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Is digital mammography reducing radiation doses to women?

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Abstract: This study aims to investigate the impact of national quality programs in mammography and technological advances in digital mammography units on the radiation doses delivered to women in Brazil. Radiation dose assessments in mammography units were conducted through a mail-based dosimetric system. For each unit of facilities that applied to one of the two national quality programs, a postal dosimetric system is dispatched, comprising an optically stimulated luminescent dosimeter (OSL) attached to the surface of a 4.0 cm thick polymethyl methacrylate (PMMA) phantom, simulating a compressed breast with 4.5 cm thickness. Testing instructions to expose the dosimetric phantom for assessing the mean glandular dose (MGD) are provided. Between 2012 and 2023, the programs evaluated the MGD in 1,687 mammography units of computed radiography (CR) and direct digital radiography (DR) technologies from 1,399 facilities located in all Brazilian regions. A total of 1,660 (70.5%) evaluations were carried out on CR technology mammography units and 696 (29.5%) on DR units, totaling 2,356 MGD evaluations. The overall average MGD was 1.60 ± 0.80 mGy, with 1.68 ± 0.83 mGy for CR technology and 1.42 ± 0.68 mGy for DR technology. A comparison of average MGD between the periods 2012 - 2018 and from 2019 onwards shows a dose reduction of 8.6% for CR systems and of 26.0% for DR systems ($p = 0.000$). As CR systems use analog mammography units, which did not undergo technological advances between the two periods, the reduction in doses observed is due to the actions of national quality certification programs and by using image plates for dual-sided reading or needle-based image plates. The reduction observed in DR systems is due to both national quality programs and technological advances in mammography units, especially the use of radiation beams generated by X-ray tubes with tungsten targets.

Keywords: mammography, mean glandular dose, national programs.

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¿ Reduce la mamografía digital las dosis de radiación que reciben las mujeres?

Resumen: Este estudio tiene como objetivo investigar el impacto de los programas nacionales de calidad en mamografía y los avances tecnológicos en las unidades de mamografía digital en las dosis de radiación administradas a las mujeres en Brasil. La evaluación de las dosis de radiación en las unidades de mamografía se realizó mediante un sistema dosimétrico por correo. Para cada unidad de las instalaciones que aplicaron a uno de los dos programas nacionales de calidad, se envía un sistema dosimétrico postal, compuesto por un dosímetro de luminiscencia ópticamente estimulada (OSL) fijado a la superficie de un bloque de polimetacrilato de metilo (PMMA) de 4,0 cm de espesor, simulando una mama comprimida con 4,5 cm de espesor. Se proporcionan instrucciones de ensayo para exponer el maniquí dosimétrico con el fin de evaluar la dosis glandular media (DGM). Entre 2012 y 2023, los programas evaluaron la DGM en 1.687 mamógrafos de las tecnologías radiografía computarizada (CR) y radiografía digital directa (DR) de 1.399 establecimientos localizados en todas las regiones brasileñas. Un total de 1.660 (70,5%) evaluaciones fueron realizadas en unidades de mamografía de tecnología CR y 696 (29,5%) en unidades DR, totalizando 2.356 evaluaciones. La DGM media global fue de 1,60 ± 0,80 mGy, con 1,68 ± 0,83 mGy para la tecnología CR y 1,42 ± 0,68 mGy para la tecnología DR. La comparación de la DGM media entre los periodos 2012 -2018 y a partir de 2019 en adelante muestra una reducción de dosis del 8,6% para los sistemas CR y del 26,0% para los sistemas DR (p = 0,000). Como los sistemas CR utilizan mamógrafos analógicos, que no experimentaron avances tecnológicos entre los dos períodos, la reducción de dosis observada se debe a las acciones de los programas nacionales de certificación de calidad, a los sistemas de doble lectura de las placas de imagen y el uso de placas de imagen basadas en tecnología de agujas. La reducción observada en los sistemas de DR se debe tanto a los programas de calidad como a los avances tecnológicos en las unidades de mamografía, especialmente al uso de haces de radiación generados por tubos de rayos X con blancos de tungsteno.

Palabras clave: mamografía, dosis media glandular, programas nacionales.

1. INTRODUCTION

Mammography is the diagnostic imaging method used in breast cancer screening programs for asymptomatic women in many countries [1]. However, as exposure to X-ray from the examination is a known risk factor for breast cancer itself, it is important to monitor the radiation doses produced by the mammography units used in these programs [2, 3].

The dosimetric quantity associated with the risk of radio-induced breast cancer is the mean glandular dose (MGD), which is the energy absorbed per unit mass of fibroglandular tissue (the most radiosensitive tissue in the breast) averaged over all the fibroglandular tissue in the breast [4]. It is calculated from values of entrance air kerma ($K_{a,i}$), compressed breast thickness and glandularity, with corrections for the X-ray spectrum used. Routine measurements carried out periodically in mammography units are necessary to ensure that MGD tolerance levels are maintained for the various breast thicknesses and are consistent with the image quality required for the detection of breast lesions [4, 5].

Regarding X-ray units, for more than four decades, analogue 2D mammography systems, known as conventional or screen-film systems (SFS), have been used. Their radiation doses became a reference for digital systems that replaced them, both computed radiography (CR) and direct digital radiography (DR) [6-8]. Some advantages of digital systems are: the mathematical image processing, obtaining better quality images through post-processing tools integrated into the systems; the Digital Imaging and Communications in Medicine (DICOM) image extension, which has been established as a standard in medical imaging. It enabled the development of Picture Archiving and Communication System (PACS) which allows the interpreting physician to analyze the images in places physically different from where they were acquired and the use of computer-aided diagnosis software (CAD), as an auxiliary tool for diagnostic reporting [9,10].

More recently, DR systems have been upgraded with the replacement of X-ray tubes using molybdenum (Mo) and rhodium (Rh) targets by tubes with target-filter combinations of tungsten and rhodium (W/Rh), tungsten and silver (W/Ag) and tungsten and aluminum (W/Al), which are capable of operating at reduced doses [11].

