Analysis of Average Glandular Dose (AGD) and Associated Parameters for Conventional and Digital X-Ray Mammography

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Abstract

In this study, we determined the average glandular dose (AGD) from the craniocaudal (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 typical patient-specific breast exposure factors were measured. 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 0.34–5.3 mGy (average: 2.46), 0.29–3.39 mGy (average: 1.50), and 0.6–7.4 mGy (average: 3.95). The proposed national diagnostic reference levels (mGy) are 3.48, 2.03, and 6.44 mGy for CC, MLO, and per woman, 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 levels and beyond. The results provide important baseline data that can be used to formulate the national diagnostic reference levels.

Introduction

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

During X-ray mammography, the glandular tissue in the breast is subject to receiving a significant radiation-absorbed dose. The current breast-weighting and risk factors are approximately double the previously identified International Commission on Radiological Protection (ICRP) estimates established for radiation-induced breast cancer deaths, mainly due to the exposure of breast tissue to ionizing radiation [6, 7].

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 the radiation dose optimizations [8]. The fact that significant variations in dose levels highlighted the need for DRL benchmarking in clinical practice. There was also a need to identify those hospitals that performed below average inpatient radiation exposure, thus necessitating optimization measures. The development of this concept has motivated several authors around the globe to propose DRLs in diagnostic and interventional radiology, including mammography [11–16]. Significant improvements in patient doses were reported as a result of establishing and implementing 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 adopting guidelines, DRLs in medical imaging, and dose constraints for different exposure scenarios. Previously, several dose surveys were carried out 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 in itself is a source of concern. As of 2018, there were only 12 units across the country serving 35 million people in the population. With a lack of mammography-related radiation dose data available from Sudan and the region of Africa at large, it is not surprising that this is the first nationwide survey to be conducted in Sudan.

Herein, we aim 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.

Material And Methods

We thought to estimate the AGD in 247 women who underwent mammographic X-ray examinations at eight clinics in Sudan. Women underwent symptomatic mammography but also screening mammography. The different types of investigated equipment included direct digital radiography (DR), computed radiography, and screen film (SF) radiography. Table 1 shows the studied mammography equipment information. For dose assessment, patient exposure parameters were retrospectively extracted from DICOM (Digital Imaging and Communications in Medicine) header. Individual patient consent was waived for this study.

Table 1
Mammography equipment information

Code	Make/model	Country of origin	Modality	Target/filter combination	Year of installation	Institution type
M1	Giotto	Italy	CR	Mo/Mo	2010	Government
M2	GE	USA	DR	Mo/Rh	2012	Government
M3	Philips	Netherlands	SF	Mo/Mo	2007	Private
M4	Lilyum/ Metaltronica	Italy	SF	Mo/Mo	2010	Private
M5	MOMMAT C/SIEMENS	Germany	CR	Rh/Al	2012	Private
M6	Lilyum/ Metaltronica	Italy	DR	Mo/Mo	2014	Private
M7	Philips	Netherlands	Dr	Mo/Mo	2014	Government
M8	OSH		Dr	Mo/Mo	2016	Government

In mammography, the radiation dose is determined in terms of the AGD, the recommended dosimetric quantitative value of interest for radiation risk assessments in mammography (NCRP 1987, 1996) [23].

AGD is estimated from the measurements of the entrance surface air kerma (ESAK) and conversion coefficients that depend on beam quality (half-value layer) [24, 25]. For each breast, the AGD is 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 beam half-value layer (HVL) and radiation output, were measured.

Determination of the Average Glandular Dose (AGD)

Average Glandular Dose (AGD) is the mean absorbed dose in the glandular tissue of the breast. Glandular tissue is the radiosensitive tissue of the breast, and therefore the AGD is recommended as a dose quantity of interest for radiation risk estimates in X-ray mammography (NCRP 1987, 1996) [23]. AGD is derived from measurements of the incident air kerma ( ) and applying conversion coefficients that depend on the radiation beam quality (HVL) determined by the anode /filter materials, breast thickness, and composition [24, 25]. AGD is estimated from the in a three-step process:

First, the normalized X-ray tube output, , is obtained of the incident air kerma ( ) measured at a 60 cm focus-to-detector distance (d) with the breast compression plate in position using calibrated dose rate meter type Piranha (RTI; Ballad, Sweden). is defined as the air kerma measured at a point at the radiation field the center at patient's entrance or phantom, excluding the backscattered radiation. The normalized X-ray tube output, , is thereafter determined according to Eq. 1.

