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Additional factors for the estimation of mean glandular breast dose using the UK mammography dosimetry protocol

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Abstract. The UK and European protocols for mammographic dosimetry use conversion factors that relate incident air kerma to the mean glandular dose (MGD) within the breast. The conversion factors currently used were obtained by computer simulation of a model breast with a composition of 50% adipose and 50% glandular tissues by weight (50% glandularity). Relative conversion factors have been calculated which allow the extension of the protocols to breasts of varying glandularity and for a wider range of mammographic x-ray spectra. The data have also been extended to breasts of a compressed thickness of 11 cm. To facilitate the calculation of MGD in patient surveys, typical breast glandularities are tabulated for women in the age ranges 40–49 and 50–64 years, and for breasts in the thickness range 2–11 cm. In addition, tables of equivalent thickness of polymethyl methacrylate have been provided to allow the simulation for dosimetric purposes of typical breasts of various thicknesses.

1. Introduction

There is a significant risk of radiation-induced carcinogenesis associated with x-ray mammography, and the determination of mean glandular breast dose (Dance *et al* 1999) forms an important part of the quality control of mammographic imaging systems. In the United Kingdom, mean glandular breast dose (MGD) is usually estimated following the protocols set out in IPSM (1989, 1994). Because of the difficulty of estimating MGD directly, the entrance air kerma, without back scatter, at the upper surface of the breast is determined and the MGD is estimated by multiplying by an appropriate conversion factor, often referred to as a g-factor. The g-factors used in the UK protocol and the European protocol (which uses the terminology 'average glandular dose' instead of 'mean glandular dose' (European Commission 1996)) are those calculated by Dance (1990) using Monte Carlo techniques and a simple model of the breast and the mammographic imaging system. This model breast has a central region that comprises an equal mixture by weight of adipose and glandular tissues (50% glandularity). The conversion factors were calculated for the breast thickness range 2–8 cm, and it was assumed that the 50% glandularity model would be sufficiently good for the whole of this thickness range. To allow for the use of different x-ray equipment, the g-factors were calculated for a variety of x-ray spectra including those produced by a molybdenum target/molybdenum filter combination and those from a tungsten target with aluminium, palladium or rhodium filtration.

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It has been realized for some time that a glandularity of 50% may be appropriate for breasts in the thickness range 4–6 cm, but that it is not appropriate for thinner or thicker breasts, which will typically be more or less glandular respectively (Young *et al* 1998, Geise and Palchevsky 1996, Klein *et al* 1997, Beckett and Kotre 2000). In addition, many modern mammographic x-ray sets use target/filter combinations such as molybdenum/rhodium and rhodium/rhodium, which were not considered when the original calculations were made. There is also a need for conversion factors for breasts of thickness greater than 8 cm. This paper presents data that extend the earlier tabulation of Dance (1990) to encompass glandularities of 0–100%, breast thicknesses of 2–11 cm and the x-ray spectra in current use. Some of these factors have been published by other workers (e.g. Wu *et al* 1991, 1994). However, our approach uses the same breast model as Dance (1990), and retains continuity with the dose prescription and g-factors given in IPSM (1989, 1994). Indeed, in many situations, the original factors can still be used without alteration.

In order to apply the extended g-factors to a survey of breast doses, it is necessary to know the glandularity of each breast for which the dose is required. This is not practicable for a routine survey. We therefore give typical glandularities for breasts of different sizes based on surveys in Guildford (Young *et al* 1998) and the Northern Region (Beckett and Kotre 2000) of women attending for mammography as part of the NHS Breast Screening Programme (NHSBSP). Tables of a relative conversion factor, called a c-factor, are also provided to facilitate the estimation of MGD for breasts with these typical glandularities.

There are many situations where it is useful to be able to simulate the attenuating properties of breasts of various sizes using a block of polymethyl methacrylate (PMMA). Dance (1990) gave a table of PMMA thicknesses that were equivalent to breasts of various thicknesses on the assumption of 50% glandularity. It is evident that the use of this tabulation will lead to over- and underestimates of dose for large and small breasts respectively. A new tabulation of equivalent thicknesses of PMMA is therefore provided for breasts in the thickness range 2–11 cm and at a typical glandularity for each thickness.

2. Method

2.1. Monte Carlo model

The Monte Carlo computer program used for the estimation of the factors relating incident air kerma without backscatter to mean glandular dose was developed for a study of the effect of mammographic x-ray spectra on image quality and MGD (Dance *et al* 2000). It was based on earlier work by Dance (1990) and Sandborg *et al* (1994). Only essential details are given here. The compressed breast was taken to be a cylinder of semicircular cross section with a diameter of 16 cm. It had a central region which was a uniform mixture of adipose and glandular tissues and an adipose surface layer 0.5 cm thick, which surrounded the central region on all sides except that adjacent to the chest wall. The breast thickness was varied in the range 2–11 cm and the composition of the central region between 99.9% adipose tissue/0.1% glandular tissue (0.1% glandularity) and 100% glandular tissue (100% glandularity) in steps of 25% glandularity. Tissue compositions and densities were taken from Hammerstein *et al* (1979). The same sizes were used for simulations of PMMA phantoms.