Considering radiation risk control, mammography screening programs in several countries maintain databases for MGD monitoring [1]. Based on these records, studies are carried out on doses and technologies, estimates of radio-induced cancer and the risk-benefit analysis of screening. Loveland et al. [12], in 2022, using data from the National Health Service Breast Screening Programme (NHSBSP), provided a representative picture of two decades of dose records (1997-2019) from UK mammography services. They observed lower MGD in 2007-2009 triennium, due to digital DR systems. Hendrick [13], in 2020, using four-decade MGD record series (1974-2014) gathered by the Food and Drug Administration (FDA) from mammography services in the United States, showed the lower doses used by digital DR systems.

In Brazil, the Image Quality and Diagnostic Interpretation Information System of the National Cancer Institute (QIID/INCA) contains dose records from hundreds of mammography services in the country [14]. The doses are obtained from assessments carried out on mammography units by INCA's Mammography Quality Programme (PQM/INCA) in partnership with the Mammography Quality Certification Programme of the Brazilian College of Radiology and Diagnostic Imaging (PCQM/CBR), in the context of the National Mammography Quality Programme (PNQM) [15-17]. Based on the QIID/INCA records, Pinheiro et al. [18], in 2018, analyzed the MGD in 845 mammography units from 716 services in 279 cities between 2011 and 2016. They observed higher values in digital systems, compared to analogue SFS. They pointed out that this increase in doses was associated with the mammography units of the CR systems.

Given the increasing number of digital systems in operation and the lack of more recent data on MGD in the country, it is timely to carry out a study to update and analyze radiation doses in mammography. The present study analyzes the MGD behavior of digital systems between 2012 and 2023 aiming to investigate the impact of more modern systems on the doses received by women undergoing mammography.

2. MATERIALS AND METHODS

The term "evaluation" used in this work refers to the assessment of dose. The term "facility" pertains to the mammography service, "unit" refers to X-ray mammography equipment and technology refers to CR and DR digital systems. Data were gathered from dose assessments carried out by the PQM/INCA and PCQM/CBR quality programs on computerized digital (CR) and direct digital (DR) mammography units, registered on the QIID/INCA platform between 2012 and 2023. The dose assessment, data organization and analysis processes are described below.

2.1. Radiation dose assessments

Radiation dose assessment in mammography units is conducted through a mail-based system which evaluates the same parameters in both programs. The process starts with a facility's application to one of the two programs. Upon receipt of the application, the National Cancer Institute (INCA/MS) or the Brazilian College of Radiology and Diagnostic Imaging (CBR) initiates the first assessment step. For each unit, a postal dosimetric phantom is dispatched, comprising an optically stimulated luminescent (OSL) dosimeter attached to the surface of a 4.0 cm thick polymethylmethacrylate (PMMA) phantom, simulating a 4.5 cm compressed breast, considered, in this study, as a "standard breast". Upon receiving the material, the phantom is removed from its packaging (Figure 1a), placed on the mammography breast support tray, positioned for the craniocaudal view of the mammogram and exposed to X-rays in the automatic mode of the exposure control (Figure 1b). Considering that the phantom exposure for MGD measurement is performed unsupervised, detailed instructions are provided for this procedure using automatic exposure control. To ensure the reproducibility of the measurement across various services, it is required that, when performing the exposure, a radiographic image (Figure 1c) is simultaneously produced and sent to the programs, along with completed forms containing information about the radiographic techniques and equipment data [19].

Figure 1: Dosimetric phantom sent to facilities by the PQM/INCA and PCQM/CBR Programs.

1a 1b 1c

1a: Dosimetric phantom in the box.
1b: Phantom positioned on the mammography breast support tray.
1c: Phantom radiography showing the OSL dosimeter.

After conducting the tests, the facility returns the exposed dosimetric phantom, the radiographic film image and completed forms with exposure data for evaluation [19]. The dosimeter is read and the incident *air kerma* ($K_{a,i}$) quantity, in mGy, is obtained. Conversion coefficients provided by international mammography quality assurance protocols [4, 20] and by Dance et al. [8] are applied to $K_{a,i}$ to estimate the MGD in mGy. According to the Dosimetry in Diagnostic Radiology: An International Code of Practice, the estimated expanded uncertainty (k=2) for the MGD calculation is approximately 14.0% [7].

The estimated MGD is compared to the tolerance value of 2.0 mGy for a 4.5 cm thick compressed breast, established by Normative Instruction No. 92 of May 27, 2021, revised on July 6, 2022, of the National Health Surveillance Agency (ANVISA) [5]. In cases of non-compliance of the MGD with the tolerance value, the mammography quality programs issue recommendations to the facilities to carry out corrective actions, related to both operational procedures, for example, adjustments to radiographic techniques; as well as equipment, for example, adjustments or repairs to components of the mammography digitizer; and also to those related to the replacement of materials, for example, aged CR image plates or other elements of the image production chain. Once the corrections have been made, the facility requests a new material dispatch (dosimetric phantom, instructions and forms) for further exposure and MGD reassessment. Re-evaluations are possible until MGD compliance with the established tolerance value is achieved. After three years, the facility must renew the dose conformity assessment [21].

