Impact of Digital Mammography on Cancer Detection and Recall Rates: 11.3 Million Screening Episodes in the English National Health Service Breast Cancer Screening Program

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Conflicts of interest are listed at the end of this article.

See also the editorial by C.I. Lee and J.M. Lee in this issue.

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Purpose: To report the impact of changing from screen-film mammography to digital mammography (DM) in a large organized national screening program.

Materials and Methods: A retrospective analysis of prospectively collected annual screening data from 2009–2010 to 2015–2016 for the 80 facilities of the English National Health Service Breast Cancer Screening Program, together with estimates of DM usage for three time periods, enabled the effect of DM to be measured in a study of 11.3 million screening episodes in women aged 45–70 years (mean age, 59 years). Regression models were used to estimate percentage and absolute change in detection rates due to DM.

Results: The overall cancer detection rate was 14% greater with DM ($P < .001$). There were higher rates of detection of grade 1 and 2 invasive cancers (both ductal and lobular), but no change in the detection of grade 3 invasive cancers. The recall rate was almost unchanged by the introduction of DM. At prevalent (first) screening episodes for women aged 45–52 years, DM increased the overall detection rate by 19% ($P < .001$) and for incident screening episodes in women aged 53–70 years by 13% ($P < .001$).

Conclusion: The overall cancer detection rate was 14% greater with digital mammography with no change in recall rates and without confounding by changes in other factors. There was a substantially higher detection of grade 1 and grade 2 invasive cancers, including both ductal and lobular cancers, but no change in the detection of grade 3 invasive cancers.

Online supplemental material is available for this article.

The English National Health Service Breast Screening Program (NHSBSP) began in 1987 following the Forrest report (1). Screening for breast cancer aims to detect invasive breast cancers at the earliest opportunity to maximize the success of treatment and thus reduce mortality from breast cancer (2). All asymptomatic women registered with a general practitioner are invited for screening every 3 years between the ages of 50 and 70 years, although since 2010 some women from age 45 years and above 70 years have been invited as part of the age extensions (or AgeX) trial (3).

Screen-film mammography (SFM) in the NHSBSP has been gradually replaced by digital mammography (DM), allowing postprocessing and easier acquisition, storage, and transfer of images. Image quality especially for microcalcification is improved (4). Use of DM began in 2008 with gradual introduction and by December 31, 2010, over 80% of units had at least one digital x-ray set (5). However, it was not until after January 2011 that DM started to fully replace SFM following recommendations in the Department of Health cancer strategy report (6). By March 2014, 95% of the units were fully digital and all but one unit were partly digital (7). The transition from SFM to DM required major changes not only in mammography equipment, but also investment in supporting computer systems for image viewing, communications, archiving, and workflow. This may explain the slow rate of transition with the NHSBSP.

A number of studies including those of population screening programs have compared the effect of DM and SFM, suggesting that DM performs at least as well as does SFM for cancer detection. However, the direct measurement of the effect of DM alone has been limited by confounding by substantial increases in recall rates as a consequence of policy changes, the use of computer-aided detection, or switching from single to two views simultaneously when changing from SFM to DM (4,8,9). In some groups (notably younger women, women with dense breasts, and pre- or perimenopausal

Abbreviations

CI = confidence interval, DCIS = ductal carcinoma in situ, DM = digital mammography, NHSBSP = National Health Service Breast Screening Program, SFM = screen-film mammography

Summary

The overall cancer detection rate was 14% greater with digital mammography compared with screen-film mammography, with substantially higher detection of grade 1 and grade 2 invasive cancers but no change in the detection of grade 3 invasive cancers.

Implications for Patient Care

- Detection of some potentially life-threatening cancers is higher with digital mammography (DM) than screening mammography.
- DM has greater sensitivity at the same recall rate as screen-film mammography.
- DM results in improved effectiveness for breast cancer screening compared with screening mammography.

women), the sensitivity of DM has been estimated to be higher than that of SFM (10,11). There is a lack of evidence in large populations on the direct effect of DM at a similar recall rate to SFM imaging.

This study examines the impact of DM on cancer detection rates and recall rates and aims to estimate the effect of DM in increasing detection rates for both prevalent (first) and incident (subsequent) screening episodes from women invited every 3 years.

Materials and Methods

The NHSBSP has gained approval to access and process patient data for the purposes of quality assuring the NHSBSP under section 251 of the Health and Social Care Act 2008 through approval of the Confidentiality Advisory Group (previously the National Information Governance Board for Health and Social Care). Because this study did not involve patient contact, intervention, or use of identifiable patient data, it was determined to be exempt from human subject ethical review in the United Kingdom. Ethics committee approval was therefore not required and written informed consent was waived.

No industry support was provided for this study. The authors had control of the information submitted for publication.