Photon histories started at the focal spot of the x-ray tube, which was positioned above the chest wall edge of the model breast and at a focus–film distance of 60 cm. Photons were followed into the model breast and the energy deposited at each interaction was scored. The energy deposited in the central region of the breast was apportioned between adipose and glandular tissues in accordance with the interaction probabilities in the two tissue types. A statistical precision of 2% or better was achieved in all relevant quantities calculated.

The model also included the simulation of the passage of the photon through the breast support plate (1.2 mm carbon fibre, density 1.45 g cm^{-3}), the antiscatter grid (grid ratio 5, lead strip frequency 31 lines/cm), the cassette front (2.92 mm polycarbonate, density 1.20 g cm^{-3}) and into the mammographic screen (34.0 mg cm^{-2} Gd_2O_2S) (Dance *et al* 2000). In this way, the ratio between the energy imparted per unit area of the screen and the incident air kerma at the upper surface of the breast could be determined. By calculating this ratio for a breast of a given thickness and composition, and for various thicknesses of PMMA, it was possible to calculate the thickness of PMMA which would require the same exposure as the breast, and hence the equivalent PMMA thickness (this assumes that equivalent exposures require the same value of this ratio).

Total cross sections were calculated using the XCOM computer program (Berger and Hubbell 1987), atomic form factors for coherent scattering were taken from Hubbell and Överbö (1979), incoherent scattering functions from Hubbell *et al* (1975) and mass energy absorption coefficients for air from Hubbell and Selzter (1995). Some of these sources are different from those used in the earlier calculations (Dance 1990).

The mammographic x-ray spectra used for the calculations were the measured spectra of Thilander-Klang (1997). These spectra were determined using a Compton spectrometer and exhibited broadening due to the resolution of this technique. A correction was therefore applied to remove this broadening in the vicinity of the characteristic x-ray lines (Dance *et al* 2000). The spectra were measured without the compression plate and were adjusted by the addition of 2 mm polycarbonate filtration to correct for the presence of the plate, which was otherwise excluded from the simulation. The following target/filter combinations were used for the calculations: molybdenum/30 μm molybdenum (Mo/Mo), molybdenum/25 μm rhodium (Mo/Rh), rhodium/25 μm rhodium (Rh/Rh), rhodium/1 mm aluminium (Rh/Al) and tungsten/50 μm rhodium (W/Rh). In each case five tube voltages were used (25 kV, 26 kV, 28 kV, 30 kV and 32 kV) apart from Rh/Al, where no data were available at 25 kV. The spectra cover the half value layer (HVL) range 0.30–0.60 mm aluminium.

2.2. Dosimetric formulation

According to Dance (1990), mean glandular breast dose, D, is calculated using

$$D = Kg \tag{1}$$

where K is the incident air kerma at the upper surface of the breast, measured without backscatter, and g is the incident air kerma to mean glandular dose conversion factor (g-factor). As noted earlier, the tabulated g-factors correspond to a glandularity of 50%. It is proposed that equation (1) is now extended to

$$D = Kgcs \tag{2}$$

where the factor g is unchanged, the factor c corrects for any difference in breast composition from 50% glandularity and the factor s corrects for any difference from the original tabulation by Dance (1990) due to the use of a different x-ray spectrum. The results given in section 3 are in accordance with this formulation.

2.3. Monte Carlo validation

As an independent validation, the g- and c-factors have also been calculated in Newcastle (Beckett and Kotre 2000) for all cases considered using the EGS4 Monte Carlo code, and mammographic x-ray spectra based on those given by Cranley *et al* (1997).

2.4. Average breast composition for different age groups and compressed breast thickness

Previous studies based in Guildford (Young *et al* 1998) and the Northern Region (Beckett and Kotre 2000) have independently estimated the breast composition of women attending for screening. In each study breast glandularity was estimated by comparing the exposure factors selected by the automatic exposure control (AEC) of the x-ray sets for compressed breasts with those selected by the AEC for tissue equivalent materials of various thicknesses and compositions. Both studies assumed that all the compressed breasts had a surface layer of adipose tissue 0.5 cm thick (top and bottom) and that the remaining adipose and glandular tissue were uniformly distributed in the rest of the breast. The data for the two studies were compared for different compressed breast thickness and age groups. One age group (age 50 to 64) corresponds to the ages of women currently invited for breast screening by the NHSBSP. The other age group (age 40 to 49) comprises women participating in a trial of the efficacy of screening in younger women. The average breast composition as a function of breast thickness was established for each age group by using a least-squares method to fit the combined data.

2.5. Determination of the equivalence between PMMA and typical breasts

The equivalence between standard thicknesses of PMMA and thicknesses of typical breasts for women in the age range 50 to 64 has been estimated using the Monte Carlo program as described in section 2.1. For this purpose the incident air kerma at fixed energy imparted per unit area of the receptor was calculated for PMMA phantoms and model breasts in 2 mm thickness steps over the thickness range 2–11 cm. Such a table of equivalence has previously been experimentally determined by comparing the tube loading (mAs) selections chosen by the AEC of an x-ray set (at a fixed tube voltage) for different thicknesses of PMMA with the average mAs selections for different thicknesses of breast for women undergoing mammographic examinations on the same x-ray set (Young *et al* 1996). The same method was used to determine tables of equivalence using the exposure data from the Guildford study. The resulting data were compared with estimates of the equivalent thickness based on the Monte Carlo calculations.

