

Scientific Paper

Comparing eDQE and eNEQ metrics – is there an alternative approach to assessing image quality in digital mammography?

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Abstract

Introduction: Early detection of breast cancer requires high-quality mammographic images that have been made possible by the introduction of new technologies, such as full-field digital mammography (FFDM). In this new study, we perform extended measurements to calculate effective detective quantum efficiency (eDQE) and introduce effective noise equivalent quanta (eNEQ). Our aim was to show how these two metrics relate to the image quality of two digital mammography systems.

Material and methods: Measurements were performed for a Siemens Mammomat Inspiration and a GE Senographe Pristina system. Each was equipped with an automatic exposure control (AEC) for use in a clinical setting. We used a polymethyl methacrylate (PMMA) phantom at thicknesses of 20, 30, 40 and 70 mm to cover the range of scatter conditions expected in mammography, with and without an anti-scatter grid. The Siemens system had an a-Se detector, and the GE system had an indirect-conversion detector. Measurements of Kerma were performed with Piranha Black 657 meter (RTI Electronics AB). The majority of our calculations were automated, using a modified version of our software.

Results: For the two mammographic systems evaluated, we characterized physical quality parameters, such as effective modulation transfer function (eMTF), effective normalized noise power spectrum (eNNPS), eDQE and eNEQ for a wide range of exposures, phantom thicknesses, with and without an anti-scatter grid. Results are presented as a function of spatial frequency. A contrast-detail analysis was performed with a CDMAM 3.4 phantom with dedicated software (CDMAM analysis 1.5.5, NCCPM) and a set of different PMMA phantoms.

Conclusions: We successfully demonstrated that the eNEQ metric can be used as a new option to evaluate image quality for images taken with and without a grid and with phantoms of different thicknesses for the Siemens and GE systems. These results were consistent with the results obtained from CDMAM.

Keywords: image quality; digital mammography; effective detective quantum efficiency; effective noise equivalent quanta.

Introduction

Early detection of breast cancer requires high-quality mammographic images that have been made possible by the introduction of new technologies, such as full-field digital mammography (FFDM). In Poland, the use of FFDM has increased rapidly in recent years.¹

In our previous studies, we attempted to improve the measurement and calculation of detective quantum efficiency (DQE) for a mammography system.^{2,3} In this new study, we extended our measurements to include effective detective quantum efficiency (eDQE) and introduce effective noise

equivalent quanta (eNEQ) in order to show how these two metrics relate to the image quality of two AEC-equipped digital mammography systems working in a clinical setting. We quantify the influence of the anti-scatter grid on eDQE and eNEQ and relate it to contrast detail characteristics obtained using CDMAM, the contrast-detail phantom for mammography.⁴⁻⁶

The digital image obtained by FFDM is composed of a finite number of points (pixels). The brightness of each pixel is described by a specific numerical value and there is a linear relationship between radiation dose and signal intensity. Using a computer, it is possible to improve the digital image to obtain

better diagnostic information, as well as to transfer or store images using mass data storage techniques.

One of the main components of FFDM technology is an automatic exposure control (AEC) system. The AEC system measures how much radiation the image receptor gets and cuts off X-ray production when the detector has received sufficient exposure. AEC also selects optimal settings for tube/filter (T/F) combination, tube potential (kV), and exposure time based on pre-measured breast thickness. Modern AEC software offers combined factors that optimize the image (contrast-to-noise ratio) at a low patient dose as specified by diagnostic protocols. We performed these evaluations on two FFDM units currently used at the Warsaw Oncological Centre: a Siemens Mammomat Inspiration and a GE Senographe Pristina. The two units differ with respect to their detectors and anti-scatter grids, their AEC systems and the subsequent choice of T/F combination, tube potential and mAs for clinical exposure.

Image quality parameters included modulation transfer function (MTF), noise power spectrum (NPS), noise equivalent quanta (NEQ) and detective quantum efficiency (DQE), all of which describe aspects of detector imaging performance.⁷ Generalized image quality metrics, which include the influence of scattered radiation in an object, geometry magnification, focal spot blur and presence of an anti-scatter grid have been developed as components of both effective DQE (eDQE)^{8,9} and generalized DQE (gDQE)^{10,11}. Calculation of eDQE is based on the MTF and NPS parameters measured in images acquired with primary and scattered radiation. Samei^{8,9} and Bertolini et al.¹² calculated eDQE for digital radiography systems and Salvagnini et al.^{13,14} calculated it for mammography systems. Salvagnini also attempted to describe the optimization of a

mammography system by dividing its eNEQ parameter by the mean glandular dose (MGD) that it delivered.

The work presented here was performed within the AEC parameters suggested and chosen by the manufacturers of the two systems we evaluated. We calculated eDQE and eNEQ for the same exposure conditions. To confirm the relationship between analyzed metrics and image quality, we compared them to Predicted Human Gold Thickness, the parameter used in the CDMAM Phantom.

Materials and Methods

Mammography imaging systems and Phantom exposures

The two mammography systems used in this study (Siemens and GE) are described in **Table 1**. For the exposures studied, the AEC systems for each unit were set in the mode that is used in clinical examinations. Anode/filter combination, tube potential (keV) and exposure level (mAs) are listed in **Table 2**. All measurements were performed for polymethyl methacrylate (PMMA) phantom thicknesses: 20, 30, 40 and 70 mm, covering the range of scatter conditions expected in mammography.

Effective detective quantum efficiency (eDQE) and effective noise equivalent quanta (eNEQ)

Effective detective quantum efficiency⁹ was measured and calculated for all T/F combination for the four Phantom thicknesses. AEC selected tube voltage for each thickness (**Table 2**).

