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FULL PAPER

Radiation doses in the United Kingdom breast screening programmes 2016–2019

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Objectives: To record the radiation doses involved in UK breast screening and to identify any changes since previous publications related to technical factors and the population screened.
Methods: Mammographic exposure factors for 68,998 women imaged using 411 X-ray sets spread across the UK were compiled. Local output and half value layer measurements for each X-ray set were used to estimate mean glandular dose (MGD) using the standard UK method.
Results: Mean MGDs in digital mammography have increased by 11% since 2010–12 for both medio-lateral oblique (MLO) and cranio-caudal (CC) views. The mean compressed breast thickness (CBT) has increased (4.8% CC, 5.2% MLO) over the same period. The mean MLO CBT value of 62.4 ± 0.1 mm is outside the 50 to 60 mm range used for diagnostic reference levels. The increase in MGD is consistent with the CBT changes. The mean MGD in the 50 to 60 mm CBT range is 1.44 ± 0.03 mGy for MLO views. CBT varies with age and peaks at 51.
Conclusions: Mean CBT has increased with time, and this has increased mean MGDs for digital mammography. CBT also varies with age.
Advances in knowledge: Updated average MGDs in the UK are provided. There is evidence that breast size is increasing in the UK and that mean CBT is affected by age-related changes in the breast.

INTRODUCTION

In 1994–95, a pilot national survey of mammographic doses in the UK[1] showed that a large-scale survey could provide technical insights in breast screening. A similar survey was undertaken in 1997–98.[2] This showed that the introduction of automatic tube voltage and filter material selection reduced doses for females with larger compressed breast thicknesses (CBT) but that on aggregate population doses were unchanged.

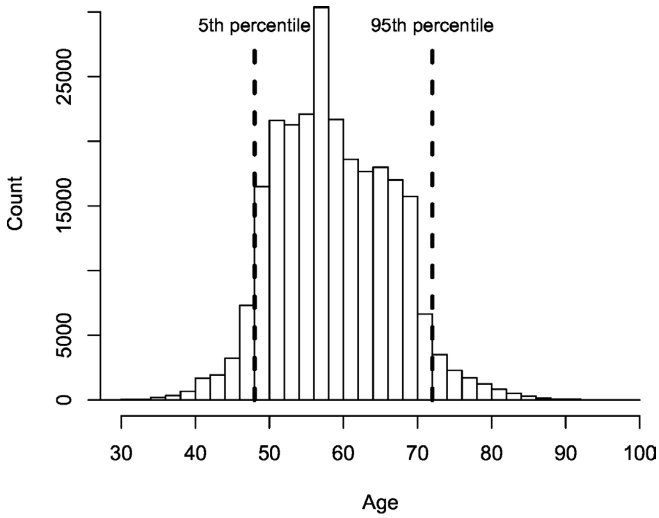
A survey in 2001–02 assessed the impact of two view versus single view screening[3] and adopted newer factors[4] for estimating mean glandular dose (MGD). The national UK surveys in 2007–09, 2010–12, and 2012–15 covered the transition from film-screen to full-field digital mammography (FFDM) and showed that FFDM reduced dose, particularly for larger CBTs.[5–7] The American College of Radiology Imaging Network Digital Mammographic Imaging Screening Trial also showed that FFDM resulted in lower doses[8] and, in addition, that FFDM provided comparable or better diagnostic performance to screen-film.[9] The Irish breast screening programme transitioned to a digital service in 2007 and a survey in 2011 found similar differences in dose by system model to those observed in the UK screening programme.[10]

Diagnostic reference levels (DRLs) are typical dose levels for groups of standard-sized individuals, or standard phantoms. For mammography, the UK National DRL (NDRL) is based on the average MGD for medio-lateral oblique (MLO) views of breasts in the 50–60 mm range of CBT.[11] A recently published Scottish survey established DRLs for several different CBT ranges to provide values relevant to a larger proportion of the population than just those in the narrow 50–60 mm CBT range.[12]

With the widespread adoption of digital imaging systems, and in some cases the introduction of dose management software into radiology practice, it has become easier to collect large sample sizes in radiological surveys. Geeraert et al[13] collected large samples automatically from General Electric (GE) mammography equipment in the geographical zones of Europe, North-America, and Asia. They found that population averages for the displayed average glandular dose agreed well with MGD estimates using the Dance model but that individual doses differed by up to 30%. Suleiman et al[14] used a similar automated approach to collect data from equipment across New South Wales for four different manufacturers. They compared the displayed average glandular doses with a calculation following each manufacturer's stated methodology and found errors of approximately 18% on some systems. This suggests that it may be necessary to independently assess the mean glandular doses in mammography surveys rather than relying on the displayed values for organ dose. An independent indicator of MGD also enables mammography dose comparisons between different systems without the confounding factor of vendor-specific implementations and definitions of average glandular dose.

The results from previous mammography dose reviews have helped to inform the justification of mammography screening, establish UK National Diagnostic Reference Levels, and have highlighted differences in the relative doses for different imaging technologies *e.g.* film-screen, computed radiography and FFDM. This paper reviews mammography doses across the UK following the completed transition to FFDM. The aim of this study is to compare doses in the UK with previous years now that all systems are digital.

