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Effective lifetime radiation risk for a number of national mammography screening programmes

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ABSTRACT

Background and purpose: The performance of mammography screening programmes is focussed mainly on breast cancer detection rates. However, when the benefits and risks of mammography are considered, the risk of radiation-induced cancer is calculated for only the examined breast using Mean Glandular Dose (MGD). The risk from radiation during mammography is often described as low or minimal. This study aims to evaluate the effective lifetime risk from full field digital mammography (FFDM) for a number of national screening programmes.

Material and Methods: Using an ATOM phantom, radiation doses to multiple organs were measured during standard screening mammography. Sixteen FFDM machines were used and the effective lifetime risk was calculated across the female lifespan for each machine. Once the risks were calculated using the phantom, the total effective lifetime risk across 48 national screening programmes was then calculated; this assumed that all these programmes use FFDM for screening.

Results: Large differences exist in effective lifetime risk, varying from 42.21 [39.12–45.30] cases/10^6 (mean [95% CI]) in the Maltese screening programme to 1099.67 [1019.25–1180.09] cases/10^6 for high breast cancer risk women in the United States of America. These differences are mainly attributed to the commencement age of screening mammography and the time interval between successive screens.

Conclusions: Effective risk should be considered as an additional parameter for the assessment of screening mammography programme performance, especially for those programmes which recommend an early onset and more frequent screening mammography.

Introduction

Breast cancer is a major public health concern and is the most frequently detected cancer among women in many countries.[1] It is the fifth largest cause of cancer death worldwide.[2] In 2012, breast cancer constituted 25% of new cancer cases in women and around 1.7 million new breast cancer cases were recorded worldwide.[3] Breast cancer morbidity differs significantly between regions and according to the American Cancer Society (ACS),[3] 39% of breast cancer cases were recorded in Asia while in Europe and North America, the figures were 28% and 15%, respectively. Early diagnosis and treatment of breast cancer is the key to reduce mortality.[4] Randomised screening trials using mammography illustrated that screening can reduce breast cancer mortality by 15–20%.[5] Since mammography is seen as a cost-effective technique for early detection of breast cancer, it remains the recommended modality for both screening and diagnosis.[6]

The performance of any screening programme should be assessed by three parameters; sensitivity, specificity, and positive predictive value.[7,8] The calculation of these parameters depends on three related quantities; mammography false negatives which represents mammography's inability to detect all breast cancers, mammography false positives which may result in extra examinations and undesired anxiety for women, and overdiagnosis of low risk breast cancers that may never cause health problems.[9,10]

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The most suitable measure of screening mammography benefit is the reduction in breast cancer mortality in women being screened compared to that in unscreened women.[11]

The risk-benefit argument resulted in the introduction of organised mammography screening programmes in many countries; though the recommendations for screening mammography are different among them in regards to the age of screening commencement and cessation age of the screens, and the time interval between screens (Table 1).[12]

The screening categories in Table 1 are recommended for average breast cancer risk women. High risk women include those with personal or familial history of breast cancer, or with mutations in breast cancer susceptibility genes BRCA1 and BRCA2, or with high breast density. Some of the mammography screening programmes exclude the high risk women and consider them as special cases, e.g. the Australian programme,[14] while other programmes have a specially designed screening category, e.g. the United States (U.S) and the United Kingdom (U.K) programmes which recommend early commencement annual mammography (Table 2). However, these strategies will result in an additional risk of cancer incidence due to radiation. Therefore some programmes use another imaging modality for screening, for example ultrasound or magnetic resonance imaging in addition to screening mammography.[15]

The risk of radiation-induced cancer from screening mammography has been considered small[17] and not included in the mortality assessment of screening programmes. This may be due to lack of availability of an accurate and reliable method to provide data about this risk. Therefore, within this study, the recently published method by M. Ali et al.[18] was utilised to evaluate the radiation risk from several national screening programmes using total effective risk during a female's lifetime. An assumption was made that all screening programmes would use FFDM for screening. The aim of this work was, therefore, to assess the radiation risk from FFDM screening for a number of national screening programmes.

