

PATIENT DOSES FROM SCREEN-FILM AND FULL-FIELD DIGITAL MAMMOGRAPHY IN A POPULATION BASED SCREENING PROGRAMME

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The aim of this study was to compare mean glandular dose (MGD) in all full-field digital mammography (FFDM) and screen film mammography (SFM) systems used in a national mammography screening program. MGD from 31 screening units (seven FFDM and 24 SFM), based on an average of 50 women at each screening unit, representing 12 x-ray models (six FFDM and six SFM) from five different manufacturers were calculated. The MGD was significantly lower for FFDM compared to SFM (craniocaudal (CC): 1.19 mGy versus 1.27 mGy, respectively, mediolateral oblique (MLO): 1.33 mGy versus 1.45 mGy, respectively), but not all of the FFDM units provided lower doses than the SFM units. Comparing FFDM's, the photon counting scanning-slit technology provides significantly lower MGDs than direct and indirect conversion digital technology. The choice of target/filter-combination influences the MGD, and has to be optimized with regards to breast thickness.

The advantages with FFDM are among others: a wider dynamic range [1] and a linear relationship between dose and signal intensity. A phantom study showed that FFDM provide lower doses than SFM [2]. The finding is supported in clinical studies [3-5]. Studies of FFDM have been conducted in order to find the target/filter materials that are optimal with respect to MGD [6] and image quality [7, 8]. It was found that softer x-ray beams are more advantageous for thin breasts and harder x-ray beams are more advantageous for thick breasts for low-contrast detection [7]. Williams et al. [8] found that the automated exposure control (AEC) of the FFDM systems were able to select exposure factors that were optimal with regard to the figure of merit (FOM), defined as the signal-to-noise ratio squared divided by the MGD, but for the Siemens Novation DR, Hologic/Lorad Selenia and GE Senographe 2000D, that all are operating in the NBCSP, there were room for improvements. Earlier studies comparing SFM and FFDM have compared radiation doses from one FFDM with one or more SFM systems [2-5]. The aim of our study is to compare the MGD per exposure from different manufacturers and models of SFM and FFDM systems.

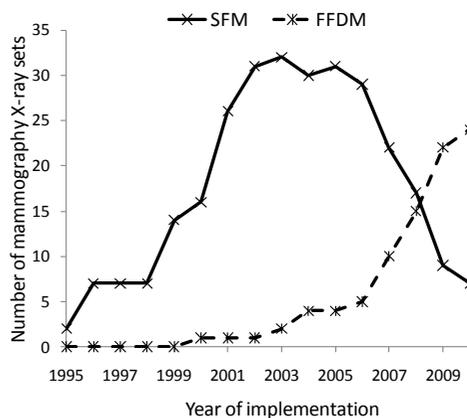


Figure 1. Change in the distribution of screen-film and full-field digital mammography units used for screening in the Norwegian Breast Cancer Screening Program from its start up in 1995 and of today (end of 2009).

MATERIALS AND METHODS

In the Norwegian Breast Cancer Screening Program (NBCSP) [9] the first full-field digital mammography (FFDM) unit, a GE Senographe 2000D, was installed in 1999 and digital systems is gradually replacing SFM (Fig. 1). Several systems from different manufacturers are represented (General Electric (GE), Hologic/Lorad,

Instrumentarium, Sectra, Siemens). As of today, FFDM outnumbers SFM.

Medical use of x-ray, including screening programmes, is regulated in Norway by the “Act and regulations on radiation protection and use of Radiation” [10]. When the NBCSP started, the Norwegian Radiation Protection Authority (NRPA) was given a particular mandate on quality assurance (QA). Daily quality controls are performed by the local radiographers in accordance with a quality manual [11, 12]. Annual quality controls are performed by a group of medical physicists centralized at the NRPA. The tests performed follow the quality manual for SFM [11] and to a large extent the European guidelines for FFDM [13, 14].

Technical parameters

As part of the quality assurance programme, the breast clinics are obligated to report technical parameters for 50 women to the NRPA upon request [11, 12], in order to calculate and monitor the doses delivered to the women participating in the screening program. The radiation output and half-value layer was measured by the NRPA for the applied radiation qualities. This was done as part of the annual quality control in close proximity to the collection of technical parameters.