Figure 1. Histogram of age



METHODS AND MATERIALS

A survey of UK mammography MGDs was conducted, using data from March 2016 to February 2019. Centres were invited to submit radiographic data for a minimum of 50 women per system. A software tool was provided to store and analyse dose data and to facilitate central collection.[15] Measurements of half value layer (HVL) and output were provided by local medical physics services following NHSBSP protocols and national guidance.[16,17] MGD was calculated using the factors of Dance et al.[4]

The standard breast model consists of a half-cylindrical breast of 16-cm total diameter. It is composed of a central homogenous mixture of glandular and adipose tissue surrounded by a 5-mm thick adipose layer on all sides except the chest wall edge.[18] The percentage glandularity of the central section varies with the breast thickness.[4] Medical physics services were asked to provide estimates of the MGD to the standard 53-mm thick breast model. These were obtained using exposures of 45-mm polymethyl methacrylate (PMMA), under automatic exposure control (AEC), which provides approximately equivalent attenuation. The resulting estimates were compared to the mean MGD to females in the 50–60 mm CBT range.

Expressed uncertainties indicate 95% confidence intervals and were estimated as twice the standard error in the mean (SEM). The validity of this method was confirmed for a subset by bootstrapping the 95% confidence intervals and comparing with the parametric approach. All statistical analysis and graphics were produced using the statistical computing software environment R.[19]

Since Student's T-test is not valid for datasets with very different sample sizes or with unequal variance, comparisons between means were performed using Welch's T-test unless otherwise specified. Where both sample sizes and variances are matched between datasets the Welch's T-test is equivalent to the Student T-test. Results are formatted to include the test statistic value, t, and the degrees of freedom are provided in parentheses for completeness. For regressions, the F statistic is quoted to indicate the significance of the fits. Correlations were assessed using Pearson's correlation coefficient, r.

RESULTS

Data included

Surveys were received for 411 X-ray sets from 30 medical physics departments covering 135 centres across England, Wales, Scotland and Northern Ireland. The mean number of females in a single survey was 160 (maximum of 1637, surveys with fewer than 10 women in the 50 to 60 mm CBT range were excluded). In total, doses were calculated and analysed for 68,998 women imaged in the period March 2016 to February 2019. The mean age of the females included in the survey was 59 years and the age distribution is shown in Figure 1. The majority of females in the survey were between the ages of 50 and 70.

X-RAY TECHNIQUE

Doses from a large sample of the X-ray systems in the NHS BSPs were submitted, including models manufactured by Fujifilm Corporation (Tokyo, Japan), GE Healthcare (Chicago, United States), Hologic Inc. (Marlborough, United States), Philips (Amsterdam, Netherlands), Planmed Oy (Helsinki, Finland), and Siemens Healthineers (Forchheim, Germany). Less than 0.1% of the exposures in the survey were performed with manual factors. The AEC system on each set selected the beam quality as well as the duration of the exposure.

The typical standard views in UK breast screening are one craniocaudal (CC) projection and one MLO projection for each breast. Additional exposures are taken if the breast is too large to be captured in a single image. There were 126,103 (49.8%) CC and 127,203 (50.2%) MLO exposures in the survey.

Figure 2 shows the distribution of CBT for CC and MLO views. The mean number of exposures per female was 4.042 ± 0.004. A small percentage of females (<0.1%) received more than eight exposures.

Figure 2. Histogram of Compressed Breast Thickness (CBT) by view

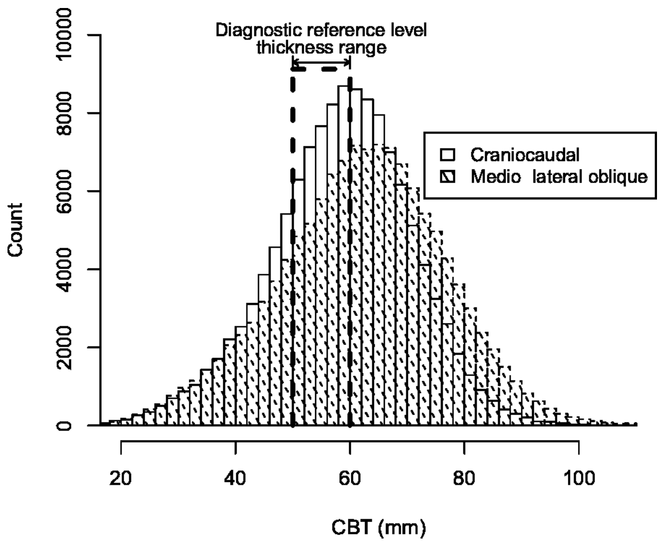
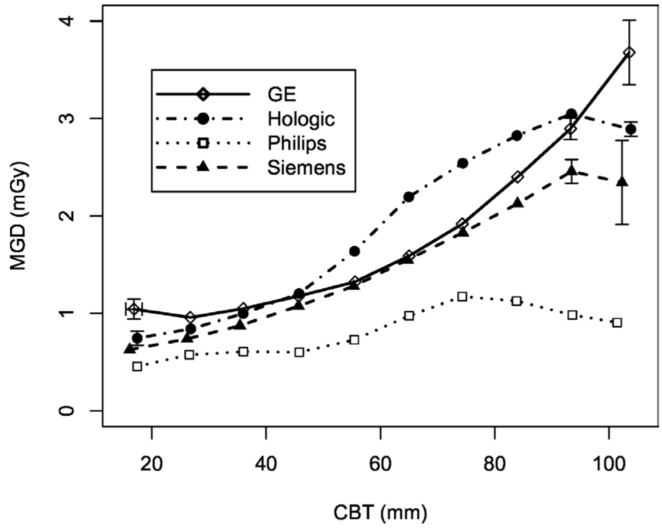


Figure 3. Mean glandular dose (MGD) averaged by Compressed Breast Thickness (CBT) and manufacturer *vs* CBT. Omitted error bars are smaller than the size of the markers.