Table 1. Parameters of used mammography units

Unit name	Conversion type	Detector material	Pixel spacing [μm]	Anode/filter combination used clinically	Grid type	Grid strip density
Siemens Mammomat Inspiration	direct	a-Se	85	W/Rh	Linear with ratio5:1, lead septa	31 lines/cm
GE Senographe Pristina	indirect	a-Si with CsI scintillator	100	Mo/Mo Rh/Ag	Linear, lead septa	67 lines/cm

Table 2. PMMA thickness, tube potential, T/F combination, mAs, MGD used for Siemens and GE systems working with and without the grid, maximum average glandular dose to equivalent breast²⁰

System	PMMA thickness [mm]	Beam quality [kV]	T/F	Exposure level [mAs]		MGD [mGy]		Maximum average glandular dose to equivalent breast [mGy]	
				Without grid	With grid	Without grid	With grid	acceptable	achievable
Siemens	20	26	W/Rh	20.6	34.4	0.24	0.40	<1.0	<0.6
	30	27		31.9	52.1	0.337	0.550	<1.5	<1.0
	40	28		44.1	77.2	0.432	0.756	<2.0	<1.6
	70	32		83.8	190.1	0.80	1.81	<6.5	<5.1
GE	20	26	Mo/Mo	8	16	0.203	0.418	<1.0	<0.6
	30	26		18	37.2	0.347	0.718	<1.5	<1.0
	40	34	Rh/Ag	11	22.3	0.482	0.976	<2.0	<1.6
	70	34		36	72.1	1.063	2.128	<6.5	<5.1

Calculations were performed according to the **Equation 1**:

$$eDQE(u') = \frac{eMTF(u')^2(1-SF)^2}{eNNPS(u') \cdot TF \cdot E_0 \cdot q} \quad \text{Eq. 1}$$

where:

$eMTF$ is the effective modulation transfer function;

SF is the scatter fraction;

$eNNPS$ is the effective normalized noise power spectrum;

TF is the narrow beam transmission factor of PMMA;

E_0 is the pre-phantom exposure corrected at the detector plane; and

q is the number of photons per μGy per unit area.

$$u' = u \cdot m \quad \text{Eq. 2}$$

u' is the spatial frequency corrected to the object plane, u is the spatial frequency at the detector plane, and m is the magnification factor.

Effective noise equivalent quanta have been calculated as follows:

$$eNEQ(u') = eDQE(u') \cdot (TF \cdot E_0 \cdot q) = \frac{eMTF(u')^2(1-SF)^2}{eNNPS(u')} \quad \text{Eq. 3}$$

In practice, major part of calculations were automated by using modified version of our software.³

Effective pre-sampling modulation transfer function eMTF

The “free-air” method introduced by Salvagnini¹³ was used for eMTF evaluation. The test device (a 1 mm thick stainless-steel plate with 2° angled polished edges) was placed on support blocks above the detector at different heights to correspond with the PMMA phantom’s thicknesses, without scattering material in the beam. This approach was taken in order not to overestimate the influence of scattered radiation. Two images were made at each height, one with the test device oriented parallel ($eMTF_x$) and one perpendicular to the chest side of the detector ($eMTF_y$). Exposures were made according to AEC settings (**Table 2**). For each image, the corresponding eMTF was obtained based on the following scheme: From the edge image, the oversampled edge spread function (ESF) was determined. ESF was then differentiated to obtain line spread function (LSF), and then eMTF was calculated as a fast Fourier transform of LSF. Two obtained curves were averaged to obtain the final eMTF.

Effective normalized noise power spectrum eNNPS

The NNPS for both systems was calculated according to IEC62220-1-2¹⁵ using the same method described in our previous work^{2,3}. Normalized noise power spectrum was determined from images of PMMA phantoms with different thickness. Each phantom was placed on the top of the support

table, with one edge matching the chest wall side of the table. Images were obtained with exposure set by the AEC system. To minimize the number of images necessary to calculate, we extracted two ROIs (regions of interest) from each image. Each ROI was then divided into squares with areas of 256 by 256 pixels, with 50% areas overlapping in both directions. Each of these areas was used as input data ($I(x_i, y_j)$) to eNPS, as described in the following equation:

$$eNPS(u_n, v_k) = \frac{\Delta x \Delta y}{M \times 256 \times 256} \sum_{m=1}^M \left| \sum_{i=1}^{256} \sum_{j=1}^{256} (I(x_i, y_j) - S(x_i, y_j)) \exp(-2\pi i(u_n x_i + v_k y_j)) \right|^2 \quad \text{Eq. 4}$$

where:

x, y is the distance between the pixel centers in the horizontal and vertical directions, respectively.

M is the total number of ROIs;

$I(x_i, y_j)$ is the linearized data; and

$S(x_i, y_j)$ is the optionally fitted two-dimensional polynomial function.¹⁶

To achieve a normalized noise power spectrum, eNPS was divided by the squared mean pixel value of the corresponding ROI. To obtain a one-dimensional eNNPS, the radial mean of two-dimensional results was calculated.

Scatter fraction (SF), transmission factor (TF), number of photons per μGy per unit(q), pre-phantom exposure (E_0)

SF was calculated using the beam stop method.¹⁷ This method assumes that total signal intensity is the sum of glare, primary radiation, and scattered radiation. Glare measurement was obtained by placing 6 Pb discs ranging from 4 to 30 mm in diameter on the top of the support table, at the beam center. The sum of glare and primary radiation was obtained by full-field image, with the PMMA phantom placed just under the tube exit, and total signal intensity was obtained from a full-field image of the PMMA phantom placed on top of the support table. The subtraction of obtained pixel values in ROIs taken from adequate images led to the calculation of primary and scattered radiation. Finally, the scatter factor was obtained by dividing the scattered radiation by primary radiation.

The narrow beam transmission factor (TF) was calculated based on measurements of Kerma performed using Piranha Black 657 meter (RTI Electronics AB). Kerma was measured behind the PMMA phantom of desired thickness placed at the output of the X-ray tube and later, with the same exposure conditions, without the phantom. TF factor is the ratio of the Kerma measured with and without phantom. Similar measurements were performed to obtain pre-phantom exposure, but by placing a Kerma meter on top of the phantom.

The number of photons per μGy per unit area was calculated using an online tool provided by Siemens company.¹⁸ This parameter can also be obtained using Monte Carlo methods.

Table 3. PMMA thickness, scatter fraction (SF) estimated with and without the grid, coefficient of variation for SF, transmission factor (TF), coefficient of variation for TF, number of photons per μGy per unit (q), pre-phantom exposure corrected at the detector plane (E_0) for AEC mode with and without the grid. The values are presented for two FFDM systems: Siemens Mammomat Inspiration and GE Senographe Pristina.

System	PMMA thickness [mm]	SF		SF cov	TF	TF cov	q [$1/\mu\text{Gy mm}^2$]	E_0 [μGy]	
		Grid out	Grid in					Grid out	Grid in
Siemens	20	0.202	0.029	3%	0.189	0.06%	5357	601	1085
	30	0.255	0.037		0.099		5702	1127	1844
	40	0.312	0.049		0.056		5986	1708	2994
	70	0.446	0.080		0.013		7325	3996	8987
GE	20	0.212	0.015	4.9%	0.104	0.02%	4329	807	1670
	30	0.277	0.016		0.046		4577	1816	3868
	40	0.325	0.016		0.063		6844	1703	3465
	70	0.480	0.021		0.014		7708	5611	10272

All calculated parameters discussed in this section are summarized in **Table 3**.