Study Population

This study was undertaken by using data from an ongoing population-based breast screening program for asymptomatic women aged 50–70 years. The NHSBSP uses a single national information technology system, the National Breast Screening Computer System, and collects standardized data on all breast screening activity by each facility. This information is published annually by National Health Service Digital and is anonymized. The study is divided into three time periods (early, middle, and late digital implementation periods) with different penetrance of digital usage. The age range of women screened is 45–70 years, with a mean age of 59 years.

Women eligible for breast screening are identified from the National Health Service database and invited every 3 years by one of the 80 breast screening facilities in England. Bilateral two-view mammography, predominantly performed in mobile vans, is independently double read by film readers with defined national standards for training, caseloads and service, and performance. Film readers include accredited breast subspecialist radiologists and advanced practice mammographers. Arbitration (usually performed by a radiologist or panel of film readers) is undertaken for mammograms where there is a discrepancy between readers' opinions. Women recalled for further investigation (assessment) attend the responsible screening service. Assessment is conducted according to national guidance and all women undergoing biopsy are discussed at multidisciplinary team meetings (12).

Data Collection

Annual categorical data returns are produced for each of the 80 screening facilities where women with screening episodes opened during April 1 to March 31 are followed up to measure recall, biopsy rates, and cancer detection for each screening type (eg, first invitation, routine invitation to previous nonattender, or routine invitation to previous attender) by using 10 age bands. All facilities report the same information with uniform definitions ensuring comparability. The full data set consisted of 12.5 million routine screening episodes, and the analysis data set restricted the data to prevalent (first invitation) screening episodes at ages 45–52 years (age bands, 45–49 years and 50–52 years) and incident (subsequent) screening episodes at ages 53–70 years (age bands, 53–54 years, 55–59 years, 60–64 years, 65–69 years, and 70 years) to ensure maximum comparability across years.

Additional annex data sets give details on all individual cancers (grade, size, and nodal status) detected within each screening type and age band and have been linked to the main returns to produce the analysis data set. Grade is given as 1, 2, or 3 for invasive cancers and as high or low to intermediate for ductal carcinoma in situ (DCIS). For prevalent screening episodes, the denominator is women but for incident screening episodes, the denominator is woman-episode because some women will have had two episodes over the study period.

Each facility has a static (hospital-based) mammography unit and several mobile vans or satellite facilities each with a mammography unit. These mammography units were gradually replaced by digital systems over the period from 2008 to 2015. Records of the change from SFM to DM for each of the 80 facilities and associated mammography units were kept by the national screening office at four different time periods over the conversion period. These records have been used to estimate the percentage of screening episodes undertaken with DM and SFM screening over the conversion period, and the estimate of percentage of digital usage at any time during the conversion process has been obtained by using a Gompertz model (Figure E1 [online]). Data analysis was conducted by R.G.B. (epidemiologist with 35 years of relevant experience).

Table 1: All Screening Episodes Ages 45–70 Years Observed Rates by Implementation Period Showing Observed Cancer Detection Rates, Percentage Change from Early to Late Implementation Period, and Estimated Full Effect of DM

Variable	Implementation Period			Change in Detection Rate, Late vs Early Period (%)*	Estimated Detection Rate†	Increase (%)‡	Absolute Increase from Digital‡
	Early (2009–2011)	Middle (2011–2014)	Late (2014–2016)				
Estimated digital usage (%)	34.6	81.0	98.0	…	…	…	…
Mean recall rate (%)	3.81	3.98	3.88	…	…	…	…
Screening episodes	3 100 963	4 918 765	3 238 892	…	…	…	…
Mean age (y)	59.4	59.1	59.4	…	…	…	…
All cancers	22 626 (7.30)	38 120 (7.75)	25 697 (7.93)	9 (<.001)	6.95/7.95	14 (11, 17) [<.001]	1.00 (0.79, 1.20) [<.001]
Unknown or missing status	29	42	21	…	…	…	…
Invasive	17 953 (5.79)	29 729 (6.04)	19 999 (6.17)	7 (<.001)	5.59/6.17	10 (7, 14) [<.001]	0.59 (0.41, 0.77) [<.001]
Grade 3	3713 (1.20)	6086 (1.24)	3894 (1.20)	0 (.81)	1.20/1.22	2 (−5, 9) [.53]	0.03 (−0.06, 0.11) [.53]
Grade 1 and 2	14 026 (4.52)	23 350 (4.75)	15 965 (4.93)	9 (<.001)	4.30/4.90	14 (10, 18) [<.001]	0.60 (0.44, 0.76) [<.001]
Unknown invasive grade	214	293	140	…	…	…	…
Microinvasive	224 (0.07)	302 (0.06)	188 (0.06)	−12 (.22)	0.10/0.08	−29 (−47, 6) [.02]	−0.02 (−0.04, 0.00) [.02]
Noninvasive	4420 (1.43)	8047 (1.64)	5489 (1.69)	19 (<.001)	1.28/1.71	32 (24, 40) [<.001]	0.43 (0.34, 0.53) [<.001]
High-grade DCIS	2509 (0.81)	4587 (0.93)	3238 (1.00)	24 (<.001)	0.71/1.00	39 (28, 50) [<.001]	0.29 (0.22, 0.36) [<.001]
Low- to intermediate-grade DCIS	1676 (0.54)	3021 (0.61)	1994 (0.62)	14 (<.001)	0.50/0.63	25 (13, 38) [<.001]	0.13 (0.07, 0.19) [<.001]
Unknown invasive grade	235	439	257	…	…	…	…
IHG	20 686 (6.67)	34 618 (7.04)	23 425 (7.23)	8 (<.001)	6.36/7.22	13 (10, 17) [<.001]	0.86 (0.67,1.05) [<.001]