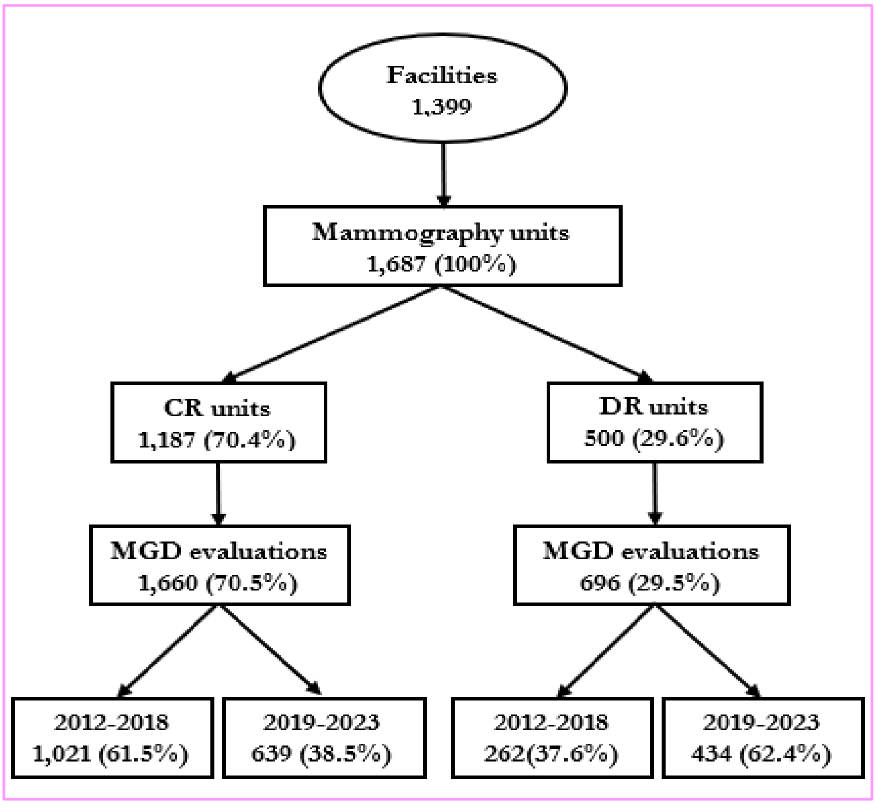
2.2. Data organization and analysis

The study data were gathered from QIID/INCA databases of dose evaluations conducted by the PQM/INCA and PCQM/CBR national quality programs between 2012 and 2023. During this period, 1,687 mammography units using CR and DR digital technologies from 1,399 services located in various regions of the country participated in the programs. Data from 2,356 evaluations were collected, considering that some mammography units were evaluated more than once due to corrections recommended by the programs or the need to renew the dose evaluation after the three-year period.

Dose assessment data were organized in Excel spreadsheets and categorized by their code number in the National Registry of Health Establishments (CNES); date of phantom exposure; manufacturer, model and year of installation of the mammography unit and CR digitizers; type of digital technology; radiographic exposure factors (kV, mAs, target/filter combination); and estimated MGD value. Average mean glandular dose ($\overline{\text{MGD}}$) was calculated for each year and technology, according to the statistical analysis to be carried out. It is important to note that the MGD estimate was used exclusively to compare technologies, since according to Kawaguchi et al. [22], doses obtained by exposure of a PMMA breast phantom may underestimate the doses in patients.

The distributions of $\overline{\text{MGD}}$ in CR and DR technologies were analyzed between 2012 and 2023 and two distinct periods were considered. The first one, between 2012 and 2018 and the second from 2019 to 2023. It was verified whether each technology contributed to the reduction in doses and the reasons that led to the reduction. When dose reductions were not observed, we also sought to identify their possible causes. The figures for the sample of facilities, mammography units and dose assessments that served as the basis for the study are shown in Figure 2.

Figure 2: Distribution of 2,356 mean glandular dose (MGD) evaluations for the standard breast of 4.5 cm thickness in 1,687 mammography units of 1,399 facilities according to the technologies (CR and DR) and the assessment periods (2012-2018 and 2019-2023).



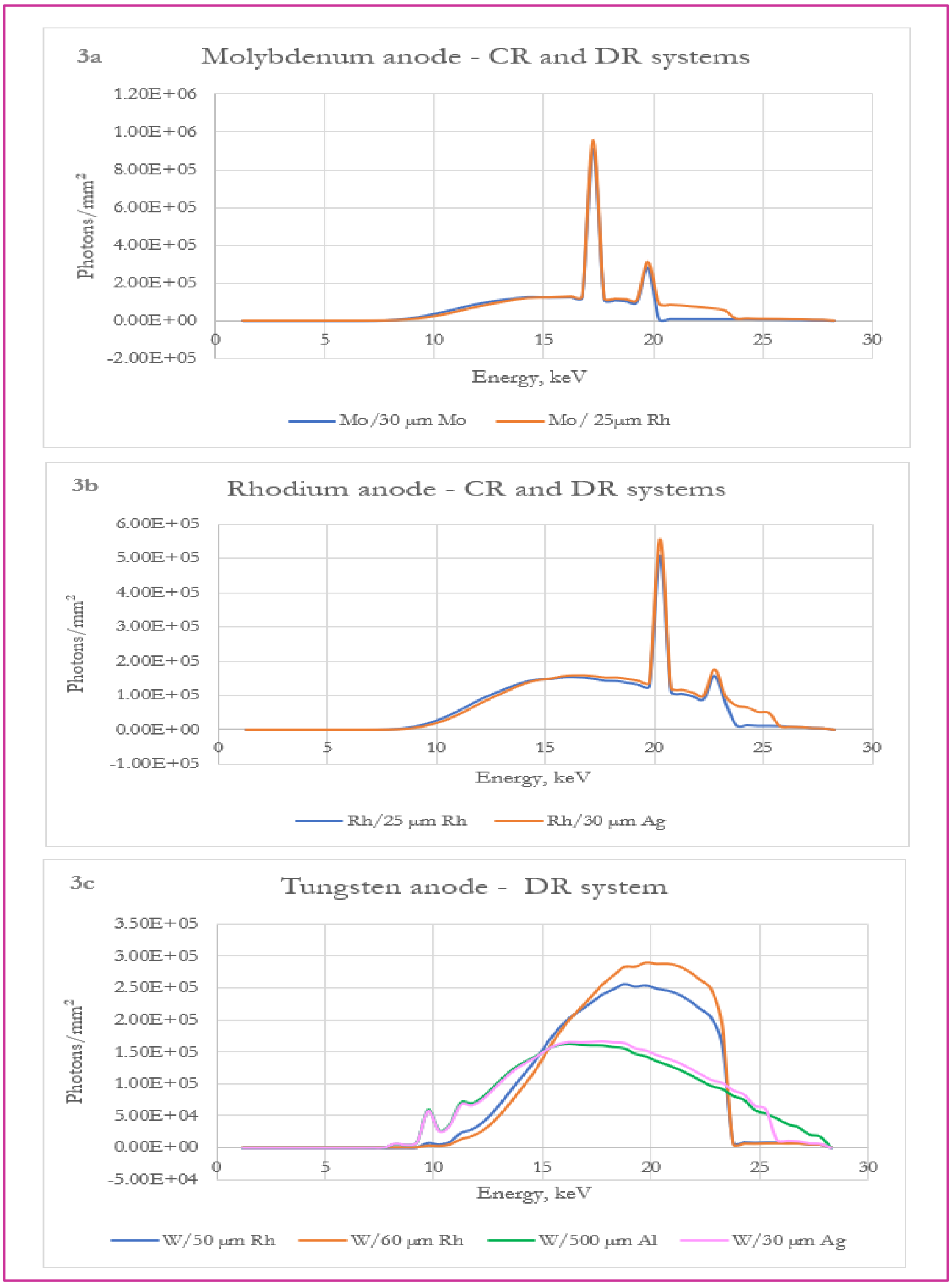
To analyze $\overline{MGD}$ behavior according to the X-ray spectra generated by the different target/filter combinations used to expose the phantom it was necessary to separate DR mammography units into two subgroups of technologies, called DR_L and DR_C. The DR_L subgroup includes DR units with molybdenum target X-ray tubes and molybdenum and rhodium filters (Mo/Mo and Mo/Rh) or rhodium target and rhodium filter (Rh/Rh), such as those used in CR technology, which generate characteristic line X-ray spectra, shown in Figures 3a and 3b. In addition to these combinations, some DR_L units use rhodium and silver (Rh/Ag) combination, which also generate line radiation spectra, shown in Figure 3b. The DR_C subgroup includes DR units with X-ray tubes that have a tungsten (W) target and rhodium (W/Rh), silver (W/Ag) or aluminum (W/Al) filters. They generate continuous and higher energy radiation spectra which produce more penetrating X-ray beams than tubes with Mo and Rh targets, as shown in Figure 3c.