Average doses

The mean MGD was 1.75 ± 0.03 mGy for MLO projections and 1.57 ± 0.03 mGy for CC projections. These were within about 2% of the values from the 2010 to 2012 national survey (1.79 ± 0.01 mGy MLO and 1.58 ± 0.01 mGy CC). However, the mean MGDs in the current study were 11% higher t(601)=9.1, $p < .001$ than the DR systems in the 2010–12 study. They were also significantly t(604)=5.3,$p < .001$ higher than the 2013–15 values (by about 6%). The mean breast doses and CBTs for main images are compared with previous studies in Table 1. Figure 3 shows the variation of mean MGD with CBT for those manufacturers for which sufficient data were available. Each data point represents the mean MGD and mean CBT in a 10 mm wide CBT bin. The 95% confidence intervals are shown where larger than the marker size.

As shown in Figure 4, the mean CBT has increased with time r(4)=0.92,$p = .01$ and is significantly larger than in the 2010–12 t(748)=12.8, $p < .001$ and 2013–15 surveys t(595)=10.4, $p < .001$. The mean compression force was 85.9 ± 0.3N (77.5 ± 0.3N for CC views and 94.2 ± 0.4N for MLO views) which is 12% higher than in the 2010–12 survey. The mean MLO compression force was about 22% higher than the mean CC compression force t(34007) = 66.6,$p < .001$.

MLO CBTs were significantly greater (5.8%) than CC CBTs t(247,180)=63.3, $p < .001$. The mean dose for two view examinations is compared with previous data in Table 2.

MGD to the standard breast

The MGD to the 53-mm-thick standard breast model, as estimated with a 45-mm-thick block of PMMA, was reported for 468 systems and the mean value was 1.28 ± 0.02 mGy. There was no significant difference compared to the 2010–12[5] digital only data t(357)=1.7,$p = 0.1$ but the 2013–15[6] mean was about 5% lower t(677)=5.4,$p < .001$. The minimum MGD to the standard breast in this review was 0.56 mGy and the maximum was 1.77 mGy.

Diagnostic reference level

The mean MGD in the 50–60 mm CBT range for MLO views was 1.44 ± 0.03 mGy which is lower t(603)=-16.9, $p < .001$ than the value in the 2010–12 survey by about 15%. However, excluding the film-screen and CR systems from the 2010 to 2012 data narrows this difference to 0.4%. There was no significant difference compared with the 2013–15 survey t(602)=-1.1,$p = 0.28$. No systems exceeded the National DRL of 2.5mGy.[18]

In Figures 5 and 6, the mean MGDs for 50–60-mm-thick breasts are plotted against the dose to the 53-mm-thick standard breast.

Table 1. Average compressed breast thickness and mean glandular dose in UK national surveys

	Film 1997–98[2]	Film 2001–02[3]	DR 2007–09[7]	DR 2010–12[5]	DR 2013–15[6]	DR 2016–19
CC MGD (mGy)	1.86 ± 0.02	1.96 ± 0.01	-	1.42 ± 0.01	-	1.57 ± 0.03
MLO MGD (mGy)	2.36 ± 0.03	2.23 ± 0.01	1.46 ± 0.02	1.58 ± 0.04	1.65	1.75 ± 0.03
CC CBT (mm)	51.5 ± 0.3	54.1 ± 0.2	-	56.3 ± 0.2	-	59.0 ± 0.1
MLO CBT (mm)	54.3 ± 0.2	56.8 ± 0.2	55.9 ± 0.5	59.3 ± 0.2	60.0 ± 0.1	62.4 ± 0.1

CBT, compressed breast thickness; CC, craniocaudal; DR, digital radiography; MGD, mean glandular dose; MLO, medio-lateral oblique.

Figure 4. Average compressed breast thickness (CBT) in UK national mammography surveys with time (where 95% confidence intervals are smaller than the marker size they have been omitted).

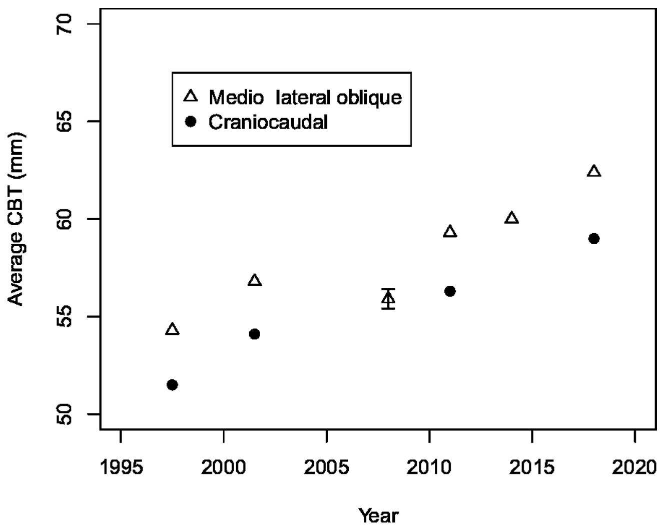
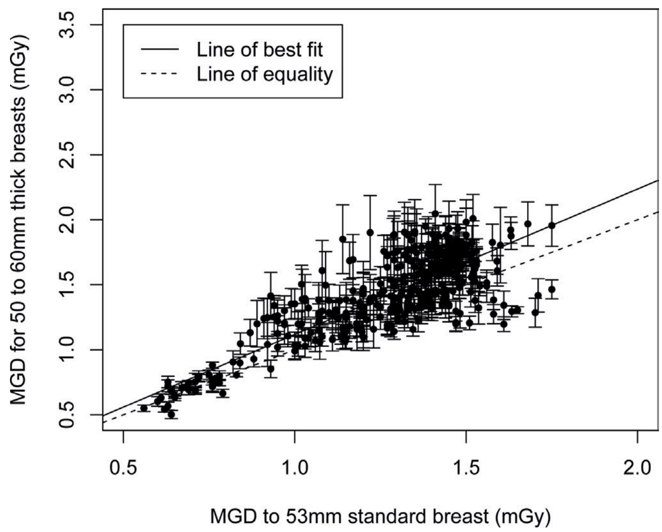