Note.—Unless otherwise specified, data in parentheses are the rate per 1000 women screened. DCIS = ductal carcinoma in situ, DM = digital mammography, IHG = invasive, microinvasive, high-grade DCIS.

* Data in parentheses are *P* values.

† Data indicates estimated rate at 100% film usage and 100% digital usage.

‡ Data in parentheses are 95% confidence intervals, with *P* values in brackets.

Analysis and Modeling

Screening with DM was first introduced in 2008 but not fully implemented until 2015. The seven screening years from 2009–2010 to 2015–2016 have been divided into three groups (early, middle, and late digital conversion periods). Mean age for each period is calculated by using a weighted mean age, where the midpoint age is multiplied by the number of screening episodes in that age band and divided by the total screening episodes from all the age bands.

In the first 2 years (2009–2010 and 2010–2011, or the early period), we estimated DM usage of 34.6%. We considered the years 2011–2012, 2012–2013, and 2013–2014 to be the transition years (or middle period) with estimated DM usage of 81%, and for the final 2 years (2014–2015 and 2015–2016, or late period) we estimated DM usage of 98%. Further details are given in Appendix E1 (online).

Statistical Analysis

The percentage change in cancer detection rate between the early and late implementation period was calculated, and the significance was calculated from a test of two proportions. Assuming negligible change in background incidence (see the Results section), this will underestimate the full effect of DM as the early implementation period had DM usage of 34.6%. To estimate the full effect and use all the data including the middle implementation period, a binomial regression model was used to determine the risk ratio and risk difference between 0% and 100% digital use by producing models with

Table 2: All Screening Episodes Ages 45–70 Years Observed Rates by Implementation Period with Detailed Histologic Type for Invasive Cancers Showing Observed Cancer Detection Rates, Percentage Change from Early to Late Implementation Period, and Estimated Full Effect of DM

	Implementation Period						
Variable	Early (2009–2011)	Middle (2011–2014)	Late (2014–2016)	Change in Detection Rate, Late vs Early Period (%)*	Estimated Detection Rate†	Increase (%)‡	Absolute Increase from Digital‡
Invasive	17 953 (5.79)	29 729 (6.04)	19 999 (6.17)	10 (<.001)	5.58/6.17	10 (7, 14) [<.001]	0.59 (0.41, 0.77) [<.001]
DN	13 139 (4.24)	21 623 (4.40)	14 312 (4.42)	4 (<.001)	4.14/4.44	7 (3, 11) [<.001]	0.30 (0.15, 0.46) [<.001]
DN grade 1	3204 (1.03)	5378 (1.09)	3657 (1.13)	9 (<.001)	0.98/1.13	15 (7, 23) [<.001]	0.15 (0.07, 0.22) [<.001]
DN grade 2	6606 (2.13)	10 950 (2.23)	7356 (2.27)	7 (<.001)	2.05/2.27	10 (5, 16) [<.001]	0.22 (0.11, 0.33) [<.001]
DN grade 3	3300 (1.06)	5249 (1.07)	3258 (1.01)	−5 (.02)	1.10/1.03	−6 (−13, 1) [.09]	−0.07 (−0.14, 0.00) [.09]
LP	1854 (0.60)	3101 (0.63)	2183 (0.67)	13 (<.001)	0.56/0.66	19 (8, 31) [<.001]	0.11 (0.05, 0.16) [<.001]
MP	236 (0.08)	441 (0.09)	301 (0.09)	10 (.02)	0.07/0.09	38 (6, 79) [.015]	0.03 (0.01, 0.05) [.012]
TP + TM	765 (0.25)	1182 (0.24)	750 (0.23)	−6 (.22)	0.26/0.23	−8 (−21, 7) [.25]	−0.02 (−0.06, 0.02) [.25]
MD + OP + OX	1161 (0.37)	1830 (0.37)	1209 (0.37)	0 (.94)	0.38/0.37	−1 (−12, 12) [.91]	−0.02 (−0.05, 0.04) [.91]
Not known	798 (0.26)	1552 (0.32)	1244 (0.38)	…	…	…	…
Mean size (mm)	16.28	16.20	16.16	…	16.53/16.16	−0.37 (.046)*	…
Node positive (%)	21.2	21.0	20.1	…	21.8/20.5	−1.2 (.053)*	…