This study is based on technical parameters collected from 1567 women examined at 31 screening units in the study period September 2006 – October 2008: 24 SFM x-ray units and seven FFDM mammography units (Fig. 2). At each screening unit, parameters from approximately 50 (range: 46-53) examinations were collected.

The mean age of the screened women was 58 years (range: 48-70 years); 58 years for FFDM and 57 years for SFM. The difference in age between SFM and FFDM was not statistically significant ($p=0.30$).

31 women were excluded from the data set, 16 due to lack of one or more technical parameters for the examination and an additional 15 due to a compressed breast thickness less than 20 mm for one or more projections. Dance et al. [15] have only published conversion factors in order to estimate the MGD for breast thicknesses 20 mm or larger. Instead of extrapolating the factors for thicknesses smaller than 20 mm, the 15 women with compressed thicknesses smaller than 20 mm were excluded from this study.

Thus, the total number of women included was 1536. For each exposure the tube potential (kVp), target/filter combination, tube current, exposure time product (mAs), compressed breast thickness and

applied compression force were recorded. In addition, the average OD or alternatively the specifications of the digital detector was recorded for SFM and FFDM, respectively. Data on compression force was however missing from two units (Hologic/Lorad Selenia and Sectra MicroDose Mammography D40).

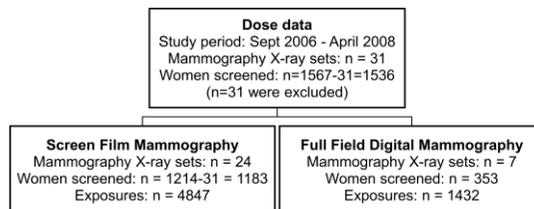


Figure 2. Distribution of mammography x-ray sets, screen film mammography (SFM) and full-field digital mammography (FFDM) x-ray sets, number of women screened and number of exposures.

SFM systems

Six SFM systems from General Electric (GE Medical Systems, Buc, France), Instrumentarium (now owned by GE) and Siemens (Siemens Medical Systems Erlangen, Germany) are represented. GE Senographe 800T (GE 800T) and GE Senographe DMR (GE DMR) have AEC that bases its choice of target/filter/kVp/mAs on the density of the breast. A short pre-exposure is given in order to find the correct choice of target/filter/kVp/mAs. For the Instrumentarium Alpha (I-Alpha), Instrumentarium Diamond (I-Diamond), Siemens Mammomat 300 (Siemens 300) and Siemens Mammomat 3000/3000 Nova (Siemens 3000) the exposure values are determined by the compressed breast thickness. Siemens 3000 has four pre-programmed choices of target/filter/kVp for four different thickness intervals.

Four SFM systems (three Siemens 300 and one Siemens 3000) had only one target/filter combination. Five SFM systems (three Siemens 300 and two Siemens 3000) did not have, or chose not to use, automatic parameter selection.

All SFM units had film/screen detector systems delivered by Kodak, Rochester, NY, USA. The film/screen combination used for the 24 SFM systems was either Kodak Min-R 2000/Min-R 2190 (Min-R 2000, 29%, 7/24) or Kodak Min-R EV/Min-R EV190 (Min-R EV 71%, 17/24), Min-R EV has a slightly better resolution than Min-R 2000 [16]. It is recommended that the optical density (OD) for Min-R EV be set at a higher level (1.8-2.0 instead of 1.4-1.6), because the shoulder of the characteristic curve is very high [16].