The $\overline{MGD}$ were calculated for the various types of system, according to their model and manufacturer. CR digitizer units include models from Agfa, Carestream/Kodak, Fuji, Konica Minolta and a created "NI" (not informed) category. DR mammography units (DR_L and DR_C) include models from General Electric, Hologic/Lorad, Siemens, Fuji, Philips/VMI and "Other", a category created for conventional mammography units retrofit systems which use slim mammography cassettes with flat-panel digital X-ray detectors.

The MGD above the tolerance value were organized by year and technology to investigate whether recommendations issued by national mammography quality programs had an impact on their reduction.

Statistical analyses used SPSS Statistics for Windows, version 17.0 (SPSS Inc., Chicago, Ill., USA) and graphs using Microsoft Excel (2016). The $\overline{MGD}$ data set for CR and DR, over 2012 to 2023, were of different sizes due to the incorporation of DR units with breast tomosynthesis platform (DBT), replacing those with CR technology. In addition, data did not have normal distributions and, in many cases, unequal variances. Due to these violations for the use of Student's T-test, comparisons between $\overline{MGD}$ for CR and DR technologies (DR_L and DR_C) were carried out using Welch's ANOVA test. When sample sizes and variances are equal between data sets, Welch's T-test is equivalent to Student's T-test.

Figure 3: X-ray spectra used in digital mammography.



3a: CR and DR_L systems; 3b: CR and DR_L systems; 3c: DR_C system.

Levene's test was used to test for equal sample variances. In 2012 and 2013, the number of mammography units in the DR_C subgroup was less than five, so the non-parametric Kruskal-Wallis test was used to compare the $\overline{MGD}$ between CR and DR_L technologies.

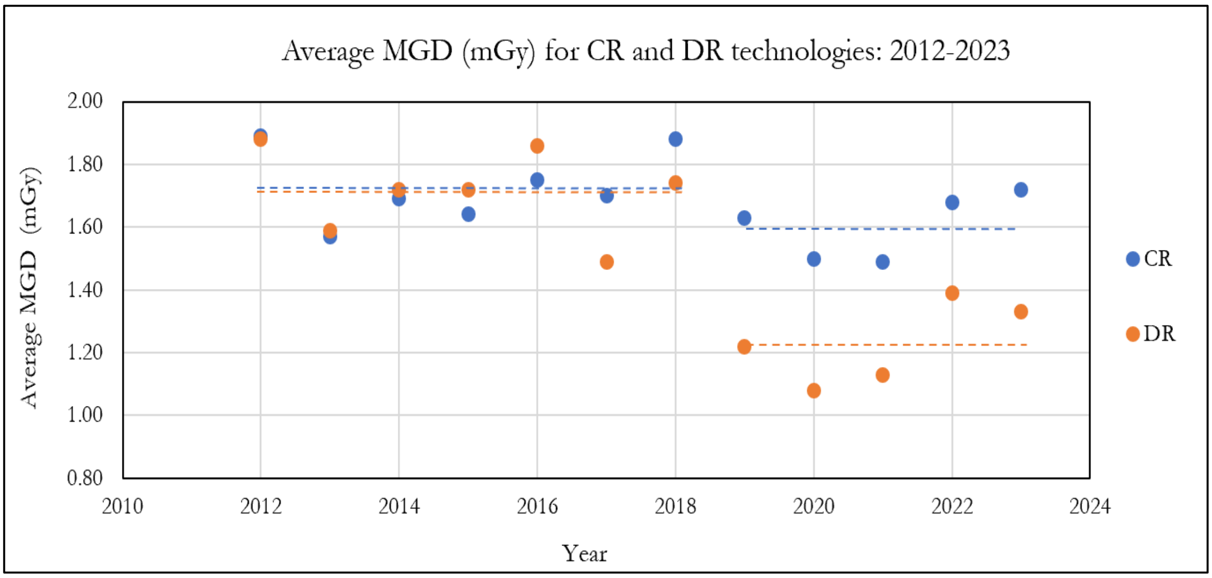
3. RESULTS AND DISCUSSIONS

The sample of 1,687 mammography units of this study represented 26.8% of the 6,305 units in use in 2023 in Brazil [23]. Therefore, this study on the impact of digital technologies on doses to women used a representative sample of country's mammography technology park.

Based on 2,356 doses estimated for the standard breast, the overall $\overline{MGD}$ was 1.60 ± 0.80 mGy. The MGD range for CR technology was 0.32 mGy to 14.83 mGy, with $\overline{MGD}$ of 1.68 ± 0.83 mGy and for DR technology, the range was 0.30 mGy to 7.96 mGy, with $\overline{MGD}$ of 1.42 ± 0.68 mGy. A statistically significant reduction of 15.6% was observed between the $\overline{MGD}$ of these two technologies ($p = 0.000$).