Note.— Unless otherwise specified, data in parentheses are the rate per 1000 women screened. Histologic types for invasive cancers are ductal (DN); lobular (LP); mixed (MP); tubular and tubular mixed (TP + TM); and medullary, other primary cancer, and other mixed (MD + OP + OM). DCIS = ductal carcinoma in situ, DM = digital mammography.

* Data in parentheses are *P* values.

† Data indicates estimated rate at 100% film usage and 100% digital usage.

‡ Data in parentheses are 95% confidence intervals, with *P* values in brackets.

proportion of digital usage (0.346, 0.810, and 0.980) against proportion of screened women with cancer detected in each of the three groups. Prevalent screening episodes (ages 45–52 years) and incident screening episodes (ages 53–70 years) were analyzed separately and combined. For the combined data, the mean age was almost the same across the implementation period. For prevalent screening episodes, there was a small difference (a trend) in mean age between the three groups (up to 10 months), and we adjusted the rate to the midpoint of 50.2 years. For incident screening episodes, the difference was 3 months (again with a trend), and we adjusted the rates to the midpoint age of 61.6 years. Adjustments used regression models of cancer detection rate with age. All statistical analyses used Stata (versions 14 or 15; StataCorp, College Station, Tex). A *P* value of < .05 was considered to indicate statistical significance.

Histologic type for invasive cancers has been grouped into five main groups: *(a)* ductal, *(b)* lobular, *(c)* mixed, *(d)* tubular and tubular mixed and medullary, and *(e)* other primary cancer and other mixed. Because of the large number of ductal invasive cancers, these have also been analyzed as grade 1, grade 2, and grade 3 cancers. Nearly all lobular invasive cancers are given as grade 2. There are insufficient numbers of the other cancers to divide further. DCIS is recorded as high nuclear grade and intermediate and low nuclear grade combined and also associated microinvasive cancer (foci of invasion, <1 mm in diameter).

Results

In the analysis data set, there were 11 258 620 routine screening episodes, of which 2 295 016 were routine prevalent (first) screening episodes at age 45–52 years and 8 963 604 incident (subsequent) screening episodes at age 53–70 years. From these screening tests, there were 86 443 (7.7 per 1000 women screened) cancers.

Table 1 shows the observed rates of recall and cancer detection for all screening episodes over the three time periods for invasive, microinvasive, and noninvasive

cancers. Recall rates are stable. For all cancers there was a 9% ($P < .001$) change in detection rates between the early (7.30 per 1000) and late (7.93 per 1000) implementation periods (22 626 of 3 100 963 vs 25 697 of 3 238 892). By using binomial regression, the estimated SFM cancer detection rate was 6.95 per 1000, which increased by 1.00 per 1000 to 7.95 per 1000 for fully digital screening ($P < .001$), an estimated increase of 14% ($P < .001$). The largest increase was for grade 1 and 2 invasive cancers (0.60 per 1000) followed by high-grade DCIS (0.29 per 1000) and low- to intermediate grade DCIS (0.13 per 1000). There was no increase in grade 3 invasive cancers. There were 13 675 grade 3 invasive cancers in the study, and the difference between film and digital was 0.03 (95% confidence interval [CI]: 0.06, 0.11) per 1000 ($P = .53$ showing little or no effect in the detection of these cancers).

Table 2 shows the results for invasive cancers by detailed histologic type, showing higher detection of invasive cancers, mostly grade 1 and 2 invasive ductal cancers and lobular cancers. The estimated mean invasive cancer size was reduced from 16.53 mm for film to 16.16 mm for digital, a difference of −0.37 mm ($P = .046$).

Further details of ductal invasive and lobular invasive cancers by size for all episodes are shown in Table 3. The models estimate that DM had higher detection of ductal invasive grade 2 cancer for both small tumors (<15 mm) by 0.14 per 1000 ($P = .001$) and larger tumors (≥15 mm) by 0.08 per 1000 ($P = .03$). In contrast, DM only increased the detection of small (<15 mm) grade 1 invasive ductal cancers (0.15 per 1000), with no increase in larger (≥15 mm) grade 1 ductal cancers. Overall, there was no change in grade 3 ductal invasive cancers and no change in the overall detection of ≥15-mm invasive ductal cancers over the implementation period ($P = .88$). If we assume the larger ductal cancers are detected by film or digital, then we can infer there was little or no change in background incidence over the period. For lobular invasive cancers (Table 3) there was also evidence that both small (<15 mm) and larger (≥15 mm) cancer detection rates increased by 0.05 per 1000 ($P = .003$) and 0.05 per 1000 ($P = .03$), respectively.

