Clinical dose performance of full field digital mammography in a breast screening programme

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Objective: BreastCheck, the Irish Breast Screening Programme, has employed three different models of a full field digital mammography (FFDM) system since its transition to a digital service in 2007. The three models from GE Healthcare, Hologic and Sectra exhibit differences in their design and function, the most significant of which include anode target/filter choice, detector technology and the type of exposure automation. **Methods:** The aim of this study was to use the results from a clinical breast dose survey to examine the differences between three different FFDM models in terms of exposure selection, breast mean glandular dose (MGD) and automatic exposure control (AEC) dose contribution.

Results: The accuracy of the dose estimation was improved by inclusion of the AEC pre-exposure dose contribution. The photon-counting system demonstrated the lowest average MGD. The GE Healthcare and Hologic flat-panel detector systems demonstrated a small but statistically significant dose difference. The pre-exposure dose contribution did not exceed 13% of the total exposure dose for any system in the survey. A comparison of the system calculated organ dose estimate from each machine with the corresponding MGD calculated from medical physics measurements indicated reasonably accurate organ dose estimates for most systems in the survey.

Conclusion: The results of this study provide a comprehensive assessment of the breast dose performance of current digital mammography systems in a clinical screening setting.

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The nationwide expansion of the Irish breast screening programme in 2007 was accompanied by a transition to full field digital mammography (FFDM) technology. Digital mammography could be still considered as a developing technology and experience with digital mammography in breast screening was limited at the time of the change. The advantages associated with digital imaging with respect to workflow efficiency and productivity are well established while the evidence base for clinical benefit associated with improved breast imaging performance through the adoption of digital imaging for mammography continues to grow [1, 2]. There are other emerging advantages of digital imaging in breast screening, including the potential for radiation dose reduction [3–5]. Currently available digital mammography systems differ from each other in many ways which can affect the patient dose and can provide system dose advantages. The most significant technical factors in digital mammography systems which impact breast dose include the anode target/filter choice, detector technology and the type of exposure automation. There are also other factors which can affect the dose, including applied breast compression and grid type [6]. A standard feature available on all digital mammography systems is the calculation and display of organ dose estimation. This feature

could be a significant factor for the user in the regulation of the patient breast dose.

The Irish National Breast Screening Programme, BreastCheck, invites women in the age range 50–64 years to participate in breast cancer screening every 2 years. All women have two views of the breast taken at each visit. Screening is performed in both static screening units and in mobile units, with all reading performed centrally. Three models of FFDM systems, the General Electric (GE, Buc, France) Essential, Hologic Selenia (Danbury, CT) and Sectra MDM L30 (Solna, Sweden), are used in BreastCheck. These systems offer three distinct options of target/filter combination. They also use three distinct detector technologies: flat-panel phosphor, selenium flat-panel and photon counting. The ongoing development of digital mammography has been accompanied by optimisation of the X-ray beam and detector technology towards minimising breast dose and optimising image quality [7, 8]. The imaging systems used in BreastCheck also employ different approaches to automation of exposures. The type of automation varies depending on the design and purpose of the control. In two models the detector is used as the automatic exposure control (AEC) sensor, which necessitates a pre-exposure, as detector operation entails separate acquisition and image-read phases [9]. This approach differs to that used by the photon-counting detector system, which permits instantaneous AEC sensor operation during image acquisition using the leading edge detector [10]. The aim of the

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automated control is to regulate the signal-to-noise ratio (SNR) or contrast-to-noise ratio (CNR) and, depending on the system design, to ensure the radiation intensities do not exceed the capacity of the detector [9, 10].

Compliance with the European Directive on health protection of individuals against the dangers of ionising radiation in relation to medical exposures 97/43/EURATOM [11] requires that all X-ray units are subject to a patient dose survey at regular intervals. This is emphasised for screening programmes, where the majority of the invited population are asymptomatic. The use of digital imaging offers the advantage that many aspects of the data collection and processing can be automated [12]. The aim of this study was to exploit the results from a comprehensive clinical breast dose survey to examine the differences between three different FFDM models in terms of exposure selection, breast mean glandular dose (MGD) and AEC dose contribution. A comparison of the organ dose estimate from each machine with the corresponding dose calculated by medical physics measurements was also performed.