2.6. Application of c-factors to dose estimates

In order to simplify the estimation of mean glandular doses, tables of c-factors for typical breasts of women in the age groups 50 to 64 and 40 to 49 have been calculated. This was achieved by using the estimates of average glandularity to calculate appropriate c-factors for a range of HVLs and breast thicknesses. Linear interpolation was used where necessary. The c-factors for the normal screening age group were used to recalculate approximately 20 000 dose estimates from screening centres across the NHSBSP which had previously been calculated without taking into account variations in breast composition (Young and Burch 2000). The average doses for different thicknesses of breast were then recalculated and compared with the doses before composition correction. This comparison was restricted to exposures using a Mo/Mo target/filter combination where a manual tube voltage selection had been made. The tube voltage selected was 28 kV in most cases (93.7%).

3. Results and discussion

3.1. g-factors

The new g-factors calculated for the Thilander-Klang (1997) spectra and updated cross sections have been compared with those calculated in Newcastle using the EGS4 code and the spectra

Table 1. Maximum and minimum percentage differences between the new g-factors and old g-factors at 50% glandularity, expressed as a percentage of the value of the old g-factor.

	% difference	
Spectrum	Minimum	Maximum
Mo/Mo	−2.0	4.2
Mo/Rh	0.5	5.0
Rh/Rh	3.6	10.9
Rh/Al	3.1	8.0
W/Rh	3.2	7.4

from Cranley *et al* (1997). For Mo/Mo spectra (HVLs 0.30–0.40 mm Al) and thicknesses of 2–10 cm, the difference between the two sets was on average 1.0% with a largest difference of 2.7%. Bigger differences, however, were found when comparing results from other spectra. Average and maximum differences were 2.7% and 4.6% for Mo/Rh (HVLs 0.35–0.45 mm Al), 2.2% and 4.5% for Rh/Rh (HVLs 0.35–0.45 mm Al), 1.9% and 4.7% for W/Rh (HVLs 0.45–0.55 mm Al), and 3.3% and 3.9% for Rh/Al (HVLs 0.50–0.60 mm Al). Taking into account the use of different spectra for the two sets of calculations, this level of agreement is considered to be good.

Table 1 shows the comparison of the newly calculated g-factors (50% glandularity) with those in Dance (1990). For standard Mo/Mo spectra (HVL range 0.30–0.40 mm Al), the agreement is on average within 1.4% and the maximum difference is 4.2%. These differences are due to differences in both cross sections and the spectra used for the calculations (measured spectra are now used). However, within the context of a model-based calculation, the differences are not considered significant and no changes to the g-factors are proposed. This choice has the important advantage that it retains the original g-factors, which are in wide use because of their incorporation in the UK (IPSM 1994) and European (European Commission 1996) protocols.

When the newly calculated g-factors for other x-ray spectra are compared with those in Dance (1990), differences of up to 11% are seen. For higher HVL values the original g-factors were calculated for spectra from a tungsten target with aluminium, molybdenum (60 μm), rhodium (50 μm) or palladium (50 μm) filters (HVL range 0.45–2.00 mm Al). The resulting g-factors were listed as a function of HVL and the central value at a given HVL was used in the tabulation. Only one of these target/filter combinations (W/Rh) was included in the spectra used for the present calculations and hence larger differences in the g-factors can be expected. In view of these differences, it was decided to introduce the s-factor, to correct for spectral dependence of the g-factor.

Table 2 gives new g-factors for breasts of 9, 10 and 11 cm thickness and 50% glandularity. These g-factors retain compatibility with those published in Dance (1990) and have been calculated from the old g-factors for a breast 8 cm thick using

$$g_{\mathrm{old},x\,\mathrm{cm}} = \frac{g_{\mathrm{new},x\,\mathrm{cm}}}{g_{\mathrm{new},8\,\mathrm{cm}}} g_{\mathrm{old},8\,\mathrm{cm}}. \tag{3}$$

The g-factors for breasts of thickness 2–8 cm from Dance (1990) are also included in table 2 for practical use.

The g-factors for breasts of 9, 10 and 11 cm thickness calculated using equation (3) have been compared with those predicted from the original g-factors for breasts of 8 cm thickness. This prediction rested on the assumption that the ratio of the energy imparted to glandular tissue to the incident air kerma remained constant for the larger breasts. Little change in this

Table 2. *g*-factors (mGy/mGy) for breast thicknesses of 2–11 cm and the HVL range 0.30–0.60 mm Al. The *g*-factors for breast thicknesses of 2–8 cm are taken from Dance (1990).

Breast thickness (cm)	HVL (mm Al)						
	0.30	0.35	0.40	0.45	0.50	0.55	0.60
2	0.390	0.433	0.473	0.509	0.543	0.573	0.587
3	0.274	0.309	0.342	0.374	0.406	0.437	0.466
4	0.207	0.235	0.261	0.289	0.318	0.346	0.374
4.5	0.183	0.208	0.232	0.258	0.285	0.311	0.339
5	0.164	0.187	0.209	0.232	0.258	0.287	0.310
6	0.135	0.154	0.172	0.192	0.214	0.236	0.261
7	0.114	0.130	0.145	0.163	0.177	0.202	0.224
8	0.098	0.112	0.126	0.140	0.154	0.175	0.195
9	0.0859	0.0981	0.1106	0.1233	0.1357	0.1543	0.1723
10	0.0763	0.0873	0.0986	0.1096	0.1207	0.1375	0.1540
11	0.0687	0.0786	0.0887	0.0988	0.1088	0.1240	0.1385

Table 3. *s*-factors for clinically used spectra and maximum errors that can be incurred when they are used.

