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FULL PAPER

Radiation risk of breast screening in England with digital mammography

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Objective: To estimate the risks and benefits of breast screening in terms of number of deaths due to radiation-induced cancers and the number of lives saved owing to modern screening in the National Health Service Breast Screening Programme (NHSBSP) in England.
Methods: Radiation risk model, patient dose data and data from national screening statistics were used to estimate the number of deaths due to radiation-induced breast cancers in the NHSBSP in England. Dose and dose effectiveness factors (DDREFs) equal to one and two were assumed. The breast cancer mortality reduction in the invited population due to screening and the percentage of females diagnosed with symptomatic breast cancer, who die from breast cancer, were collated from the literature. The number of lives saved owing to screening was calculated.
Results: Assuming, a total of 1,770,436 females between the ages of 50–70 years were screened each year, and a breast cancer mortality reduction of 20% due to screening in the invited population, the number of screen-detected cancers were 14,872 annually, resulting in 1071 lives saved. Conversely, for the same mortality reduction, the number of radiation-induced cancers was 36 and 18 for DDREFs of 1 and 2, respectively. This resulted in seven and three deaths due to radiation-induced cancers annually for DDREFs of 1 and 2, respectively. The ratios of lives saved owing to screening to radiation-induced cancers were 30 : 1 and 60 : 1 for DDREFs of 1 and 2. The ratios of lives saved owing to screening to deaths due to radiation-induced cancers were 156 : 1 and 312 : 1 for DDREFs of 1 and 2. For the 1.8% of the screening population with very thick breasts, the latter ratios decrease to 94 : 1 and 187 : 1 for DDREFs of 1 and 2.
Conclusion: The breast cancer mortality reduction due to screening greatly outweighs the risk of death due to radiation-induced cancers.
Advances in knowledge: Estimation of the radiation risk for modern breast screening in England using digital mammography.

INTRODUCTION

In the National Health Service Breast Screening Programme (NHSBSP) in England, females are invited for screening every 3 years between the ages of 50 and 70 years. During the screening examination, two views of both breasts are acquired using a mammography system. An ongoing randomized control trial (RCT) is investigating the use of an age extension to 47–73 years.[1] This would result in each female receiving two extra screening invitations during her lifetime.

During a mammography screening examination, the breast is exposed to ionizing radiation. There have been a number of publications estimating the radiation risks of screening programmes worldwide.[2–5] These studies consider different screening regimes and age ranges than those in the NHSBSP. Studies relating to the breast screening programme in the UK include the NHSBSP Report 54,[6] Berrington de González and Reeves[7] and the Report of the Independent Advisory Group on Ionizing Radiation.[8] Berrington de González and Reeves[7] compared the radiation risk with the mortality benefits of screening females under the age of 50 years, outside the current screening age range in the NHSBSP. A review of the radiation risks of breast screening was published in NHSBSP Report 54.[6] There are several differences between the assumptions made in that report and current practice. At the time of the report, only two-view mammography was performed at the prevalent screen and one-view mammography was performed thereafter. In modern screening, two-view mammography is performed at all screening rounds. In addition, since the time of this report, mammography systems have transitioned from using film-screen mammography to digital mammography and use different X-ray target and filter materials, causing changes in the average breast dose per examination. In addition, recent publications have provided updated radiation risk coefficients from those used in NHSBSP Report 54.[6] Finally,

assumptions about mortality due to breast cancer outside screening have also changed owing to improved treatments.

The Report of the Independent Advisory Group on Ionising Radiation[8] estimates the radiation risk and benefit of screening in the UK breast screening programme. Two-view examinations were assumed as performed in current screening and an extended age range of 47–73 years was considered. However, the mean glandular dose (MGD) used was based on data using film-screen mammography,[9,10] and the description of the calculations and assumptions is very brief.

In this report, the radiation risk has been compared with the lives saved owing to screening for the current imaging protocol used in the breast screening programme in the UK and taking account of the new information discussed above. There are additional harms of screening such as false positives, pain and psychological distress from procedures and overdiagnosis.[11] These harms are not considered in this article. This is not because they are unimportant but because the risk associated with the use of radiation in screening is the focus of this work.