Materials and methods

A total of 28 X-ray units (11 GE Essential, 10 Hologic Selenia, 7 Sectra MDM L30) encompassing a mixture of static and mobile settings were included in the survey. The GE Essential is powered by a high-frequency multi-phase X-ray generator and has a dual-track anode composed of molybdenum (Mo) and rhodium (Rh) targets in combination with Mo or Rh filters. The Essential has an indirect-conversion flat-panel detector unit composed of an amorphous silicon (a-Si) diode array constructed from a matrix of a-Si thin film transistors (TFTs) deposited on a glass substrate. Thallium-activated caesium iodide (CsI(Tl)) crystals deposited as linear columns on the a-Si detector array enable minimum light divergence from the scintillator. The detector consists of 2394×3062 detector elements, each of $100 \mu\text{m}$ size on a 24×30.7 cm area.

The GE Essential uses a feature called automatic optimisation of parameters (AOPs) to optimise image quality under constraints of breast MGD, exposure time and other technical limitations [13]. It uses a 4 mAs pre-exposure to determine the radiological thickness at the most glandular part of the breast and from this, along with the mechanical compressed breast thickness, the breast composition is estimated. Based on the radiological thickness, the composition and system configuration, the final exposure parameters (target, filter, kV and detector dose) are chosen from a pre-computed AOP table. Finally, the tube current exposure time (mAs) value needed to reach the required detector dose is computed and used to control the exposure. There are three fully automated exposure modes available on the Essential: contrast, standard and dose AOP modes. According to the manufacturer, all three modes are equally optimal in terms of dose *vs* image quality but provide different levels of dose and image quality depending on the user's needs [13]. Thus the contrast mode prioritises image quality, the dose mode prioritises dose and the standard mode gives equal priority to each.

The Hologic Selenia system is equipped with a tungsten (W) anode and a choice of Rh or silver (Ag) filtration. The detector in the Selenia is a flat-panel amorphous-selenium

detector, which performs a direct conversion of X-rays to a digital signal. It comprises a $200 \mu\text{m}$ layer of amorphous selenium bonded to a TFT array. The detector has a pixel pitch of $70 \mu\text{m}$, an array size of 3328×4096 detector elements and provides a field of view of 24×29 cm. The Selenia has four modes of automatic exposure control: auto-filter, auto-KV, auto-time and thickness equivalent control (TEC). All the systems in BreastCheck are operated in the auto-filter mode. In this mode the compressed breast thickness is used to determine the kV and filter selection and the required exposure mAs is determined from a pre-exposure of between 2 mAs and 10 mAs depending on the breast thickness (personal communication, Hologic). There are four selectable operating dose levels on the Selenia that require calibration by a field engineer. These are named standard screening dose, low screening dose, limited dose and auxiliary and correspond to the four nominal dose levels of 1.35 mGy, 1 mGy, 0.6 mGy and 1.8 mGy obtained with 4.5 cm polymethyl methacrylate (PMMA) phantom [14]. All units in BreastCheck are used in the Standard Screening Dose setting. The Sectra MDM L30 is a multiple-slit scanning-photon counting system with a W/Al anode-filter combination. It has a pixel pitch of $50 \mu\text{m}$ and an array size of 4800×5200 with a field-of-view of 24×26 cm. The MDM L30 uses the compressed breast thickness to set the tube potential and sets the initial scan speed to give a specific mAs. It also incorporates a form of exposure control called *SmartAEC*TM, which continuously adjusts the exposure and optimises the dose level to the local density of the breast throughout the scan. The AEC attempts to maintain as far as possible a constant CNR [10]. There are three dose operating levels on the MDM: C120, C100 and C70. The C100 dose configuration corresponds to measures of image quality that meet the acceptable limiting values in the European Guidelines [15]. The C120 configuration corresponds to measures of image quality with 20% greater CNR and the C70 configuration corresponds to measures of image quality with 30% lower CNR. All units in BreastCheck are set to the C120 level.