Figure 4 presents an overview of the $\overline{MGD}$ behavior for the standard breast in both technologies in two periods between 2012 and 2023, showing a dose reduction in the second period from 2019 onwards, which was statistically significant in the $\overline{MGD}$ of both technologies. For CR systems, the reduction in $\overline{MGD}$ was 8.6% and for DR systems 26.0% ($p = 0.000$). Regarding CR systems, as they use analog mammography units, which did not undergo technological advances between the two periods, the reduction in doses observed is due to the actions of national quality certification programs and by using image plates for dual-sided reading or needle-based image plates. However, for DR units, in addition to the actions of quality programs, the dose reduction in the second period may be attributed also to the introduction of new mammography units with breast tomosynthesis technology. They use more penetrating X-ray beams and consequently deliver lower radiation doses to women.

Figure 4: Average mean glandular dose ($\overline{MGD}$) for the standard breast for digital technologies CR and DR – Brazil, 2012 - 2018 and 2019 - 2023.



In the first period, 2012-2018, there was no statistically significant difference between the $\overline{MGD}$ of CR systems, 1.74 ± 0.77 mGy and DR systems, 1.69 ± 0.83 mGy, (p = 0.406), which was similar to the results of Pinheiro et al. [18] between 2011 and 2016. As of 2019, there was a significant difference between the two technologies, showing the $\overline{MGD}$ of DR systems, 1.25 ± 0.50 mGy, 21.1% lower than that of CR systems, 1.59 ± 0.91 mGy (p=0.000). Therefore, over the past five years, DR mammography units in facilities enrolled in national mammography quality programs have offered significantly lower doses to screened women compared to CR units. There was also a 65.6% increase in the participation of DR systems and a 37.4% reduction of CR systems in national quality programs, which shows a positive trend towards dose reduction in the country.

National studies on mammography doses, such as those by Young and Oduko [24] and Oduko et al. [25] in the UK; Yaffe et al. [26] in Canada; Hendrick [13] in the United States; Timmermans et al. [27] in Belgium; and Mora et al. [28] in Costa Rica, which involved doses from several Latin American countries, including Brazil, already showed results in the same direction. The $\overline{\text{MGD}}$ of DR systems in the second period was similar to that obtained by Loveland et al. [12] in the UK digital mammography, between 2016 and 2019.

Over a decade ago, McCullagh et al. [29] observed that DR systems present differences in technical aspects that affected dose, notably the type of image detector and the target/filter combination used to generate the X-ray beams. In this context, Table 1 shows the number of evaluations per year and the respective $\overline{\text{MGD}}$ for each technology, with DR subdivided into the DR_L subgroup, whose anode/filter combinations generate X-ray line spectra, and DR_C subgroup, whose anode/filter combinations generate continuous X-ray spectra, shown in Figure 3. For the total number of digital mammography units evaluated, there was no significant difference between $\overline{\text{MGD}}$ of CR and DR_L systems (p=0.199), but between these and the $\overline{\text{MGD}}$ of DR_C systems, there were statistically significant differences, showing a reduction of 26.2% compared to the CR and 23.5% compared to the DR_L (p=0.000).

During the first period, from 2012 to 2018, there was no statistically significant difference between the $\overline{\text{MGD}}$ of the three different systems: CR with 1.74 ± 0.77 mGy, DR_L with 1.77 ± 0.89 mGy, and DR_C with 1.54 ± 0.67 mGy (p=0.052). In the second period, from 2019 to 2023, there were no significant differences between the $\overline{\text{MGD}}$ of CR systems with 1.59 ± 0.91 mGy and DR_L systems with 1.45 ± 0.58 mGy (p=0.108). However, between these and the $\overline{\text{MGD}}$ of DR_C systems with 1.13 ± 0.40 mGy, there were statistically significant differences, showing a reduction in doses for DR_C by 28.9% compared to CR and by 22.1% compared to DR_L systems (p=0.000). These results demonstrate the strong influence of DR_C systems, which use anode/filter combinations of W/Rh, W/Ag and W/Al, in reducing doses in mammography. In the second period there was a 194.6% increase in the participation of these systems, which makes it clear that the reduction in doses observed in DR systems (Figure 4) occurred in those with W target X-ray tubes and not in all DR systems evaluated.

Table 1: Number of evaluations (N) and average mean glandular dose ($\overline{MGD}$) to the standard breast as a function of digital technologies CR, DR_L and DR_C by year - Brazil, 2012 - 2018 and 2019 - 2023.

YEAR	EVALUATIONS (N), $\overline{MGD}$ ± SD, AS A FUNCTION OF TECHNOLOGY AN TARGET/FILTER COMBINATION					
	CR		DR_L		DR_C	
	N	$\overline{MGD}$ ± SD (mGy)	N	$\overline{MGD}$ ± SD (mGy)	N	$\overline{MGD}$ ± SD (mGy)
2012	111	1.89 ± 0.77	12	1.93 ± 0.90	1	1.24
2013	86	1.57 ± 0.64	10	1.71 ± 0.27	2	1.00 ± 0.17
2014	118	1.69 ± 0.67	14	1.75 ± 0.26	6	1.66 ± 0.17
2015	191	1.64 ± 0.65	26	1.57 ± 0.64	3	1.15 ± 0.25
2016	124	1.76 ± 1.07	38	2.05 ± 1.49	19	1.48 ± 0.76
2017	197	1.70 ± 0.72	27	1.46 ± 0.47	25	1.52 ± 0.57
2018	194	1.88 ± 0.77	43	1.83 ± 0.60	36	1.64 ± 0.74
2019	144	1.63 ± 0.89	36	1.32 ± 0.49	36	1.12 ± 0.41
2020	122	1.50 ± 1.41	22	1.29 ± 0.27	44	0.98 ± 0.40
2021	172	1.49 ± 0.62	31	1.31 ± 0.44	51	1.02 ± 0.32
2022	96	1.68 ± 0.70	44	1.64 ± 0.85	82	1.25 ± 0.33
2023	105	1.72 ± 0.68	30	1.61 ± 0.27	58	1.18 ± 0.49
Total	1,660	1.68 ± 0.83	333	1.62 ± 0.77	363	1.24 ± 0.52

CR : Target/filter combinations Mo/Mo, Mo/Rh and Rh/Rh.