METHODS AND MATERIALS

Published risk factors for risk of radiation-induced cancers

There is an extensive literature estimating the lifetime risk of breast cancer from X-ray exposure.[12–17]

Preston et al[12,13] conducted a pooled analysis of eight cohorts using follow-up data for each cohort. They developed equations for the excess absolute risk (EAR) and the excess relative risk (ERR) of breast cancer induction from which risk factors can be calculated for any given age or population. In the ERR model, the increased risk is taken to be proportional to the natural underlying incidence of the cancer concerned, whereas in the EAR model, the increase is taken to depend on dose and age at exposure but to be independent of the underlying incidence.[14]

Three international advisory bodies[15–17] have calculated the lifetime attributable risk of breast cancer incidence and mortality using EAR and ERR models. Both the International Commission of Radiological Protection (ICRP) 103[16] and Biologic Effects of Ionizing Radiation VII (BEIR VII)[15] use the Life Span Study incidence data from Preston et al[12] and an EAR model. The Environment Protection Agency (EPA) report[18] states that the ICRP 103 model and EPA model (based on the BEIR VII model) are essentially the same (although they are applied to estimate the risk in different populations). The United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) 2006 Report[17] has alternative ERR and EAR models which could be used to calculate the risk of radiation-induced cancers, although the report does not conclude which of the ERR or EAR models (or a mixture) is appropriate.

The choice of EAR or ERR model is open to discussion. The Committee on the Biologic Effects of Ionizing Radiation VII[15] suggests that theoretically the preferred transportation model between populations for breast cancer should be based on a multiplicative (relative) risk model. However, observations by Land et al[19] found that risks calculated using the absolute risk model were comparable for Japanese A-bomb survivors, patients undergoing tuberculosis fluoroscopy in Massachusetts and New York females treated with radiation for mastitis, whereas risks were much larger in the Japanese cohort when a relative risk model was used. However, BEIR VII authors suggest this finding may have been due to the fractionated exposures and lower energy photons in the latter two cohorts compared with the A-bomb exposure. Preston et al[12] confirmed the finding by Land et al[19] that the risks calculated using the absolute model were similar for the Caucasian cohorts and A-bomb survivors, whereas the relative model results in much higher risks for the A-bomb survivors. Based on this finding by Preston et al,[12] ICRP based their model solely on the absolute model.

For a particular data set, it does not matter whether the risk is expressed in terms of ERR or EAR. What is important is how the excess risk is transferred between populations with different background risks. The absolute model has been used in this work because it is considered to be more stable when applied to populations other than those from which the model was developed.[2] For this purpose, the ICRP 103 model[16] has been used, since this model is backed by a large international agency. The data used for the lifetime risk of cancer incidence over the range of ages seen in breast screening have been taken from Health Protection Agency the Centre for Radiation, Chemicals and Environmental Hazards Report 28 (HPA CRCE-028) report.[20]

As with choice between EAR and ERR, the choice of dose and dose rate effectiveness factor (DDREF) is a topic of much discussion and research. Some authors suggest a DDREF of 1.0.[2,7,21,22] They argue that a reduction factor does not apply in cases where fractionated high-dose rate radiation is received. Some suggest a DDREF of 1.5[15] based on estimates of curvature of the dose–response curve from experimental animal data and from the latest Life Span Study data on solid cancer incidence. Others suggest a DDREF of 2.0[16,17] on the basis of observations in various epidemiologic data sets. In this report, results are given for DDREFs of 1.0 and 2.0, since the appropriate choice of DDREF is uncertain.

Calculation of the number of lives saved and lost owing to radiation-induced cancers in the National Health Service Breast Screening Programme in England

In this section, the numbers of lives saved owing to screening and lost owing to radiation-induced breast cancers are calculated for the age range 50–70 years (current regime in NHSBSP) and also for the age extension being piloted in an RCT of 47–73 years.[1]

In order to calculate the number of radiation-induced cancers, it was assumed that all screening examinations included two views. For the age range 50–70 years, it was assumed that females attended seven screening rounds at ages 51, 54, 57, 60, 63, 66 and 69 years. For the age range 47–73 years, it was assumed females attended two extra screening rounds, one at age 48 years and a second at age 72 years. The attendance rate and the number of females in each screening round were calculated using data from the NHSBSP statistics for the year 2013–14 for England.[23] Summed over all screening rounds, the total number of females screened was 1,770,436 for the age range 50–70

years and would be 2,312,525 if the age range was extended to 47–73 years. The number of females who would be screened in the screening rounds at ages 48 and 72 years was estimated by extrapolating the number of females in the standard age range to this wider age range.

