

Patient-Specific Radiation Dose Estimation in Breast Cancer Screening

Keeping Patients Safe and Informed

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Introduction

Millions of women are screened each year using mammography and/or tomosynthesis in order to detect breast cancer at an early stage. Although the radiation doses used are relatively low [1], the breast is one of the most radiation-sensitive organs so constant vigilance is necessary to ensure that the radiation dose is as low as reasonably achievable (the ALARA principle). Despite this vigilance by X-ray vendors and regulatory bodies, patients and clinicians alike are increasingly raising concerns about the risk of radiation-induced cancers and, for some women, this risk is sufficient to reduce adherence to screening programs or deter them from undergoing breast screening altogether [2].

Although imaging of phantoms has provided a certain level of dose monitoring, new technology is now allowing the real-time monitoring and reporting of more standardized, patient-specific doses across a range of mammography and tomosynthesis units. This paper explains the scientific background and rationale behind VolparaDose™, a tool for patient-specific, standardized radiation dose estimation.

Mean Glandular Dose Estimation Today

Mean glandular dose (MGD) is widely accepted as the most appropriate measurement for predicting the risk of radiation-induced cancer. It is MGD (used synonymously with average glandular dose or AGD) that is the focus of mammographic dose regulations and quality assurance guidelines internationally.

In the US, for example, the FDA stipulates, “The average glandular dose delivered during a single cranio-caudal view of an FDA-accepted phantom simulating a standard breast shall not exceed 3.0 milligray (mGy) (0.3 rad) per exposure. The dose shall be determined with technique factors and conditions used clinically for a standard breast” [3]. EU guidelines also recommend maximum dose levels according to phantom exposures (see Table 1) [4].

X-ray manufacturers provide an MGD estimate for each image. Unfortunately, however, several different algorithms exist for estimating MGD and different ones have been chosen by each manufacturer. Furthermore, one of the key inputs to those algorithms is breast density and, in the absence (to date) of reliable measurements for each patient, the manufacturers have had to make rather crude estimations.

A maximum average glandular dose is set per PMMA thickness:

Thickness of PMMA [cm]	Equivalent breast thickness [cm]	Maximum average glandular dose to equivalent breasts	
		acceptable level [mGy]	achievable level [mGy]
2.0	2.1	< 1.0	< 0.6
3.0	3.2	< 1.5	< 1.0
4.0	4.5	< 2.0	< 1.6
4.5	5.3	< 2.5	< 2.0
5.0	6.0	< 3.0	< 2.4
6.0	7.5	< 4.5	< 3.6
7.0	9.0	< 6.5	< 5.1

Table 1: European guidelines for acceptable and achievable AGD, according to breast thickness of a polymethylmethacrylate (PMMA; also known under the trade names Lucite, Plexiglas or Perspex) phantom [4].

Once computed, manufacturers insert their dose estimates into the DICOM images sent out by their mammography units, and those values can be viewed by the radiologist or technologist on their workstations. VolparaDose builds upon the manufacturers’ dose estimations but improves on these by: (1) using VolparaDensity’s assessment of density; and (2) using a consistent algorithm across all manufacturers.

Dance's MGD Algorithm

The MGD estimation algorithms used by the X-ray manufacturers appear to come from the models of either Wu [5-7] or Dance [8-11], but also of note are the FDA's 1987 "Handbook of Glandular Tissue Doses in Mammography" [12] and Boone's work [13]. Wu's algorithm allows for the consideration of the specific breast density in the MGD estimate, but it is unclear how, if indeed at all, any given manufacturer's implementation estimates breast density. Although the algorithm of Dance et al. also allows for consideration of breast density in the MGD estimate, they utilize a crude estimate of breast density that is derived solely from the compressed breast thickness.

VolparaDose is based on Dance's model for estimation of MGD, as it is widely accepted and now covers most mammography and tomosynthesis equipment. Furthermore, comparisons with Wu and Boone indicate high correlations between the various models. Dance's model is outlined in Box 1, and the various inputs are described below.

$$\text{MGD (mGy)} = K g c s$$

Where:

K (mGy) is the incident air kerma (i.e. the "Entrance Dose" at the surface of the breast)

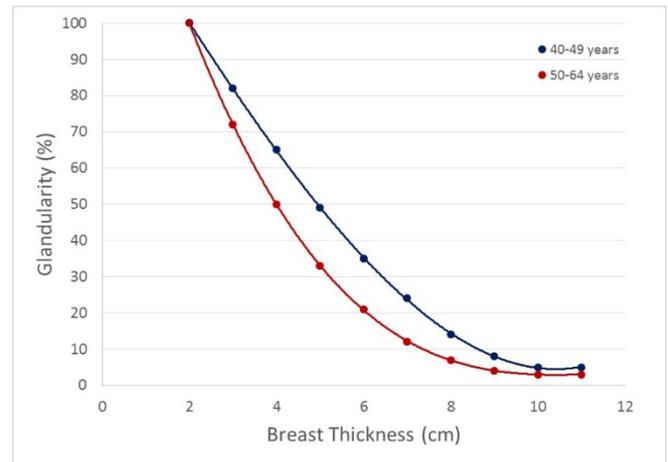
g is a conversion factor describing the fraction of 'K' that is absorbed by the glandular tissue in the breast, assuming a breast of 50% adiposity and 50% glandularity

c is the correction factor for breast composition (i.e. corrects for any difference in glandularity from 50%)

s is the correction factor for X-ray spectrum that corrects for differences in the X-ray spectrum when a target/filter combination other than Molybdenum/Molybdenum is used. This correction is independent of the HVL.