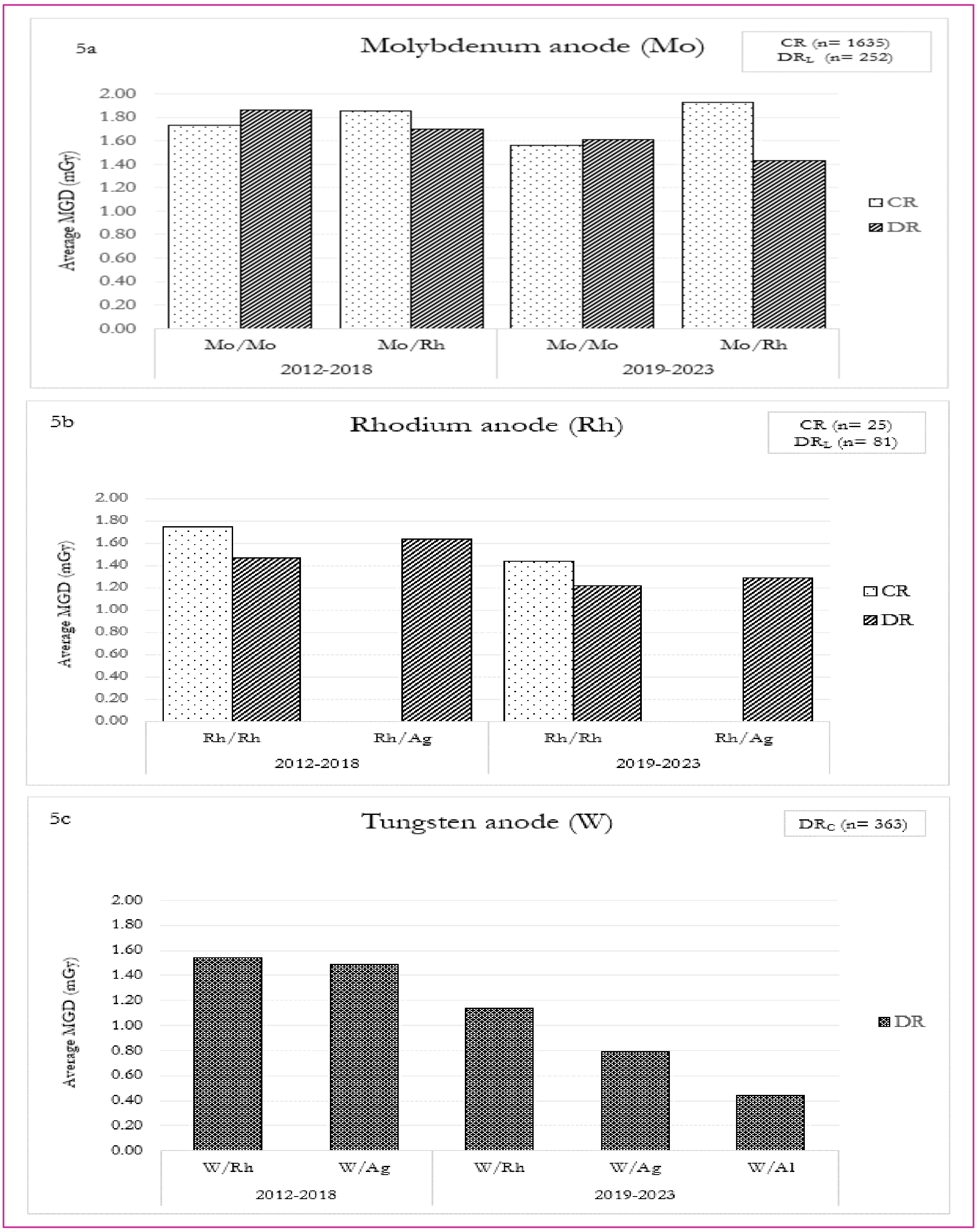
DR_L : Target/filter combinations Mo/Mo, Mo/Rh, Rh/Ag and Rh/Rh.

DR_C : Target/filter combination W/Ag, W/Rh and W/Al.

Figure 5 shows $\overline{MGD}$ for the standard breast, according to the anode/filter combination of the mammography units in each period. Considering the $\overline{MGD}$ evaluations of each technology, the Mo/Mo combination was used in 89.5% of CR systems and in 56.5% of DR_L systems. In old mammography units, this combination was the only available in most X-ray tubes of analog systems [30].

Regarding CR digital mammography, all 1,660 radiation dose evaluations were done using Mo/Mo, Mo/Rh or Rh/Rh target/filter combinations. None of them used the exposure technique with the W/Al target/filter combination. Consequently, less penetrating X-ray beams are produced with these target/filter combinations.

Figure 5: Average mean glandular dose ($\overline{MGD}$) for the standard breast in digital mammography, according to the technology and target/filter combinations used in the exposure of the dosimetric phantom - Brazil, 2012-2018 and 2019 - 2023.



CR systems have difficulty producing images that meet the minimum CNR requirements for compressed breasts thicker than 6.0 cm while maintening MGD tolerance levels established in Brazilian legislation and international mammography quality assurance protocols [5, 20, 31]. Therefore, optimizing radiographic techniques using Mo/Mo, Mo/Rh or Rh/Rh target/filter combinations is the only tool for reducing doses in CR units.

The $\overline{MGD}$ of CR systems operating with Mo/Mo, Mo/Rh and Rh/Rh are shown in Figures 5a and 5b. The statistical comparison between the $\overline{MGD}$ of the two periods showed a reduction of only 9.8% in doses of mammography units operating with the Mo/Mo combination. For the other target/filter combinations, there was no statistically significant reductions between the two periods. For DR_L systems, there was also no statistically significant difference between the $\overline{MGD}$ of the two periods for any target/filter combination.