OD for the SFM units was estimated by averaging OD from the daily phantom exposures over the same month that the collection of the technical parameters

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had been conducted. Data on film OD was supplied by the breast clinics and obtained for 21 of the 24 SFM units. The distribution between the two film/screen detector systems was 24% (5/21) Min-R 2000 and 76% (15/21) Min-R EV. One GE 800T (n=1/1, 100%), one GE DMR (n=1/1, 100%), four (n=4/6, 67%) I-Diamond systems and one (n=1/3, 33%) Siemens 300 system all used Min-R 2000, but data on OD was missing for GE 800T and GE DMR. Data on OD for one Siemens 300 utilising Min-R EV was missing

For the 21 SFM systems the mean film OD was 1.66 ± 0.08 (range: 1.40-1.91). The OD was 1.65 ± 0.20 for Min-R 2000 and 1.66 ± 0.09 for Min-R EV. In the NBCSP the lower limit is 1.20 for the OD, and the upper limit is 1.80. A total of 86% (n=18/21) had an average film OD within the reference value 1.20-1.80. One Siemens 300 (using Min-R 2000), one Siemens 3000 (using Min-R EV) and one I-Diamond (using Min-R EV) had an average OD higher than 1.80.

SFM operates with two different image formats, standard size (18 cm x 24 cm) and large size (24 cm x 30 cm). For two of the 24 SFM x-ray sets (8%) only the standard size image format was used. Standard size image format was used in 89% of the exposures performed on SFM sets.

FFDM systems

The FFDM systems included six models from four manufacturers (GE, Hologic Inc. (Bedford, MA, USA), Sectra (Linköping, Sweden) and Siemens). The detector size and detector technology differs between the systems (Table 1). The GE Senographe 2000D (GE 2000D) model was replaced by GE Senographe DS (GE DS), and the latest model from GE is the GE Senographe Essential (GE Essential). Improvements for the GE Essential are: larger detector, completely new tube design and better performance for the detectors. Sectra uses a photon counting scanning-slit detector that counts the individual x-rays detected. This way, the electronic noise is reduced, and by utilising a high energy spectrum this reduces the patient dose by 55-65% [17, 18]. The name of the model from Sectra included in this study is Sectra MicroDose Mammography D40 (Sectra D40).

For GE 2000D and GE DS only a standard detector format is available. Automatic selection of target, filter and tube voltage (kVp) is available, and applied, for all FFDM systems. GE 2000D, GE DS and GE Essential use a similar automatic exposure control system as the GE 800T and GE DMR.

For the Hologic/Lorad Selenia (Selenia) the kVp is chosen by applying a lookup table based on compressed breast thickness. Siemens Mammomat Novation DR (Novation) uses a similar AEC as

Siemens 3000. For both systems the beam quality is selected based upon the compressed breast thickness.

Information regarding image size was supplied for all but two FFDM systems (5/7, 86%). Standard image format size was used in 71% of the exposures performed on FFDM sets, for which information on image size was provided.

Mean glandular dose (MGD)

MGD per exposure was estimated based on the reported exposure factors from the women attending screening, and a model published by Dance et al. based on Monte Carlo simulations [15]:

$$MGD = Kgcs \quad (1)$$

Here K is the entrance surface air kerma without backscatter, while g, c and s are conversion factors to account for both x-ray beam characteristics and breast composition (various percentages of fat and glandular tissue). The s-factors used for Mo/Mo, Mo/Rh, Rh/Rh and W/Rh were those listed in Dance et al. (2000). The value 1.05 was applied for the W/Al target/filter-combination, as suggested in Hemdal et al. [19], but the s-factor for W/Al has since been modified by Dance et al. [20]. Dance et al. have found that different s-factors for the W/Al target/filter-combination apply for different thicknesses. When applying the s-factors for W/Al found by Dance et al., our estimated MGDs were on average 9% lower than the MGDs estimated when using the new s-factors.

The tube output (mGy/mAs) and the half value layer (HVL) were measured for all the screening units and all applied beam qualities (target/filter/kVp). These measurements were performed with an ionization chamber assembly (Radcal Corporation, Monrovia, CA, USA) and with the compression plate in the radiation field. High purity (99.9%) aluminium foils were used when measuring the half value layer. For all the screening units, with the exception of the Sectra unit, the centre of the ion chamber was placed 60 mm in from the chest wall side of the breast support edge and 45 mm above the table, and centred laterally. The aluminium foils were placed in the compression plate approximately 180 mm from the breast support table. The Sectra unit has a multi-slit pre-collimator that scans 115 mm above the breast support table, and the compression paddle and aluminium foils therefore had to be placed closer to the breast support table [19]. For the Sectra unit, the HVL was measured in a narrow beam geometry by placing a lead diaphragm on the compression plate, underneath the aluminium foils.

