Journal of Medical Imaging

MedicalImaging.SPIEDigitalLibrary.org

Mean glandular dose in digital mammography: a dose calculation method comparison

Moayyad E. Suleiman
Patrick C. Brennan
Mark F. McEntee

Mean glandular dose in digital mammography: a dose calculation method comparison

Moayyad E. Suleiman,^{*} Patrick C. Brennan, and Mark F. McEntee

The University of Sydney, Faculty of Health Sciences, M205, Cumberland Campus, 75 East Street, Lidcombe, New South Wales 2141, Australia

Abstract. Our objective was to analyze the agreement between organ dose estimated by different digital mammography units and calculated dose for clinical data. Digital Imaging and Communication in Medicine header information was extracted from 52,405 anonymized mammograms. Data were filtered to include images with no breast implants, breast thicknesses 20 to 110 mm, and complete exposure and quality assurance data. Mean glandular dose was calculated using methods by Dance et al., Wu et al., and Boone et al. Bland–Altman analysis and regression were used to study the agreement and correlation between organ and calculated doses. Bland–Altman showed statistically significant bias between organ and calculated doses. The bias differed for different unit makes and models; Philips had the lowest bias, overestimating Dance method by 0.03 mGy, while general electric had the highest bias, overestimating Wu method by 0.20 mGy, the Hologic organ dose underestimated Boone method by 0.07 mGy, and the Fujifilm organ dose underestimated Dance method by 0.09 mGy. Organ dose was found to disagree with our calculated dose, yet organ dose is potentially beneficial for rapid dose audits. Conclusions drawn based on the organ dose alone come with a risk of over or underestimating the calculated dose to the patient and this error should be considered in any reported results. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JMI.4.1.013502](https://doi.org/10.1117/1.JMI.4.1.013502)]

Keywords: dosimetry; screening mammography; radiation; organ dose.

Paper 16146PRR received Jul. 17, 2016; accepted for publication Dec. 27, 2016; published online Jan. 24, 2017.

1 Introduction

Screening mammography invites healthy women for an x-ray examination of the breast, with the aim of early detection of breast cancer. The benefits of screening mammography have been scientifically examined and it has been shown, on the basis of randomized controlled trials, that screening mammography reduces breast cancer mortality by up to 25%.^{1–4} This evidence was revisited in 2015 to find out if it is still valid today. The International Agency for Research on Cancer conducted a review of all published peer-reviewed literature through which they concluded that mammography screening is still effective in reducing breast cancer mortality.⁵

Mammography efficacy in detecting breast cancer in early stages comes with a small but nonnegligible risk of radiation-induced cancer to the fibroglandular tissues of the breast⁶ and possibly other exposed organs.⁷ Monitoring the breast-absorbed dose is thus vital to ensure unnecessarily high doses do not occur; therefore, many quality assurance (QA) protocols have included breast dose assessments to govern the diagnostic adequacy of the imaging techniques in mammography.^{8–11}

Mean glandular dose (MGD) is the main descriptor of absorbed dose to the breast. MGD is calculated using conversion factors established by Monte-Carlo simulations. Dance et al.,^{12–14} Sobol and Wu,¹⁵ Wu et al.,¹⁶ and Boone et al.^{17–19} have established conversion factors that are widely used to estimate MGD. The three models differ slightly in the simulation method, but all reported conversion factors dependent on breast thickness, glandularity, x-ray spectra, and beam quality. The conditions

underlying Monte-Carlo simulation employed by different authors can impact the estimated dose by up to 19%.²⁰

The estimation of MGD is dependent on the values of half value layer (HVL) and output, while these values are also dependent on the measurement methods and can change substantially depending on the dosimeters and how they are used.²¹ Furthermore, MGD is estimated using Monte-Carlo simulations, which utilize a computer model of the breast to simulate photon absorption in the glandular tissue of the breast, hence making MGD a dose to a breast model rather than a dose to the breast. This makes the estimation of MGD prone to errors regardless of the method used, hence, it is important to highlight that MGD is and will always be an estimation as it is not possible to measure the dose absorbed by the glandular tissue directly as well as the differences in density distribution of the glandular tissue that also depend on the thickness of the breast and age of women.

