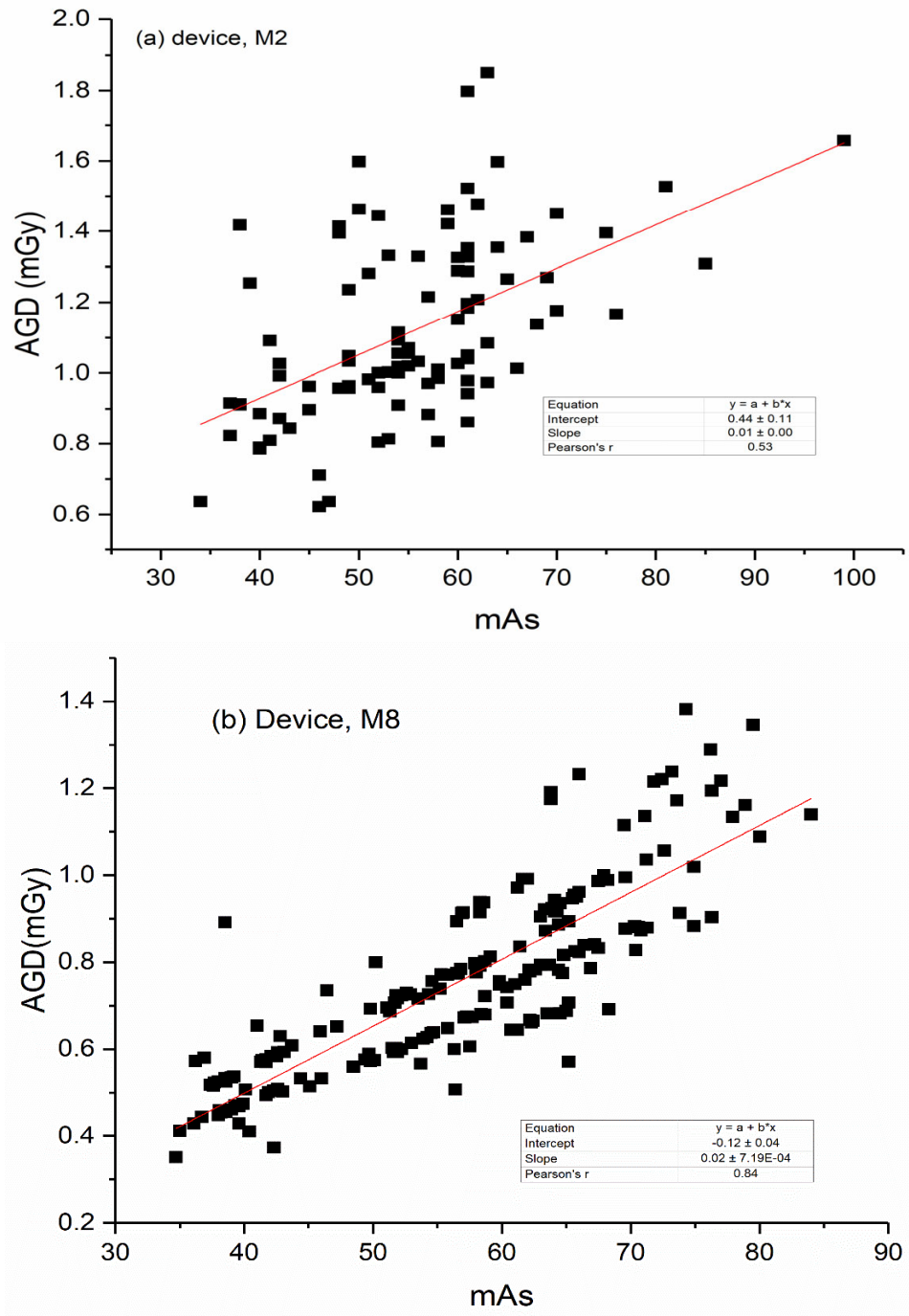


Figure 2. Correlation between AGD and mAs DR mammography devices: (**a**) M2; (**b**) M8.