For the analysis of MGD with respect to the type of equipment, the MGD per exposure (CC and MLO) was used as parameter. The MGD per examination was

found by adding the MGD per exposure for all the exposures conducted per woman and dividing the sum by a factor of two (since the breast “as organ” consists of two breasts). The quality manual [12] states that one craniocaudal projection (CC) image and one mediolateral oblique (MLO) image is to be performed for each of the two breasts. The MGD per examination was estimated without any extra frames.

A two-tailed t-test with significance level 0.005 was used to analyze the significance of the difference between SFM and FFDM, the different equipment models, etc.

RESULTS

Average MGD per exposure varied substantially between the screening units (range: 1.27 mGy (CC), 1.44 mGy (MLO) (Fig 3).

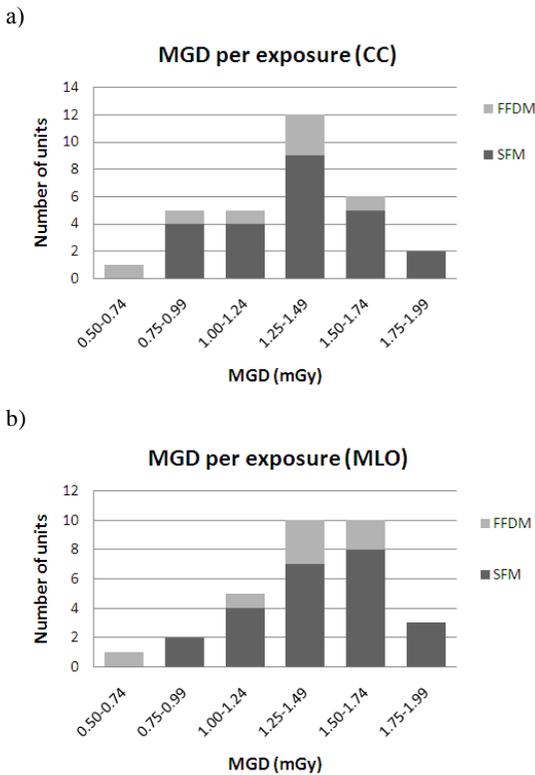


Figure 3. Average MGD per exposure for the screening units for a) the craniocaudal (CC) and b) the mediolateral oblique (MLO) projection.

The smallest average MGD per exposure was found for a Sectra D40 unit, the largest for a I-Diamond. The variation in average MGD was larger for the seven FFDM units (CC: 59.2%, MLO: 59.9%) compared to

the 24 SFM units (CC: 55.5%, MLO: 57.8%). Some x-ray models were represented by multiple units and for these the smallest range in average MGD for the same x-ray set model was found for GE Essential (range: 0.10 mGy (CC), 0.08 mGy (MLO)) and the largest range was found for Siemens 300 (range: 0.70 mGy (CC), 1.00 mGy (MLO)).

The number of exposures per woman varied from 2 to 13, resulting in an average of 4.1 images per woman. The distribution of MGD per examination per screening unit, without any extra images, is shown in Fig. 4. Overall, the average MGD per screening examination was 2.71 mGy (range: 1.31–3.87 mGy).

The range in MGD for one single image was larger for SFM than for FFDM (FFDM: 0.33-3.26 mGy (CC) and 0.30-3.12 mGy (MLO), SFM: 0.24-6.34 mGy (CC) and 0.09-7.10 mGy (MLO)).

The MGD was 11.5% lower for FFDM compared with SFM for the CC projection and 12.4% lower for the MLO projection (Table 2). The difference was statistically significant for both projections (p<0.001).

The variation in average MGD between the different FFDM x-ray models (CC: 59.6%, MLO: 60.0%) was larger compared to the variation in average MGD for the different SFM x-ray models (CC: 35.4%, MLO: 30.0%).