1

Where is the air kerma measured using a range of the tube voltage and exposure-time current product (mAs) 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, patient incident air kerma was determined from the X-ray tube output, Y (d), corresponding to the specific kV value used during mammography corrected for the focal spot-to-surface distance, d_{FSD} , and mAs, according to Eq. 2:

2

AGD is then estimated from the measured values using conversion coefficients according to equations 3

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

Result

The results are presented for the 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 thickness used for the examinations. As shown, the exposure factors used kV and mAs across hospitals and ranged from 25.9–35.1 (average: 30.6) and 14.6–65.9 (average: 39.4), respectively. The mean compressed breast thickness (CBT) for the CC and MLO projections ranged from 29.0–42 mm (average: 37 mm) and 30–50 mm (average: 39 mm), respectively. All X-ray sets used the manual mode, with the beam quality selected by the technician. The selected tube voltage ranged from 23–36 kV. Figure 1. Shows the histogram of compressed breast thickness across the eight mammography devices; (a) CC view; (b) MLO view. As shown, BCT 40–45 cm have the highest frequency in both views.

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

Code	Age (y)	kV	mAs	BCT (mm) per view		The use of AEC
				CC	MLO	
M1	29	32	45	30	50	Manual
M2	27	29(26–31)	55(37–99)	48	54	AEC
M3	29	35 (32–35)	40(32–50)	35	45	Manual
M4	22	32 (28–35)	30 (25–40)	35	30	Manual
M5	30	29(22–32)	14(12–18)	40	50	Manual
M6	30	26 (24–27)	25	30	33	AEC
M7	30	33(32–35)	32	43	43	AEC
M8	50	29(27–33)	58(35–120)	40	42	AEC
Median	29	31	36	38	44	
^a Fixed kV and mAs were used for all patient irrespective of the CBT; ^b Fixed mAs values were used for all patient irrespective of the CBT;						

The automatic exposure control (AEC) was used only for center M2, and the range of mAs varied widely between 34 and 316 at this center. At center M1, the operator maintained the mAs at a value of 45, irrespective of breast thickness. At centers M3 and M4, the mAs were selected manually and ranged from 32–50 and 25–40 at each center, respectively. The highest mean mA value was 65 at mammography device M2. The lowest mean mA value was 31 at mammography device M4.

Table 3 presents the measured average kerma in the air and the calculated AGD for two views and 247 female patients at each mammography system (based on the measurement of 8 mammography devices). Figure 2 shows the boxplot distributions of the mean AGD at each hospital per CC and MLO projection. As illustrated, the AGD per CC and MLO projection and per woman ranged from 0.34–5.3 mGy (average: 2.46 mGy), 0.29–3.39 mGy (average: 1.50 mGy), and 0.6–7.4 mGy (average: 3.95 mGy), respectively.

Table 3

Median values for the air kerma and the calculated average MGD for two views and for 247 female patients for each mammography system (based on the measurement of 8 mammography systems)

Unit	N	HVL (mm Al _{eq})	Ki (mGy)	MGD (mGy) per projection		MGD (mGy) Per woman
				CC	MLO	
M1	50	0.38	0.20	2.90	1.7	4.60
M2	47	0.42	0.10	1.06	1.11	2.17
M3	43	0.42	0.23	2.42	1.97	4.39
M4	46	0.47	0.10	0.93	0.94	1.87
M5	44	0.21	1.25	0.33	0.30	0.63
M6	48	0.20	2.86	0.79	0.87	1.66
M7	50	0.39	0.18	1.10	1.10	2.20
M8	50	0.36	0.33	3.3	3.3	6.60
Median		0.39	0.22	1.08	1.11	2.19
First Quartile		0.32	0.16	0.90	0.92	1.82
Third Quartile		0.42	0.56	2.54	1.77	4.44
Interquartile ratio		1.3	3.5	2.8	1.9	2.4

In the present study, two hospitals (25%) presented doses that were higher than the established international DRLs. The ratio (max/min) of AGD was as high as 16 for CC projections and 12 for MLO projections per woman.

Discussion

Relationship between AGD and breast compressed thickness

Automatic exposure control in imaging adjusts exposure factors according to patient characteristics, such as the breast compressed thickness in mammography. In this regard, devices were of three types: devices where AEC control both kV and mAs (M2 & M8); devices that use the same mAs for all patients but kV is slightly varied (M6 & M7); devices with manual selection of both kV and mAs but use exposure charts (M3, M4 & M5); and hospital which used fixed exposure factors (M1) resulting.

Figure 3 presents the estimated Mean Glandular dose as a function of compressed breast thickness (CBT). Several authors studied the correlation between MGD and CBT in X-ray mammography to

investigate their influence in inpatient doses, showing a positive correlation between MGD and CBT [24, 25]. Figures 1a & b follow this pattern showing 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 are greatly affected by using AEC or manual settings during a particular X-ray procedure.

Dose optimization

As suggested in the literature, optimization is needed when typical patients' doses exceed the corresponding established DRLs or doses associated with significant variations that cannot be explained either among hospitals or individual patients. In X-ray mammography, AGD depends on several factors: (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). This study's correlation between MGD and CBT demonstrated the importance of using AEC in all mammography procedures. Furthermore, the AGD ratio (the maximum to minimum) among the studied eight centers were 16 and 12 in the CC and MLO views, respectively. Dose variations are clear evidence that radiation dose optimization is possible without risking the quality of diagnostic information.