As shown in Table 2, other hospitals use fixed kVp or fixed kVp and mA values (Table 2), implying that patients can receive either a high AGD value that could increase patient risk or a low dose that could adversely affect the quality of diagnostic information. Automatic exposure control in imaging adjusts exposure factors according to patient characteristics such as breast compression thickness in mammography.

Several authors have studied the correlation between MGD and CBT in X-ray mammography, showing a linear correlation between MGD and CBT [24,25]. Figure 4 shows a

positive correlation between MGD and CBT because of the use of AEC to control both kV and mAs values. The correlation between MGD and CBT in other devices is significantly affected using AEC or manual settings during a particular X-ray procedure.

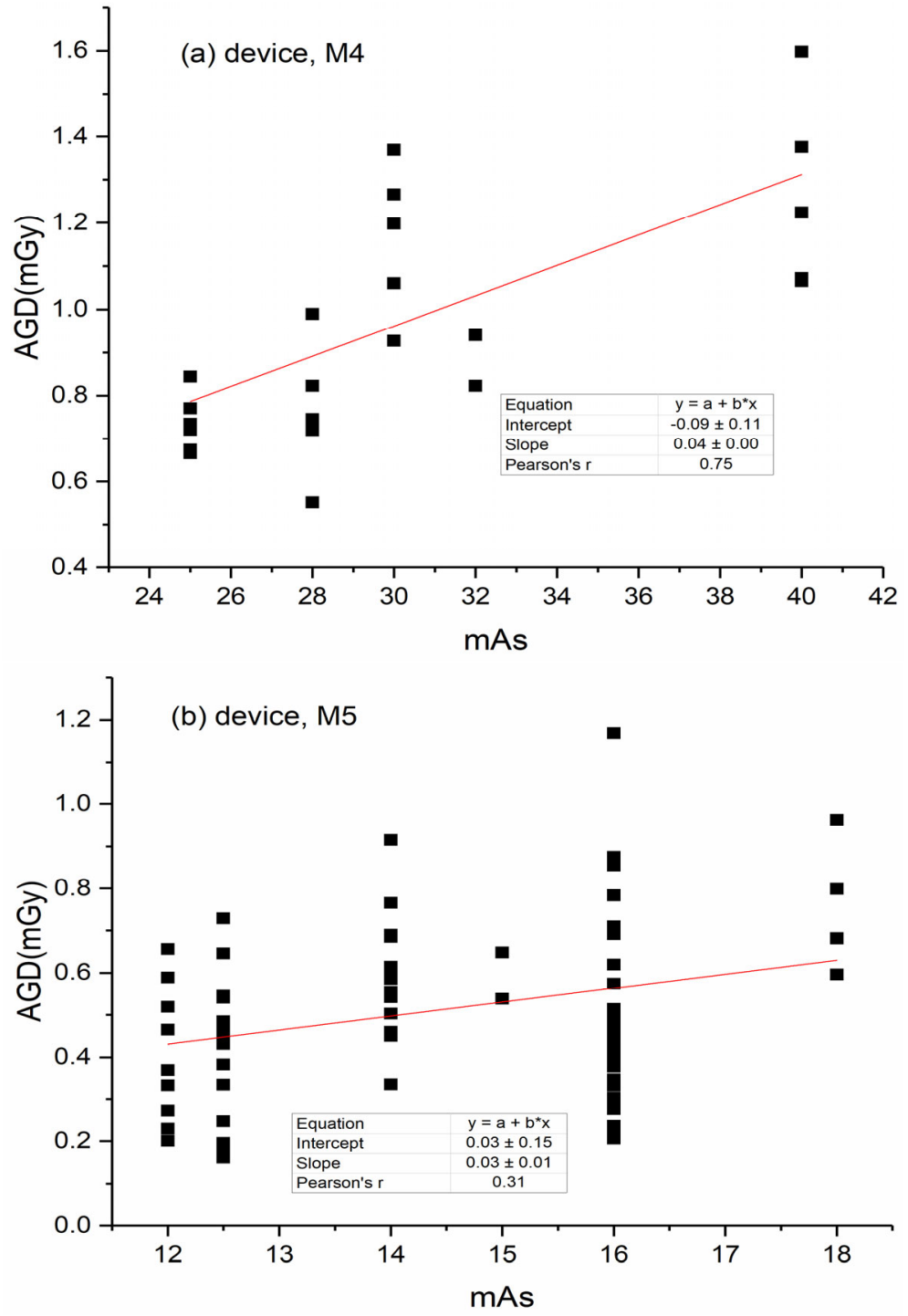


Figure 3. Correlation between the AGD and mAs DR mammography devices: (**a**) M4 device and (**b**) M5 device.