Table 3: All Screening Episodes Ages 45–70 Years Observed Rates by Implementation Period for Ductal Invasive Cancers by Size with Percentage Small (<15 mm) or Large (≥15mm) Change over Implementation Period and Estimated Increase from DM

	Observed Rate by Size	
Variable	<15 mm	≥15 mm
Ductal invasive cancer, grade 1		
Implementation period		
Early	2288 (71) [0.74]	913 (29) [0.29]
Middle	3932 (73) [0.80]	1444 (27) [0.29]
Late	2726 (75) [0.84]	929 (25) [0.29]
Change in rate, late vs early*	0.10 (<.001)	0.00 (.58)
Estimated increase from DM*	0.15 (<.001)	0.00 (.65)
Ductal invasive cancer, grade 2		
Implementation period		
Early	3640 (55) [1.17]	2958 (45) [0.95]
Middle	6053 (55) [1.23]	4889 (45) [0.99]
Late	4100 (56) [1.27]	3256 (44) [1.01]
Change in rate, late vs early*	0.09 (<.001)	0.05 (.04)
Estimated increase from DM*	0.14 (.001)	0.08 (.03)
Ductal invasive cancer, grade 3		
Implementation period		
Early	1323 (40) [0.43]	1972 (60) [0.64]
Middle	2072 (40) [0.42]	3171 (60) [0.64]
Late	1320 (41) [0.41]	1937 (59) [0.60]
Change in rate, late vs early*	−0.02 (.24)	−0.0.04 (.06)
Estimated increase from DM*	0.00 (.30)	0.00 (.19)
Lobular invasive cancers		
Implementation period		
Early†	650 (35) [0.21]	1201 (65) [0.39]
Middle‡	1119 (36) [0.23]	1978 (64) [0.40]
Late§	801 (37) [0.25]	1379 (63) [0.43]
Change in rate, late vs early*	0.04 (.002)	0.04 (.02)
Estimated increase from DM*	0.05 (.003)	0.05 (.03)

Note.—Unless otherwise specified, data in parentheses are percentages and data in brackets are the rate per 1000 women screened. Overall rate for all grades of <15 mm increased from 2.34 per 1000 to 2.52 per 1000 (test of trend $P < .001$) over the early to late periods, but for all grades ≥15 mm the rate increased from 1.88 to 1.89 (test of trend $P = .88$). There is, therefore, no change in the larger ductal invasive cancers over the early to late periods suggesting no major change in background incidence, and the effect of digital is mostly in the detection of small invasive ductal cancers. DM = digital mammography.

* Data in parentheses are *P* values.

† 3 100 963 screening episodes.

‡ 4 918 765 screening episodes.

§ 3 238 892 screening episodes.

Table 4: Estimated Effect of DM for Prevalent (First) and Incident (Subsequent Screening Episodes) by Grade of Cancer and Histologic Type

A: Grade of Cancer

	Prevalent Screening Episode (45–52 y)*				Incident Screening Episode (53–70 y)†			
Variable	Estimated Rate, 100% Film	Estimated Rate, 100% Digital	Increase (%)‡	Absolute Increase‡	Estimated Rate, 100% Film	Estimated Rate, 100% Digital	Increase (%)‡	Absolute Increase‡
All cancers	6.33	7.59	19 (<.001)	1.26 (<.001)	7.11	8.02	13 (<.001)	0.91 (<.001)
Invasive	4.72	5.29	12 (.005)	0.57 (.004)	5.81	6.39	10 (<.001)	0.59 (<.001)
Grade 3	0.84	0.99	17 (.08)	0.15 (.07)	1.31	1.30	−1 (.85)	−0.01 (.84)
Grade 1 and 2	3.88	4.30	11 (.019)	0.42 (.017)	4.50	5.09	13 (< .001)	0.59 (.001)
Microinvasive	0.08	−0.06	−24 (.40)	0.02 (.42)	0.08	0.06	−31 (.02)	−0.02 (.03)
Noninvasive	1.52	2.24	43 (<.001)	0.72 (<.001	1.22	1.57	27 (<.001)	0.35 (<.001)
High-grade DCIS	0.71	1.23	64 (<.001)	0.52 (<.001)	0.76	1.00	31 (< .001)	0.24 (<.001)
Low- to intermediate-grade DCIS	0.82	1.02	23 (.02)	0.20 (.02)	0.47	0.57	22 (.001)	0.10 (.001)
IHG	5.52	6.58	19 (<.001)	1.06 (<.001)	6.64	7.44	12 (<.001)	0.80 (<.001)