All X-ray units in the breast screening programme are operated using automated selection of exposure factors. The control mode used depends on the model of machine and all models of one particular type are operated in the same mode. Thus the GE Essentials are set to STD mode, the Lorad Selenia units are set to auto-filter mode and the Sectra units operate in the only automatic exposure control mode available. The choice of control mode and dose level was based on the manufacturer's recommendations provided the resultant image quality was consistent with the requirements of the European Guidelines [16]. The change to the C120 configuration on the Sectra units was made once it was found that acceptable image quality could not be obtained at the C100 setting. All systems in the survey estimate the organ dose per exposure and display it on the console following an exposure. The Sectra MDM L30 uses the Dance [17–19] conversion factors, whereas, the GE Essential and Hologic Selenia models both use the conversion factors published by Wu et al [20].

The images from at least 100 examinations from each digital mammography system acquired over a 3 month period between July and September 2009 were downloaded from the picture archiving and communication

system (PACS) system. The exposure data for the survey were obtained from images stored on the central archive of the BreastCheck PACS system. The parameters required for dose calculation are stored in the Digital Imaging and Communications in Medicine (DICOM) header. Once the examinations for each system were downloaded from the PACS the parameters could be extracted from the DICOM headers using a locally developed Matlab routine (Mathworks, Cambridge, UK) and transferred to a Microsoft Office Excel spreadsheet for further analysis. The parameters extracted from the header for this survey included the patient's identification, age, compressed breast thickness, compression force, view position, laterality, exposure voltage, exposure mAs, target material, filter material and organ dose.

The MGD for each acquired image was calculated according to Dance et al [17–19] using the formula:

$$\text{MGD} = Kgc s \quad (1)$$

where K is the entrance surface air kerma (ESAK) at the upper surface of the breast and g , c and s depend on both X-ray beam and breast characteristics. In particular, the factor s corrects for any difference due to the use of an X-ray spectrum different from Mo/Mo. K was calculated from the tube output a fixed distance above the detector, the tube current exposure time (mAs), the source-to-detector distance and the thickness of the compressed breast. Values for K and the half-value layer (HVL) for each unit in the survey were obtained from medical physics quality assurance test results contemporaneous with the survey period. Once the acquisition parameters were extracted from the DICOM header file, dose calculation was carried out using software developed by KC Young for the National Health Service Breast Screening Programme (NHSBSP) [21] with some modification made to take into account new c , g and s factors for HVL values associated with the spectral data for new mammography systems. Further modifications were made to the dose calculations to account for the larger HVL found in the new mammography systems. The s -factor values used in dose calculations with tungsten/aluminium target/filter combinations were obtained from a table of s factors provided by Dance et al [19]. The examination MGD was calculated by summing the dose from all exposures and averaging over both breasts [22].

The Essential stores the pre-exposure factors in a separate field to the main exposure factors in the DICOM header. These were extracted and the associated dose contribution was added to the total dose for each image. The pre-exposure mAs for images acquired by the Selenia were determined using a simple algorithm (personal communication, Hologic).

The accuracy and reproducibility of tube voltage, X-ray tube outputs and HVL measurements for different kVp settings and target/filter combinations are periodically checked following the recommendations of the European Protocol [16]. The accuracy of the measurement of compressed breast thickness is also regularly checked, in accordance the procedures recommended in the European protocol. Radiation output values were measured with a number of Radcal ionisation chamber devices (model 10X6-6M, Radcal Corp., Monrovia, CA), each factory calibrated within the previous 12 months.