Repeatability

Due to the complex characterization of eDQE and eNEQ, the repeatability of calculated values was estimated instead of uncertainty. For each unit, a set of full measurements was created. For Siemens, 12 sets (six sets each for 3 and 7 cm PMMA thicknesses) were created, and for GE – 4 sets were created for a 4 cm PMMA. Additionally, all SF calculations, which contain manually drawn ROIs, were repeated to control for the influence of a human operator. TF measurements were also repeated to include kerma meter uncertainty. The number of repetitions was matched to the number of sets for each unit/PMMA thickness combination, after which eDQE was calculated for each set of data. The repeatability was expressed as coefficient of variation (cov) – standard deviation over sets divided by their mean value. Values of cov for SF and TF alone are listed in **Table 3**. Cov values for eDQE and eNEQ are listed under the corresponding diagrams.

Contrast-detail analysis

A contrast-detail analysis was performed with the CDMAM phantom.¹⁹ Results of CDMAM measurement have been taken as an image quality parameter, based on European recommendations.²⁰ Measurements were made using CDMAM 3.4 phantom with dedicated software (CDMAM analysis 1.5.5, NCCPM) and a set of different PMMA phantoms. The set of 8 images for each phantom thickness and two FFDM systems were made using the same AEC settings as in **Table 2**. Sets were then analyzed to obtain Predicted Human Gold Thickness for each CDMAM disc with a diameter from 1.00 to 0.06 mm.

Results

eMTF and eNNPS

The eMTF and eNNPS were calculated using the imaging parameters given in the previous section for the two mammographic systems, operating with and without an antiscatter grid, for 20, 30, 40 and 70 mm of PMMA. **Figure 1** and **Figure 2** present results for the systems working with grid.

eDQE vs. eNEQ

Figures 3, 4 and **5** show eDQE and eNEQ for Siemens Mammomat Inspiration at different phantom thicknesses, with and without the grid. **Figures 6, 7** and **8** show the eDQE and eNEQ for the GE Pristina Senographe at different phantom thicknesses, with and without the grid.

CDMAM

Figures 9 and **10** show results for Predicted Human Gold Thickness as a function of CDMAM disc diameter, with and without grid, for four different phantom thicknesses, for images received with the Siemens Mammomat Inspiration and GE Pristina Senographe, respectively.

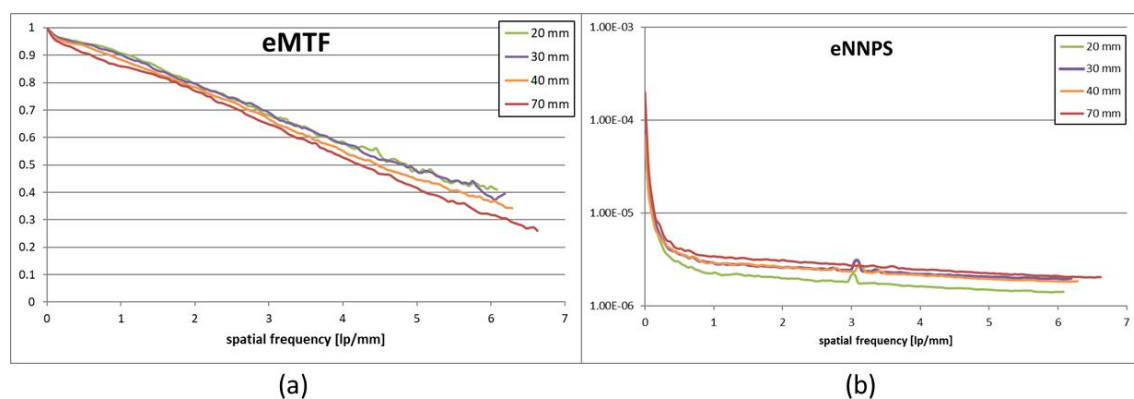


Figure 1. eMTF (a) and eNNPS (b) for Siemens Mammomat Inspiration for different phantom thicknesses, with grid.

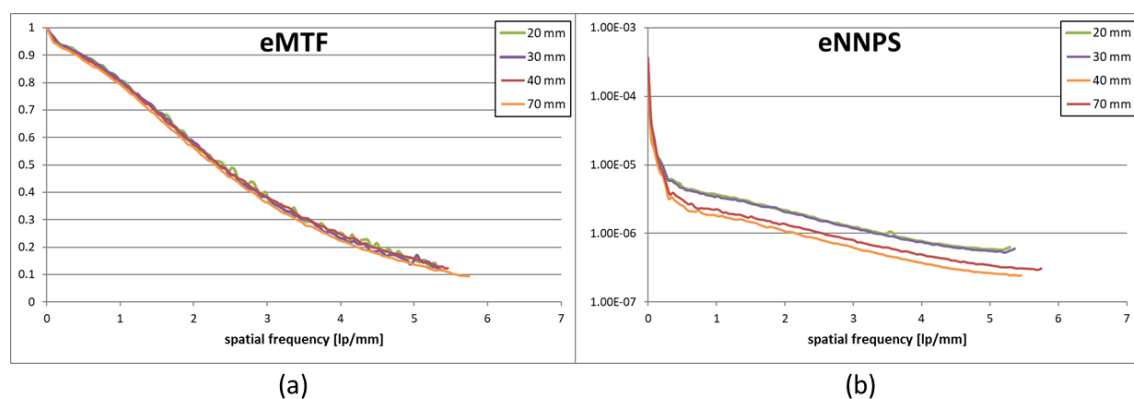


Figure 2. eMTF (a) and eNNPS (b) for GE Pristina Senographe for different phantom thicknesses, with grid.