B: Histologic Type

	Prevalent Screening Episode (45–52 y)§				Incident Screening Episode (53–70 y)‖			
Variable	Estimated Rate, 100% Film	Estimated Rate, 100% Digital	Increase (%)‡	Absolute Increase‡	Estimated Rate, 100% Film	Estimated Rate, 100% Digital	Increase (%)‡	Absolute Increase‡
Invasive	4.72	5.29	12 (.004)	0.57 (.004)	5.81	6.39	10 (<.001)	0.59 (<.001)
DN	3.43	3.77	10 (.04)	0.34 (.04)	4.32	4.60	6 (.002)	0.28 (.002)
DN grade 1	0.97	1.03	7 (.44)	0.07 (.44)	0.99	1.15	16 (<.001)	0.16 (<.001)
DN grade 2	1.71	1.92	12 (.07)	0.22 (.06)	2.15	2.34	9 (.002)	0.20 (.002)
DN grade 3	0.76	0.80	6 (.55)	0.05 (.53)	1.18	1.09	−8 (.03)	-0.10 (.03)
LP	0.43	0.51	19 (.17)	0.09 (.15)	0.59	0.70	18 (.001)	0.11 (.001)
MP	0.04	0.04	8 (.85)	0.00 (.85)	0.07	0.11	43 (.01)	0.03 (.01)
TP + TM	0.33	0.27	−20 (.17)	−0.06 (.18)	0.24	0.22	−5 (.53)	−0.01 (.53)
MD + OP + OX	0.34	0.32	−8 (.57)	−0.03 (.56)	0.38	0.39	1 (.92)	0.00 (.92)

Note.—Unless otherwise specified, data are the rate per 1000 women screened. Histologic type for invasive cancers are ductal (DN); lobular (LP); mixed (MP); tubular and tubular mixed (TP + TM) and medullary; other primary cancer and other mixed (MD + OP + OM). DCIS = ductal carcinoma in situ, DM = digital mammography, IHG = invasive, microinvasive, high-grade DCIS.

* Mean age for early, middle, and late periods was 50.8 years, 50.2 years, and 50.0, years, respectively. By using prevalent screening episode data for all years, the association between age and cancer detection rate at these ages ranges was estimated and corrected to the middle period age of 50.2 years (early rates multiplied by 0.966 and digital by 1.011).

† Mean age for early, middle, and late periods was 61.4 years, 61.6 years, and 61.7 years, respectively. By using the modeled association between age and cancer detection rate, mean age was adjusted to 61.6 years (early rates multiplied by 1.0095 and late by 0.995). These correction factors were applied to all types of cancer (all rows).

‡ Data in parentheses are *P* values.

§ All three groups adjusted to age 50.2 years.

‖ Adjusted to age 61.6 years as per Table 4A.

Table 4 shows the estimated detection rates for film and digital and the increase in detection rates at prevalent and incident screening episodes. At prevalent screening episodes (ages 45–52 years), there was an increase in all cancers of 19% from 6.33 to 7.59 per 1000, which was a difference of 1.26 per 1000 ($P <$ .001). Invasive cancers increased by 12% (0.57 per 1000 from 4.72 to 5.29 per 1000 [$P = .004$]) and high-grade DCIS by 64% (0.52 per 1000 from 0.71 to 1.23 per 1000 [$P < .001$]).

The incident screening episode cancer detection rates increased by 13% from 7.11 to 8.02 per 1000 ($P < .001$), an absolute increase of 0.91 per 1000 (Table 4A). There were increases for grade 1 and 2 invasive cancers (13%; $P < .001$), high-grade DCIS (31%; $P < .001$), and low- to intermediate-grade DCIS (22%; $P = .001$). The exception was for grade 3 invasive cancers, where there was no change in the cancer detection rate of DM compared with SFM (−1%; $P = .85$). Table 4B shows the results by histologic type and grade of invasive cancer. Grade 1 and 2 ductal cancers (16% [$P < .001$] and 9% [$P = .002$], respectively) and lobular invasive cancers (18% [$P < .001$]) all showed