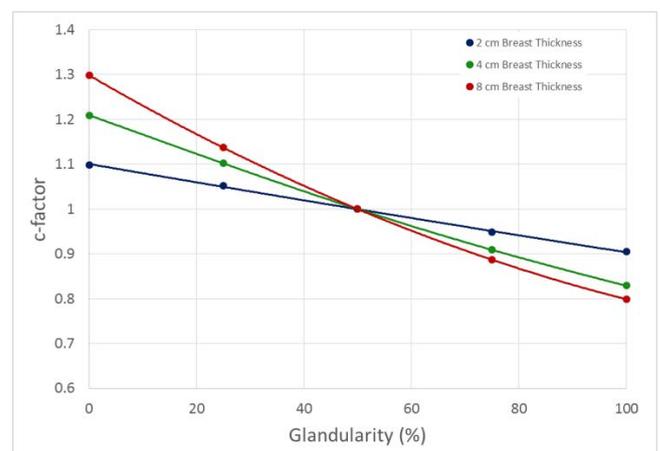
Box 1: Dance's model for estimation of Mean Glandular Dose (MGD).

The entrance dose, or 'K', is provided by the manufacturers in the DICOM header and is routinely calibrated per machine each year. The 's' correction factors are provided by Dance in a simple lookup table for various target/filter combinations. The 'g' conversion factors are also provided in a lookup table as a function of breast thickness and half-value layer (HVL). Dance's 'g' conversion factor assumes a 50% glandularity, however, in reality there is wide heterogeneity in breast composition. In order to correct for glandularity differences (i.e. the 'c' factor), Dance first makes a fairly crude estimate of glandularity based on varying breast thickness and age group. Dance's estimates of glandularity were originally derived from measurements on a small number of women in the United Kingdom (see Graph 1).



Graph 1: Dance's estimation of glandularity for women aged 40-49 years and 50-64 years, based on breast thickness. Reproduced from Dance et al. [9].

To determine the glandularity correction factor 'c' (i.e. the remaining unknown variable in the equation), Dance provides a lookup table of c-factors for various HVL, breast thicknesses and glandularity. Graph 2 shows how c-factors vary by glandularity at a fixed HVL, and for several breast thicknesses. Working through one example, Dance estimates that a 40 year old women with a 2 cm breast thickness would have 100% glandularity (see Graph 1). To determine the correction factor 'c' for this particular breast, one can extrapolate from the blue line in Graph 2, giving a c-factor of 0.9. In this case, the assumption of a 50% glandularity breast would lead to an overestimation of MGD by 10%. As another example, a 40 year old women with an 8 cm breast thickness would have a 14% glandularity breast and a c-factor of 1.2. In this case, MGD is under-estimated by 20%.



Graph 2: Variation of Dance's 'c' correction factor according to glandularity, at a fixed HVL (0.45 mm) and 2, 4, or 8 cm breast thicknesses. Reproduced from Dance et al [9].

VolparaDose™ Patient-Specific Glandularity

The glandularity input is very important in dose estimation. Dance's estimation derived solely from breast thickness might work on average, but clearly fails in certain cases. The example in Figure 1 shows two breasts with exactly the same breast thickness but with very different amounts of glandular tissue.

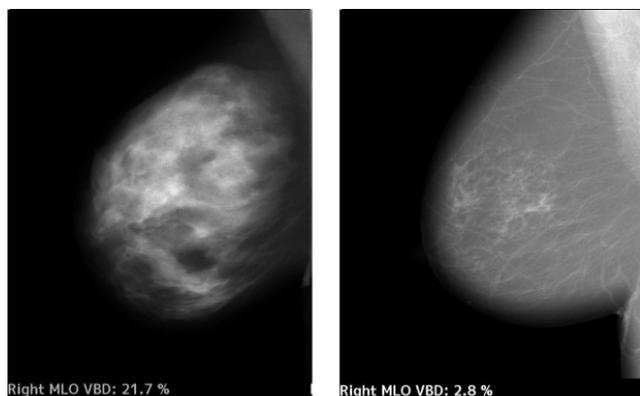


Figure 1: Right mediolateral oblique (MLO) mammograms for different women with the same breast thickness but varying breast density.

As described below, VolparaDose resolves this by using VolparaDensity's volumetric breast density (VBD) to more accurately estimate glandularity and, hence, to derive a patient-specific MGD.