The W/Rh anode/filter combination was used in 97.5% of the DR_C systems. Figure 5c shows that, for this combination, there was a statistically significant difference of 24.0% in the $\overline{MGD}$ from the first to the second period. The W/Ag anode/filter combination was used in 1.7% of these systems and the $\overline{MGD}$ in the two periods were 1.49 ± 0.17 mGy and 0.79 ± 0.15 mGy. The W/Al combination had the lowest participation, 0.8% of DR_C, but with the lowest $\overline{MGD}$ in the last five years, 0.44 ± 0.08 mGy.

Bearing in mind that each new model of mammography unit launched by a manufacturer introduces technical changes, Table 2 shows the $\overline{MGD}$ for various models of CR digitizers and DR mammography units from various manufacturers. An ANOVA comparison of the $\overline{MGD}$ between the most used CR models in Brazil, from Agfa, Carestream/Kodak, Fuji, Konica Minolta and a fifth set of "not informed" models (NI), showed no statistically significant difference ($p = 0.186$).

Table 2: Number of evaluations (N) and average mean glandular dose ($\overline{MGD}$) to the standard breast as a function of manufacturers and models of CR, DR_L and DR_C units - Brazil, 2012 - 2023.

SYSTEM	MANUFACTURER	PROCESSING UNIT MODEL	N (%)	$\overline{MGD}$ ± SD (mGy)
CR	Agfa	CR DX-M; 30-Xm; 35X; 85X; CR 75	384 (23.1)	1.67 ± 0,70
	Carestream/Kodak	CR 850; 975; Classic; Elite; Max	615 (37.1)	1.70 ± 0.92
	Fuji	Capsula; Console; IR 392, 364, 368; Profect CS	448 (27.0)	1.72 ± 0.84
	Konica Minolta	Regius 110 HQ	80 (4.8)	1.59 ± 0.73
	NI		133 (8.0)	1.54 ± 0.71
	Subtotal		1,660 (100)	1.68 ± 0.83
DR	**MANUFACTURER**	**X-RAY UNIT MODEL**		
DR_L	Fuj	Amulet	25 (7.5)	1.34 ± 0.50
	General Eletric	Senographe Pristina	48 (14.4)	1.34 ± 0.42
		Senographe Essential	47 (14.1)	1.37 ± 0.41
		Senographe DS	10 (3.0)	1.25 ± 0.63
		Senographe 2000D	9 (2.7)	1.44 ± 0.38
	Hologic/Lorad	Selenia	164 (49.2)	1.85 ± 0.86
	Siemens	Mammomat Inspiration	21 (6.3)	1.31 ± 0.45
	Other	Sistema Retrofit	9 (2.7)	1.69 ± 1.12
	Subtotal		333 (100)	1.62 ± 0.77
DR_C	Fuji	Amulet Innovality	38 (10.5)	1.33 ± 0.27
	General Eletric	Senographe Crystal	19 (5.2)	1.19± 0.31
	Hologic/Lorad	Dimensions	191 (52.6)	1.36 ± 0.55
	Siemens	Mammomat Fusion	43 (11.8)	1.02 ± 0.34
		Mammomat Inspiration	55 (15.2)	1.00 ± 0.43
		Mammomat Revelation	11 (3.0)	0.88 ± 0.26
	Philips/VMI	Digimamo and Graph Mamo	3 (0.8)	0.85± 0.22
		MicroDose	3 (0.8)	0.44 ± 0.08
	Subtotal		363 (100)	1.24 ± 0.52
All			2,356	1.60 ± 0.80

NI: manufacturer of the mammography unit not informed.

For the various models of DR_L mammography units, the ANOVA showed that in this technology there are two homogeneous subgroups regarding the equality of $\overline{MGD}$. One is made up of the Amulet/Fuji, the Inspiration - Mo target/Siemens and the Senographes Pristina, Essential, DS and 2000D/GE units. This subgroup delivers lower $\overline{MGD}$ to women when compared to the other subgroup made up of the Selenia/Hologic and the set of "other" models/manufacturers. The same statistical analysis also found two homogeneous subgroups for DR_C mammography. One is made up of the Amulet Innovality/Fuji and Dimensions/Hologic and other, with lower doses made up of the Mammomats Revelation, Inspiration and Fusion/Siemens and Senographe Crystal/GE.

The UK's National Health Service Breast Screening Program (NHSBSP) has published technical evaluation reports on how well mammography systems meet the program's compliance standards. These reports present MGD values used to produce image quality of satisfactory level of contrast to noise ratio (CNR) for the standard breast. In relation to DR systems, the MGD for Amulet/Fuji was 0.97 mGy [32]; for recent version Dimensions/Hologic was 1.00 mGy and for previous versions it was 1.19 mGy [33-35]; and for Senographe Pristina/GE was 1.13 mGy [36]. When compared with $\overline{MGD}$ for these units presented in Table 2, it can be seen that, although a reduction in mammography doses was observed in the present study, it is still possible to optimize the radiographic techniques and image processing in some facilities aiming dose reduction. The same situation occurs in relation to the MGD of CR mammography systems.

Given the increasing number of DR systems with new technologies for breast tomosynthesis, this study provides reference values for local MGD for the standard breast to be adopted by services using these and old technologies, the so-called "*Local Diagnostic Reference Levels - DRLs*" [37]. Table 3 shows standard breast local DRLs for DR systems by equipment manufacturer and model. For the Philips DR_C systems, the small number of units evaluated, mad it impossible to establish DRL. For the CR systems, it was found that the DRL of 2.0 mGy is the one that best applies.