Table 5: Comparison of Study with Previous Screening Observational Studies

Year	Author	Age Range (y)	No. of Screening Episodes Studied	Screening Frequency (y)	Recall Rate at First Screening (%)*	Recall Rate at Subsequent Screening Episodes (%)*	Cancer Detection Rate at First Screening Episode (%)*	Cancer Detection Rate at Subsequent Screening Episodes (%)*	Confounders
2018	Blanks et al	45–70	11.3 million	3	7.7/7.7 (.93)	2.9/2.9 (.99)	0.633/0.759 (<.001)	0.711/0.802 (<.001)	…
2007	Del Turco et al (4)	50–69	28 770	2	7.8/7.53 (.77)	3.44/4.15 (<.003)	0.82/0.74 (0.79)	0.55/0.72 (0.09)	Recall rate increased
2013	Van Luijt et al (15)	50–75	6.0 million	2	3.2/4.6 (<.001)	1.7/1.6 (<.001)	0.56/0.7 (<.001)	0.46/0.53 (<.001)	Recall rate increased, introduction of CAD
2014	Seradour et al (9)	50–74	162 257	2	6.11/7.78 (<.001)†	…	0.66/0.71†	…	Recall rate increased

Note.—CAD = computer-aided detection.

* Indicates screen-film mammography versus digital mammography. Data are the rate per 1000 women screened, with *P* values in parentheses.

† Indicates all screenings.

highly significant greater detection rates from DM for incident screening episodes. In contrast, grade 3 ductal invasive cancers showed a reduction of 8% ($P = .03$).

Discussion

In this very large study of the NHSBSP, we found that DM was associated with significantly greater cancer detection rates without changing recall rates. Our main findings are that the overall cancer detection rate was 14% greater with DM, with substantially higher detection of grade 1 and grade 2 invasive cancers, including both ductal and lobular cancers, but no change in the detection of grade 3 invasive cancers.

Many previous studies of the introduction of DM have been associated with higher rates of recall for assessment in both American and European programs (9,13,14). A large study from Holland (15) of 6 million screening episodes showed higher detection rates of DCIS. However, in that period there was a deliberate policy to increase recall rates, which almost doubled in the incident screening episode from 2.3% to 4.4% (8,16). Previous studies have struggled to separate the absolute effect of DM from the higher detection rates that would occur from use of SFM by merely increasing recall rates (Table 5). We adjusted for small variations in mean age between the study periods where required and inferred negligible change in background incidence over the study period. With no change in recall rates, we therefore conclude that our study reports the unbiased impact on detection rates of changing from SFM to DM.

Higher Cancer Detection Is Seen in Both Older and Younger Women

Early studies of the introduction of DM indicated that the principle gain in cancer detection occurred in younger women and those with dense breasts. In the Digital Mammography Screening Trial (or DMIST) study, women younger than 50 years at screening showed an increase of 0.15 in area under receiver operating characteristic curve, with only an increase of 0.03 in women of all ages (4,10).

At prevalent screening episodes (ages 45–52 years), the impact of DM is highest for the detection of high-grade DCIS with a substantial increase of around 64% (0.52 per 1000; $P < .001$)). There was a smaller increase in low- to intermediate-grade DCIS of 0.20 per 1000 ($P = .016$). This supports previous findings of a large increase in the detection of DCIS at initial screening examinations with DM probably related to improved visualization of microcalcifications (4,8). Calcification representing DCIS is well seen at DM (Fig 1). In agreement with previous studies, we also showed superiority of DM over SFM for demonstration of invasive cancers, which are more likely to manifest as soft-tissue lesions radiologically (17,18).

There was no evidence of an increase in grade 3 invasive cancers (Fig 2). The absolute increase at both prevalent and incident screening episodes combined was 0.03 (95% CI: 0.06, 0.11) per 1000 ($P = .53$), thereby ruling out any large increase in the detection of these cancers. This is counter to previous findings of an increase in grade 3 invasive ductal carcinoma in the French screening program with DM (9).

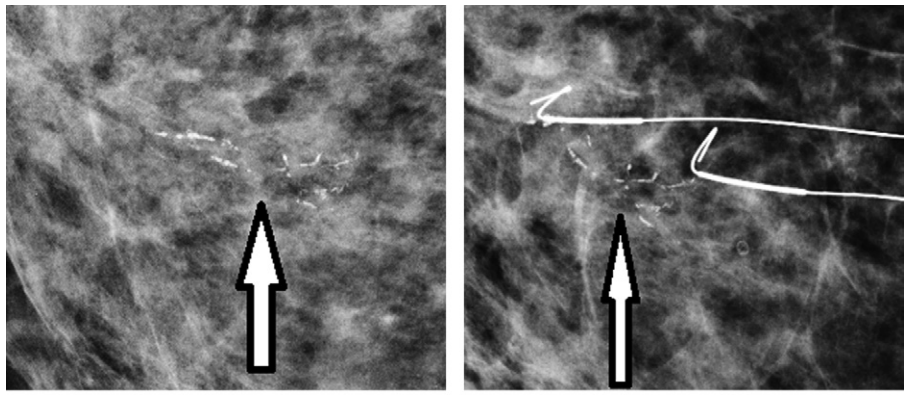
That recall rates were largely unchanged in our study may be because there are carefully monitored target rates within the program and screening facilities tend to maintain stable rates over time. Facilities are also are reluctant to reduce recall rates in case cancers are missed.