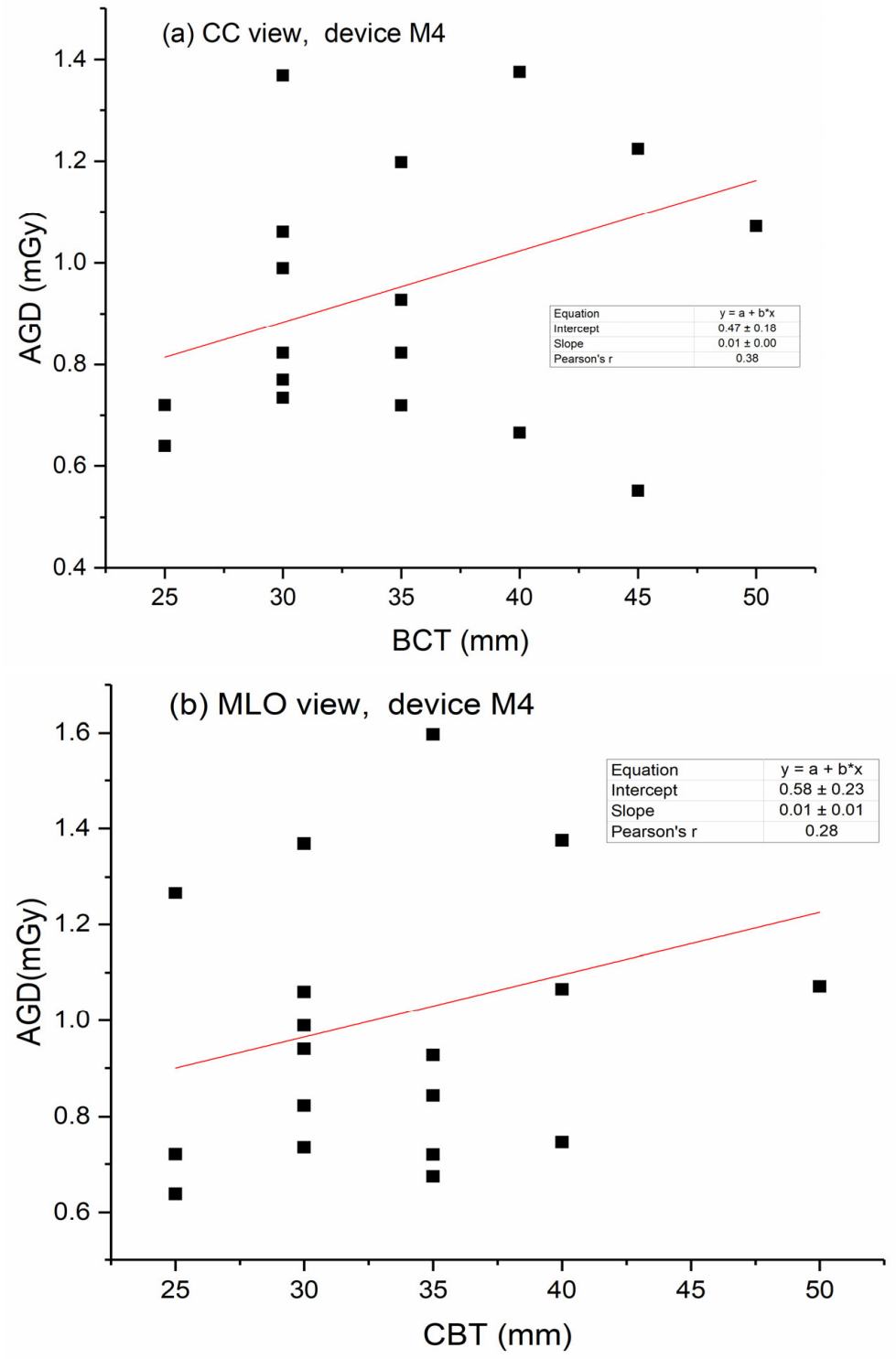


Figure 4. Mean glandular dose as a function of compressed breast thickness (CBT): (**a**) M4, CC View; (**b**) M4, MLO view.

4.2. Dose Optimization

As suggested in the literature, optimization is needed when typical patient doses exceed the corresponding established DRLs or doses associated with significant variations that cannot be explained among hospitals or individual patients. In X-ray mammography, AGD depends on several factors, such as the following: (1) parameters that affect the incident air kerma (e.g., exposure factors, beam quality, and focus-to-skin distance) and (2) mammography-related parameters (e.g., breast thickness and breast graduality). The

correlation between MGD and CBT demonstrates the importance of using AEC in all mammography procedures. Dose variations provide clear evidence that radiation dose optimization is possible without increasing the quality of diagnostic information.

As shown in Tables 2 and 3, a high MGD was associated with high exposure and average breast thickness. Almost seven of the eight mammography devices used 28 kV or higher for their examination. The use of high kV increases the beam penetrability and spatial resolution required for mammography. Hospital M6 used the lowest tube voltage (25 kV), which corresponded to the lowest average breast thickness (29 mm), in contrast to the dose used at hospital M2, which corresponded to 52 mm. High MGD per woman was associated with high mAs values (M1 and M8). Implementing a technique chart for M1 and M7 is essential for the dose optimization of these manual devices using fixed exposure factors. In contrast, the lowest doses are shown for devices M5, M6, and M7, which correspond to