Table 1
Illustrates the recommendations of mammography screening programmes in different countries for women with an average risk of developing breast cancer.[12,13]

Country(s)	Age of screening	Time interval between screens	Number of screens
Australia, Japan, Korea, United States (AAFP, NCI, and USPSTF)[a]	40–75	2 years	18
Belgium, Croatia, Cyprus, Denmark, Finland, Germany, Italy, Latvia, Lithuania, Luxembourg, Norway, Poland, Slovenia, Spain (Catalonia), Switzerland	50–69	2 years	10
Canada, France, Israel, Netherlands	50–74	2 years	13
China	40–59	3 years	7
Czech	44–75	2 years	16
Estonia	50–62	2 years	7
Hungary	45–65	2 years	11
Iceland	40–69	2 years	15
India	40–74	1 year (40–49) 2 years (50–74)	23
Ireland	50–64	2 years	8
Malta	50–60	3 years	4
New Zealand, Portugal, Spain (Navarra)	45–69	2 years	13
Nigeria	40–70	2 years	16
Sweden	40–74	18 months (40–49) 2 years (50–74)	19
United Kingdom	47–73	3 years	9
United States (ACOG)[b]	40–75	2 years (40–49) 1 year (50–75)	31
United States (ACS, ACR, and NCCN)[c]	40–75	1 year	36
Uruguay	40–69	2 years (40–49) 1 year (50–69)	25

[a] American Academy of Family Physicians, National Cancer Institute, and US Preventive Services Task Force.
[b] The American Congress of Obstetricians and Gynaecologist.
[c] American Cancer Society, American College of Radiology and National Cancer Comprehensive Network.

Table 2
Illustrates the recommendations of mammography screening programmes in different countries for women with a high risk of breast cancer.[15,16]

Country(s)	Age of screening	Time interval between screens	Number of screens
Canada	40–74	1 year (40–49) 2 years (50–74)	23
United Kingdom	40–73	1 year	34
United States (ACS)	30–75	1 year	46
United States (NCCN)	25–75	1 year	51

Method

An experimental approach was used to measure organs' doses using thermoluminescence dosimeters (TLDs) for standard four-view screening mammography. To achieve this, an adult ATOM dosimetry phantom and a bespoke breast phantom were used (Fig. 1). The absorbed dose for critical organs was measured for several different FFDM units. Dose data were used to calculate lifetime effective risk (equation (2)).

To simulate a women's body, an adult ATOM dosimetry phantom (CIRS Inc, Norfolk, Virginia, USA) was used. Within this phantom, there are detector holes in 20 radiosensitive organs. Manufacturer supplied breast attachments were used to simulate contralateral breasts each with a grid of holes inside to accommodate the dosimeters.[19]

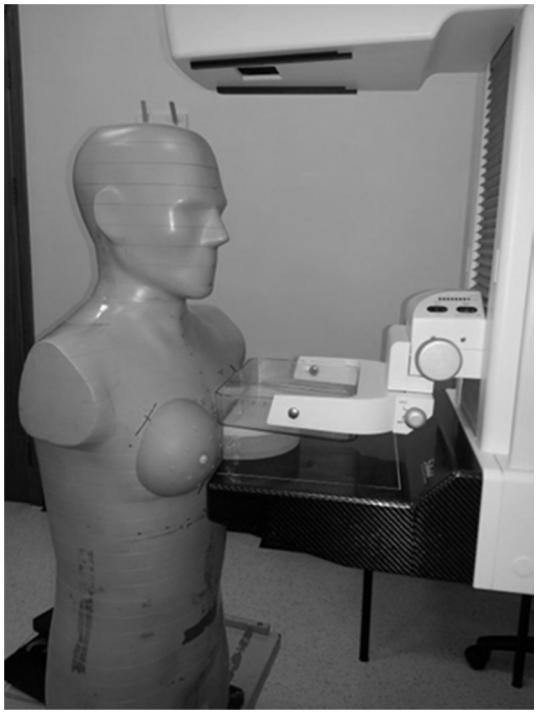

Figure 1. ATOM and breast phantoms positioned on a FFDM machine in the cranio-caudal (CC) position.