Exposure time and voltage measurement were performed, where possible, with a Radcal Accu-kV TM kV block (Model 40X10-10, Radcal). Otherwise invasive voltage measurements were performed by service engineers. The overall dependence of breast dose on model type was tested through a one-way analysis of variance (ANOVA) F -test using Microsoft Office Excel 2003. A two-sample t -test with unequal variance performed on the Matlab Statistics Toolbox 7 (Mathworks, Cambridge, UK) was used for comparisons of breast MGD and examination dose between models.

Results

There were 2910 examinations included in the survey. Extra views were performed in 12% of examinations. The image data included 5817 craniocaudal (CC) and 5817 mediolateral oblique (OB) views, 230 extra CC views and 240 extra OB views. Data cleaning removed a total of 52 (1.7%) patients from the original survey data for a variety of reasons, including patients with implants, patients outside the age range of the programme, incorrect manual exposures and incorrect breast paddle selection by the users on the Sectra systems. Thickness accuracy varied depending on the system type. It was typically less than 1 mm for the Essential and approximately 2 mm for the Selenia and the MDM L30. Over the period of the survey the X-ray tube voltage accuracy was typically 0.4 kV and reproducibility was 0.1 kV on the GE Essential; kV meter calibrations were not available for spectra of the other systems. Some of the Selenia systems were assessed by invasive tube potential measurement with the assistance of field service engineers and typically the accuracy was <0.5 kV and reproducibility was <0.1 kV. We achieved accurate calibration of the non-invasive kVp meters for the Selenia and Sectra systems recently, and retrospective measurement demonstrated good accuracy and consistency. Comparison of current HVL measurements with those made during the survey allows inference of tube potential accuracy during the survey period. Measurements of the tube output and HVL were stable on Essential and Selenia systems over the period of the survey. Typically the coefficient of variation (CV) of the tube output was less than 4% and the CV of the HVLs was less than 3% for both systems. The Sectra tube output quality assurance (QA) data were less stable (CV ~12%) so the HVL measurements and the tube output measurements were repeated on all the Sectra units in the survey. The resulting measurements of HVL were all within 0.03 mmAl of the corresponding Sectra reference values (personal communication, Sectra).

The compression force recorded in the survey ranged from 22 N to 215 N and from 22 N to 273 N for the CC and OB views, respectively. The mean compression force applied was 100 N and 119 N for the CC and OB views, respectively. As shown in Table 1, these values are very close to the mean compression forces recorded on the individual models. The compressed breast thicknesses recorded in the survey ranged from 14 mm to 109 mm for CC views and 17 mm to 107 mm for OB views. The mean compressed breast thickness was 60.5 mm and 63 mm for the CC and OB views, respectively. Regarding the differences between systems (Table 1) included in

Table 1. Average breast dose, thickness and compression according to model (errors represent 95% confidence limits)

Model	View	Average MGD per exposure (mGy)	Average thickness (mm)	Average compression (N)
MDM L30	CC	0.90 ± 0.01	64.5 ± 0.6	102 ± 2
	OB	0.88 ± 0.01	64.9 ± 0.7	123 ± 2
Selenia	CC	1.36 ± 0.02	61.6 ± 0.5	99 ± 1
	OB	1.44 ± 0.02	63.4 ± 0.6	119 ± 2
Essential	CC	1.39 ± 0.01	57.1 ± 0.5	100 ± 1
	OB	1.52 ± 0.02	61.3 ± 0.6	119 ± 1

CC, craniocaudal; OB, mediolateral oblique. MGD, mean glandular dose.

this survey, the difference between the mean compressed thickness were statistically significant for both the CC views ($F(2, 6044) = 210, p < 0.001$, mean square (MS) = 14;150, ANOVA single factor test) and the OB views ($F(2, 6054) = 35, p < 0.001$, MS = 210, ANOVA single factor test). It may be observed from Table 1 that the largest mean compressed thickness among the three systems was recorded on the MDM L30 for both the CC and OB views. The difference in the CC mean compressed breast thickness measured on the MDM L30 and the Selenia was 2.9 mm, with a 95% confidence interval from 2.3 mm to 3.9 mm, and similarly, the difference in the OB mean compressed breast thickness was 1.6 mm, with a 95% confidence interval from 0.7 mm to 2.6 mm. The difference in the CC mean compressed breast thickness measured on the Selenia and the Essential was 4.5 mm, with a 95% confidence interval from 4.2 mm to 5.6 mm, and the difference in the OB mean compressed breast thickness was 2.1 mm, with a 95% confidence interval from 1.4 mm to 3.1 mm.