Modern technology and the introduction of digital mammography provide valuable utility to easily collect data required to facilitate dose audits. The readily available estimation of MGD displayed by the digital systems provides a digital indication of the breast dose named organ dose, as well as information on radiographic technique and the performance of the imaging system. However, this estimated organ dose needs to be validated against other calculation methods before it can be used for dose audits or as an alternative approach to establish diagnostic reference levels (DRLs). Borg et al.²² studied two mammography units [General Electric (GE) Essential and Hologic Selenia] to establish the correlation between organ dose and the dose calculated for different thickness phantoms using the three Monte-Carlo estimations mentioned earlier. The authors concluded that

^{*}Address all correspondence to: Moayyad E. Suleiman, E-mail: msul1801@uni.sydney.edu.au

organ dose compares well with the Monte-Carlo estimations within small to medium phantom thicknesses and differs slightly with thicker phantoms.

This study aims to analyze the agreement and correlation between organ dose displayed by four types of digital mammography units and calculated dose values for clinical data with a wide range of breast thicknesses using methods published by Dance et al.,¹²⁻¹⁴ Sobol and Wu,¹⁵ Wu et al.,¹⁶ and Boone et al.¹⁷⁻¹⁹

2 Materials and Methods

2.1 Data Collection

Ethical approval was granted by the Human Research Ethics Committee of the Cancer Institute of NSW (No. 2014/08/552). The dose assessment included 61 mammography units from 50 BreastScreen centers and mobile vans throughout the state of NSW Australia. 52,405 (12,034 women) anonymized mammograms were downloaded from the Picture Archiving and Communication System located at the Cancer institute of NSW.

The following information was extracted from the Digital Imaging and Communication in Medicine (DICOM) headers using a third party software (YAKAMI DICOM Tools ver. 1.4.1.0, Kyoto University, Japan), namely: age, study date, compressed breast thickness (CBT), presence of implants, view, laterality, tube voltage (kVp), tube current exposure time product (mAs), target material, filter material, exposure control mode, organ dose, detector ID, and mammographic unit model. Further QA data required for the calculation of MGD were collected from the annual QA medical physics reports of participating centers through the Cancer Institute of NSW. These reports consisted of dose measurements on 20, 42 American College of Radiology (ACR) mammography accreditation phantom, and 60 mm phantom thicknesses for different anode/filter combinations. It should be noted here that as QA reports vary in detail given, some estimation is necessitated to calculate the output and HVL. The normal QA practice for mammography units is made on three different phantoms, hence, different sets of data (HVL, output, and mAs) were provided for different anode/filter combinations. Extrapolation was used to estimate the HVL for mammograms taken by anode/filter combinations that had one set of QA data using the method published by Robson et al.²³ and expanded by Borg et al.²² Different dosimeters utilized to measure the output may have slight differences some of which are stated in the calibration certificates provided from the manufacturers and could carry up to 5% error in calibration.^{24,25}

2.2 Data Preparation

Only mammograms for women with no breast implants, aged 40 to 64 and a CBT 20 to 110 mm, were included. Any exposure information with manual exposure settings, no organ dose in DICOM header, or missing QA data were excluded due to the lack of exposure information to calculate MGD. The final data set included 27,869 mammograms from 40 BreastScreen centers and mobile vans (53 digital mammography units).

2.3 Mean Glandular Dose Estimation

Mammography system vendors utilize different methods for the estimation of organ dose displayed by the imaging systems. Philips (Sectra) and Fujifilm utilize Dance method, while

Table 1 Calculation methods and glandularities known to be used by each system included in this study for the estimation of displayed organ dose (vendor Method).

Manufacturer	Displayed organ dose	
	Calculation method	Glandularity
Philips (Sectra)	Dance	Unknown
GE Medical systems	Wu	Proprietary measure
Hologic	Boone	Unknown
Fujifilm	Dance	Unknown

Hologic utilize Boone method and GE utilizes Wu method²⁶ (it is important to stress here that the calculation methods are not clear) (Table 1). Hence, for each mammogram, MGD was calculated using an in-house developed excel workbook utilizing the three methods published by Dance et al.,¹²⁻¹⁴ Sobol and Wu,¹⁵ and Boone et al.¹⁷⁻¹⁹

2.3.1 Dance's method

Dance et al. method utilizes the following equation to calculate MGD:

MGD = Kgc.s,

where K is the incident air kerma (IAK) at the upper surface of the breast. g converts IAK to MGD for a breast with 50% glandularity. This method incorporates an estimation of glandularity provided as the c factor, which corrects for differences in glandularity other than the 50% and is given for two age groups 40 to 49 and 50 to 64 years. g and c are dependent on HVL and CBT. s is spectra dependent, it corrects for different types of spectra where s = 1 for Mo/Mo anode/filter combination and changes for other combinations.