A breast phantom was constructed which replicated the thickness of a standard simulated breast during screening mammography. A polymethyl methacrylate (PMMA)-polyethylene (PE) breast phantom was utilised as described by Bouwman et al.[20] This phantom is composed of 32.5 mm PMMA and 20.5 mm PE resulting in a total thickness of 53 mm which is the thickness of standard breast in the craniocaudal (CC) position.[20] However, as reported by the International Atomic Energy Agency,[21] the breast thickness in the mediolateral oblique position (MLO) is more than that in CC position by 5 mm. Therefore, 32.5 mm PMMA and 25.5 mm PE were used to simulate the standard breast in MLO position. Since the radiation dose to an organ is likely to result from scattered radiation, the breast phantom shape, area, and volume were of great importance. Accordingly, two different breast phantoms were used - one to simulate the breast in CC position which was semi-circular with 95 mm diameter, and the other to simulate the standard breast in MLO position which was a rectangular shape of 100 by 150 mm. In general, the breast phantom used in this work represents a simple model and may not be representative of typical breast sizes and densities in different countries.

280 TLD-100H (Thermo Scientific, USA) were accommodated inside the ATOM phantom to measure the radiation dose received by body tissues and organs. Before use, TLDs underwent a process of preparation which includes the determination of errors associated with their readings. These errors are mainly attributed to differences in sensitivity and consistency between TLDs. The method described by M.Ali et al.[18] was utilised to assess these errors. TLDs used in this experiment had a 4% total error, which is within that accepted by the European Commission[22] which recommends a maximum error of 10% in TLDs measurements.

Prior to use, all TLDs were annealed at 240 °C for 10 min to remove any residual stored energy. Three TLDs were used to measure background radiation which was subtracted from the reading of each TLD. To convert the TLDs' charge to equivalent radiation absorbed dose, they were calibrated against a solid state dosimeter (Multi-O-Meter, Unfors, Billdal, Sweden) using the same beam quality from each mammographic machine that was utilised for the phantom exposures.

The ATOM phantom, loaded with TLDs, and the breast phantom were positioned on 16 FFDM machines and exposed as per standard screening mammography technique (CC and MLO for each breast) using automatic exposure control (AEC) (Table 3). All the FFDM machines were quality tested against standard NHSBSP protocols which incorporated IPEM quality control recommendations.[23] In order to minimise random error the breast phantom was exposed three times in each position and mean dose values were obtained. The 16 FFDM machines were located in eight hospitals within the United Kingdom and no consideration was taken about the potential of exposure factors variations between different countries. The machines included GE, Hologic, Siemens and Giotto. To identify each mammography machine and its site, each was given a unique identification number from 1 to 16 (Table 3). For the first two machines, the process was repeated on three separate occasions in order to assess data reliability.

The organs dose, MGD and effective risk assessment were calculated for each of the sixteen FFDM machines.

MGD was calculated using Dance's equation (equation (1))[24] and as described by IPEM[23] by multiplying breast phantom entrance air kerma (without backscatter), measured using the solid state dosimeter which was attached to the lower surface of the compression paddle at a midpoint about 4 cm from the chest wall,[25] with conversion factors g_{53} and s. The g_{53} conversion factor is used to convert the incident air kerma for the phantom to MGD for standard breast and the s factor to correct for different target/filter combinations. However, the glandularity conversion factor (c_{53}) was not used (considered equal to 1) because it is used for the correction of MGD from the equivalent glandularity of the phantom which is 29% to 50% glandularity breast. To illustrate, using this factor means that the MGD is calculated for a 50% glandularity breast while other organ doses were measured for a 29% glandularity breast.

$$MGD = K.g_{53}.c_{53}.s \quad (1)$$

Effective risk, the number of cancer cases produced by the exposure to X-ray, for each year of clients age from 25 to 75 was calculated using Brenner's equation[26] (equation (2)) and BEIR VII[27] lifetime attributable risk factors. Since these factors are only available for each decade of a women's age, they were plotted against age to adjust for unpublished data for each year of life. In this context, to minimise the error associated with the fitting process, two graphs have been plotted for each type of tissue: one graph for obtaining the risk for 20–29 inclusive and another one for 30–39, 40–49, 50–59, 60–69, and 70–79 inclusive. These steps were undertaken because of the tissue radiosensitivity change during 20–29 greatly differs from that of the other ages. Next, the total effective lifetime risk for each identified screening programme

Table 3
The sixteen FFDM machines used in this study with their recorded exposure factors.