HPA CRCE-028[20] provides ICRP risk factors for radiation-induced breast cancer for age bands of 10 years, between the ages of 0 and 99 years. In order to determine the risk factor at the age for each screening round (Table 1), a Gaussian curve was fitted to the data, from which the risk factor at the age for each screening round was interpolated.

Three different dose situations were investigated. First, the whole screening population was considered. The MGD was assumed to be equal to 3 mGy for a two-view examination. This is based on average doses of 1.5 mGy per view for digital mammography systems in the NHSBSP between 2010 and 2012.[24]

The second situation considered was for a subgroup of the population with larger breasts, who are therefore likely to receive higher doses without an increase in cancer detection. From a dose survey of breast screening centres in the UK over the period of 2010–12,[24] for breasts with thickness above 90 mm, imaged on digital radiography systems, the average MGD was 2.3 mGy for the craniocaudal view and 2.7 mGy for the mediolateral oblique view. Therefore, an average MGD of 5.0 mGy for a two-view examination has been assumed. Only a small proportion of females will have breasts thicker than 90 mm (1.8%).

The final dose situation assumed that females with largest breasts may have multiple images per view. For the worst-case scenario that the females with largest breasts have two images per view, such that the entire breast is imaged twice, the resultant MGD would be 10 mGy. However, it is likely females would actually receive an MGD in between 5 and 10 mGy, since usually only part of the breast is exposed twice. In a dose survey of breast screening centres in the UK over the period of 2010–12, <0.1% of females had two images per view and received an MGD of >5 mGy (personal communication, Young and Oduko, 2016).

The number of induced cancers (I) for 1 year of screening was calculated using the following equation for each dose situation and age range of screening:

$$I = \sum_{j=1}^{m} DR_j S_j, \quad (1)$$

where D is the MGD (in milligray) of a screening examination, j is the screening round, m is the total number of the screening rounds attended by the females, R_j is the lifetime risk of radiation-induced cancer (per million females per milligray) for the age of females in screening round j and S_j is the number of females screened in screening round j per year (expressed in millions).

Next, the total number of detected cancers was calculated. The average detection rate in England per screening visit was 8.4 per 1000 females, taken from the NHSBSP statistics for the year 2013–14 for England.[23] The average detection rates were the same for the age ranges 50–70 and 47–73 years.[23] Using the detection rates and the total number of females screened, the number of screen-detected cancers were calculated for each age range.

Overdiagnosed cancers will not be detected in the absence of screening; so, the number of cancers must be reduced accordingly before calculating the number of lives saved owing to screening.

There is no uniform method of estimation of overdiagnosis, and estimates vary considerably from <5 to around 50%.[25] The independent review of the UK NHSBSP[11] suggests that 19% of diagnosed cancers in the screened population (screen detected and interval) are overdiagnosed. They also note that although this is calculated from old RCTs and therefore may not reflect current screening programmes, there is no clear evidence to suggest that the current rate of overdiagnosis would be lower or higher than that in the original trials. Therefore, it has been assumed here that the overdiagnosis has not changed since the RCTs.

Table 1. Lifetime risk of radiation-induced breast cancer for UK females for dose and dose effectiveness factors (DDREFs) of 1 and 2

Age (years)	Radiation risk factor (per million per mGy)	
	DDREF = 1	DDREF = 2
48	13.8	6.9
51	11.4	5.7
54	9.3	4.7
57	7.5	3.8
60	6.0	3.0
63	4.7	2.4
66	3.6	1.8
69	2.8	1.4
72	2.1	1.0

Using detection rates from the NHSBSP interval cancer review,[26] it was calculated that 25% of cancers in the population who attended screening were interval cancers. Screening 1,770,436 females per year, at a detection rate of 8.4 per 1000 females screened, results in 14,872 screen-detected cancers per year and 4957 ($1/3 \times 14{,}872$) interval cancers (T_I). Therefore, there are 3768 overdiagnosed cancers [$0.19 \times (14{,}872 + 4957)$] and 16,061 non-overdiagnosed cancers. By definition, an interval cancer cannot be overdiagnosed, so there are 11,104 ($14{,}872 - 3768$) screen-detected cancers which are not overdiagnosed (T_{SC}).