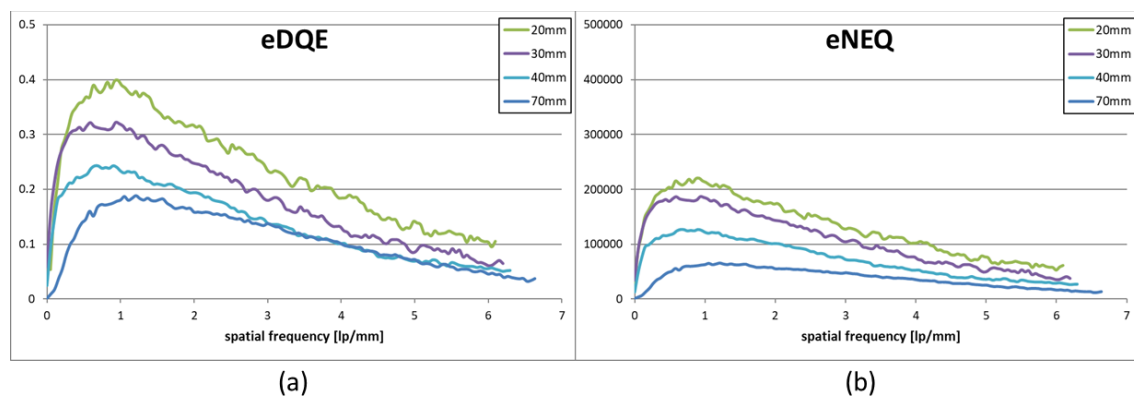


Figure 3. eDQE (a) and eNEQ (b) for Siemens Mammomat Inspiration for different phantom thicknesses, without grid.

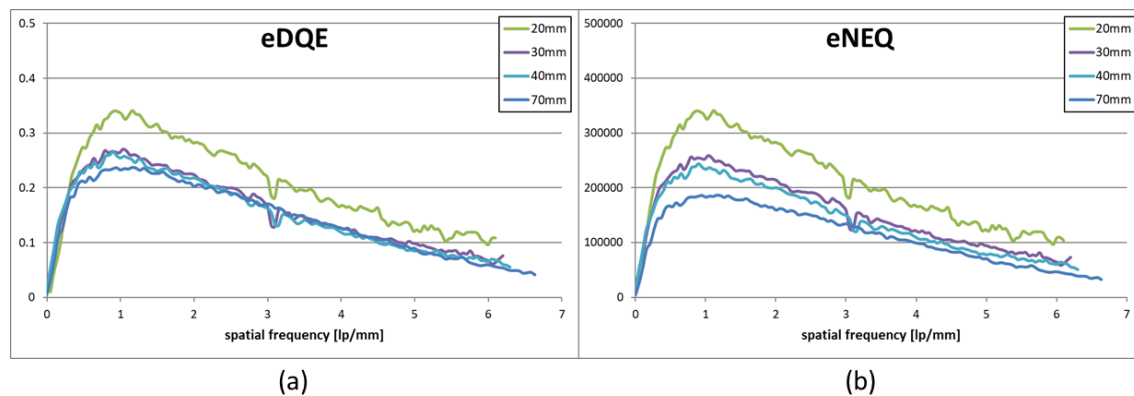


Figure 4. eDQE (a) and eNEQ (b) for Siemens Mammomat Inspiration for different phantom thicknesses, with grid.

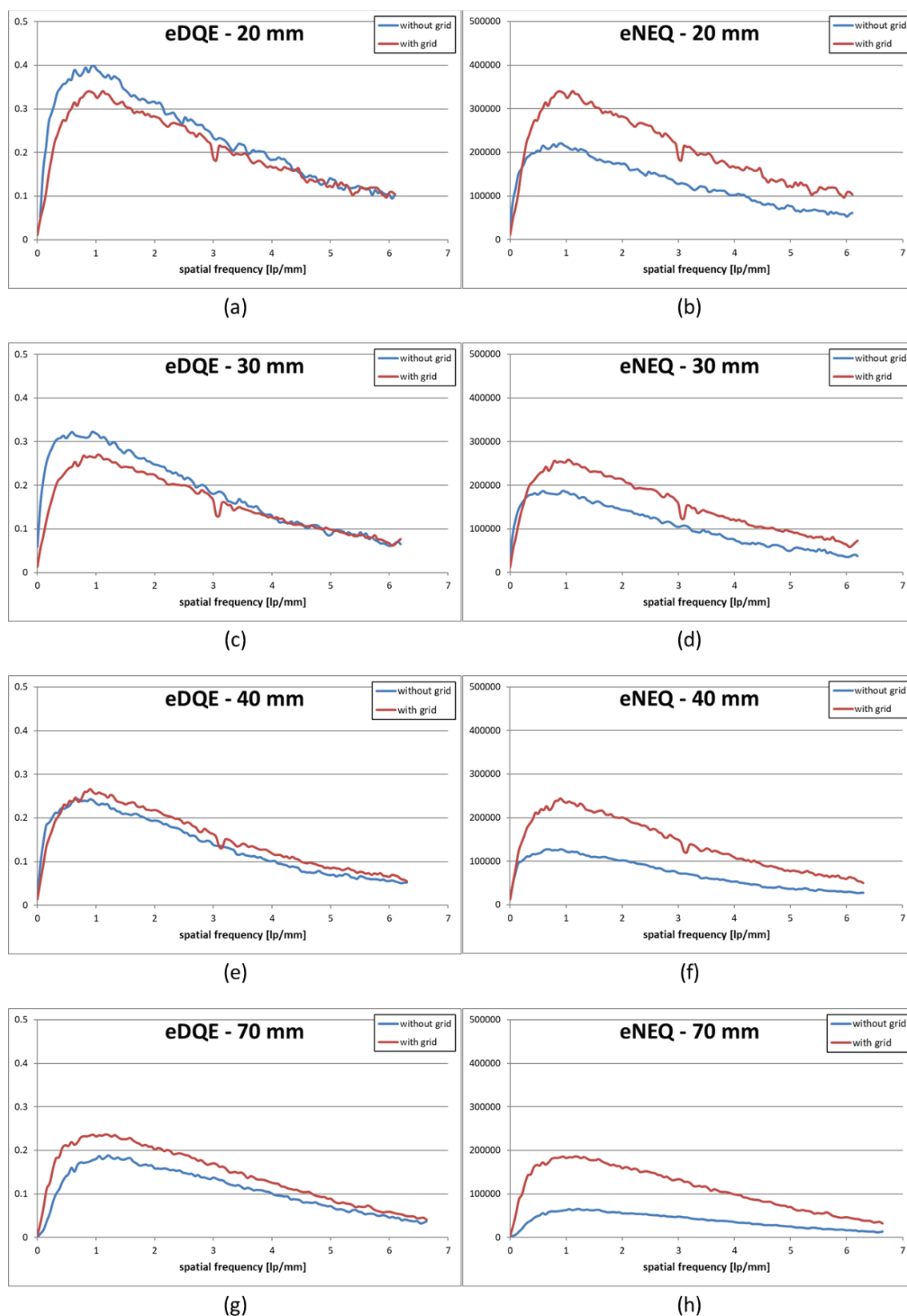


Figure 5. eDQE (a, c, e, g) and eNEQ (b, d, f, h) for Siemens Mammomat Inspiration for different phantom thicknesses, with and without grid.