Machine Number	Site	Machine Brand	Target/filter combination	Exposure factors			
				CC		MLO	
				kV	mAs	kV	mAs
1	A	Hologic Selenia	Mo/Mo	29	65	30	72
2	B	Hologic Selenia	Rh/Rh	28	122	29	130
3	C	Hologic Selenia Dimensions	W/Rh	30	142	31	162
4	C	Hologic Selenia	Rh/Rh	28	137	29	143
5	D	GE Seno Essential	Rh/Rh	29	57	29	63
6	D	GE Seno Essential	Rh/Rh	29	50	29	53
7	D	Hologic Selenia Dimensions	W/Rh	30	122	31	148
8	D	Giotto	W/Ag	29	57	30	59
9	E	GE Seno Essential	Rh/Rh	29	52	29	52
10	E	GE Seno Essential	Rh/Rh	29	60	29	60
11	E	GE Seno Essential	Rh/Rh	29	50	29	50
12	F	GE Seno Essential	Rh/Rh	29	55	29	60
13	G	GE Seno Essential	Rh/Rh	29	55	29	55
14	G	GE Seno Essential	Rh/Rh	29	55	29	58
15	H	Siemens Mammomat Inspiration	W/Rh	28	108	29	111
16	H	Siemens Mammomat Inspiration	W/Rh	29	88	29	106

was calculated during a female's lifetime. Finally, the total effective risk from screening programmes with the number of screened women in 2010 were used to calculate the predicted number of cancer cases induced by radiation for each of the programmes, again assuming that all of these programmes used FFDM for screening.

$$R = \sum r_T H_T \quad (2)$$

Where R is the effective risk, r_T is the lifetime cancer risk for tissue T per unit equivalent dose of that tissue, and H_T is the equivalent dose for tissue T.[26]

Results

Data generated from reliability experiments are presented in (Fig. 2) and (Fig. 3) for the first and second FFDM machines, respectively.

The possible effect of measured dose variations on total effective risk during female lifetime, for different mammography screening programmes, for both first and second FFDM machines are presented in (Table 4).

Upon data review, it is evident that some organs did not receive any radiation dose during screening mammography (Table 5). However, other organs (other than examined breast) received a radiation dose ranging from less than 1 μGy (e.g. oesophagus, heart and stomach) to more than 25 μGy (contralateral breast).

Differences exist between screening programmes with regard to total effective risk during a female's lifetime. The highest total effective risk resulted from early commenced mammography screening programmes especially those designed for high-risk women who commence screening mammography younger than 30 years old (Table 6).

The predicted number of radiation-induced cancers from different mammography screening programmes (Table 7) highlights that the highest number of radiation-induced cancers would result from the screening programme in Korea because of the high total effective risk which was 193.86 with CI 95% [179.67, 208.04] as well as the large number of participants (more than 2.5 million).

Discussion

Reliability study data using machines 1 and 2 (Figs. 2 and 3, respectively) illustrate that there were some differences amongst the measured organ doses across the three visits. These differences may be attributable to the consistency of the AEC because different exposure factors were recorded for the three visit/exposures. Also, the random nature of the X-ray beam and some experimental errors, such as that due to minor positioning alterations, may contribute to these differences. However, these radiation dose differences do not introduce appreciable differences in the calculated total effective risk between the three experiments (Table 4). The comparison of the sixteen FFDM machines studied in relation to the total effective risk shows some differences. For instance, for 10 biennial screens starting from age 50 to 69 years, the total effective risk ranged from 59.23 (machine 11 which results in lowest risk) to 99.58 cases/10^6 (machine 7 which results in highest risk).