As shown in Table 2, the most common target/filter combination recorded in the survey was Rh/Rh (35%). The other commonly used combinations were W/Rh (24.3%) and W/Al (25%). The Mo/Mo target/filter combination was selected in only 0.3% of examinations included in the survey. As dictated by the auto-filter control mode, the target/filter and tube voltage selection on the Selenia depended on the breast thickness. The W/Rh combination was selected for breast thicknesses up to 70 mm and W/Ag was selected for greater breast thicknesses. The selected voltage increased with thickness and ranged between 26 kV and 32 kV for the W/Rh combination and between 27 kV and 36 kV for the W/Ag combination. The histogram in Figure 1 shows that voltage selection peaked for 28 kV for both the W/Rh and W/Ag combinations with a greater preference toward higher voltage selections for the latter combination. The majority of exposures on the Sectra MDM unit were performed at 35 kV (76.7%). The results from the survey indicated that tube potential selection varied with breast thickness with some variation in the switching

point between units. For smaller breast thicknesses (less than 45 mm), 32 kV (7.8%) was selected and for the larger breast thicknesses (greater than 70 mm), 38 kV (15.3%) was selected. As GE automatic exposure selection depends on both compressed breast thickness and density, this would have suggested a varied combination of selections due to differences in density for similar thicknesses. However, most exposures (71.7%) occurred at a single target/filter combination and voltage selection (29 kV Rh/Rh). These factors were selected for breast thicknesses ranging between 30 mm and 84 mm. The remaining recorded exposures were 1 of 3 predominant combinations: 27 kV Mo/Rh (8.5%), 30 kV Rh/Rh (7%) or 31 kV Rh/Rh (9.7%). Analysis of the survey results indicated that the 27 kV Mo/Rh combination was selected for thicknesses ranging between 22 mm and 58 mm, 30 kV Rh/Rh was selected for thicknesses ranging between 56 mm and 106 mm, and 31 kV Rh/Rh was selected for thicknesses ranging between 51 mm and 91 mm. The overlap of these compressed thickness ranges were most likely a reflection of dependence of the AOP operation on both breast thickness and density.

The average pre-exposure dose recorded in the survey was 110 µGy for all views. The range of pre-exposure doses measured in the survey ranged from 23 µGy up to 250 µGy. The pre-exposure dose as a percentage of the total exposure dose was calculated for each image and Figure 2 shows a plot of the average values *vs* the compressed breast thickness for the Hologic Selenia and GE Essential systems in the survey. The pre-exposure dose percentage ranged from 3% to 9% for the Essential and ranged from 6% to 13% for the Selenia. As can be seen from Figure 2, the AEC pre-exposure dose levels were comparable for the two models with the Selenia slightly larger.

Table 1 demonstrates that the Sectra MDM L30 clearly has the lowest MGD of the three systems for both views. The average MGD for the Essential was slightly greater

Table 2. Proportion of exposures using the different target/filter combinations

Target/filter combination	Proportion of exposures (%)
Mo/Mo	0.3
Mo/Rh	3.9
Rh/Rh	35.0
W/Rh	24.3
W/Ag	11.6
W/Al	25.0

Figure 1. Histogram of tube potential and target/filter selection for the Selenia.