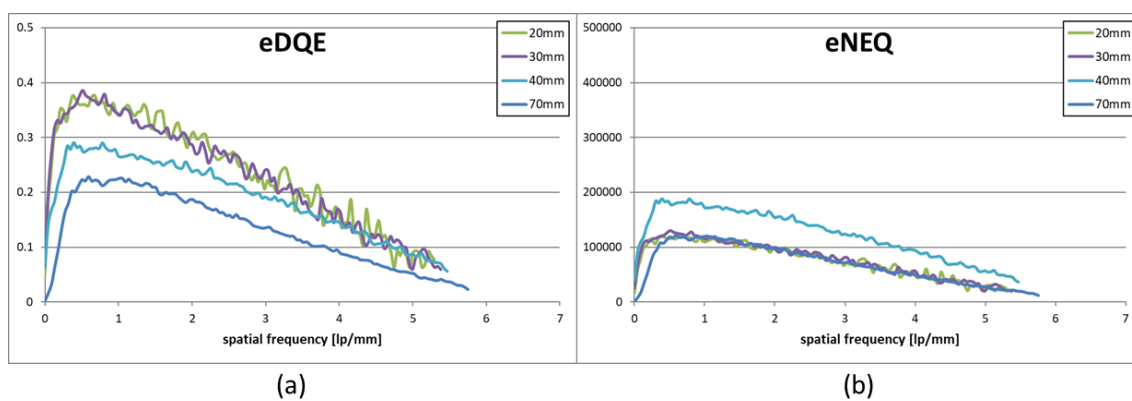


Figure 6. eDQE (a) and eNEQ (b) for GE Pristina Senographe for different phantom thicknesses, without grid.

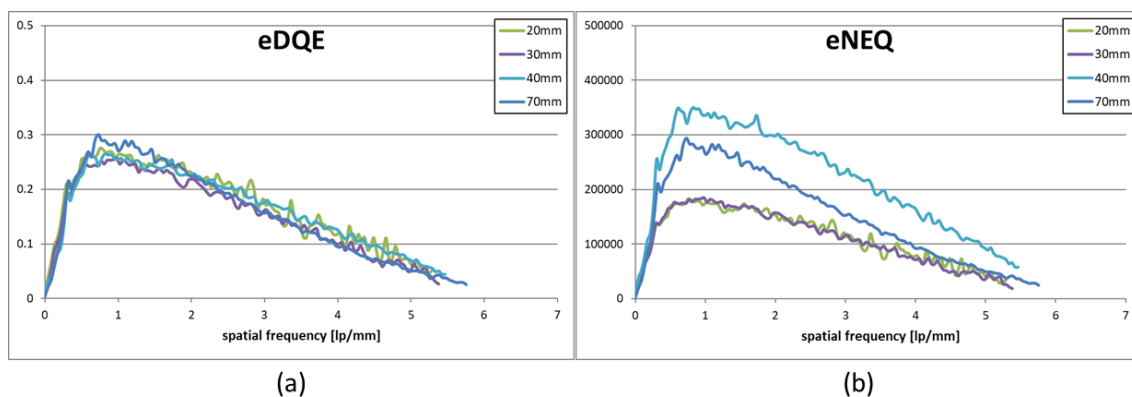


Figure 7. eDQE (a) and eNEQ (a) for GE Pristina Senographe for different phantom thicknesses, with grid.