With regard to total effective risk, the number of radiation-induced cancers, the comparison of different country based mammography screening programmes showed that, if they all use the same screening modality (FFDM) and 2 views (CC and MLO) for each breast, the lowest total effective risk resulted from screening programme in Malta, while the highest resulted from the U.S screening programme for high-risk women (Table 6). For any screening programme, the main factor which affects the total effective risk is the commencement age of screening; as younger tissues are more radiosensitive.[33] For example, the total effective risk resulting from the Chinese screening programme, which invites the women 7 times for triennial screening mammography

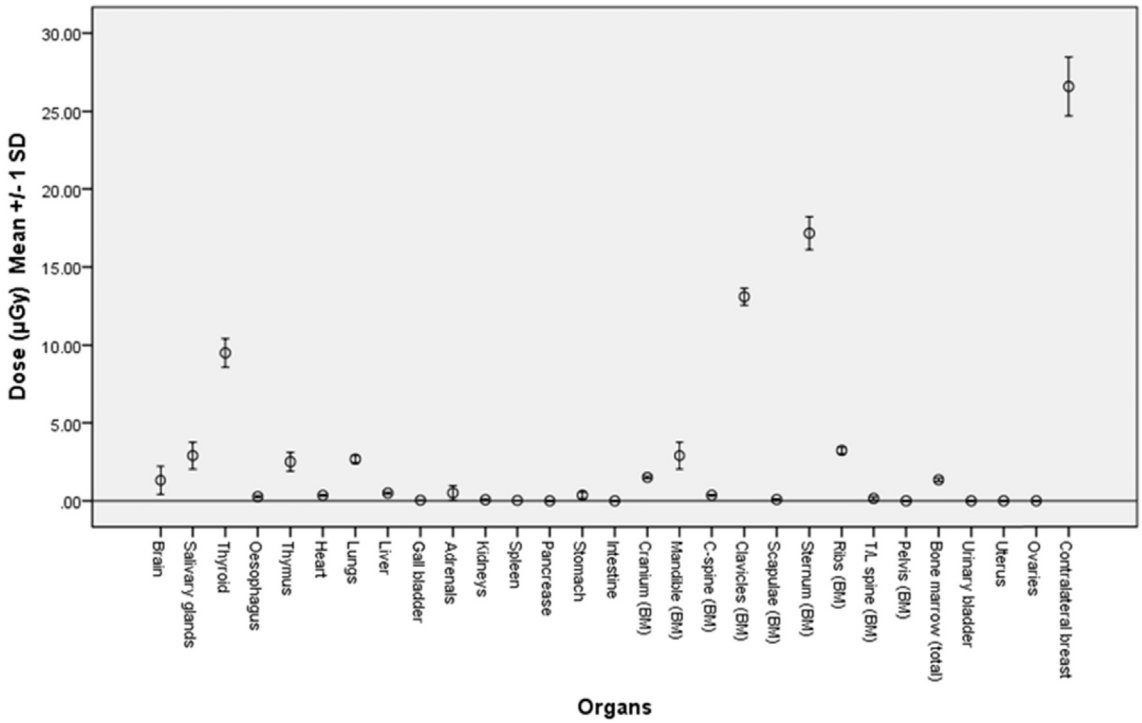

Figure 2. Organ dose variations (mean ± 1SD) measured for three different visits/exposures for FFDM machine number 1.