Lead time describes the amount of time a diagnosis of cancer is brought forward owing to screening and is estimated to be around 40 months.[27] Although the cancers are detected earlier with screening, they would still be detected in the absence of a screening programme (unlike overdiagnosed cancers). Therefore, there has been no reduction in the number of cancers detected owing to lead time when calculating the number of lives saved.

The final two pieces of information required to calculate the total number of lives saved owing to screening are the breast cancer mortality reduction in the population invited for screening and the probability of females with a symptomatic cancer dying from the disease.

There are several publications[11,28–37] which have estimated mortality reduction due to breast screening, which are summarized in Table 2. Since the mortality reduction in the population invited to screening found in the literature was mainly 20% with a range of 15–30% in the invited population, this value and range have been used in this work.

The total number of lives saved (L_S) for 1 year of screening was found from the following equation:

$$L_s = M_{NS} r \frac{T_{SC} + T_I}{f}. \quad (2)$$

Here, T_{SC} and T_I are the number of screen-detected cancers which are not overdiagnosed and the number of interval cancers, r is the breast cancer mortality reduction in the invited population, M_{NS} is the probability of a female with a symptomatic cancer dying of the disease and f is the attendance rate for breast screening. The derivation of this equation is given in Appendix A.

The attendance rate was assumed to be 72%, based on national screening statistics for 2013–14 for England.[23] Mook et al[38] found that 24% of females diagnosed with symptomatic cancer died from the disease (based on 10-year survival). However, the study by Mook et al[38] included only invasive cancer. From NHSBSP statistics for England during 2013–14, 22% of screen-detected cancers are *in situ*. It has been assumed that the overdiagnosed cancers are primarily *in situ* and that the cancers which are not overdiagnosed have a mortality rate of 24% found by Mook et al.[38] This is reduced from a mortality rate of 50% used in NHSBSP Report 54,[6] taking account of the improvement in treatment over time.

The number of lives lost owing to radiation-induced cancers (L_L) for 1 year of screening was estimated by multiplying the number of radiation-induced cancers by the fraction of females with a radiation-induced breast cancer, who later die from the radiation-induced cancer. If the radiation-induced cancers are detected whilst the females are participating in the screening programme, the survival of the females from radiation-induced breast cancer would be the same as that from screen-detected cancers. However, owing to the long delay in the appearance of these breast cancers, some radiation-induced cancers will occur at ages beyond the screening programme and will therefore have the same survival as symptomatic cancers. Therefore, the fraction of females with a radiation-induced breast cancer, who later die from the radiation-induced cancer, has been assumed to be the average of the fraction for screen-detected and symptomatic cancers. The effect of this assumption on the results is considered in the Discussion section of this article.

Table 2. Mortality benefit to the invited population found in previous publications

Publication	Mortality benefit to invited population
Marmot et al[11]	20%
Gotzche et al[28]	15%
US Task Force[29]	19%
Canadian Task Force[30]	21%
Demissie et al[31]	30%
Tabar et al[32]	27%
Broeders et al[33]	25%
Weedon-Fekjaar et al[34]	28%
Lauby-Secretan et al[35]	23%
Duffy et al[37]	21%
Nyström et al[36]	15%

Finally, from the number of lives saved owing to screening and the number of lives lost owing to radiation-induced cancers, it was possible to calculate the number of females who must be screened (NNS) regularly over their lifetime to save a life:[3,39]

$$\mathrm{NNS}=\frac{S}{n(L_s-L_L)}, \quad (3)$$

where n is the number of screening rounds attended by the females over their lifetime and S is the total number of females screened per year (*i.e.* summed over all screening rounds).

In addition, the number of females screened over their lifetime, which results in one radiation-induced breast cancer death (NSD), was calculated using:

$$\mathrm{NSD}=\frac{S}{nL_L}. \quad (4)$$

RESULTS

For the age range 50–70 years, and a 20% breast cancer mortality reduction in the population invited to screening, a total of 1,700,436 females were screened per year, resulting in the detection of 14,872 cancers and 1071 lives saved. For the average MGD of 3 mGy, this corresponds to 36 radiation-induced breast cancers and 7 radiation-induced cancer deaths for a DDREF of 1 and 18 radiation-induced breast cancers and 3 radiation-induced breast cancer deaths for a DDREF of 2. The ratios of the number of lives saved owing to screening to the number of radiation-induced cancers were therefore 30 : 1 for a DDREF of 1 and 60 : 1 for a DDREF of 2. For the assumed mortality reduction of 20%, the ratios of the number of lives saved owing to screening to the number of lives lost owing to radiation-induced breast cancer were 156 : 1 for a DDREF of 1 and 312 : 1 for a DDREF of 2.