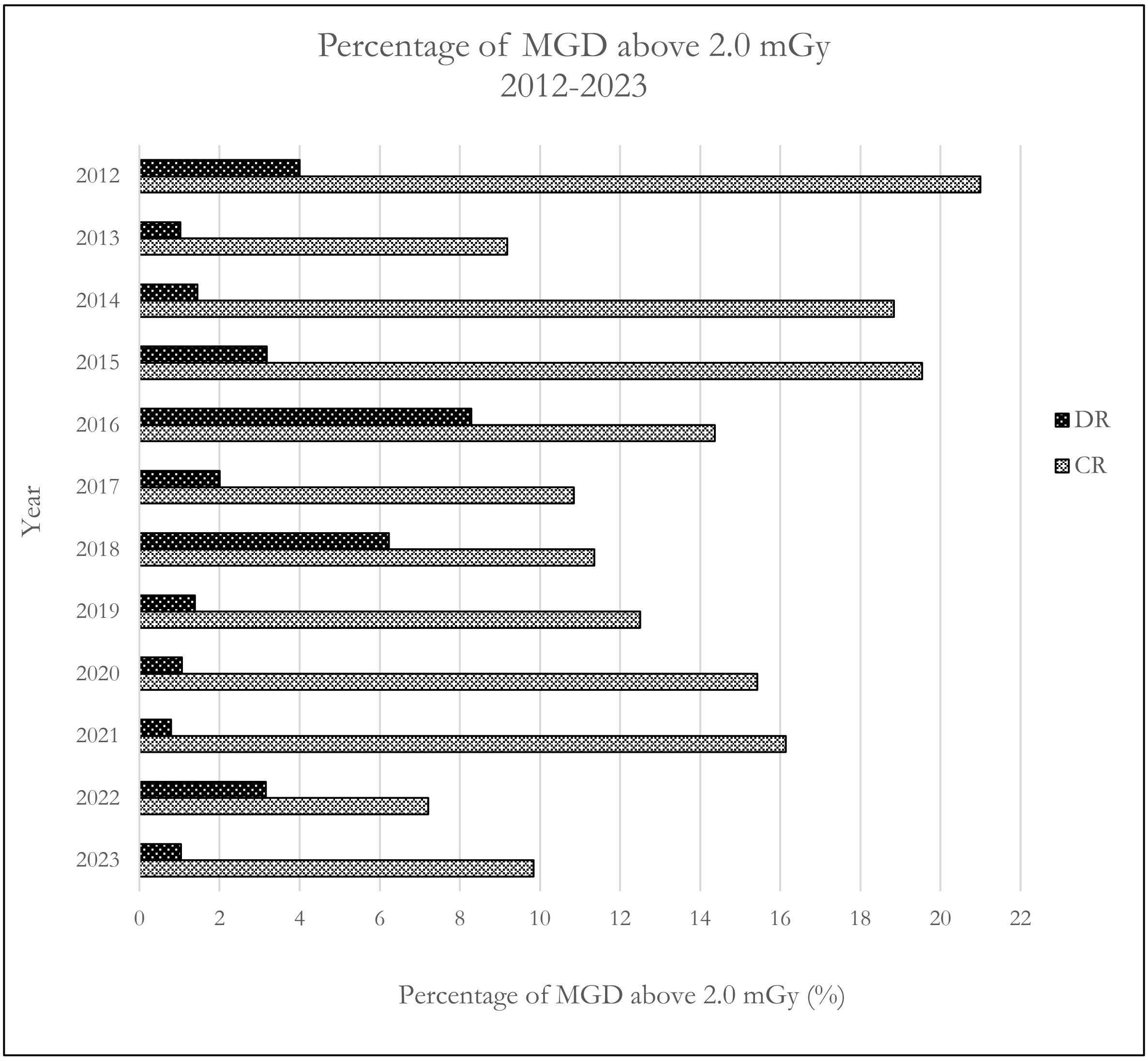
Table 3: Local Dose Reference Level -DRL to the standard breast as a function of manufacturers and models of DR_L and DR_C units - Brazil.

SYSTEM	MANUFACTURER	PROCESSING UNIT MODEL	DRL (mGy)
DR_L	Fuj	Amulet	1.6
	General Eletric	Senographe Pristina	1.5
		Senographe Essential	1.7
		Senographe DS	1.6
		Senographe 2000D	1.5
	Hologic/Lorad	Selenia	2.0
	Siemens	Mammomat Inspiration	1.6
	Other	Sistema Retrofit	2.0
DR_C	Fuji	Amulet Innovality	1.5
	General Eletric	Senographe Crystal	1.4
	Hologic/Lorad	Dimensions	1.5
	Siemens	Mammomat Fusion	1.1
		Mammomat Inspiration	1.2
		Mammomat Revelation	1.0

Figure 6 shows the percentage of MGD above the tolerance value of 2.0 mGy, for each technology and year. Of the 2,356 dose assessments between 2012 and 2023, there were 388 (16.5%) above this value, 320 (82.5%) for CR systems and 68 (17.5%) for DR systems. The highest rates of non-compliance of MGD occurred in CR systems, notably in 2012. In this year, was published the Ministry of Health Ordinance that created the National Quality Program in Mammography (PNQM) [38], which certainly motivated the registration of new services not previously evaluated by quality programs in mammography.

Among the 68 non-compliances of DR systems, 51 (75.0%) were for DR_L technology and 17 (25.0%) for DR_C. Despite the increasing participation of DR_C units in the second period, 12 non-compliances in MGD (70.6%) occurred in the first period (2012-2018) of this study.

Figure 6: Non-compliance rate of MGD above the tolerance value of 2.0 mGy in CR and DR mammography units, by year – Brazil, 2012 - 2023.



Finally, not only the reduction over time in non-compliance rates with tolerance value but also in the MGD delivered to women undergoing mammography screening may be attributed to the actions of the PQM/INCA and PCQM/CBR national programs of quality in mammography.

4. CONCLUSIONS

This study demonstrates that national mammography quality programs and technical advances in digital mammography units reduced radiation doses delivered to women in Brazil, between the periods 2012 - 2018 and 2019 - 2023. This reduction was, on average, 8.6% for CR systems and 26.0% for DR systems. As CR systems use analog mammography units, which did not undergo technological advances between the two periods, the reduction in doses observed is due to the actions of national quality certification programs and the use of image plates for dual-sided reading or needle-based image plates. The reduction observed in DR systems is due to both quality programs and technical advances in mammography units. Notably, the use of radiation beams generated by X-ray tubes with tungsten targets, which produce more penetrating X-ray beams and, consequently, deliver lower doses in the glandular breast tissue with image quality of satisfactory level for radiological interpretation. This study also demonstrates that the reduction in doses observed in DR systems occurred only in those with tungsten target X-ray tubes and not in all DR systems evaluated.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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