Interval Cancers and Mortality

Interval cancer data from this period were incomplete and therefore not included in our study. Previous studies have shown conflicting impact of DM on interval cancer rates with some evidence of a reduction in interval cancer rates associated with increased sensitivity of DM (11) and other studies showing no difference in rates (19).

Technical Considerations around Conversion to Digital

Digital screening in England during the early years of the period studied included a small amount of computed radiography. This was inferior to DM in cancer detection (9). From 2010, no new computed radiography units were installed and those in use were phased out; the number of units was too small to impact our results. During the introduction of DM, a number of units would print out the digital image and read the hard copy (20), reducing the potential gains in efficiency and image quality, but allowing a mixed economy of DM and SFM to be managed during a transition period. The quality of such hard-copy images was not inferior to SFM (20).



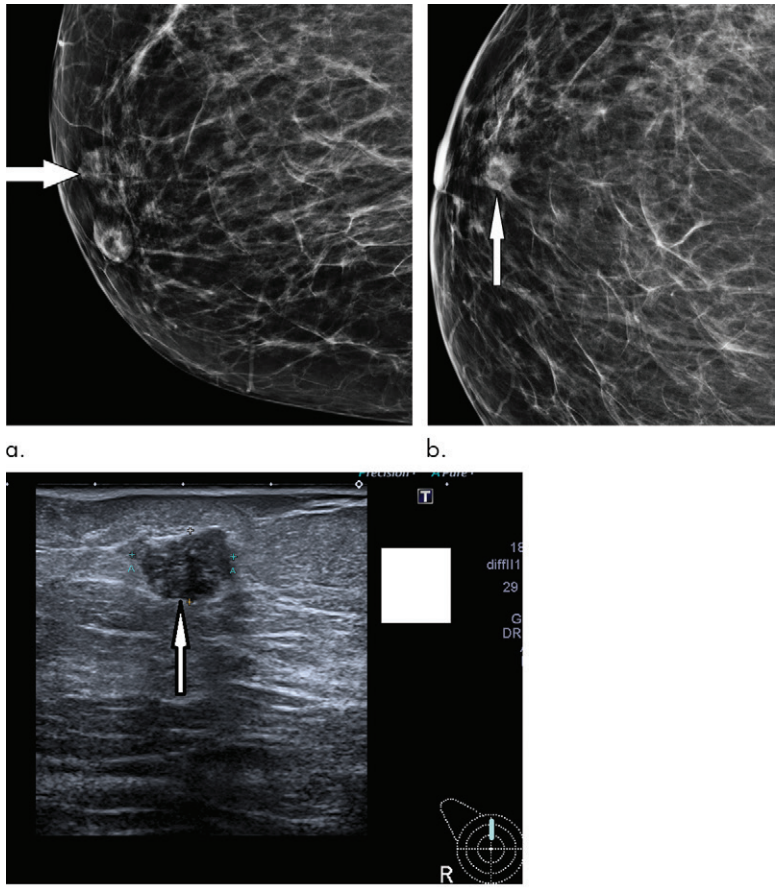
a. b.

Figure 1: Routine screening mammograms from a 73-year-old woman show **(a)** 25-mm new casting calcifications representing ductal carcinoma in situ (DCIS) (arrow) in medial right breast. **(b)** Patient was treated with surgical excision guided by bracketed wires. Histologic examination showed high-nuclear-grade DCIS.

Limitations of the Study

The NHSBSP data set uses aggregated data and does not provide information on factors such as breast density, tumor receptors, or radiologic features prompting recall. Other limitations were the estimated use of DM with time and the assumption of no confounding by background incidence. These weaknesses are counterbalaced by the size of the overall data set and uniformity of screening practice and data collection. The introduction of DM units at screening facilities as older mammography units were replaced means that the study is unlikely to be biased by population characteristics.

In conclusion, we have shown that the overall cancer detection rate was 14% greater with digital mammography but had no effect on the detection of grade 3 invasive cancers. Future studies should seek to determine how digital mammography could be improved to increase detection of grade 3 invasive cancers.



a. b.

c.

Figure 2: Routine screening mammogram in a 67-year-old woman shows subtle 12-mm asymmetric density with ill-defined margins representing small grade 3 cancer (arrow) on **(a)** lateral oblique view and **(b)** craniocaudal view; it is difficult to see even on digital mammogram in a nondense breast. Subsequent clinical examination was normal. **(c)** US confirmed 12-mm irregular hypoechoic mass (arrow). Patient underwent wire-guided surgical excision and sentinel node biopsy. Final histologic examination showed 14-mm grade 3 invasive ductal carcinoma, which was node negative.

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