There is some uncertainty over the breast cancer mortality reduction in the population invited to screening, with the range in the literature covering 15–30%. The ratio of the number of lives saved owing to screening to the number of lives lost owing to radiation-induced breast cancer for this range of breast cancer mortality reductions ranges from 110 to 268 for a DDREF of 1 and 220–535 for a DDREF of 2.

The ratios of the number of lives saved owing to screening to the number of radiation-induced breast cancers and to the number of radiation-induced breast cancer deaths have also been investigated for different subgroups of the screening population and different age ranges (Table 3). It was found that the calculated values of these ratios for the extended age range of 47–73 years are very similar to the values of the ratios for the age range 50–70 years.

Table 3 also shows that for the small subgroup of the population (1.8%) with breasts of thickness 90 mm and above, the ratios of the lives saved owing to screening to the number of radiation-induced breast cancers and to the number of lives lost owing to radiation-induced breast cancers decreased, compared with the corresponding ratios for the entire screening population. The ratio of the number of lives saved owing to screening to the number of radiation-induced cancers was 18 : 1 for a DDREF of 1 and 36 : 1 for a DDREF of 2. The ratio of the number of lives saved owing to screening to the number of deaths owing to radiation-induced breast cancers was 94 : 1 for a DDREF of 1 and 187 : 1 for a DDREF of 2.

Finally, for the even smaller subgroup of the population (<0.1%) who receive an MGD of 10 mGy, the ratio of the number of lives saved owing to screening to the number of radiation-induced cancers was 9 : 1 for a DDREF of 1 and 18 : 1 for a DDREF of 2. For this subgroup, the ratio of number of lives saved owing to screening to the number of deaths owing to radiation-induced breast cancers was 47 : 1 for a DDREF of 1 and 94 : 1 for a DDREF of 2.

The number of females who must be screened in all screening rounds to save a life and the number of females attending all screening rounds per radiation-induced breast cancer and radiation-induced breast cancer death are given in Table 4 for

Table 3. Ratio of lives saved owing to screening to number of radiation-induced cancers and to the number of lives lost owing to radiation-induced breast cancer

DDREF	MGD (mGy)	Lives saved/induced cancers		Lives saved/lives lost	
		Age range = 50–70 years	Age range = 47–73 years	Age range = 50–70 years	Age range = 47–73 years
1	3[a]	30 (22–45)	28 (21–42)	156 (110–268)	145 (102–249)
	5[b]	18 (13–27)	17 (13–25)	94 (66–161)	87 (61–149)
	10[c]	9 (7–13)	8 (6–13)	47 (33–80)	43 (31–75)
2	3[a]	60 (45–90)	56 (42–83)	312 (220–535)	290 (205–497)
	5[b]	36 (27–54)	33 (25–50)	187 (132–321)	174 (123–298)
	10[c]	18 (13–27)	17 (13–25)	94 (66–161)	87 (61–149)

DDREF, dose and dose effectiveness factor; MGD, mean glandular dose.
The ratios are given for the age ranges 50–70 years and 47–73 years, DDREFs of 1 and 2, three MGDs and a 20% reduction in breast cancer mortality in the invited population. The bracketed values show results for 15–30% reductions in breast cancer mortality.
[a]Average MGD for all thicknesses.
[b]Average MGD for breasts of thickness 90 mm or greater (1.8% of females with breasts of thickness 90 mm or greater).
[c]MGD assuming females with breasts 90 mm or greater have two images per view of the entire breast (<0.1% of females).

Table 4. Number of females screened to save a life, number of females screened per radiation-induced-breast cancer death and number of females screened per radiation-induced breast cancers

DDREF	Age range (years)	Screening rounds attended	Females screened to save a life	Females screened per radiation-induced breast cancer death	Females screened per radiation-induced breast cancer
1	50–70	7	238 (158–318)	36,856	7068
	47–73	9	185 (123–247)	26,634	5108
2	50–70	7	238 (158–318)	73,712	14,137
	47–73	9	185 (123–247)	53,268	10,216

DDREF, dose and dose effectiveness factor.
Data are given for the age ranges 50–70 years and 47–73 years, for DDREFs of 1 and 2, for MGD of 3 mGy and a 20% reduction in breast cancer mortality in the invited population. The bracketed values show results for 15–30% reductions in breast cancer mortality.

the DDREFs, MGDs and breast cancer mortality benefits to the invited population considered.