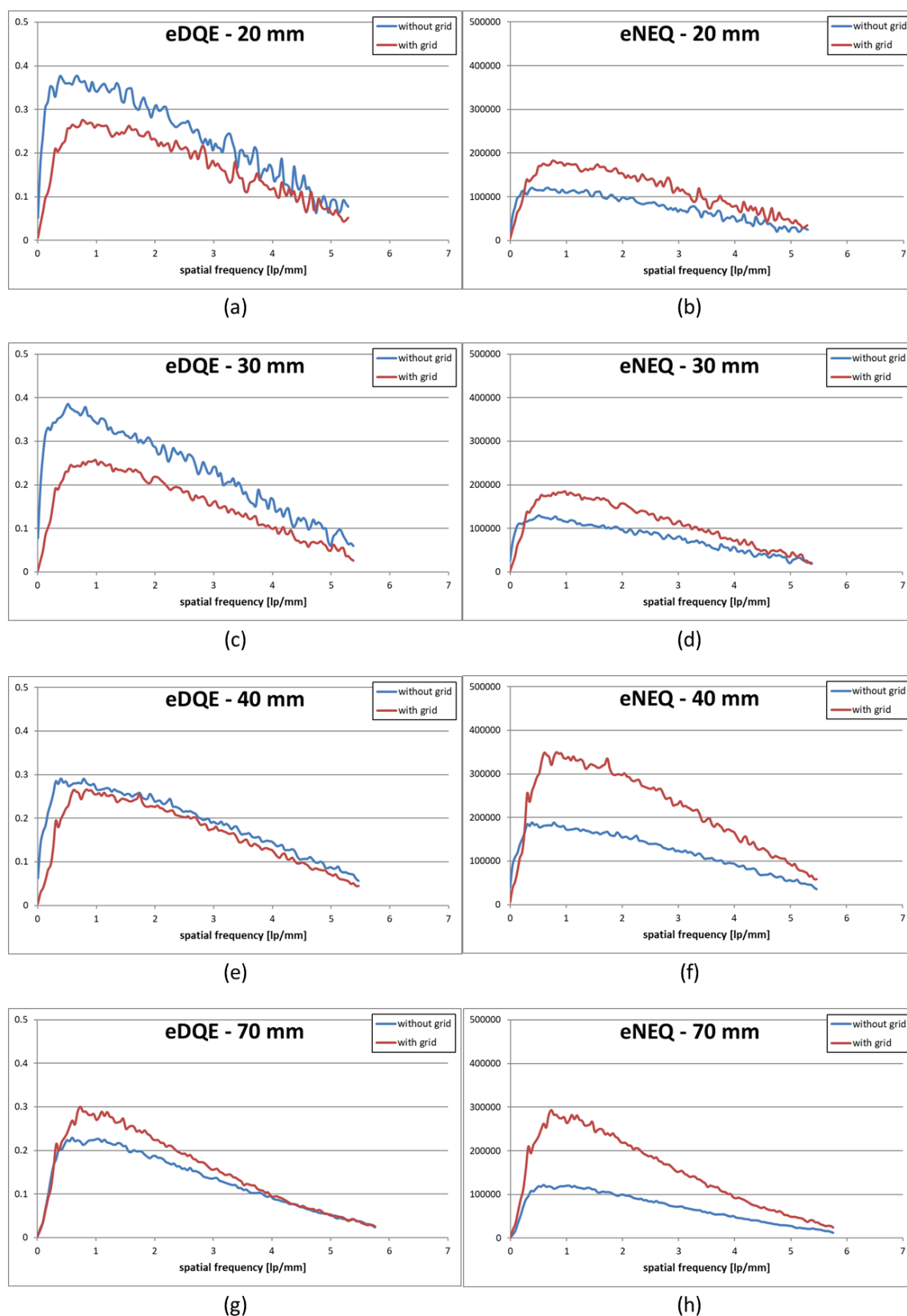


Figure 8. eDQE (a, c, e, g) and eNEQ (b, d, f, h) for GE Pristina Senographe for different phantom thicknesses, without and with grid.

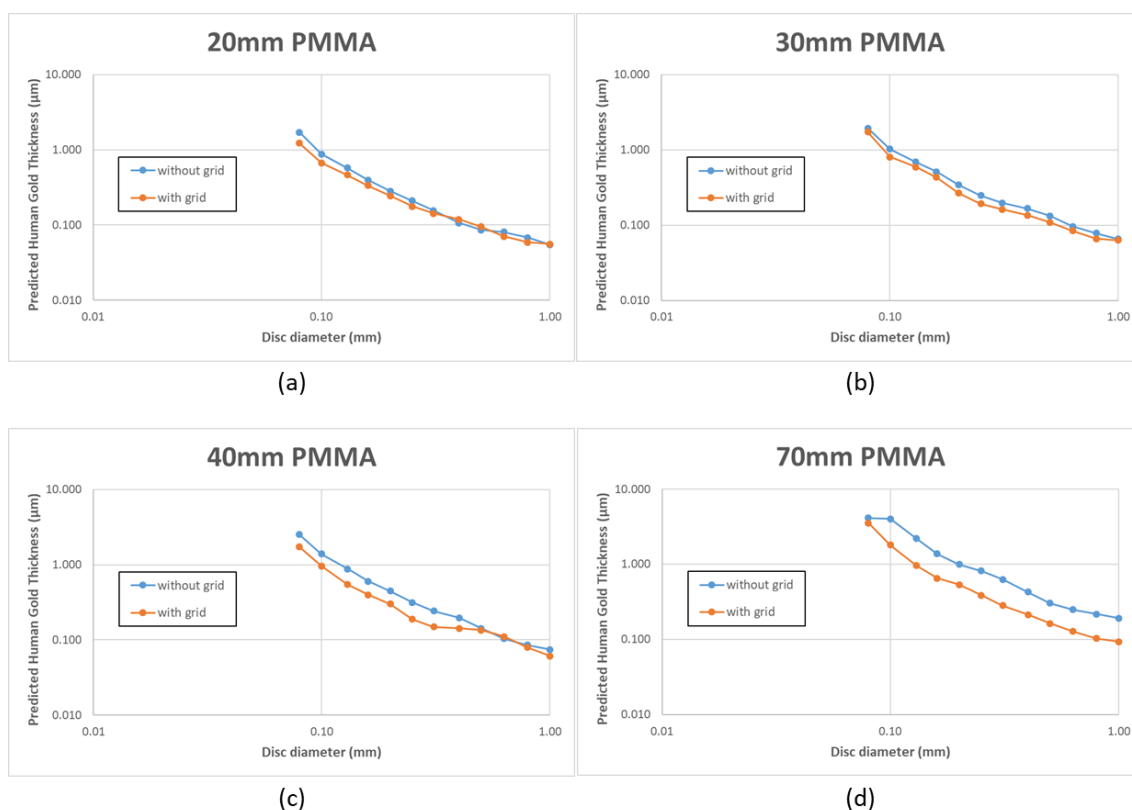


Figure 9. Predicted Human Gold Thickness resulted from CDMAM Phantom: for different PMMA thickness at (a) 20 mm PMMA, (b) 30 mm PMMA, (c) 40 mm PMMA, (d) 70 mm PMMA, with and without grid, for Siemens Mammomat Inspiration.