Spectrum	*s*-factor	Maximum error (%)
Mo/Mo	1.000	3.1
Mo/Rh	1.017	2.2
Rh/Rh	1.061	3.6
Rh/Al	1.044	2.4
W/Rh	1.042	2.1

ratio was expected because of the low transmission of mammographic x-ray spectra through large thicknesses of breast tissue. The values calculated using the two approaches agreed to within 2%.

3.2. s-factors

Table 1 indicates that the new *g*-factors are dependent on the spectrum used. In order to apply the old *g*-factors to clinically used spectra, a spectral correction factor (*s*-factor) is used. Table 3 gives the *s*-factors for each target/filter combination. For simplicity a single *s*-factor has been assigned to each target/filter combination independent of HVL and breast thickness. Table 3 also gives the maximum value of the relative error that can be incurred by this simplification when each factor is used.

In order to retain compatibility with the existing methodology, the *s*-factor is set to unity for spectra from the molybdenum target/molybdenum filter combination. The relative errors incurred from using the *s*-factors thus normalized are sufficiently small for practical purposes. The greatest error will occur for a spectrum with a rhodium target and rhodium filter, and is then no more than 3.6%. It should be noted that the factor for Rh/Rh corresponds to the spectrum of a GE DMR (GE Medical Systems, Milwaukee, USA) x-ray unit measured by Thilander-Klang (1997). This spectrum shows characteristic x-ray lines from both rhodium and molybdenum. For this unit, the rhodium anode is deposited onto a molybdenum backing. X-rays generated within the rhodium layer can reach the molybdenum layer and can in turn generate molybdenum characteristic x-rays following a photoelectric interaction (Dance *et al* 2000).

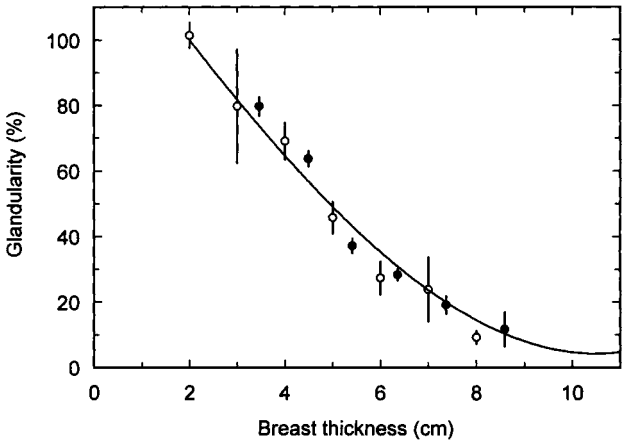

Figure 1. Estimates of average breast composition for different compressed breast thickness in Guildford (open circles) and the Northern Region (full circles), for women in the age range 40 to 49. The error bars correspond to ±1 standard error on the mean.

Table 4. Coefficients for the polynomial fit of glandularity as a function of breast thickness (equation (4)). Data are given for women of ages 40–49 years and 50–64 years.

Coefficient	Age 40 to 49	Age 50 to 64
a	0.000 052 09	−0.000 1118
b	0.001 254 94	0.039 32
c	−1.988	−4.544
d	138.8	176.0

3.3. Average breast composition for different age groups and compressed breast thicknesses

The estimates of average breast composition for different compressed breast thicknesses in Guildford and the Northern Region are shown, for women in the age range 40 to 49, in figure 1. The estimates of average breast composition for women in the age range 50 to 64 are shown in figure 2. For both age groups a polynomial fit is also shown, which has the form

$$\text{glandularity}(\%) = at^3 + bt^2 + ct + d. \tag{4}$$

In this equation the glandularity is the percentage of glandular tissue after allowing for the 0.5 cm surface layers of adipose tissue, t is the compressed breast thickness in mm and a, b, c and d are fitted coefficients whose values are given in table 4. The polynomial fits were constrained to give glandularities of less than or equal to 100%. This was to ensure compliance with the model used, and had little effect on the fit to the glandularity for the older women. However, for the younger women the assumption that there is a 0.5 cm thick adipose layer becomes unrealistic for very thin breasts (less than about 2.5 cm) and can lead to estimated glandularities of more than 100%. In practice, very few breasts are as thin as this on compression and the error in estimating the appropriate c-factor for such breasts is judged to be acceptable. The values of the glandularity found from the fits are given in table 5.