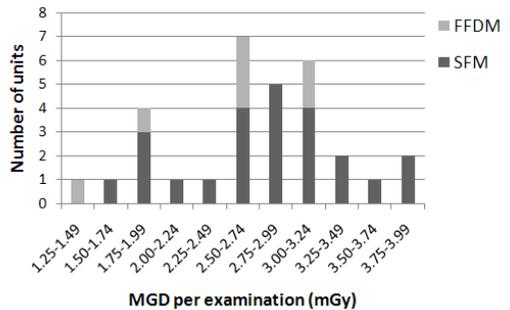


Figure 4. Average MGD per examination, without any extra images, for all the screening units.

Applied target/filter combinations for the units

Figure 5 shows the applied target/filter combinations for different thicknesses for the CC projection for SFM and FFDM. The results for the MLO projection have been omitted, but are similar to the CC projection.

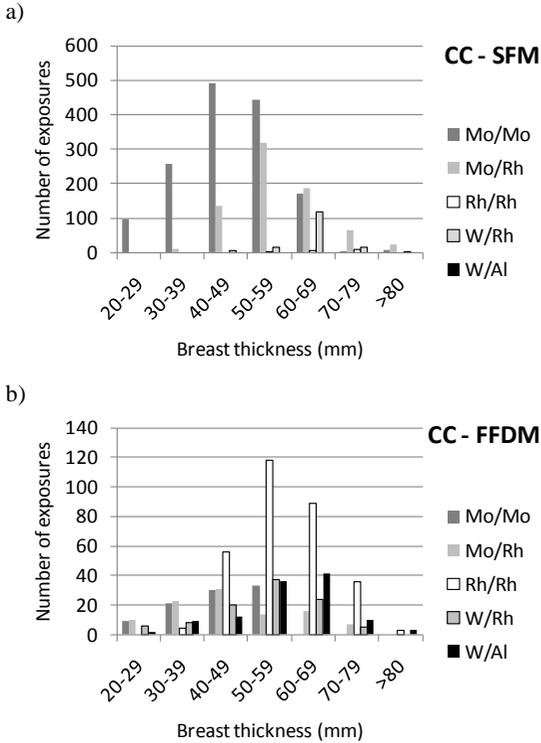


Figure 5. Selection of target/filter combination based on compressed breast thickness (mm) for a) screen-film mammography (SFM) and the craniocaudal (CC) projection and b) full-field digital mammography (FFDM) and the CC projection.

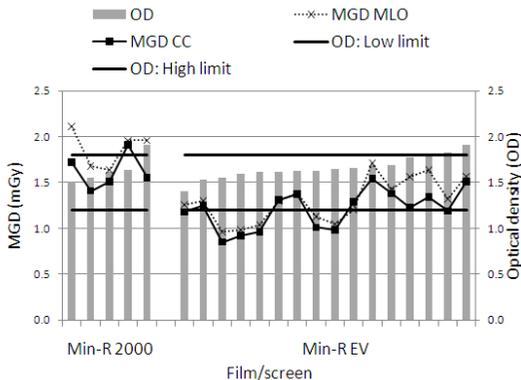


Figure 6. The mean glandular dose (MGD) as a function of optical density (OD) for the two film/screen combinations Kodak Min-R 2000/Min-R 2190 and Kodak Min-R EV/Min-R EV190. Also shown are the limits in use for the OD in the Norwegian breast cancer screening program.

Different film/screen combination: implication on mean glandular dose (MGD)

The OD was not statistically different for the two film/screen combinations Min-R 2000 and Min-R EV ($p=0.844$), but the average MGD for the systems using Min-R EV (CC: 1.22 ± 0.02 mGy, MLO: 1.32 ± 0.03 mGy) was significantly smaller (CC: $p=0.001$, MLO: $p<0.001$) than for the systems utilising Min-R 2000 (CC: 1.22 ± 0.02 mGy, MLO: 1.32 ± 0.03 mGy) (Fig. 6).

The average MGD for the FFDM systems are not significantly different (CC: $p=0.128$, MLO: $p=0.031$) from the average MGD for the systems utilising Min-R EV.