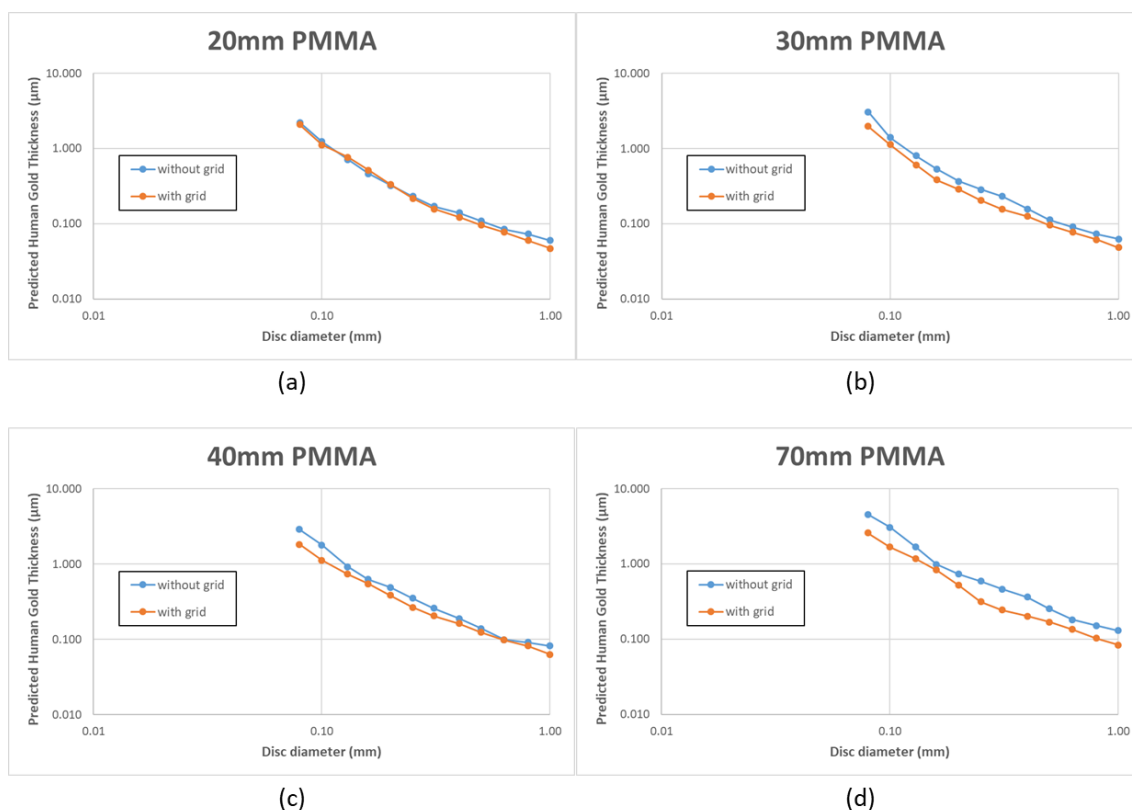


Figure 10. Predicted Human Gold Thickness resulted from CDMAM Phantom: for different PMMA thickness at (a) 20 mm PMMA, (b) 30 mm PMMA, (c) 40 mm PMMA, (d) 70 mm PMMA, with and without grid, for GE Pristina Senographe.

Table 4. Predicted Human Gold Thickness and measured eNEQ for different PMMA phantom thicknesses, with and without grid, for Siemens Mammomat Inspiration and GE Pristina Senographe

	Predicted Human Gold Thickness (μm) for $d = 0.13 \text{ mm}$		eNEQ at $f = 3.85 \text{ lp/mm}$	
	without grid	with grid	without grid	with grid
20 mm				
Siemens	0.575 ± 0.060	0.464 ± 0.048	108084.4 ± 4647.6	173907.2 ± 7478.0
GE	0.715 ± 0.075	0.765 ± 0.076	51459.83 ± 1338.0	85992.47 ± 2235.8
30 mm				
Siemens	0.689 ± 0.072	0.592 ± 0.058	78572.4 ± 3378.6	125583.2 ± 5400.1
GE	0.801 ± 0.087	0.608 ± 0.066	55814.27 ± 1451.2	78026.57 ± 2028.7
40 mm				
Siemens	0.877 ± 0.093	0.543 ± 0.059	55703.7 ± 2395.3	117105.4 ± 5035.5
GE	0.924 ± 0.107	0.735 ± 0.078	94826.47 ± 2465.5	171016.4 ± 4446.4
70 mm				
Siemens	2.197 ± 0.240	1.136 ± 0.119	37490.3 ± 1612.1	104135.4 ± 4477.8
GE	1.672 ± 0.178	1.165 ± 0.115	54505.69 ± 1417.1	106327.9 ± 2764.5

	Predicted Human Gold Thickness (μm) for $d = 0.25 \text{ mm}$		eNEQ at $f = 3.85 \text{ lp/mm}$	
	without grid	with grid	without grid	with grid
20 mm				
Siemens	0.210 ± 0.024	0.176 ± 0.022	173791.4 ± 7473.0	281870.0 ± 12120.4
GE	0.231 ± 0.027	0.216 ± 0.027	97798.7 ± 2542.8	153186.5 ± 3982.8
30 mm				
Siemens	0.247 ± 0.031	0.193 ± 0.025	143103.4 ± 6153.4	212456.5 ± 9135.6
GE	0.286 ± 0.033	0.205 ± 0.024	96364.4 ± 2505.5	157517.1 ± 4095.4
40 mm				
Siemens	0.316 ± 0.038	0.189 ± 0.026	101688.6 ± 4372.6	200491.5 ± 8621.1
GE	0.352 ± 0.040	0.267 ± 0.033	153978.5 ± 4003.4	230954.2 ± 6004.8
70 mm				
Siemens	0.960 ± 0.110	0.388 ± 0.043	55120.9 ± 2370.2	158787.9 ± 6827.9
GE	0.590 ± 0.067	0.315 ± 0.042	100094.6 ± 2602.5	218753.3 ± 5687.6

Comparison of CDMAM and eNEQ results of image quality

Table 4 shows the Predicted Human Gold Thickness (resulting from CDMAM Phantom) and measured eNEQ for different PMMA phantom thicknesses, with and without grid, for Siemens Mammomat Inspiration and GE Pristina Senographe.

Discussion

We calculated eMTF using a Fourier transformation of a two-dimensional function oversampled from the image, as described above. Differences in the shape of the eMTF curves observed from the Siemens and GE mammographs, which are shown in **Figures 1a** and **2a** were due to their different detector pixel sizes: $85 \mu\text{m}$ for Siemens and $100 \mu\text{m}$ for GE. Smaller pixels produce wider eMTF curves, which are associated with better imaging of smaller objects. Changes in eMTF for the Siemens system varied with the thickness of PMMA phantoms used; the greater changes were observed with a 20 mm phantom and the smaller ones were seen with the 70 mm phantom.

In **Figures 1b** and **2b** the results for eNNPS are plotted for different phantom thicknesses for each mammographic system. With the Siemens system, we can observe that eNNPS values

vary with phantom thickness, and are higher with thicker phantoms, especially at high frequencies. These higher noise values result from beam attenuation and additional radiation scatter by the phantom.

At all phantom thicknesses the Siemens system produces a higher eNNPS than seen with GE. The GE system demonstrated a notable phantom thickness dependence, with the curves separated into two main groups: at 40 and 70 mm, and at 20 and 30 mm. This observation may well have resulted from the use of two different T/F compositions, Rh/Ag for 40- and 70-mm phantoms and Mo/Mo for 20 and 30 mm ones.

The peak seen in **Figure 1b** is a characteristic one that is associated with the presence of grid lines. Grid strip density for Siemens is 3.1 lines/mm, and it is at this frequency that we observed the eNNPS peak. Grid strip density for GE is 6.7 lines/mm, and it was not possible to observe a peak because this frequency is out of the measured range.

Figure 3 presents eDQE and eNEQ results for the Siemens Mammomat Inspiration system using different phantom thicknesses without a grid. Both eDQE and eNEQ are higher at smaller phantom thicknesses, which can be explained simply: at a smaller phantom thickness, MTF values are higher eNNPS are

smaller (as seen in **Figure 1**), and SF values are smaller (as shown in **Table 3**).