2.3.2 Wu's method

Wu's method utilizes the following equation:

MGD = K × DgN,

where K is the IAK at the upper surface of the breast and DgN is the normalized glandular dose per unit IAK. This method was applied using the paper published by Sobol and Wu,¹⁵ which provides parameterization equations to calculate DgN for different anode/ filter combinations and different glandularities. The parameterization equations were implemented into our excel workbook using 50% glandularity. Wu's method is limited to three spectra namely Mo/Mo, Mo/Rh, and Rh/Rh, hence it could only be applied on the GE units.

2.3.3 Boone et al. method

Boone's method¹⁷⁻¹⁹ utilizes Wu's equation to calculate the MGD with data tables having an extended utility to include more anode/filter combinations (W/Rh and W/Ag) and thicker breasts. Boone data tables are provided for 0%, 50%, and 100% glandularities and those tables were used to calculate the MGD with the assumption of 50% glandularity.

Table 2 Average MGD for system displayed dose, three dose calculation methods and their SD for 27,869 digital mammography images from four different mammography unit makes.

Make	Model	Images	Average MGD (mGy), SD			
			System	Dance	Wu	Boone
Philips (Sectra)	L30	6210	0.86, 0.25	0.83, 0.26	N/A	0.95, 0.27
GE Medical systems	All	11249	1.42, 0.31	1.45, 0.34	1.22, 0.26	1.60, 0.41
Hologic	Selenia dimensions	9504	1.73, 0.66	1.97, 0.74	N/A	1.80, 0.68
Fujifilm	Amulet	906	0.93, 0.32	1.01, 0.42	N/A	0.91, 0.41

2.4 Data Analysis

Bland–Altman analysis was used to study the agreement between organ dose and each of the three other calculation methods. Multiple regression analysis was performed to study the correlation between organ dose and each calculation method (SPSS v22, Excel 2011).

3 Results

Table 2 shows the average MGD values and standard deviation (SD) for the organ dose and the three calculation methods.

The Bland–Altman analysis revealed statistically significant bias between organ dose and the three calculation methods with bias values, 95% limits of agreements (LOA), and *p* values shown in Table 3. Linear regression models for each mammography unit make are shown in Figs. 1(a), 2(a), 3, and 4.

4 Discussion

The variation in methods used to estimate MGD makes international comparisons difficult.²⁷ The same issue exists for the organ dose displayed by the imaging system, where different

Table 3 Bland–Altman bias and 95% LOA to study the agreement between organ dose (displayed by the digital mammography unit) and dose calculated using three Monte-Carlo methods (Dance et al., Wu et al., and Boone et al.) for different mammography unit models from 27,869 digital mammography images.

Make	Model	Systems	Images	Organ versus Dance			Organ versus Wu			Organ versus Boone		
				Bias (mGy)	LOAs (mGy)	<i>p</i> value	Bias (mGy)	LOAs (mGy)	<i>p</i> value	Bias (mGy)	LOAs (mGy)	<i>p</i> value
Philips (Sectra)	L30	11	6210	0.03	−0.15, 0.21	<0.001	N/A	N/A	<0.001	−0.09	−0.33, 0.15	<0.001
GE Medical Systems	Senographe Essential ADS_54.11	14	8282	−0.03	−0.29, 0.35	<0.001	0.21	−0.13, 0.54	<0.001	−0.20	−0.68, 0.28	<0.001
	Senographe Essential ADS_54.10	1	488	0.03	−0.27, 0.22	<0.001	0.26	0.00, 0.53	<0.001	−0.14	−0.54, 0.26	<0.001
	Senographe Essential ADS_53.40	1	727	−0.08	−0.13, 0.29	<0.001	0.13	−0.13, 0.38	<0.001	−0.22	−0.54, 0.10	<0.001
	Senograph DS ADS_54.11	2	982	−0.07	−0.17, 0.30	<0.001	0.12	−0.17, 0.42	<0.001	−0.14	−0.50, 0.23	<0.001
	Senograph DS ADS_53.40	1	454	0.13	−0.16, 0.43	<0.001	0.36	0.01, 0.71	<0.001	−0.04	−0.44, 0.37	<0.001
	Senograph 2000D ADS_17.4.5	1	316	−0.10	−0.37, 0.17	<0.001	0.17	−0.47, 0.126	<0.001	−0.04	−0.43, 0.35	<0.001
	GE Systems	20	11249	−0.03	−0.34, 0.28	<0.001	0.20	−0.14, 0.54	<0.001	−0.18	−0.64, 0.28	<0.001
	GE Systems with glandularity	20	11249	−0.03	−0.34, 0.28	<0.001	0.03	−0.14, 0.21	<0.001	−0.18	−0.64, 0.28	<0.001
	Selenia dimensions	21	9504	−0.24	−0.74, 0.27	<0.001	N/A	N/A	<0.001	−0.07	−0.67, 0.53	<0.001
	Amulet	1	906	−0.09	−0.35, 0.18	<0.001	N/A	N/A	<0.001	0.01	−0.28, 0.30	<0.001
Overall		53	27869	−0.09	−0.52, 0.34	<0.001	N/A	N/A	<0.001	−0.12	−0.60, 0.37	<0.001