It is noted that for a screening population aged 50–64, the typical glandularities of breasts of thicknesses 4.5 and 5.0 cm are 41% and 33% respectively. These two thicknesses correspond to the 'standard breasts' used in the UK and European mammography dosimetry protocols respectively, whereas the corresponding glandularities are different from that assumed in both protocols for the 'standard breast' (50%). However, it is not considered appropriate to change

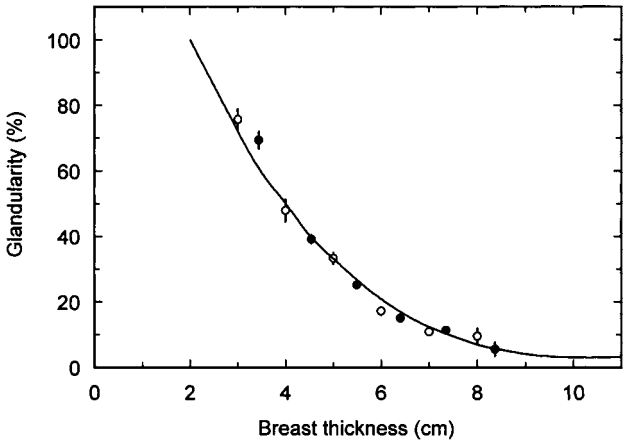

Figure 2. Estimates of average breast composition for different compressed breast thickness in Guildford (open circles) and the Northern Region (full circles), for women in the age range 50 to 64. The error bars correspond to ±1 standard error on the mean. In some cases the error bars are too small to show.

Table 5. Average breast composition as a function of compressed breast thickness. Surface layers of 100% adipose tissue 0.5 cm thick are assumed.

Compressed breast thickness (cm)	Glandularity age 40–49 (%)	Glandularity age 50–64 (%)
2	100	100
3	82	72
4	65	50
5	49	33
6	35	21
7	24	12
8	14	7
9	8	4
10	5	3
11	5	3

the composition of the standard breast. The standard breast is simply intended to give a dose estimate which is representative. In general it will not correspond to the average breast thickness and corresponding glandularity for a particular population of women.

3.4. c-factors

Table 6 gives the c-factors that correct for the glandularity of the breast. Comparison of the results in the table with those calculated in Newcastle using EGS4 shows agreement to within 2%. The values in the table may also be compared with c-factors deduced from g-factors for different glandularities and x-ray spectra published by other authors. Klein *et al* (1997) used the same breast model as the present work. The c-factors can be deduced from their work for glandularities of 0% and 100% and spectra from Mo/Mo, Mo/Rh, Rh/Rh and W/Mo covering the HVL range 0.35–0.60 mm Al and the thickness range 2–9 cm. Very good agreement was found with a maximum difference of 3% and average differences of −0.5%

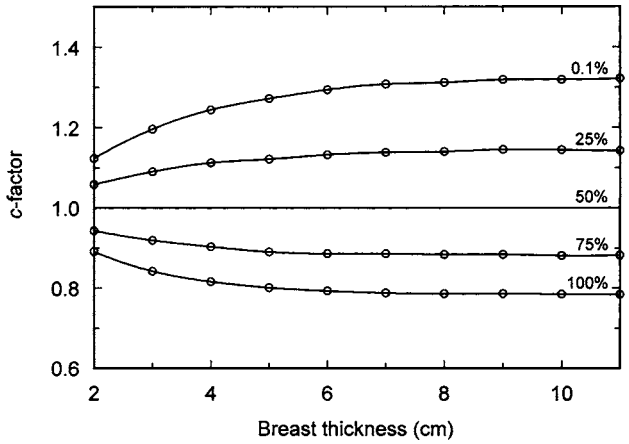

Figure 3. Variation of the *c*-factor with breast thickness at fixed HVL and glandularity. Results are shown for an HVL of 0.35 mm Al and glandularities of 0.1%, 25%, 50%, 75% and 100%.

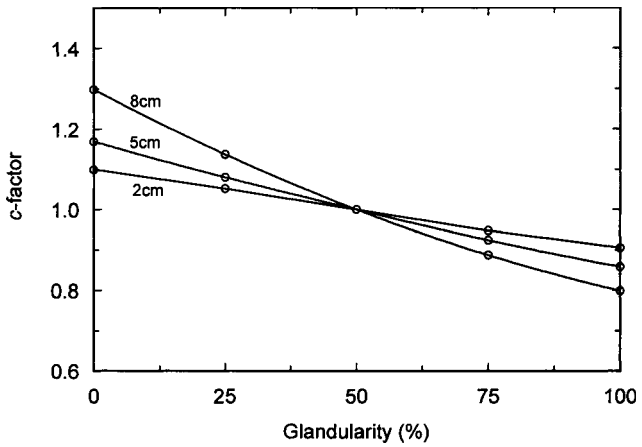

Figure 4. Variation of the *c*-factor with glandularity at fixed HVL and breast thickness. Results are shown for an HVL of 0.45 mm Al and breast thicknesses of 2, 5 and 8 cm.

and 1.5% for glandularities of 0% and 100% respectively. The corresponding differences from a comparison with *c*-factors deduced from the work of Wu *et al* (1991, 1994) were 3%, 2% and −1%. In this case the comparison was made for the thickness range 3–8 cm and Mo/Mo, Mo/Rh and Rh/Rh target/filter combinations covering the HVL range 0.30–0.50 mm Al. The good agreement in the latter case demonstrates the robustness of the *c*-factor as a method of correcting for glandularity. In this context it should be noted that the *g*-factors calculated by Wu *et al* differ from those calculated by us by up to 16% (due to differences in the breast model, x-ray spectra and interaction cross sections). Finally, the *g*-factor tabulation of Boone (1999) is noted. This tabulation uses the same model as Wu and gives *g*-factors for 0% and 100% glandularities only. However, it is assumed that *g*-factors at other glandularities can be obtained by linear interpolation and results are not provided for a glandularity of 50%. As this involves an additional approximation, no comparison of *c*-factors has been made for this case.