Figure 5. Average mean glandular dose (MGD) for females in the 50 to 60 mm compressed breast thickness range for cranio-caudal views *vs* mean glandular dose to a 53 mm standard breast



The Pearson correlation coefficients were 0.81 and 0.82 for MLO and CC views, respectively. Linear regressions were constrained to pass through the origin and were highly significant for both MLO $F(1,384)=21630$, $p < .001$ with a gradient of 1.12 and CC $F(1,408)=24670$, $p < .001$ with a gradient of 1.08. The mean MGDs in the 50–60 mm CBT range are provided by X-ray model in Tables 3 and 4.

High-dose subgroups

Some groups of females who receive a higher than average dose can be identified. The relationship between CBT and MGD (Figure 3) implies that females with larger breasts typically receive a higher dose. Females with a CBT of 90 mm or greater represent the top 2.7% of the survey population for MLO views and the top 0.6% for CC. The mean MLO MGD for this subset is 2.73 ± 0.03 mGy which is approximately 1.6x higher than the unrestricted mean.

Some females receive many more than four exposures during their examination. Determining the additional dose burden from this is non-trivial because the degree of overlap between images is unknown. However, a calculation based on 100% overlap gives an upper limit. The greatest number of exposures in a single examination was 13. This female received an MGD of at most 7.9mGy. Six females received 11 exposures in a single examination (all but one had a CBT >= 90 mm). The highest resulting MGD for the examination would be at most 15.4 mGy assuming 100% overlap.

Compressed breast thickness with age

Figure 7 shows that CBT varies with age. The mean CBT rises to a peak at approximately 51 years and falls thereafter. The mean force applied remains relatively constant with age.

DISCUSSION

Data included

This was the biggest national mammography dose survey in the UK to date with more than double the sample size of the next largest. This is mainly due to the increased use of automatic data extraction from digital systems. The proportions of the different X-ray models were broadly comparable with those in the UK national mammography equipment database.[20] This is an online facility which screening centres use to log their mammography equipment. Although there were no data received from IMS Giotto systems, these represent less than 1% of the sets in the screening programmes.

X-ray technique

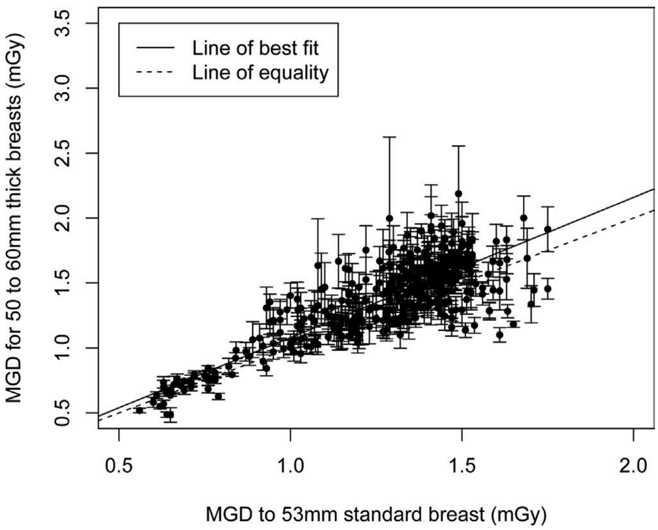
Oduko and Young[5] reported that FFDM systems used higher energy spectra than film-screen systems. They predicted that the use of higher energy spectra would therefore increase as the proportion of digital systems increased. Tungsten and Rhodium anodes are associated with higher energy spectra in mammography. All the systems in this survey were digital and less than 2% of the exposures used a Molybdenum anode compared to 99% for previous surveys of film-screen systems. In contrast, 92% of

Table 2. Average mean glandular dose per two view examination

	Film 1997–98[2]	Film 2001–02[3]	Film 2010–12[5]	DR 2010–12[5]	DR 2016–19
MGD	4.19 ± 0.09	4.32 ± 0.05	4.01 ± 0.02	3.03 ± 0.01	3.44 ± 0.01
Number of females	3,081	9,562	9,105	14,969	51,753

MGD, mean glandular dose

Figure 6. Average mean glandular dose (MGD) for females in the 50 to 60 mm compressed breast thickness range for medio lateral oblique views *vs* mean glandular dose to a 53 mm standard breast



the exposures were made using a Tungsten anode and about 7% were made with a Rhodium anode. It is important to note that, since the target and filter materials are model-dependent, these proportions are influenced by the installation base.

MGD vs CBT

Figure 3 shows that system model has a large impact on the variation of mean MGD with mean CBT. The Philips systems delivered the lowest doses across the full CBT range. These are the only systems in the survey with photon counting detectors and a slot scanning mechanism. However, from Figure 3, it is evident that these systems are also dose limited. Inspection of the tube power suggests that this is a result of the maximum tube load that can be sustained. At a CBT of approximately 75 mm, the maximum tube load has been reached and MGD falls with increasing thickness thereafter. This raises questions about the image quality achievable for females with larger breasts relative to those with smaller CBTs. More than 1 in 5 of the females in the survey had a CBT exceeding 75 mm in the MLO view.