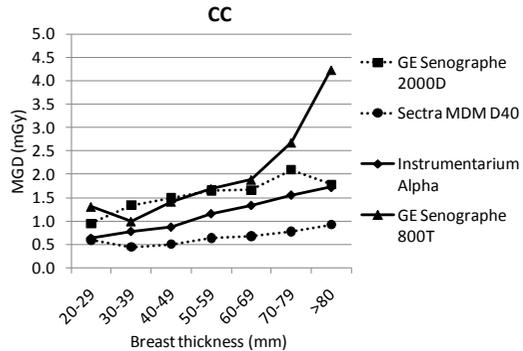


Figure 7. The distribution of MGD per exposure for one SFM and one FFDM system that provided the smallest MGD and one SFM and FFDM that provided the largest MGD.

Different target/filter combination: implication on mean glandular dose (MGD)

With the exception of the thinnest compressed breasts (20-29 mm), Sectra D40 provided the lowest MGD (Fig. 7).

For breasts with compressed breast thicknesses ≥ 50 mm the doses were significantly smaller for FFDM than for SFM ($p<0.001$ (CC and MLO)) (Fig. 8).

Table 3 shows the MGD for the target/filter combination chosen for SFM and FFDM for the CC projection for breasts with thicknesses 20-49 mm and ≥ 50 mm.



Figure 8. The average MGD (mGy) for SFM and FFDM systems versus compressed breast thickness (mm) for craniocaudal (CC) and mediolateral (MLO) oblique projection.

DISCUSSION

MGD for FFDM versus SFM

One argument for changing from SFM to FFDM systems has been that FFDM provide a lower radiation dose to the screened women. Previous studies have shown that FFDM systems are capable of producing lower doses compared with SFM systems [2-4, 21]. This study shows that using FFDM does not guarantee a lower MGD per exposure than SFM and are illustrated in Fig. 7. MGDs vary for the different SFM and FFDM models. Two FFDM models (Selenia and GE 2000D) provided an average MGD higher than four of the SFM models in this study (Siemens 300, Siemens 3000, I-Alpha and GE DMR), which is in accordance with earlier findings [3, 4, 22].

For SFM, Mo/Mo dominated as the most frequently applied target/filter combination, although four out of 24 SFM systems have Mo/Mo as their only choice of target/filter combination. Because Min-R EV is a faster film-screen combination than Min-R 2000, the dose for Min-R EV is expected to be smaller than for Min-R 2000 [16].

For FFDM, Mo/Mo target/filter combination is in use for compressed breast thicknesses up to 60 mm. Although Mo/Mo is not the first choice, Mo/Rh dominates for thicknesses up to 40 mm, and Rh/Rh dominates for thicker breasts. This is not in accordance with Dance et al. [23], who recommends that Mo/Mo only should be applied for 2 cm compressed breast thicknesses. The systems that use Mo/Mo were Selenia and GE 2000D. Williams et al. [8] found that the exposure parameter that produced the maximum FOM for both Selenia and GE 2000D was Mo/Rh 27 kV, with the exception of the thickest and densest breasts where Rh/Rh and a higher kV should be used for GE

2000D and Mo/Rh 28 kV should be used for Selenia. Our study shows that GE 2000D applied Mo/Mo, Mo/Rh and Rh/Rh for the exposures, and that Selenia primarily applied Mo/Mo, but also Mo/Rh. An optimization of the two systems is recommended.

The Sectra technology is different than the other FFDM systems, and our results show that Sectra provides the lowest doses, which is also reported in a study by Oduko et al. [24] and Hemdal et al. [19]. The doses provided by Novation were also quite low, and this is also found in the study by Oduko et al. [24].

CONCLUSION

Our study showed that FFDM has a potential to decrease the MGD in mammography screening. Overall, the average MGD per examination was 2.5 mGy for FFDM and 2.8 mGy for SFM. However, the dose range indicates substantial differences between the models, both in FFDM and SFM. Reference values may be used as a tool in the optimization process, and for choosing the best equipment for a national screening program.

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