Table 6. *c*-factors for glandularities of 0.1–100% in the central region of the breast, breast thicknesses of 2–11 cm and HVLs of 0.30–0.60 mm Al. Surface layers of 100% adipose tissue 0.5 cm thick are assumed.

HVL	Thickness	Breast glandularity				
(mm Al)	(cm)	0.1%	25%	50%	75%	100%
0.30	2	1.130	1.059	1.000	0.938	0.885
0.30	3	1.206	1.098	1.000	0.915	0.836
0.30	4	1.253	1.120	1.000	0.898	0.808
0.30	5	1.282	1.127	1.000	0.886	0.794
0.30	6	1.303	1.135	1.000	0.882	0.785
0.30	7	1.317	1.142	1.000	0.881	0.784
0.30	8	1.325	1.143	1.000	0.879	0.780
0.30	9	1.328	1.145	1.000	0.879	0.780
0.30	10	1.329	1.147	1.000	0.880	0.780
0.30	11	1.328	1.143	1.000	0.879	0.779
0.35	2	1.123	1.058	1.000	0.943	0.891
0.35	3	1.196	1.090	1.000	0.919	0.842
0.35	4	1.244	1.112	1.000	0.903	0.816
0.35	5	1.272	1.121	1.000	0.890	0.801
0.35	6	1.294	1.132	1.000	0.886	0.793
0.35	7	1.308	1.138	1.000	0.886	0.788
0.35	8	1.312	1.140	1.000	0.884	0.786
0.35	9	1.319	1.145	1.000	0.884	0.786
0.35	10	1.319	1.144	1.000	0.881	0.785
0.35	11	1.322	1.142	1.000	0.882	0.784
0.40	2	1.111	1.054	1.000	0.949	0.900
0.40	3	1.181	1.087	1.000	0.922	0.851
0.40	4	1.227	1.105	1.000	0.907	0.825
0.40	5	1.258	1.120	1.000	0.899	0.810
0.40	6	1.276	1.125	1.000	0.890	0.798
0.40	7	1.292	1.132	1.000	0.887	0.793
0.40	8	1.302	1.136	1.000	0.885	0.790
0.40	9	1.308	1.138	1.000	0.884	0.789
0.40	10	1.311	1.138	1.000	0.883	0.788
0.40	11	1.315	1.140	1.000	0.885	0.791
0.45	2	1.099	1.052	1.000	0.948	0.905
0.45	3	1.169	1.080	1.000	0.924	0.858
0.45	4	1.209	1.102	1.000	0.909	0.829
0.45	5	1.248	1.115	1.000	0.898	0.815
0.45	6	1.267	1.125	1.000	0.891	0.801
0.45	7	1.283	1.129	1.000	0.892	0.797
0.45	8	1.298	1.137	1.000	0.887	0.799
0.45	9	1.301	1.135	1.000	0.886	0.792
0.45	10	1.305	1.138	1.000	0.886	0.791
0.45	11	1.312	1.138	1.000	0.885	0.789
0.50	2	1.098	1.050	1.000	0.955	0.910
0.50	3	1.164	1.078	1.000	0.928	0.864
0.50	4	1.209	1.094	1.000	0.912	0.835
0.50	5	1.242	1.111	1.000	0.903	0.817
0.50	6	1.263	1.120	1.000	0.896	0.807
0.50	7	1.278	1.127	1.000	0.890	0.800
0.50	8	1.289	1.132	1.000	0.889	0.794
0.50	9	1.295	1.134	1.000	0.887	0.793
0.50	10	1.302	1.138	1.000	0.886	0.791
0.50	11	1.303	1.140	1.000	0.885	0.789

Table 6. (Continued)

HVL (mm Al)	Thickness (cm)	Breast glandularity 0.1%	25%	50%	75%	100%
0.55	2	1.086	1.043	1.000	0.955	0.914
0.55	3	1.154	1.071	1.000	0.932	0.870
0.55	4	1.196	1.093	1.000	0.918	0.843
0.55	5	1.227	1.105	1.000	0.906	0.824
0.55	6	1.252	1.115	1.000	0.900	0.814
0.55	7	1.267	1.122	1.000	0.896	0.805
0.55	8	1.278	1.125	1.000	0.890	0.800
0.55	9	1.285	1.128	1.000	0.890	0.798
0.55	10	1.290	1.133	1.000	0.889	0.796
0.55	11	1.293	1.134	1.000	0.888	0.793
0.60	2	1.089	1.045	1.000	0.959	0.919
0.60	3	1.142	1.065	1.000	0.933	0.874
0.60	4	1.185	1.090	1.000	0.923	0.850
0.60	5	1.216	1.102	1.000	0.910	0.830
0.60	6	1.238	1.113	1.000	0.904	0.820
0.60	7	1.252	1.120	1.000	0.899	0.812
0.60	8	1.266	1.123	1.000	0.894	0.806
0.60	9	1.272	1.124	1.000	0.893	0.801
0.60	10	1.279	1.125	1.000	0.891	0.797
0.60	11	1.284	1.129	1.000	0.893	0.798