Figure 3 shows that Hologic systems are also dose limited but that this occurs at a higher CBT of approximately 94 mm. Just over 1% of the females in the survey had a CBT exceeding this. The data are consistent with a similar limit for the Siemens systems but here the number of females at the higher CBT end (>90 mm) is insufficient to be conclusive. GE systems delivered the highest MGDs at the highest and lowest CBT values whilst Hologic delivered the highest MGDs across the central CBT range 45 to 95 mm. It is important to note that these results should not be considered in isolation and that image quality was not assessed as part of this survey.

Average doses

Oduko and Young[5,6] showed that DR exposures resulted in 22–25% lower doses than film-screen exposures. It may be expected that the completed transition to digital systems in UK would therefore cause a decrease in the mean MGD. However, both CC and MLO doses were within about 2% of the 2010–12 survey in which nearly 40% of the systems were film-screen or CR. This is because there has been an 11% increase in the mean FFDM doses which has balanced the removal of higher dose film-screen and CR systems. The mean MGD in the 50 to 60 mm CBT range was within 0.4% of the equivalent 2010–12[5] and 2013–15 values.[6] This suggests that any changes to AEC design, configuration and installation base have not impacted average doses.

The mean CBT has increased relative to the results of Oduko and Young[5,6] and this could explain the observed dose changes. Figure 8 shows the MLO MGD plotted against the CBT averaged over all systems. A third-order polynomial regression ($p < .001$) through this curve permits the prediction of the average MGD in the UK, accounting for the installation base, for any given CBT. Using the mean CBTs from Oduko and Young[5,6] produces MGDs within 1.2 and 0.5% of the 2010–12 and 2013–15 values, respectively. This implies that the CBT increase alone can account for the observed MGD differences.

Figure 4 shows that the CBT has generally increased for each national survey. There is a discontinuity between 2001–02 and 2007–09 when averages for film-screen change to averages for DR The mean compression force was approximately 12% higher than in the 2010–12 survey but this would tend to reduce CBT not increase it. On average the MLO views have a significantly higher compression force than CC views ($p < .001$). This may be because they contain more pectoral muscle which is less compressible. The mean CBT was 5.8% higher in MLO views than in CC views. Oduko and Young[5] found a similar 5.3% difference between the two views.

Oduko and Young[5] suggested that the increase in mean CBT from 2001 to 2012 was primarily a result of changes to equipment. This was deduced by comparing DR and film-screen CBTs and noting that CBTs for the Hologic Selenia Dimensions were 7 mm larger than for the Hologic Selenia. However, an increasing CBT is still apparent when comparisons are restricted to digital systems only (Figure 4 2008 onwards) and the CBT difference between the Dimensions and the Selenia was less than 1 mm here. There is some limited evidence that breast sizes have been increasing in the UK over the last 20 years.[21] There is also a strong positive association between CBT and UK female average body mass index[22] (BMI) ($R(2) = .99$, $p < .001$). As seen in Figure 4 the increase in CBT observed from 1997 to 2018 is approximately linear. It is not possible to determine whether the change in CBT is a result of increased adipose tissue, increased glandularity, or both. Some studies have found a link between breast size and cancer risk[23,24] whilst others have found no such association.[25]

Dose to the standard breast

In Figures 5 and 6, the mean MGDs within the 50 to 60 mm CBT range are plotted against the MGD to a 53 mm thick standard breast as estimated using 45 mm of PMMA. The gradients of the regression lines are very similar to those found by Oduko and Young[5,6] and there is still a good correlation. There was no

Table 3. Average mean glandular dose (MGD) and compressed breast thickness by model for medio-lateral oblique exposures in the 50 to 60 mm compressed breast thickness (CBT) range

Manufacturer and model	Number of systems	Number of main images	Mean MGD (mGy) (±2 SEM)	Mean thickness (mm) (±2 SEM)
Fujifilm Amulet	2	107	1.82 ± 0.11	54.6 ± 0.7
GE DS	11	342	1.35 ± 0.04	55.3 ± 0.3
GE Essential	61	1963	1.29 ± 0.01	55.6 ± 0.1
GE Pristina	5	211	1.62 ± 0.05	55.7 ± 0.4
Hologic 3Dimensions	5	480	1.68 ± 0.04	55.2 ± 0.3
Hologic Selenia (Mo)	3	64	2.0 ± 0.2	54.8 ± 0.8
Hologic Selenia (W)	62	3036	1.43 ± 0.01	55.49 ± 0.1
Hologic Selenia Dimensions	159	1,8294	1.67 ± 0.01	55.48 ± 0.05
Philips MicroDose L30	29	4151	0.73 ± 0.01	55.4 ± 0.1
Philips Microdose L50	1	67	0.55 ± 0.03	56.1 ± 0.8
Planmed Clarity 2D	1	166	1.30 ± 0.03	55.3 ± 0.5
Siemens Inspiration	69	2289	1.28 ± 0.02	55.3 ± 0.1

MGD, mean glandular dose

significant difference ($p = 0.1$) in the dose to the 53 mm standard breast compared to the DR only systems of Oduko and Young.[5] This further supports the hypothesis that the increase in breast dose is population rather than system related.