As seen in Tables 2 and 3, high MGD is associated with high exposure and average breast thickness. Almost 7 out of the eight mammography devices used 28 kV or higher for their examinations. The use of high kV increases the beam penetrability and increases the spatial resolution required in mammography. Hospital M6 used the lowest tube voltage (25 kV), corresponding to the lowest average breast thickness (29 mm), contrasting the dose used at hospital M2, which corresponds to 52 mm. In general, mammography devices operate in an auto-filter mode, where the compressed breast thickness determines the kV and filter selection. The required tube current–exposure time was determined either via pre-exposure settings or by automatic exposure control, depending on device breast thickness. High MGD per woman is associated with high mAs values (M1 & M8) devices.

In contrast, the lowest doses have shown at devices M5, M6 & M7 correspond to the deployed lowest mAs. 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 craniocaudal view images was lower than that for the mediolateral oblique view because the thickness for CC images was lower than that for MLO images. Generally, MGD is higher in MLO view are attributed to greater inclusion of pectoral muscle in MLO view, which is denser and has higher attenuation and hence higher radiation dose.

Comparison with the literature

Table 4 presents a comparison of AGD values obtained in this study with the results in the literature [28–35]. The CC, MLO, and per-woman AGD values obtained in this study: 2.46 mGy, 1.5 mGy, and 3.95 mGy, respectively. These values can be compared to the results of a study by Moran et al., who reported the AGD for CC and MLO projections, and per woman, of 1.8 mGy, 1.95 mGy, and 3.7 mGy, respectively in Spain. In another study in Malaysia, the AGD was 1.54 mGy, 1.82 mGy, and 3.37 mGy, respectively. In contrast, Thiele et al. in Australia reported AGD values of 1.6 mGy and 4.6 mGy in per view and per

woman, respectively whereas Alizadeh in Iran the reported AGD values of 2.0 mGy, 2.4 mGy, and 4.4 mGy in CC, MLO, and per woman, respectively.

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

Data origin	Sample	Mean BCT (cm)	AGD (mGy)		Ref.
			Per view	Per woman	
Spain	5,034	52; 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:1.4; Mean CC:1.2 Mean MLO:1.5	Mean 2.7	[30]
Malta	759	57.51 CC:53.8 MLO63.4	Mean:1.07 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	2,910	61.4 CC:60.5 MLO:63	Mean CC:1.27 Mean MLO:1.34	Mean 2.61	[34]
Malaysia	300	41.0; CC:37.51 MLO:44.5	Median CC:1.44 Median MLO: 1.65	Median CC:3.37 Median MLO:3.21	[35]
1.1 Sudan	247	CC = 37.36 MLO = 39.18	Median: CC = 1.08 MLO = 1.11	Median 2.19	This study

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 CC and MLO projections, and per woman, respectively. This study reported an average breast thickness of 49.5 mm and 56.0 mm for CC and MLO projections,

respectively, compared to the average breast thickness of 37.6 mm and 39.2 mm. Several studies have shown that assuming comparable exposure factors, MGD increases with breast thickness. 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 low AGD of 2.13. Among the centers included in this study, the AGD per CC projection was higher than that presented for the MLO projection at six (75%) of the hospitals studied. Even there is 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]. The doses documented in this report are higher than the results of a study conducted by Baldelli in Ireland, who reported AGD values of 1.72 mGy, 1.34 mGy, and 2.61 mGy in CC and MLO projections, and per woman, respectively. The present study results are also higher than those reported in Malta and Greece (Table 4). From the obtained results, we propose that AGD values of 3.48 mGy, 2.03 mGy, and 6.44 mGy for CC and MLO projections, and per woman, respectively, be established as the NDRLs for Sudan. These represent the 75th percentile of the dose distributions of the mean hospital values. When compared with the other DRL values established in the literature, our values are comparable to those used in the United Kingdom (3.5 mGy) [37] and Belgium (2.46 mGy) [38].

Our study has its limitations. Due to the 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. This criterion was met in two hospitals, M7 & M8, mainly because the authors manually collected the data. Further, some difficulties were faced when obtaining these data, particularly for SF mammography, where patient exposure data were not archived.

Conclusions

This study revealed significant differences in radiation dose levels among 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 the AGD per CC and MLO projections in mammography, and per woman in the country. The average breast thickness reported in this study could be used as the standard breast thickness 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. The study provides an important baseline data for dose optimizations and setting National Diagnostic Reference Levels.

Declarations

Conflict of interest

The author has no conflict of interest to declare.

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Figures

Figure 1

histogram of compressed breast thickness across the eight mammography devices, (a) CC view , (b) MLO view

Figure 2

Mean Glandular dose as a function of compressed breast Thickness (CBT) (a) d) M4: Mo/Mo, SF, manual, (h) M8: Mo/Mo, Dr, AEC

Figure 3

presents the estimated Mean Glandular dose as a function of compressed breast thickness (CBT). Several authors studied the correlation between MGD and CBT in X-ray mammography to investigate their influence in inpatient doses, showing a positive correlation between MGD and CBT [24,25].