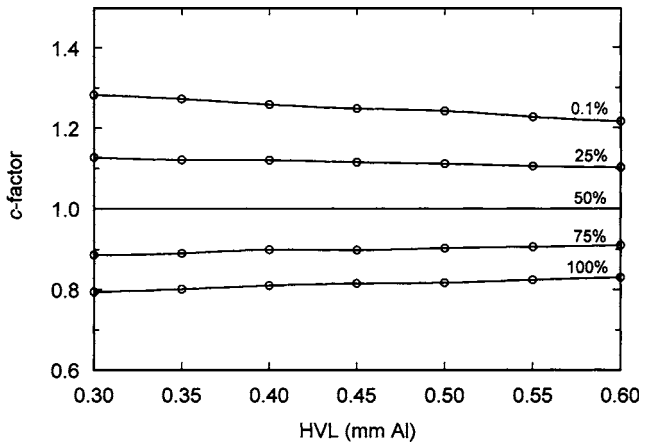

Figure 5. Variation of the c-factor with HVL at fixed glandularity and breast thickness. Results are shown for a breast thickness of 5 cm and glandularities of 0.1%, 25%, 50%, 75% and 100%.

In table 6, a single c-factor is given at each half value layer for each breast thickness and percentage glandularity. At most HVLs, however, c-factors were calculated for a variety of spectra. It was found that the variation in c-factor for different spectra at a given HVL, breast thickness and glandularity is very small and does not exceed 1%. Figures 3, 4 and 5 illustrate the variation of the c-factor with breast thickness, glandularity and HVL. It can be seen (figure 3) that the variation of c with thickness is largest for small breasts and that there is only a small variation above a thickness of 6 cm. The variation of c with HVL is also small (figure 5). The variation of c with glandularity is larger (figure 4) and the range of variation increases

Table 7. *c*-factors for average breasts for women in age group 40 to 49.

Breast thickness	HVL (mm Al)						
(cm)	0.30	0.35	0.40	0.45	0.50	0.55	0.60
2	0.885	0.891	0.900	0.905	0.910	0.914	0.919
3	0.894	0.898	0.903	0.906	0.911	0.915	0.918
4	0.940	0.943	0.945	0.947	0.948	0.952	0.955
5	1.005	1.005	1.005	1.004	1.004	1.004	1.004
6	1.080	1.078	1.074	1.074	1.071	1.068	1.066
7	1.152	1.147	1.141	1.138	1.135	1.130	1.127
8	1.220	1.213	1.206	1.205	1.199	1.190	1.183
9	1.270	1.264	1.254	1.248	1.244	1.235	1.225
10	1.295	1.287	1.279	1.275	1.272	1.262	1.251
11	1.294	1.290	1.283	1.281	1.273	1.264	1.256

Table 8. *c*-factors for average breasts for women in age group 50 to 64.

Breast thickness	HVL (mm Al)						
(cm)	0.30	0.35	0.40	0.45	0.50	0.55	0.60
2	0.885	0.891	0.900	0.905	0.910	0.914	0.919
3	0.925	0.929	0.931	0.933	0.937	0.940	0.941
4	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	1.086	1.082	1.081	1.078	1.075	1.071	1.069
6	1.164	1.160	1.151	1.150	1.144	1.139	1.134
7	1.232	1.225	1.214	1.208	1.204	1.196	1.188
8	1.275	1.265	1.257	1.254	1.247	1.237	1.227
9	1.299	1.292	1.282	1.275	1.270	1.260	1.249
10	1.307	1.298	1.290	1.286	1.283	1.272	1.261
11	1.306	1.301	1.294	1.291	1.283	1.274	1.266

with increasing breast thickness. The increase of the *c*-factor with decreasing glandularity is due to the increased percentage depth dose for fattier breasts. Linear interpolation of the data in table 6 can be used to determine the *c*-factor for intermediate values of breast thickness, glandularity and HVL. The *c*-factor has values between 0.779 and 1.329, demonstrating the importance of including this factor in equation (2).

In order to simplify the estimation of mean glandular doses, tables of *c*-factors for typical breasts in the age groups 40 to 49 and 50 to 64 have been calculated. These are given in tables 7 and 8. It can be seen that the *c*-factors in these tables change more rapidly with breast thickness than those in table 6. This is because of the associated change in glandularity with thickness. The impact of applying the *c*-factor is shown in figure 6. This figure shows calculations of average MGD based on the review of breast doses by Young and Burch (2000). The two curves show the variation of MGD with breast thickness and were calculated using just the *g*-factor and both the *g*- and the *c*-factors. The same set of air kerma values was used in both cases. For the largest breasts, the use of the *c*-factor increases the estimate of MGD by 30%. For the smallest breasts the MGD estimate is decreased by 11%. The effect of applying the *c*-factor on the calculated average MGD per film is estimated to be an increase of 11% for cranio-caudal views and 14% for medio-lateral oblique views. The increase is greater for medio-lateral oblique views because the average compressed breast thickness is greater.