The MGDs in the 50–60 mm CBT range are approximately 8% (CC) and 12% (MLO) higher than the dose to the 53 mm standard breast as estimated using 45 mm of PMMA. However, it was noted that the mean CBTs in the 50–60 mm range were 55.4 ± 0.04 mm (CC) and 55.5 ± 0.04 mm (MLO). Interpolating the mean MGD *vs* CBT curve (Figure 8) using a third order polynomial fit suggests that at 53 mm the MLO MGD would be 1.34 ± 0.04 mGy and the CC MGD would be 1.30 ± 0.04 mGy. These are both consistent with the PMMA measurement of 1.28 ± 0.02 mGy suggesting that on average there is no difference in the performance of the AEC when exposing breast tissue as opposed to an equivalent thickness of PMMA.

DRLs

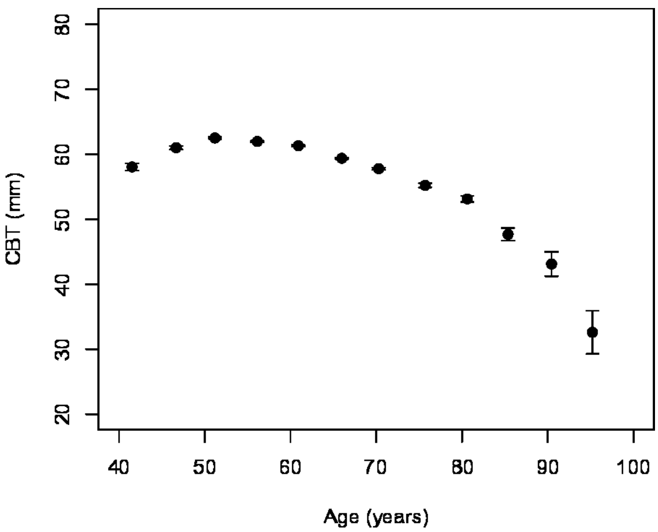
The mean MGD in the 50 to 60 mm CBT range was within 0.4% of the equivalent 2010–12[5] and 2013–15 values.[6] This suggests that any changes to AEC systems, software, calibration and installation base since 2012 have not impacted the MGD on aggregate. No systems exceeded the current UK NDRL of 2.5 mGy.[18]

Table 4. Average mean glandular dose and compressed breast thickness by model for craniocaudal exposures in the 50 to 60 mm compressed breast thickness (CBT) range

Manufacturer and model	Number of systems	Number of main images	Mean MGD (mGy) (±2 SEM)	Mean thickness (mm) (±2 SEM)
Fujifilm Amulet	2	97	1.78 ± 0.11	55.5 ± 0.6
GE DS	11	430	1.29 ± 0.03	55.4 ± 0.3
GE Essential	61	2609	1.24 ± 0.01	55.4 ± 0.1
GE Pristina	5	259	1.57 ± 0.04	54.9 ± 0.4
Hologic 3Dimensions	5	642	1.63 ± 0.04	55.1 ± 0.2
Hologic Selenia (Mo)	3	71	1.82 ± 0.01	54.4 ± 0.8
Hologic Selenia (W)	63	4126	1.38 ± 0.01	55.4 ± 0.1
Hologic Selenia Dimensions	159	2,4045	1.61 ± 0.01	55.5 ± 0.04
Philips MicroDose L30	29	5219	0.73 ± 0.004	55.5 ± 0.1
Philips Microdose L50	1	123	0.52 ± 0.02	55.6 ± 0.6
Planmed Clarity 2D	1	271	1.18 ± 0.02	55.7 ± 0.4
Siemens Inspiration	69	2904	1.20 ± 0.01	55.2 ± 0.1

MGD, mean glandular dose

Figure 7. Mean compressed breast thickness *vs* age in years

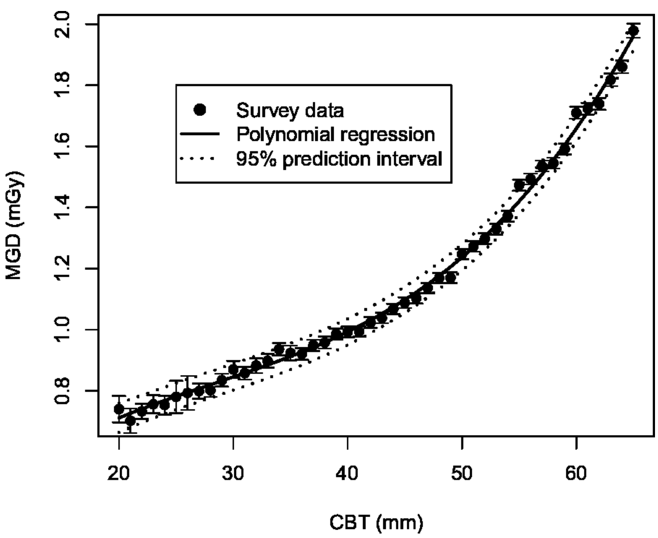


The UK DRL CBT range of 50–60 mm was established based on a mean CBT for the MLO view of 56 mm as found in NHSBSP surveys from 1994 to 1998.[11] However, given that the mean MLO CBT now lies outside this range (Figure 2,[5]) it is instructive to investigate other ranges. Centring closer to the current mean gives an MGD more representative of the full population average. A range of 60 ± 5 mm would give values within roughly 5% of the total population average. The advantage of a more representative range must be balanced against the administrative burden of changing DRL definitions and the additional complexity for historic comparisons.