Figures 4a and **4b** show that eDQE behaves differently than eNEQ with grid use. The eNEQ will vary with phantom thickness, with or without a grid. The eDQE without grid varies with phantom thickness, but with the grid is almost the same at thicknesses of 30, 40, and 70 mm and higher only for 20 mm phantom. This was why we decided to analyze eDQE and eNEQ with and without grid at different phantom thicknesses in the separate **Figures 5a, c, e, g, and 5b, d, f, and h**. These Figures show that with a 20- and 30-mm phantom, eDQE values are slightly higher without a grid (ca. 25.6% and 32.8% for 1 lp/mm) than with one. Grid use is associated with decreases in eDQE, which indicates that the reduction in the percentage of scattered radiation in the beam does not compensate for the loss of photons absorbed in the grid. From our analysis of grid-in and grid-out results, the shapes of the eDQE curves are similar, and higher eDQE values observed with the 20- and 30-mm phantoms reflect lower scatter radiation in those examples. With the larger 40 and 70 mm PMMA phantoms, eDQE values with grid-in are higher than those with grid-out (with maximum difference 18.1%). It is apparent that eDQE value is dependent on changes in eMTF, SF, eNNPS and E_0 that occur with grid use, as presented in **Table 3**.

The eNEQ values for all phantom thicknesses are higher when measurements are performed with an anti-scatter grid, as shown in **Figure 5b, d, f, h**. This behavior is related to **Equation 3**, where the value $(TF \cdot E_0 \cdot q)$ is not present. **Equation 3** only uses image parameters described by the Signal to Noise Ratio (SNR); in this instance, eDQE is expressed as the relation of $(SNR_{out})^2 / (SNR_{in})^2$, and eNEQ is equal to $(SNR_{out})^2$.

The eNEQ values (with and without grid) are smaller for thicker PMMA phantoms, which is presented in **Figures 4b** and **5b, d, f, and h**, and in **Table 4**.

Figures 3, 4, and 5 present eDQE and eNEQ values at different phantom thicknesses (to simulate actual differences in breast thickness) with grid-on or grid-out for measurements performed with the Siemens system.

Similar behavior of the eDQE and eNEQ metrics were observed with the GE mammography system, as shown in **Figures 6, 7, and 8**. An exception is presented in **Figures 6b** and **7b**, which show that eNEQ values with 20 and 30 mm PMMAs are the same, most likely due to the use of a different T/F configuration (Mo/Mo).

We also performed a contrast-detail analysis with a CDMAM phantom, in order to compare our eNEQ measurements with an image quality parameter that is based on European recommendations. These results are presented in **Figure 9** for the Siemens unit and in **Figure 10** for the GE one. Detailed analyses of eNEQ values and Predicted Human Gold Thickness values for CDMAM discs with diameters of 0.13 and 0.25 mm are presented in **Table 4** and show that eNEQ values are higher

for measurements with a grid than without a grid for all phantom thicknesses and for both systems.

It is important to understand that a higher quality image is correlated with lower Predicted Human Gold Thickness. Higher eDQE and eNEQ also correlate with better imaging performance. The results shown in **Table 4** demonstrate that both the lower Predicted Human Gold Thickness values obtained from CDMAM and the higher eNEQ values calculated for the mammographs' measurements are correlated with higher image quality.

As we could not change AEC settings, we experienced some difficulties in comparing eNEQ values due to the different tube filter (T/F) combinations, tube potential (kV) and exposure time they use for two different mammographs. When we used eNEQ values in this unit's comparison, we received the same image quality results as seen with CDMAM for phantoms with thicknesses of 20, 30, and 70 mm, but not for a phantom whose thickness was 40 mm. In this case, the tube potential in the Siemens mammography unit was set by AEC to 28 kV, while in the GE unit, it was 34 kV. This difference in applied beam quality did not permit the comparison of eNEQ values between the two units.

Conclusions

For the two mammographic systems evaluated, we characterized physical quality parameters such as eMTF, eNNPS, eDQE and eNEQ for a wide range of exposures and phantom thicknesses, with and without an anti-scatter grid.

The Siemens system had an a-Se detector, and the GE system had an indirect-conversion detector. The GE system's indirect-conversion flat panel detector is made of amorphous silicon (a-Si) that is coupled with a scintillator of cesium iodine doped with thallium CsI (TI). FFDM systems that use indirect-conversion detectors are known to have a poorer spatial resolution compared to systems whose detectors use a direct conversion process.²¹ GE has developed special software to restore this loss in spatial resolution, but as we used images in DICOM format as RAW data for this work, we didn't use this software.

Based on the findings reported here, we could not use the eDQE parameter to estimate image quality. The previous literature does state that higher eDQE values relate to better imaging performance. However, in our work, the eDQE we measured with an antiscatter grid was lower than the values we obtained when we measured without a grid for different phantom thicknesses. These results are not consistent with those we obtained with a European recommended CDMAM phantom.

We successfully demonstrated that the eNEQ metric can be used as a new option to evaluate image quality for images taken with and without grid and with phantoms of different thicknesses for Siemens and GE systems. These results were consistent with the results obtained from CDMAM. When we compared the findings for our experimental measurement

parameters with image quality assessments of these two mammography systems obtained with CDMAM, we observed that for disk diameters of 0.13 mm and 0.25 mm, the Siemens unit produced better imaging results than GE for all phantom thicknesses except 70 mm.

We did observe some limitations when we compared image quality measured with eNEQ for the two mammography units studied, due to their very different types of detectors.

It should be noted that all our measurements were performed on mammography systems that are in current use in the clinical setting, with AEC in operation. AEC software optimizes images (contrast-to-noise ratio) at a low patient dose, as specified by protocols. As we could not change AEC settings, we experienced some difficulties in comparing eNEQ values due to the different tube filter (T/F) combinations, tube potential (kV) and exposure time they used for two different mammographs.

When we used eNEQ values (measured with or without grid) in this comparison, we received the same image quality results as seen with CDMAM (measured with or without grid) for phantoms with thicknesses of 20, 30, and 70 mm, but not for a phantom whose thickness was 40 mm. To explain this difference, we believe it would be necessary to conduct additional eNEQ measurements with different tube filter combinations (T/F), tube potential (kV) and exposure times, but this can only be done by overriding the AEC software.

Despite these small discrepancies, our work demonstrates that eNEQ measurements can be used to estimate image quality, especially for a mammography system working with and without a grid and with phantoms of different thicknesses.

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