Fig. 1 Linear regression scatter plots showing the line of best-fit between MGD calculated using Dance method and organ dose displayed by Philips (Sectra) units for 6210 digital mammograms: (a) full data and (b) data after removing a problematic unit. (Philips systems utilize Dance method for the estimation of organ dose).

vendors are using different methods to estimate the organ dose, although it is important to emphasize here that the calculation methods employed by different vendors are not clear. Organ dose displayed by the system could be used as a robust method to evaluate the dose for a wide range of breast thicknesses and systems, as well as facilitating larger sample sizes. However, the use of organ dose needs to be validated against other dose calculation methods before it can be implemented. This study examined the agreement and correlation between MGDs calculated using three Monte-Carlo methods and the organ dose displayed by the mammography systems.

Philips systems showed a statistically significant bias indicating the displayed organ dose is overestimating Dance MGD by an average of 0.03 mGy, while Boone MGD underestimated the organ dose by a higher bias (Table 3). This is expected as the Philips (Sectra) systems employ Dance conversion factors for the organ dose estimation. On the other hand, the scatter plot for the Philips systems revealed a group of dose points that have a higher difference between the organ and Dance MGD [Fig. 1(a)]. These belonged to one system and are due to an error in the QA data collection for that system or an error in the system calibration. A scatter plot with those dose points removed shows a higher correlation increasing from $R^2 = 0.87$ to $R^2 = 0.96$ [Fig. 1(b)]. Removing that system from the analysis increased the bias from 0.03 to 0.047 mGy. Therefore, as the bias is small in comparison to the clinical dose of 2.0 mGy, and there is a narrow upper and lower 95% LOA (Table 3), we can conclude that the calculated and organ doses are in agreement.

GE systems varied in performance depending on the model and version; in total though, they showed an average bias

Fig. 2 Linear regression scatter plots showing the line of best-fit between (a) MGD calculated using Wu method assuming 50% glandularity and organ dose displayed by GE units and (b) MGD calculated using Wu method and using the DICOM glandularity (0040,0310 comments on radiation dose) and organ dose displayed by GE units for 11,249 digital mammograms. (GE systems utilize Wu method for the estimation of organ dose).

Fig. 3 Linear regression scatter plot that shows the line of best-fit between MGD calculated using Boone method and organ dose displayed by Hologic units for 9504 digital mammograms. (Hologic systems utilize Boone method for the estimation of organ dose).

overestimated the organ dose by a 0.20 mGy, a few units had higher or lower bias, one of which overestimated the calculated dose by an average of 0.36 mGy. Figure 2(a) shows the correlation between calculated dose (Wu method) and the organ dose with $R^2 = 0.85$. Due to the higher bias, further investigation was carried out and it was discovered that GE systems utilize a proprietary measure of glandularity and they enter this into the DICOM header at tag 0040,0310 “Comments on radiation dose.” It was also found that the glandularity estimation

was set to 50% in some centers and many mammograms had 0% or 100% estimations, regardless of the breast thickness. Neither the glandularity estimation method nor its accuracy is described in the literature. Nonetheless, once the calculations were adjusted to account for the proprietary glandularity estimation the bias was substantially reduced (Table 3) and showed a much better correlation with an $R^2 = 0.92$ [Fig. 2(b)]. Although the GE organ dose had a higher level of agreement with the Wu method after the inclusion of the proprietary glandularity estimation, these 0% glandularity estimations in many of the GE systems mean that these organ doses cannot reflect the calculated MGD correctly as they do not account for any glandularity.