High dose subgroups

Females with CBTs of 90 mm or greater in the MLO view received approximately 1.6x higher than average doses. If the mean CBT has increased, it may be anticipated that there will be a higher percentage of females in this category. In the current survey, 2.7% of the females had CBTs greater than 90 mm in the MLO view. This is approximately 1.5 times higher than the figure from Oduko et al.[5]

Figure 8. Average mean glandular dose (MGD) *vs* average compressed breast thickness (CBT) for all systems (CBT range restricted for polynomial interpolation)



Some of these females also received more exposures than the typical four. The resulting maximum examination dose for females with more than four exposures was estimated as 15.4 mGy. This can be compared to a typical dose of 3.4 mGy for a two view examination. It should be noted that in absolute terms the radiological risks can still be considered as low.[26] If the assumption of 100% overlap between the extra exposures were reduced to 50% (which is still fairly conservative), then this would reduce the estimated dose by about 30%.

Compressed breast thickness with age

There is a peak in CBT at 51 years of age followed by an accelerating decline thereafter (Figure 7). Since the UK currently has an ageing population, this may serve to limit the magnitude of the increases in CBT observed in national surveys. The compression force remains relatively constant with age and so it is assumed that the variations in CBT are a consequence of age-related changes to breast tissue. Breast glandularity[4] and density[27] are already known to decrease with age and here we see that these compositional changes are accompanied by a decrease in CBT. However, whilst the compositional changes exhibit a monotonic decrease, the CBT exhibits a clear peak. This peak coincides closely with the average age of onset of menopause in the UK (51 years[28]) suggesting that the relationship may be a result of hormonal changes in the lead up to and following menopause. Hormone replacement therapy could also be a possible contributory factor.

Limitations

The Dance[4,29–31] method of estimating MGD used here makes several simplifying assumptions. The most significant of these is that of a homogenous fibro-glandular distribution within a 5 mm adipose outer layer. The distribution of fibro-glandular tissue in real breasts is less uniform and Hernadez, Siebert, and Boone[32] propose a heterogenous breast model based on an average radial Gaussian distribution of glandular tissue. Their model results in 20 to 23% lower estimates of glandular doses.[32] Sarno et al[33] used voxelised breast models for individual patients and found that this leads to maximum dose differences of between −33% and +28% compared to the Dance model. However, despite such large differences in MGD for some individuals, Sarno et al[33] found that on average the differences were within 1–2%. This would suggest that for large scale surveys the results may not be affected. However, it is worth noting that the sample size used by Sarno et al was very small given the wide range in dose differences found. Despite the potential limitations of a homogenous breast model, comparisons in the current work are made only with studies that are based on the same model. The conclusions are therefore unlikely to be affected.

In early dose surveys in the UK, all data were gathered manually by recording them at the time of exposure or retrospectively from the images. Data from females with breast implants were excluded. With some datasets now extracted automatically, it is possible that a few cases with augmented breasts were included. These would be large breasts with high doses, unless the Eklund technique (pushing the implant back to the chest wall) was used. However, Figure 2 shows that the mean CBT is centred over the peak of the distribution and has not been skewed by higher values. It is therefore very unlikely that implant data in this survey has impacted the average CBTs to any meaningful extent.

CONCLUSION

There has been an increase in the mean CBT in the UK which has almost exactly balanced out the reduction in dose achieved through the completed transition to digital mammography. There is evidence that the increase in CBT reflects an increase in population breast size rather than a change in compression method or CBT calibration. CBT was found to vary with age and to peak at 51, the average age of menopause.

The mean dose within the DRL range of 50 to 60 mm CBT was 1.44 ± 0.03 mGy for MLO views. This is consistent with the 2010–12 and 2013–15 data. The mean CBT of 62.4 ± 0.1 mm for MLO views is outside the 50 to 60 mm range currently used for establishing DRLs.