DISCUSSION

The number of cancers detected per radiation-induced cancer was found to be five times larger in this work compared with NHSBSP Report 54.[6] This is due to several differences in the analyses performed, which have competing impacts on the number of cancers detected per radiation-induced cancer. Firstly, the radiation risk factors used in this work provided in the HPA CRCE-028 report,[20] using the ICRP 103 model,[16] are lower for the age range used in this work compared with the National Radiological Protection Board (NRPB) model[40] used in NHSBSP Report 54.[6] For the age range 50–70 years, on an average, the risk factors are three times lower in this work compared with NHSBSP Report 54[6] (for the same value of DDREF), causing a proportionate increase in the ratio of the number of cancers detected to the number of radiation-induced cancers.

Secondly, the cancer detection rates in this work are 1.05 times higher in this work than that in the NHSBSP Report 54.[6]

Finally, the MGD used is lower in the presented work than that in NHSBSP Report 54,[6] causing a decrease in the number of radiation-induced cancers, and therefore an increase in the ratio of the number of detected cancers to radiation-induced cancers. In NHSBSP Report 54,[6] an MGD of 4.5 mGy was assumed for the whole population and an MGD of 7 mGy was assumed for the subgroup of the population with breasts of thicknesses of 90 mm and above. This compares with 3 and 5 mGy for the whole population and the subgroup with the largest breasts in the present work. This is due to the switch from film-screen to digital mammography systems and due to the adoption of higher energy X-ray spectra. Young and Oduko[24] found that the average MGD for a two-view examination using digital radiography mammography systems is about 25% lower than that for film screen. It should be noted that specific manufacturer designs can lead to consistently higher or lower doses than this average.

Some females require multiple images per breast. Young and Oduko[24] estimated that 1.6% of females had one extra image per view and 0.4% of females had two extra images per view. This may be due to repositioning, reacquisition owing to the quality of the image or "tiling" to image the entire breast. The additional dose will depend on the area of overlap of the images of the breast. As a worst-case scenario, one could assume that these females who have two extra images per view have the largest breasts (>90 mm) and the entire breast is imaged twice, doubling the dose. As seen in Table 3, this causes the ratio of lives saved owing to screening to lives lost owing to radiation-induced breast cancers for this group of females to reduce from 94 : 1 to 47 : 1. In reality, it is unlikely that the entire breast will be imaged twice, only part of it and therefore, the ratio for these females will be somewhere between these two values.

It is assumed in this work that the survival of a female from radiation-induced breast cancer was the same as that of a female with the average of screen-detected and symptomatic cancers. If instead the survival of a female from radiation-induced breast cancer was the same as that of a female with a screen-detected cancer or symptomatic cancer, the ratio of the lives saved to lived lost ranges from 125 : 1 to 208 : 1 for a DDREF of 1. In reality, the ratio will be somewhere between these two values, because for some females, the radiation-induced cancers will be detected whilst they are still participating in the screening programme and for others, the cancer will be detected at ages beyond the screening programme.

For the results presented, the average breast cancer detection rates from national breast screening statistics for 2013–14[23] were used for the age ranges considered. Alternatively, the detection rate at the age for each screening round has also been used, found by interpolating the data given in the 2013–14 breast screening statistics.[23] The calculations have been performed both ways (not presented) and the results did not change between methods. Therefore, the average detection rates were used to improve the readability of the article.

It was found in our analysis that around 240 females needed to be screened in 7 screening rounds between the ages of 50 and 70 years to save a life. Tabar et al[32] estimated that 414 females would need to be screened every 2–3 years for 7 years to save a life. This corresponds to 145 females screened every 2–3 years for 20 years between the ages of 50 and 70 years to save a life. The difference in estimates is likely to be due to the difference between the mortality rate at the time of the Swedish Two-County Trial and the more recent estimate used in our calculations.

In this work, the number of females who must be screened in all screening rounds to save a life and the number of females attending all screening rounds per radiation-induced breast cancer death were higher for the age range 50–70 years than that for the age range 47–73 years. This is due to the greater number of screening rounds attended in the age range 47–73 years—more cancers were detected, but the total radiation dose received by the females was higher.