Hologic system's organ dose reported a small bias (Table 3) underestimating the Boone calculated MGD, nonetheless, it shows a difference of up to 0.67 mGy, which represents the complete absorbed dose for small breast thicknesses. The correlation between calculated dose (Boone method) and organ dose show an $R^2 = 0.8$, which although good, is the lowest correlation out of the four vendors. We can conclude that in our study the Hologic system organ dose did not accurately reflect our calculated dose.

Fujifilm constitutes less than 4% of the total sample. Only one Fujifilm amulet unit was included in this survey, hence no intrasystem comparison was possible. Other Fujifilm units were computed radiography (CR) systems that did not record organ dose. The Fujifilm amulet unit showed average results underestimating Dance MGD with a small positive bias of 0.09 mGy. Linear regression showed an excellent correlation with $R^2 = 0.94$ (Fig. 4).

Organ dose from the four systems showed a statistically significant bias when compared to the calculated dose. It has been reported that the statistical significance of the bias in the Bland-Altman method should not be the only value considered; the clinical significance of that value and the LOA should be considered as well. In this study, the bias reported for Philips (Sectra), Hologic, and Fujifilm are considered clinically insignificant, being much smaller than the clinical dose. Nonetheless, when considering how wide the LOA are, it can be concluded that a disagreement between organ and calculated doses was found. Furthermore, it should be stressed that vendors using different methods of estimating the organ dose make reporting the dose across systems unreliable, as the dose reported by the three methods differ by up to 19%. Nonetheless, with vendors using various algorithms, some of which are not particularly well

Fig. 4 Linear regression scatter plot that shows the line of best-fit between MGD calculated using Dance method and organ dose displayed by Fujifilm units for 906 digital mammograms. (Fujifilm systems utilize Dance method for the estimation of organ dose).

defined, there is a need for further work to establish a benchmark and allow comparison of doses between systems.

MGD calculation methods are all estimates; they are prone to systematic errors throughout measurement and calculation. Earlier methods of measuring the entrance dose using TLDs, although difficult, time consuming, and having smaller sample sizes, offered more accurate measurements. The bias reported here for some systems was 0.36 mGy, which is 18% of the acceptable dose level of 2.00 mGy reported by the European commission for a 4.5-mm breast thickness.¹¹ This is still within the error value that is reported for the dose calculation methods. However, choosing to use organ dose may risk underestimating the dose by up to an overall average of 0.09 mGy with a range from -0.52 to 0.34 mGy. This range of bias could result in a clinically important discrepancy between calculated and organ dose of up to 0.52 mGy. Considering that the European protocol DRL for a 45-mm breast thickness is 2.0 mGy,¹¹ this could have important implications for reporting doses locally and nationally. Further work might examine actual air kerma using TLDs on select phantoms, such as the ACR phantom and phantoms with different thicknesses.

5 Conclusion

Organ dose was found to disagree with calculated dose, with a bias ranging from -0.24 to 0.36 mGy. However, organ dose is potentially beneficial for rapid dose audits in centers using mammography units of the same make. Conclusions drawn based on the organ dose alone, whether to establish DRLs or for dose audits, come with a risk of over or underestimating the calculated dose to the patient by up to 18% for a standard breast and this error should be considered in any reported results.

Disclosures

The authors have nothing to disclose.

References

1. H. Vainio and F. Bianchini, "Breast cancer screening, IARC handbooks of cancer prevention," in *IARC*, Lyon, pp. 157–170 (2002).
2. K. C. Chu, C. R. Smart, and R. E. Tarone, "Analysis of breast cancer mortality and stage distribution by age for the health insurance plan clinical trial," *J. Natl. Cancer Inst.* **80**(14), 1125–1132 (1988).
3. A. B. Miller et al., "Canadian National Breast Screening Study: 2. breast cancer detection and death rates among women aged 50 to 59 years," *CMAJ* **147**(10), 1477–1488 (1992).
4. L. Nyström et al., "Breast cancer screening with mammography: overview of Swedish randomised trials," *Lancet* **341**(8851), 973–978 (1993).
5. B. Lauby-Secretan et al., "Breast-cancer screening—viewpoint of the IARC Working Group," *N. Engl. J. Med.* **372**(24), 2353–2358 (2015).
6. M. J. Yaffe and J. G. Mainprize, "Risk of radiation-induced breast cancer from mammographic screening," *Radiology* **258**(1), 98–105 (2011).
7. R. M. Ali et al., "A method for calculating effective lifetime risk of radiation-induced cancer from screening mammography," *Radiography* **21**(4), 298–303 (2015).
8. R. Hendrick et al., *Mammography Quality Control Manual*, American College of Radiology, Reston, Virginia (1999).
9. IAEA, *Quality Assurance Programme for Digital Mammography*, Human Health Series. No. 17, IAEA, Vienna (2011).
10. A. Moore, The Commissioning and Routine Testing of Mammographic X-ray Systems: A Protocol Produced by a Working Party of the Diagnostic Breast Screening Quality Assurance Coordinating Group for Physics, Institute of Physics and Engineering in Medicine (2005).
11. N. Perry et al., *European Guidelines for Quality Assurance in Breast Cancer Screening and Diagnosis*, 4th ed., Luxembourg office for