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REFERENCES

1. Burch A, Goodman DA. A pilot survey of radiation doses received in the united kingdom breast screening programme. *Br J Radiol* 1998; **71**: 517–27. https://doi.org/10.1259/bjr.71.845.9691897
2. Young KC, Burch A. Radiation doses received in the UK breast screening programme in 1997 and 1998. *Br J Radiol* 2000; **73**: 278–87. https://doi.org/10.1259/bjr.73.867.10817044
3. Young KC, Burch A, Oduko JM. Radiation doses received in the UK breast screening programme in 2001 and 2002. *Br J Radiol* 2005; **78**: 207–18. https://doi.org/10.1259/bjr/41095952
4. Dance DR, Skinner CL, Young KC, Beckett JR, Kotre CJ. Additional factors for the estimation of mean glandular breast dose using the UK mammography dosimetry protocol. *Phys Med Biol* 2000; **45**: 3225–40. https://doi.org/10.1088/0031-9155/45/11/308
5. Young KC, Oduko JM. Radiation doses received in the united kingdom breast screening programme in 2010 to 2012. *Br J Radiol* 2016; **89**(1058): 20150831. https://doi.org/10.1259/bjr.20150831
6. Oduko J, Young K. Patient dose survey of mammography systems in the UK in 2013-2015. *International Workshop on Digital Mammmography* 2016; **9699**: 327–34.
7. Oduko JM, Young KC, Burch A. A survey of patient doses from digital mammography systems in the UK in 2007 to 2009. *International Workshop on Digital Mammography* 2010; 365–70.
8. Hendrick RE, Pisano ED, Averbukh A, Moran C, Berns EA, Yaffe MJ, et al. Comparison of acquisition parameters and breast dose in digital mammography and screen-film mammography in the american college of radiology imaging network digital mammographic imaging screening trial. *AJR Am J Roentgenol* 2010; **194**: 362–69. https://doi.org/10.2214/AJR.08.2114
9. Pisano ED, Gatsonis C, Hendrick E, Yaffe M, Baum JK, Acharyya S, et al. Diagnostic performance of digital versus film mammography for breast-cancer screening. *N Engl J Med* 2005; **353**: 17: 1773–83: . https://doi.org/10.1056/NEJMoa052911
10. McCullagh JB, Baldelli P, Phelan N. Clinical dose performance of full field digital mammography in a breast screening programme. *Br J Radiol* 2011; **84**: 1027–33. https://doi.org/10.1259/bjr/83821596
11. Kulama E, Burch A, Castellano I, Lawinski CP, Marshall N, Young KC. Commissioning and routine testing of full field digital mammography systems. In: *NHS Cancer Screening Programmes*. Sheffield; 2009.
12. Institute of Physics and Engineering in Medicine. *Guidance on the Establishment and Use of Diagnostic Reference Levels for Medical X-ray Examinations*. York: IPEM; 2004.
13. Weir A, Schofield KA, McCurrach A. Setting scottish diagnostic reference levels for mammography incorporating both craniocaudal and oblique projections between 30 and 80 mm. *J Radiol Prot* 2021; **41**: 97–117. https://doi.org/10.1088/1361-6498/abcf8b
14. Geeraert N, Klaus R, Muller S, Bloch I, Bosmans H. Breast characteristics and dosimetric data in X-ray mammography - a large sample survey. International Conference on Radiation Protection in Medicine - Setting the scene for the next decade. Bonn; 2012.
15. Suleiman ME, Brennan PC, McEntee MF. Mean glandular dose in digital mammography: a dose calculation method comparison. *J Med Imaging (Bellingham)* 2017; **4**: 013502. https://doi.org/10.1117/1.JMI.4.1.013502
16. Young K. Breast dose surveys in the NHSBSP: software and instruction manual. 2004. Available from: https://medphys.royalsurrey.nhs.uk/nccpm/files/other/PatDoseManV2_0Rev_A.pdf
17. Moore AC, Dance DR, Evans DS, Lawinski CP, Pitcher EM, Rust A. The commissioning and routine testing of mammographic X-ray systems. In: *Institute of Physics and Engineering in Medicine*. York; 2005.
18. Dance DR. Monte carlo calculation of conversion factors for the estimation of mean glandular breast dose. *Phys Med Biol* 1990; **35**: 1211–19. https://doi.org/10.1088/0031-9155/35/9/002
19. R Core Team. *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing; 2020.
20. Public Health England. National Diagnostic Reference Levels (NDRLs). 2019. Available from: https://www.gov.uk/government/publications/diagnostic-radiology-national-diagnostic-reference-levels-ndrls/ndrl (accessed 4 Nov 2021)
21. NCCPM. NCCPM NHSBSP Equipment database. Available from: https://medphys.royalsurrey.nhs.uk/faults/login/
22. Brown N, Scurr J. "Breasts are getting bigger". where is the evidence? *J Anthropol Sci* 2016; **94**: 237–44. https://doi.org/10.4436/JASS.94020
23. NHS digital. Explore the trends: Weight. 2018. Available from: http://healthsurvey.hscic.gov.uk/data-visualisation/data-visualisation/explore-the-trends/weight.aspx
24. Kusano AS, Trichopoulos D, Terry KL, Chen WY, Willett WC, Michels KB. A prospective study of breast size and premenopausal breast cancer incidence. *Int J Cancer* 2006; **118**: 2031–34. https://doi.org/10.1002/ijc.21588
25. Williams PT. Breast cancer mortality vs. exercise and breast size in runners and

walkers. *PLoS ONE* 2013; **8**(12): e80616. https://doi.org/10.1371/journal.pone.0080616

26. Chen L, Malone KE, Li CI. Bra wearing not associated with breast cancer risk: a population-based case-control study. *Cancer Epidemiol Biomarkers Prev* 2014; **23**: 2181–85. https://doi.org/10.1158/1055-9965.EPI-14-0414
27. Martin CJ. Effective dose: how should it be applied to medical exposures? *Br J Radiol* 2007; **80**: 639–47. https://doi.org/10.1259/bjr/25922439
28. Checka CM, Chun JE, Schnabel FR, Lee J, Toth H. The relationship of mammographic density and age: implications for breast cancer screening. *AJR Am J Roentgenol* 2012; **198**: W292-5. https://doi.org/10.2214/AJR.10.6049
29. NHS. Overview: Menopause. Available from: https://www.nhs.uk/conditions/menopause (accessed 10 Nov 2021)
30. Dance DR, Young KC, van Engen RE. Further factors for the estimation of mean glandular dose using the united kingdom, european and IAEA breast dosimetry protocols. *Phys Med Biol* 2009; **54**: 4361–72. https://doi.org/10.1088/0031-9155/54/14/002
31. Dance DR, Young KC, van Engen RE. Estimation of mean glandular dose for breast tomosynthesis: factors for use with the UK, european and IAEA breast dosimetry protocols. *Phys Med Biol* 2011; **56**: 453–71. https://doi.org/10.1088/0031-9155/56/2/011
32. Hernandez AM, Seibert JA, Boone JM. Breast dose in mammography is about 30% lower when realistic heterogeneous glandular distributions are considered. *Med Phys* 2015; **42**: 6337–48. https://doi.org/10.1118/1.4931966
33. Sarno A, Mettivier G, Di Lillo F, Bliznakova K, Sechopoulos I, Russo P. Homogeneous vs. patient specific breast models for monte carlo evaluation of mean glandular dose in mammography. *Phys Med* 2018; **51**: 56–63. https://doi.org/10.1016/j.ejmp.2018.04.392