the lowest deployed mAs. A high MGD is generally associated with high mAs values, irrespective of whether the device detector is an SF, CR, or DR device. The median dose for the craniocaudal view images was lower than that for the mediolateral oblique view because the thickness of the CC images was lower than that of the MLO images. Generally, MGD is higher in the MLO view because of the greater inclusion of the pectoral muscle in the MLO view, which is denser and has higher attenuation and hence higher radiation dose.

As presented in Table 2, only clinics M2 and M8 are using AEC where exposure factors (kV and mAs) are selected based on the CBT. Hospitals M1, M3, M6, and M7 are utilizing fixed exposure factors irrespective of the CBT. The devices are based on CR or SF mammography and are associated with higher doses than DR systems. As a result, the transition from SF to DR is essential for reducing the radiation doses (Table 3).

An analysis of variance (ANOVA), which involves two hypotheses, was performed: (1) null hypothesis—the means of all levels are equal; (2) alternative hypothesis—the means of one or more levels are different. A one way ANOVA test was performed on the AGD values determined at eight clinics for the CC and MLO views. The population means were deemed significantly different at a significance level of 0.05. The results could be explained by the different type of mammography units involved in the study sample, as well as the technology involved.

4.3. Comparison with the Literature

Table 4 presents a comparison of the AGD values obtained in this study with those in the literature [28–35]. The CC, MLO, and per woman AGD values obtained in this study were 1.36, 1.19, and 5.10 mGy, respectively.