- official publications of the European Communities, Luxembourg (2006).
12. D. Dance, "Monte-Carlo calculation of conversion factors for the estimation of mean glandular breast dose," *Phys. Med. Biol.* **35**(9), 1211–1220 (1990).
 13. D. R. Dance et al., "Additional factors for the estimation of mean glandular breast dose using the UK mammography dosimetry protocol," *Phys. Med. Biol.* **45**(11), 3225–3240 (2000).
 14. D. R. Dance, K. C. Young, and R. E. van Engen, "Further factors for the estimation of mean glandular dose using the United Kingdom, European and IAEA breast dosimetry protocols," *Phys. Med. Biol.* **54**(14), 4361–4372 (2009).
 15. W. T. Sobol and X. Wu, "Parametrization of mammography normalized average glandular dose tables," *Med. Phys.* **24**(4), 547–554 (1997).
 16. X. Wu et al., "Normalized average glandular dose in molybdenum target-rhodium filter and rhodium target-rhodium filter mammography," *Radiology* **193**(1), 83–89 (1994).
 17. J. M. Boone, "Glandular breast dose for monoenergetic and high-energy X-ray beams: Monte Carlo assessment," *Radiology* **213**(1), 23–37 (1999).
 18. J. M. Boone, "Normalized glandular dose (DgN) coefficients for arbitrary X-ray spectra in mammography: computer-fit values of Monte Carlo derived data," *Med. Phys.* **29**(5), 869–875 (2002).
 19. J. M. Boone, T. R. Fewell, and R. J. Jennings, "Molybdenum, rhodium, and tungsten anode spectral models using interpolating polynomials with application to mammography," *Med. Phys.* **24**(12), 1863–1874 (1997).
 20. J. Zoetelief and J. T. M. Jansen, "Calculation of air kerma to average glandular tissue dose conversion factors for mammography," *Radiat. Prot. Dosim.* **57**(1–4), 397–400 (1995).
 21. S. Avramova-Cholakova et al., "An estimate of the influence of the measurement procedure on patient and phantom doses in breast imaging," *Radiat. Prot. Dosim.* **129**(1–3), 150–154 (2008).
 22. M. Borg, I. Badr, and G. J. Royle, "A study to determine the differences between the displayed dose values for two full-field digital mammography units and values calculated using a range of Monte-Carlo-based techniques: a phantom study," *Radiat. Prot. Dosim.* **154**(2), 217–228 (2012).
 23. K. J. Robson, "A parametric method for determining mammographic X-ray tube output and half value layer," *Br. J. Radiol.* **74**(880), 335–340 (2001).
 24. RaySafe, "RaySafe Xi classic specifications," 2015, <http://mediabank.raysafe.com/A/RaySafe+Media+Bank/1599?encoding=UTF-8> (10 October 2016).
 25. RTIgroup, "Piranha specification," 2016, http://rtigroup.com/content/downloads/brochures/Specifications_Piranha.pdf (10 October 2016).
 26. J. B. McCullagh, P. Baldelli, and N. Phelan, "Clinical dose performance of full field digital mammography in a breast screening programme," *Br. J. Radiol.* **84**(1007), 1027–1033 (2011).
 27. M. E. Suleiman, P. C. Brennan, and M. F. McEntee, "Diagnostic reference levels in digital mammography: a systematic review," *Radiat. Prot. Dosim.* **167**(4), 608–619 (2015).

Biographies for the authors are not available.