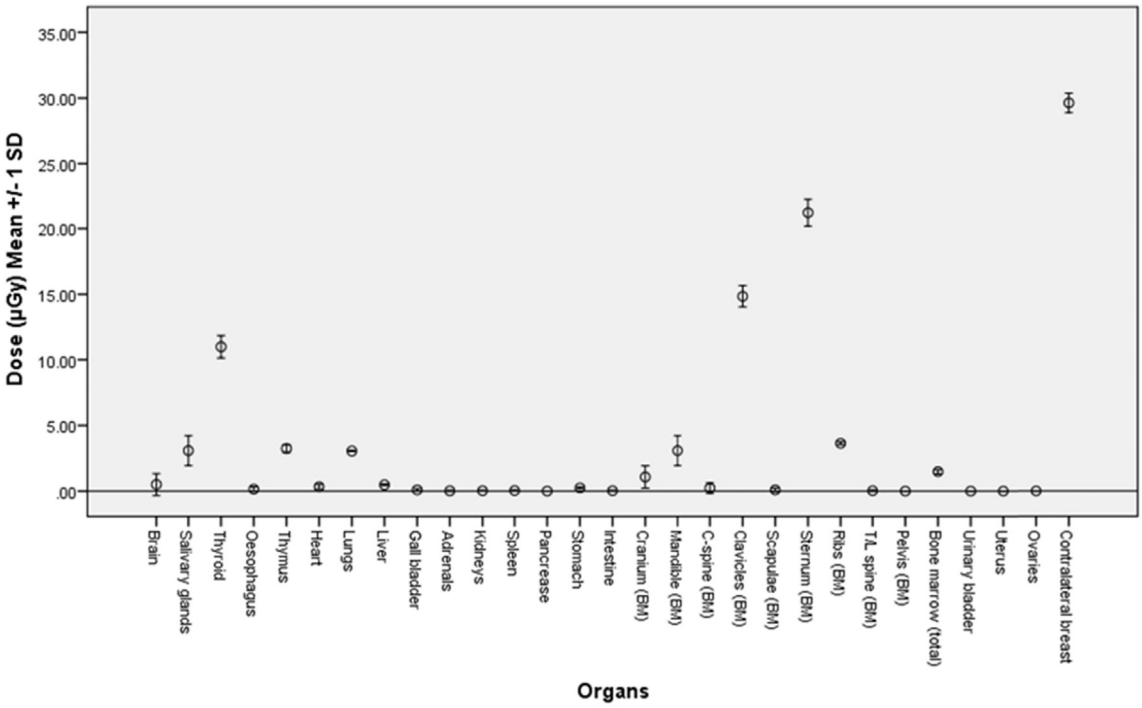

Figure 3. Organ dose variations (mean ± 1SD) measured for three different visits/exposures for FFDM machine number 2.

Table 4
Highlights variations in total effective risk for a series of national screening programmes, which could result from the variations in organ doses as measured on three visits/exposures for FFDM machines 1 and 2.

Programme[a]	Total effective risk (case/10^6), Mean (SD[b]) of the three visits	
	Machine 1	Machine 2
Malta	50.57 (0.05)	48.48 (0.04)
Estonia	77.40 (0.08)	74.20 (0.07)
Ireland	81.10 (0.09)	77.76 (0.07)
United Kingdom	84.75 (0.09)	81.27 (0.08)
Belgium, Croatia, Cyprus, Denmark, Finland, Germany, Italy, Latvia, Lithuania, Luxembourg, Norway, Poland, Slovenia, Spain (Catalonia), Switzerland	85.55 (0.10)	82.05 (0.08)
Canada, France, Israel, Netherlands	88.64 (0.11)	85.04 (0.10)
Hungary	142.63 (0.14)	136.70 (0.11)
New Zealand, Portugal, Spain (Navarra)	146.32 (0.15)	140.27 (0.12)
China	147.26 (0.13)	141.07 (0.09)
Czech	163.44 (0.17)	156.69 (0.14)
Iceland	229.20 (0.22)	219.63 (0.16)
Nigeria	230.46 (0.22)	220.84 (0.17)
Australia, Japan, Korea, United States (AAFP, NCI, and USPSTF)	232.29 (0.23)	222.63 (0.17)
Sweden	270.71 (0.26)	259.42 (0.19)
Uruguay	305.88 (0.31)	293.18 (0.24)
United States (ACOG)	311.81 (0.33)	298.93 (0.26)
India	366.72 (0.35)	351.38 (0.25)
United States (ACS, ACR, and NCCN)	446.24 (0.45)	427.69 (0.34)
Canada	366.72 (0.35)	351.38 (0.25)
United Kingdom	444.46 (0.44)	425.97 (0.33)
United States (ACS)	942.16 (0.84)	902.53 (0.57)
United States (NCCN)	1318.68 (1.15)	1263.04 (0.74)

Screening programmes designed for high breast cancer risk women are highlighted in grey.
[a] The programmes are ordered according to total effective risk.
[b] (SD) is the standard deviation.

Table 5
Lists organs radiation dose from one screening visit, mean [95% CI] for the sixteen FFDM machines.