Marmot et al[11] found that inviting females aged 50–70 every 3 years prevents around 1300 breast cancer deaths a year. This difference is likely to be due to the uncertainty associated with estimating the amount of overdiagnosis and the mortality rate of the symptomatic cancers. If overdiagnosis were 5% rather than 19%, the overdiagnosis would increase from 1071 to 1256 lives saved per year. If the mortality rate were to increase from 24 to 28%, this would increase the number of lives saved per year from 1071 to 1249.

A limitation of this work is that only the number of lives saved owing to screening and lives lost owing to radiation-induced cancers has been considered and not the number of life-years gained or lost. Estimating the number of life-years saved or gained would take into account that deaths due to induced cancers are likely on an average to occur later than the deaths prevented by screening. The ratios of lives saved owing to screening to the number of lives lost owing to radiation-induced cancers can be calculated for each screening round. For the screening rounds at age 48 and 72 years, these ratios are 76 : 1 and 500 : 1, respectively, for a DDREF of 1. However, if life-years gained were to be compared for these two screening ages, this difference is likely to reduce.

An additional limitation of this work is that the additional radiation exposure due to mammography at assessment was not considered. However, the average percentage of females recalled for further imaging in the NHSBSP is only about 4%.[23] Since repeat imaging is usually more limited than the original screening, the increase in the population dose due to assessment mammography is likely to be $<4\%$.

There are several different radiation risk models available. In this work, the EAR model used by ICRP 103 has been used. Analyzing the same data using the EAR model by Berrington de Gonzalez et al[41] instead (adaptations of the BEIR VII model) caused no change to the ratio of lives saved owing to screening to the lives lost owing to radiation-induced breast cancers. A larger difference would be expected if an ERR model were to be used instead of an EAR model. However, the authors feel that the use of an EAR model is more appropriate, as discussed earlier in this article.

UK data indicate that the radiation dose in mammography has decreased significantly with the advent of digital mammography. The benefit of reducing the dose further should be balanced against the possible resultant change in cancer detection when optimizing a mammography system.

CONCLUSION

For a breast cancer mortality reduction of 20% to the population invited to screening in England, the number of deaths caused by radiation-induced cancers is estimated to be around 150 times smaller than the number of lives saved owing to screening.

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APPENDIX A

Derivation of number of lives saved owing to screening per year

The number of cancers in the invited population is given by:

$$T_T = T_{SC} + T_{SOD} + T_I + T_{NS}, \quad \text{(A1)}$$

where T_{SC} is the number of screen-detected cancers, which are not overdiagnosed, T_{SOD} is the number of screen-detected cancers, which are overdiagnosed, T_I is the number of interval cancers and T_{NS} is the number of cancers detected in non-attendees.

The number of cancers detected in the non-attendees is related to the proportion of females accepting the screening invitation f according to:

$$T_{NS} = (T_{SC} + T_I)\frac{(1-f)}{f}. \quad \text{(A2)}$$

The number of deaths in the invited population ($D_{Invited}$) and the number of deaths in the same population when not invited to screening ($D_{NotInvited}$) are given in Equations (A3) and (A4), where M_{SC} and M_{NS} are the mortality rates for females with screen-detected and symptomatic cancers.

$$D_{Invited} = M_{SC}T_{SC} + M_{NS}(T_I + T_{NS}), \quad \text{(A3)}$$

$$D_{NotInvited} = M_{NS}(T_{SC} + T_I + T_{NS}). \quad \text{(A4)}$$

The mortality reduction to the invited population (r) is given by:

$$r = 1 - \frac{D_{Invited}}{D_{NotInvited}}. \quad \text{(A5)}$$

Substituting (A3) and (A4) into (A5) and rearranging gives:

$$M_{SC} = \frac{M_{NS}}{T_{SC}}[(1-r)T_{SC} - r(T_I + T_{NS})]. \quad \text{(A6)}$$

The number of lives saved is given by the following equation:

$$\text{Lives saved} = (M_{NS} - M_{SC})T_{SC}. \quad \text{(A7)}$$

Substituting (A2) and (A6) into (A7) gives:

$$\text{Lives saved} = M_{NS}r\frac{(T_{SC} + T_I)}{f}.$$