Figure 2. Plot of the average of the pre-exposure dose percentages vs compressed breast thickness.

than the Selenia. A two sample *t*-test with unequal variance revealed a significant difference between the Essential and the Selenia for the CC view, *t* (degrees of freedom (df), 4172)=2.9, *p*=0.004, whereby the Essential had a larger CC MGD (2.4%). Similarly, there was a significant difference for the OB view, *t* (df, 4133), *p*<0.0001, whereby the Essential had a greater OB MGD (4.6%). The average examination dose for each model in the survey is shown in Table 3. The examination dose for the MDM L30 was over 30% lower than that for the other two models in the survey. There was a significant difference in examination dose between the Essential and the Selenia, *t* (df, 1957)=2.54, *p*=0.005, whereby the Essential had a greater MGD (4.1%) than the Selenia. The average MGD per view for both CC and OB views for each model in the survey are shown as a function of compressed breast thickness in Figure 3. All three models demonstrate increasing mean glandular dose with increasing breast thickness. The breast dose with the MDM L30 appears to plateau for breast thicknesses greater than 60 mm.

Table 4 shows the average MGD per exposure obtained by measurement with the average MGD per exposure obtained from the displayed doses, and the percentage differences for each type of system in the survey. It is clear the measured and displayed estimates were reasonably close for the GE Essential and Hologic Selenia systems but less so for the Sectra systems with a difference of almost 20%. When the Sectra dose calculations were repeated using a single *s* factor only (*s*=1.05) the comparison between measured and displayed estimates was much better (9.6% and 9.4% for the CC and OB views, respectively). The average difference between

Table 3. Examination dose according to model (errors represent 95% confidence limits)

Model	Average MGD per examination (mGy)	Examination dose range (mGy)
MDM L30	1.86 ± 0.04	0.71–4.2
Selenia	2.91 ± 0.06	0.8–9
Essential	3.03 ± 0.05	1.3–12.2

MGD, mean glandular dose.

Figure 3. Average mean glandular dose per view as a function of compressed breast thickness.

the measured and displayed dose was calculated over a nominal range of breast thicknesses to assess the equivalence between measured and displayed dose over a nominal range for each unit. The system in best agreement had an average difference of 2.1% and the system in least agreement had an average difference of 22%. Only 50% of the units in the survey, of which only one was a Sectra unit, gave an average difference between measured and organ dose of less than 10%. This percentage improved when the Sectra dose calculations were repeated with a single *s* factor (*s*=1.05) in which case all the Sectra units gave an average difference between measured and displayed of less than 10%.

Discussion

The mean compression forces recorded in the survey were very similar between the different systems. The overall mean compression forces observed are similar compared with the values recorded on digital mammography systems by Hendrick et al [23]. The range of compression forces measured in this survey compare well with results obtained by Chevalier et al [12] even though they found that most compressions lay in the range of 190 N to 210 N. Better comparison was found with results obtained by Rosenberg and Hunt [24], who recorded mean compression forces of 71 N and 107 N for CC and OB views, respectively. They found that the most frequent users of the system were using compression forces between 80 N and 134 N.

The range and distribution of compressed breast thicknesses measured for all views in this survey were similar to results obtained by Chevalier et al [12] and Young et al [22]. The mean breast thicknesses for CC and OB views found in this survey were greater than that found in older surveys. For example, Young et al [22] found an average compressed breast thickness of 56.8 mm and 54.1 mm for oblique and craniocaudal views, respectively, and Hendrick et al [23] recorded a mean compressed breast thickness of 54 mm. A more recent study by Robinson and Kotre [25] found an average compressed breast thickness of 60 mm which is comparable to this study. Robinson and Kotre [25] explained the increase in compressed breast thickness since the earlier surveys as due to an associated increase in the proportion of women in the breast screening age range classified as overweight and obese. Robinson and Kotre [25] did not completely eliminate changes in equipment design and differences between different models as a cause of an overall upward

Table 4. Measured and displayed mean glandular dose (MGD) breast dose according to model

Model	View	Measured average MGD per exposure (mGy)	Organ dose average MGD per exposure (mGy)	Percentage difference (%)
MDM L30	CC	0.90 ± 0.01	0.72 ± 0.01	19.6
	OB	0.88 ± 0.01	0.71 ± 0.01	19.7
Selenia	CC	1.36 ± 0.02	1.24 ± 0.02	8.6
	OB	1.44 ± 0.02	1.31 ± 0.02	8.8
Essential	CC	1.40 ± 0.01	1.34 ± 0.01	4.2
	OB	1.52 ± 0.02	1.44 ± 0.02	5.1