Organ		Absorbed dose, μGy	
		Mean	95% CI
Brain		0.91	0.32–1.51
Salivary glands		2.79	2.33–3.25
Thyroid		9.45	7.96–10.95
Oesophagus		0.26	0.15–0.36
Thymus		2.43	1.82–3.03
Heart		0.39	0.28–0.50
Lung		3.06	2.54–3.58
Liver		0.69	0.55–0.83
Gall bladder		0.19	0.11–0.27
Adrenal		0.10	0.03–0.17
Kidney		0.05	0.03–0.07
Spleen		0.09	0.04–0.14
Pancreas		0.04	0.01–0.07
Stomach		0.42	0.32–0.53
Intestine		0.03	0.01–0.05
Bone Marrow (BM)	Cranium (7.6%)[a]	1.56	0.88–2.25
	Mandibles (0.8%)[a]	2.79	2.33–3.25
	C-spine (3.9%)[a]	0.30	0.13–0.47
	Clavicles (0.8%)[a]	9.25	6.68–11.82
	Scapulae (2.8%)[a]	0.17	0.10–0.24
	Sternum (3.1%)[a]	19.07	16.08–22.07
	Ribs (16.1%)[a]	3.57	2.93–4.21
	T/L spine (28.4%)[a]	0.07	0.04–0.09
	Pelvis (27.4%)[a]	0.00	0.00–0.00
	Total BM dose	1.42	1.22–1.62
Urinary bladder		0.00	0.00–0.00
Uterus		0.00	0.00–0.00
Ovaries		0.00	0.00–0.00
Contralateral breast		28.75	24.56–32.93
Examined breast (MGD)		2018.50	1871.34–2165.66

[a] These percentages represent the portion of bone marrow (BM) in different locations. They were adapted from ICRP report 70 (1995).[28]

Table 6
Illustrates total effective risk (mean [95% CI] for the sixteen FFDM machines) for different national screening programmes.

Programme	Total effective risk (case/10^6)	
	Mean	95% CI
Malta	42.21	39.12–45.30
Estonia	64.62	59.89–69.35
Ireland	67.72	62.76–72.68
United Kingdom	70.77	65.59–75.95
Belgium, Croatia, Cyprus, Denmark, Finland, Germany, Italy, Latvia, Lithuania, Luxembourg, Norway, Poland, Slovenia, Spain (Catalonia), Switzerland	71.45	66.22–76.68
Canada, France, Israel, Netherlands	74.06	68.64–79.49
Hungary	119.04	110.33–127.75
New Zealand, Portugal, Spain (Navarra)	122.15	113.21–131.08
China	122.83	113.85–131.81
Czech	136.45	126.46–146.43
Iceland	191.25	177.26–205.24
Nigeria	192.30	178.24–206.37
Australia, Japan, Korea, United States (AAFP, NCI, and USPSTF)	193.86	179.67–208.04
Sweden	225.89	209.37–242.42
Uruguay	255.30	236.62–273.98
United States (ACOG)	260.32	241.27–279.37
India	305.96	283.58–328.34
United States (ACS, ACR, and NCCN)	372.42	345.18–399.67
Canada	305.96	283.58–328.34
United Kingdom	370.92	343.79–398.06
United States (ACS)	785.82	728.35–843.30
United States (NCCN)	1099.67	1019.25–1180.09

Screening programmes designed for high breast cancer risk women are highlighted in grey.

commencing at the age of 40 years, is higher than that produced by U.K programme, which invites women from the age of 47 years for triennial screening 9 times.

In our work, the total effective risk data are applicable to UK based exposure factors and FFDM set-up parameters and average sized women with a standard breast thickness (53 mm). With regard to simulated breast density, the breast phantom simulated the breast density of 29%. As recommend by Yaffe et al.,[29] who studied breast composition in 2831 Canadian women, this glandularity (29%) represents the most common breast density because 95% of their study participants had a breast density of less than 45%. Accordingly, calculations reported within our work are applicable for common breast densities only.

Compared to previous studies, which considered the total lifetime attributable risk (LAR) of cancer incidence in breast tissue only, the calculated total effective risk in our study, which includes the risk of radiation-induced cancer in all body tissues, tends to be comparable because the MGD contribution in total effective risk is approximately 98%. In work by Yaffe and Mainprize[30] the total risk of radiation-induced breast cancer from annual screening mammography between 40 and 49 years was found to be 159 cases/10^6/mGy. In our study the total effective risk for the same screening regimen was found to be 114.85 [106.46–123.25] cases/10^6/mGy (mean with 95% CI). Hendrick[31] found that the total incident of breast cancer due to annual screening mammography between 25 and 80 years ranged between 551.35 and 702.70 cases/10^6/mGy. In our work the calculated total effective risk for annual screening mammography between 25 and 75 years was 544.66 [504.83–584.49] cases/10^6/mGy.