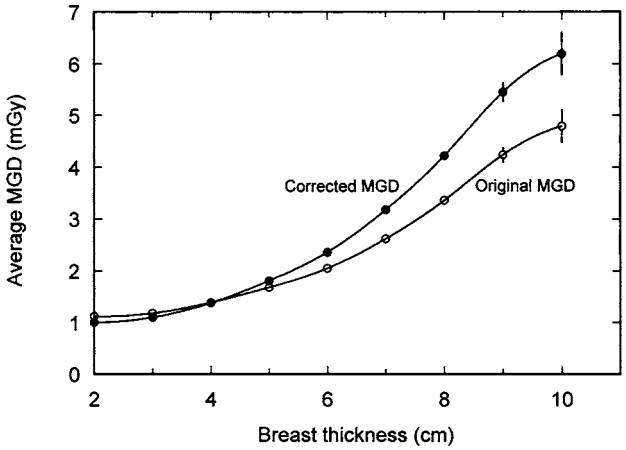

Figure 6. Effect on mean glandular dose estimates of applying composition correction. The error bars correspond to ±1 standard error on the mean. In most cases the error bars are too small to show.

Table 9. Simulation of typical breasts for women aged 50–64 years using blocks of PMMA. Surface layers of 100% adipose tissue 0.5 cm thick are assumed.

Thickness of PMMA (cm)	Equivalent breast thickness (cm)	Glandularity for age 50 to 64 (%)
2.0	2.1	97
3.0	3.2	67
4.0	4.5	40
4.5	5.3	29
5.0	6.0	20
6.0	7.5	9
7.0	9.0	4
8.0	10.3	3
8.5	10.9	3

3.5. Equivalence between PMMA and typical breasts

Tables 9 and 10 show the calculated values of equivalent thickness for blocks of PMMA and typical breasts of women in the age range 50 to 64. The corresponding breast compositions are given by equation (4) and are also listed.

The originally published table of equivalence between blocks of PMMA and typical breasts in the age range 50 to 64 (Young *et al* 1996) was found to provide a good fit to the current experimental data from Guildford, and shows good agreement with the values calculated using the Monte Carlo program. The difference between the calculated and experimental values does not exceed 5.0% or 2.1 mm at any breast thickness or glandularity. The theoretical values were preferred to the experimental values for the tabulation as they correspond to the glandularities estimated using the data from Guildford and the Northern Region.

To determine the effect of using the new data when breasts are simulated using PMMA phantoms, entrance air kerma and MGD have been calculated using both the old (Dance 1990) and new PMMA equivalence values and conversion factors for breast thicknesses in the range 2–8 cm and for the 50–64 age group. Figure 7 shows ratios of both entrance air kerma and

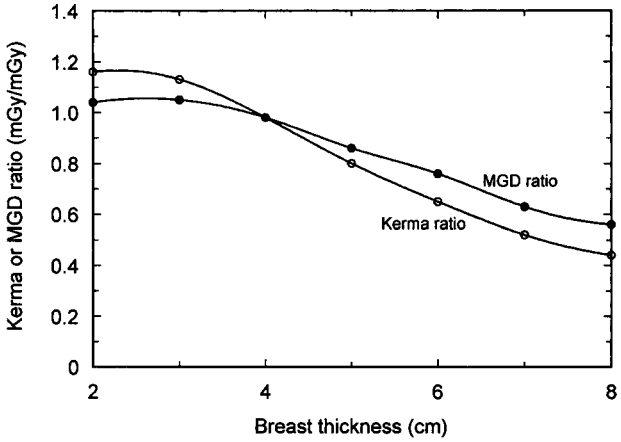

Figure 7. Ratios of entrance air kerma values and of MGD (mean glandular dose) values for breast thicknesses in the range 2–8 cm calculated using PMMA equivalent thicknesses and MGD conversion factors from the current work to values calculated using data from Dance (1990).

Table 10. Simulation of typical breasts for women aged 50–64 years using blocks of PMMA. Surface layers of 100% adipose tissue 0.5 cm thick are assumed.

Breast thickness (cm)	Glandularity age 50 to 64 (%)	Equivalent thickness of PMMA (cm)
2.0	100	1.9
3.0	72	2.8
4.0	50	3.6
5.0	33	4.3
6.0	21	5.0
7.0	12	5.6
8.0	7	6.3
9.0	4	7.0
10.0	3	7.8
11.0	3	8.6

mean glandular dose calculated for the two cases. The results are for a spectrum from a molybdenum target and molybdenum filter with an HVL of 0.35 mm Al. Mean glandular dose was calculated using the g-factors in Dance (1990) with the old PMMA equivalence data, and using the old g-factors and new c-factors with the new PMMA equivalence data. Figure 7 shows that for a breast of 2 cm thickness, using the new PMMA equivalence data and a c-factor results in increases in entrance air kerma and mean glandular dose of 16% and 4% respectively compared with using the old PMMA equivalence data. For this breast thickness, the new PMMA thickness is greater than before but the c-factor is less than unity. For a breast of 8 cm thickness, using the new PMMA equivalence data and a c-factor results in decreases in entrance air kerma and mean glandular dose of 56% and 44% respectively compared with using the old PMMA equivalence data. For this breast thickness, the new PMMA thickness is less than before but the c-factor is greater than unity.

4. Conclusions

The MGD conversion factors presented in this work provide an extension of those in routine clinical use in accordance with the UK (IPSM 1994) and European protocols (European Commission 1996) for mammographic dosimetry. The introduction of relative conversion factors, to allow for breasts of varying glandularity and the use of different x-ray spectra, provides a simple approach that retains continuity with the protocols in current use. The determination of the glandularity of an individual breast is difficult. The provision of typical breast glandularities and equivalent PMMA thicknesses for breasts of various thicknesses should be a valuable aid to dose surveys.

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