CC, craniocaudal; OB, mediolateral oblique.

trend. Differences in equipment design were also evident from the results in this survey which showed a significant difference in the measurement of compressed breast thickness between different models. A useful finding in the survey revealed that less than 0.25% of breast thicknesses exceeded 100 mm. This result alleviates concerns raised about the Sectra MDM L30 as it originally had a maximum compression thickness of 100 mm which has recently been extended to allow a maximum thickness of 105 mm.

In the survey by Young et al [22] conducted in the period 2001/2002, where all systems were using film/screen, the beam quality results indicated that Mo/Mo usage was 58.5%. The results from this survey of an entirely digital screening programme reveal the significant decline in the use of Mo/Mo (0.3%). There was an obvious difference in the pattern of beam selection between the Selenia and the two other systems in the survey. Beam quality selection on the Selenia exhibited a continuous relationship with compressed breast thickness whereas the two other systems appeared to operate over a limited discrete number of selections. The majority of exposures on the Sectra unit were performed at one exposure voltage with one lower voltage selection for the smaller breasts and one larger voltage selection for the larger breasts. Similarly the beam quality selection range for the GE Essential was dominated by a limited number of combinations. This approach may reflect the basis of the automated control in each of the systems. Automated control of the Sectra and Essential is designed to regulate the CNR in the image whereas the purpose of control in the Selenia is to regulate the image pixel count across compressed thickness [10, 13, 26].

Although the recent publication by Hendrick et al [23] is one of the few studies which have compared the dose performance of different digital systems, it was based on data collected between 2001 and 2003. There have been significant developments since, so this study could be considered a more current reflection of FFDM dose performances. The photon-counting system demonstrated a significantly lower average MGD result than the other two systems which was consistent with the literature [10]. Notwithstanding the significant dose difference, objective and subjective image quality results indicate that all systems in the survey are consistent with the image quality requirements of the European Guidelines [16]. By the inclusion of the pre-exposure dose with the image exposure dose the accuracy of the dose estimates for the Essential systems in the survey was improved. Thus the difference in average MGD between the Essential and Selenia was smaller and so neither system exhibited much dose advantage over the other. As expected, the average

MGD increased with compressed thickness for all systems included in the survey. Figure 3 clearly demonstrates the lower breast dose of the MDM L30 *vs* the other two models across the range of breast thicknesses in the survey. The Selenia has a lower breast dose for smaller breasts than the Essential. The rate of increase in dose with breast thickness appears to be similar for all three models except the dose level of the Sectra unit, which plateaus for breast thicknesses greater than 60 mm.

On initial calculation the GE Essential and Hologic Selenia systems provided similar estimates of measured and organ dose for the average MGD to the breast whereas the Sectra units were significantly different. This was contrary to expectation as this system uses the same Dance et al [17, 18] conversion factors as used by the dose calculation software, whereas the GE Essential and Hologic Selenia models both use the conversion factors published by Wu et al [20]. However, when the Sectra dose calculations were repeated using a single *s* factor the comparison between the measured and organ dose was commensurate with other systems in the survey. Similarly, it was found the average difference between the measured and the organ dose over a nominal range of compressed breast thickness improved for all the Sectra systems when the dose calculations were repeated with a single *s* factor. Although the Sectra organ dose calculation is compliant with European Guidelines this result indicates the organ dose is less consistent with the most recent recommendations from Dance et al [19].

Conclusion

These results are a current indication of the clinical dose performance of a number of different types of modern FFDM systems in use in a breast screening programme. The lowest breast dose values were recorded on the photon-counting systems and similar dose values were recorded on the two flat detector systems. Although routinely performed QA ensure that image quality performance is consistent with European guidelines there is scope for further investigation of dose in combination with image quality performance.

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