Our results can be compared to the results of a study by Moran et al., who reported the AGD values of 1.8 mGy, 1.95 mGy, and 3.7 mGy in the CC and MLO projections and per woman, respectively, in Spain. In another study in Malaysia, the AGD values were 1.54 mGy, 1.82 mGy, and 3.37 mGy, respectively. Similarly, Thiele et al. in a study on patients in Australia reported AGD values of 1.6 mGy and 4.6 mGy in per view and per woman, respectively, whereas, in Iran, Alizadeh reported AGD values of 2.0 mGy, 2.4 mGy, and 4.4 mGy in CC and MLO views and per woman, respectively.

Our AGD values are almost half the doses reported by Ciraj-Bjelac et al. in Serbia, who reported AGD values of 2.8 mGy, 4.3 mGy, and 7.1 mGy in the CC and MLO projections and per woman, respectively. This study reported an average breast thickness of 49.5 mm and 56.0 mm for the CC and MLO projections, respectively, compared to the average breast thickness of 38 mm and 43 mm in our study. Several studies have shown that MGD increases with breast thickness (assuming comparable exposure factors). Among the different studies presented in Table 4, only the study by Borg et al. in Malta showed a high average breast thickness of 53.8 mm and 63.4 mm but a relatively low AGD of 2.13 per view.

Table 4. Comparison of MGD values obtained in this study with the results presented in similar studies in the literature.

Data Origin	Sample	Mean CBT (mm)	AGD (mGy)		Ref.
			per View	per Woman	
Spain	5034	CC: 49.0 MLO:54	Mean CC:1.8 Mean MLO:1.95	Mean 3.75	[28]
Australia		42.0	Mean:1.6	Mean: 4.6	[29]
Greece	250	42	Mean CC:1.2 Mean MLO:1.5	Mean 2.7	[30]
Malta	759	CC:53.8 MLO63.4	Mean CC:1.06 Mean MLO:1.07	Mean 2.13	[31]
Serbia	53	CC:49.5 MLO:56	Mean CC:2.8 Mean MLO:4.3	Mean 7.1	[32]
Iran	298	CC:49.7 MLO:58.5	Mean CC:2.0 Mean MLO:2.4	Mean 4.4	[33]
Ireland	2910	CC:60.5 MLO:63	Mean CC:1.27 Mean MLO:1.34	Mean 2.61	[34]
Malaysia	300	CC:37.51 MLO:44.5	Median CC:1.44 Median MLO: 1.65	mean: 3.37	[35]
Sudan	247	CC:38 MLO:43	Mean:CC = 1.36 MLO = 1.19	Mean 5.10	This study

Among the centers included in this study, the AGD per CC projection was higher than that presented for the MLO projection in six (75%) of the hospitals studied. Although there is a consensus that AGD increases with CBT, breasts with a similar average thickness may show differences in granularity, which is a significant determinant of radiation-induced risk. Pectoral muscle was denser than the rest of the breast muscles, which may be a reasonable explanation underlying this phenomenon [36]. Based on the 75th percentile of average hospital dose distributions, Sudan's NDRLs based on CC and MLO projections were 1.12, 1.13, and 4.65 mGy. Our values were comparable to those used in the United Kingdom (2.5 mGy) [37,38] and Belgium (2.46 mGy) [39].

Our study has several limitations. Owing to significant variations in compressed breast thickness, the ICRP recommends a minimum sample size of 50 women per mammography device for dosimetric studies to minimize dose variations. Furthermore, most hospitals were not utilizing the AEC, meaning that exposure factors were not tailored to the patient's habitat. Therefore, the current study's results did not show a significant correlation between mAs and CBT in terms of AGD values, as expected.

5. Conclusions

This study revealed significant differences in radiation dose levels between hospitals and within the same hospital for the same type of examination. This is important when establishing recommendations for dose optimization. The results presented here provide the first dosimetric information related to AGD per CC and MLO projections in mammography and per woman in the country. The average breast thickness reported in this study can be used as the standard for Sudanese women. These results constitute important steps when protecting patients from radiation exposure and will help promote dose optimization in X-ray mammography nationally and beyond. This study provides important baseline data for dose optimization and setting national diagnostic reference levels. The present study reveals the need for projects that establish consistency in mammographic practice across all sites before any further dose audits.

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