Recently, Warren, Dance, and Young[32] evaluated the total risk, during a female's lifetime, of radiation-induced breast cancer from the UK screening recommendations and found that it ranged between 30.7 and 61.2 cases/10^6/mGy. This is consistent with data presented in our study where 35.05 [32.49–37.62] cases/10^6/mGy were reported. In general, the differences in total effective risk between previously published articles and our study may be attributed to different imaging techniques (image receptors) and/or different risk models used to derive the LAR factors which were used to calculate total effective risk. Compared to breast cancer mortality reduction by screening mammography, this radiation risk can be considered as extremely small but not zero. The results of our study demonstrate that the previously published method by M.Ali et al.[18] can be considered suitable for the estimation of radiation risk from screening mammography. This can be evidenced by its ability to consider the risk of radiation-induced cancer for all body tissues from screening mammography and for women of different ages.

Table 7
The predicted number of radiation-induced cancer cases from screening mammography in different countries for the sixteen studied machines.

Country(s)	Number of Screened women[a]	Total effective risk (case/10^6)		Number of cancer cases	
		Mean	95% CI	Mean	95% CI
Korea	2602928	193.86	179.67–208.04	504.60	467.67–541.51
Japan	2492868	193.86	179.67–208.04	483.27	447.89–518.62
Sweden	1414000	225.89	209.37–242.42	319.41	296.05–342.78
France	2343980	74.06	68.64–79.49	173.60	160.89–186.32
China	1200000	122.83	113.85–131.81	147.40	94.88–158.17
UK	1957124	70.77	65.59–75.95	138.51	128.37–148.64
Italy	1340311	71.45	66.22–76.68	95.77	88.76–102.78
Uruguay	352000	255.30	236.62–273.98	89.87	83.29–96.44
Netherlands	961766	74.06	68.64–79.49	71.23	66.02–76.45
Poland	985364	71.45	66.22–76.68	70.40	65.25–75.56
Spain Catalonia	527000	71.45	66.22–76.68	37.65	34.90–40.41
New Zealand	211922	122.15	113.21–131.08	25.89	23.99–27.78
Denmark	275000	71.45	66.22–76.68	19.65	18.21–21.09
Israel	220000	74.06	68.64–79.49	16.29	15.10–17.49
Canada	196187	74.06	68.64–79.49	14.53	13.47–15.59
Norway	199818	71.45	66.22–76.68	14.28	13.23–15.32
Portugal Central	100348	122.15	113.21–131.08	12.26	11.36–13.15
Spain Navarra	40016	122.15	113.21–131.08	4.89	4.53–5.25
Switzerland	60700	71.45	66.22–76.68	4.34	4.02–4.65
Iceland	20517	191.25	177.26–205.24	3.92	3.64–4.21
Luxembourg	14586	71.45	66.22–76.68	1.04	0.97–1.12
Portugal Alentejo	7298	122.15	113.21–131.08	0.89	0.83–0.96

[a] These numbers represent the participants for 2010 in different screening mammography programmes.[12]

Data from our study, which are applicable for breast cancer screening using FFDM, may be associated with a degree of error; this error results from the fitting process of lifetime attributable risk. Also, according to Alonzo-Proulx et al.,[33] the volumetric breast density (VBD) reduces by 2% per year as women age increased from 35 to 75 years. This reduction in breast density, not considered in our phantom study, may result in minor overestimation of effective risk and this should be considered within future work. Also, cancer incidence varies between countries and even between women due to genetic factors and these should be considered in future work. Further work should also be undertaken in order to simulate a range of breast sizes and densities, exposure factors and set-up differences in different countries.

Conclusion

The total effective risk should be considered for use as an additional parameter for the assessment of screening mammography programme performance, especially for those programmes which recommend an early onset and more frequent screening mammography. For total effective risk, the MGD contribution is more than 98%, while all body tissues other than the examined breast contribute up to 2%. Therefore, for any screening programme the most important factors affecting the total effective risk are screening commencement age, screening frequency and MGD. Although the effective risk differences amongst the 16 FFDM machines are not significant statistically, the MGD variation of different FFDM machines should be considered.

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