Dance's definition of glandularity is rather different to the volumetric breast density (VBD) output by VolparaDensity. Typical VBDs range from 0–35%, whereas Dance's glandularity ranges from 3–100%, depending on the compressed breast thickness and the age band into which the patient falls (refer to Graph 1). The differences are due to VBD from VolparaDensity including both the fatty breast edge and the subcutaneous fat into the overall percentage, whereas Dance's glandularity input is the breast density only of a centralized region of the breast (see Figure 2). Furthermore, Dance's glandularity is by weight, not by volume.

In short, to convert VBD to Dance's glandularity, VolparaDose does the following:

1. Removes the subcutaneous fat from the volume of breast (this can raise the density by 20% or more)
2. Removes the uncompressed breast edge from the volume of breast (this can raise the density by 3-8%)
3. Changes the density from volume to weight (this can be another increase of 6% or so). This is achieved using the known densities of fibroglandular and fatty tissue (i.e. 1.04 g/cm³ and 0.93 g/cm³, respectively [14]).

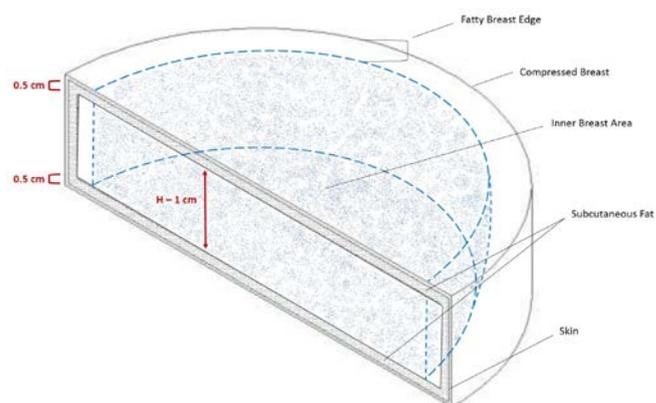
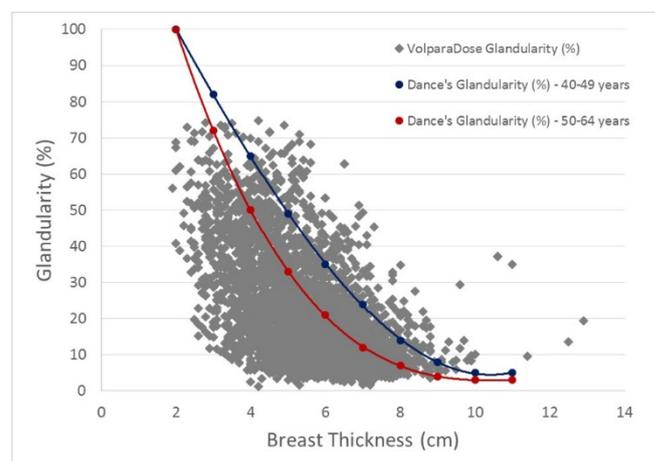


Figure 2: Diagram of a compressed breast and the regions important for glandularity estimations. The centralized region of the breast (shaded blue region) is used by Dance to determine glandularity (%). In estimating glandularity Dance excludes the fatty breast edge (i.e. where the breast thickness reduces due to no, or little, compression) and the subcutaneous fat layer. In contrast, VolparaDensity only excludes the skin in its density estimation. The centralized region has a height equal to [compressed breast thickness (H) cm – 1 cm].

After these conversion steps, the range of glandularity values, as estimated by VolparaDensity, are much more comparable to those provided by Dance based on breast thickness and age (see Graph 3). It should also be noted that work is currently underway to better determine the location of dense tissue in 3D, as taking the distribution of glandular tissue into consideration can further improve dose estimation [15].



Graph 3: Dance's estimation of glandularity [9] based on breast thickness (blue and red data points are Dance's glandularity for the 40-49 year and 50-64 year age ranges, respectively) overlaid onto VolparaDose's estimation of glandularity for 1000 patients (grey data points), as derived from the volumetric breast density generated by VolparaDensity. Note, the majority of images analyzed by VolparaDensity were from women aged >50 years, thus, the glandularities align more closely with Dance's estimates of glandularities for 50-64 year olds.

VolparaDose™ vs Manufacturer-reported MGD

In general, the MGD estimated by VolparaDose correlates well to the MGD reported by manufacturers in the DICOM header. However, the impact of each manufacturer using different dose models and/or making different assumptions about glandularity becomes clear when MGD is stratified by breast density. Some manufacturers clearly assume low density across all breasts, as the VolparaDose MGD values match well on BI-RADS (or Volpara Density Grade, VDG) 1, but then diverge on BI-RADS (VDG) 4 (see Figure 3). Conversely, some manufacturers assume a high density, as shown by a higher correlation for BI-RADS 4 and a lower correlation for BI-RADS 1 (see Figure 4).

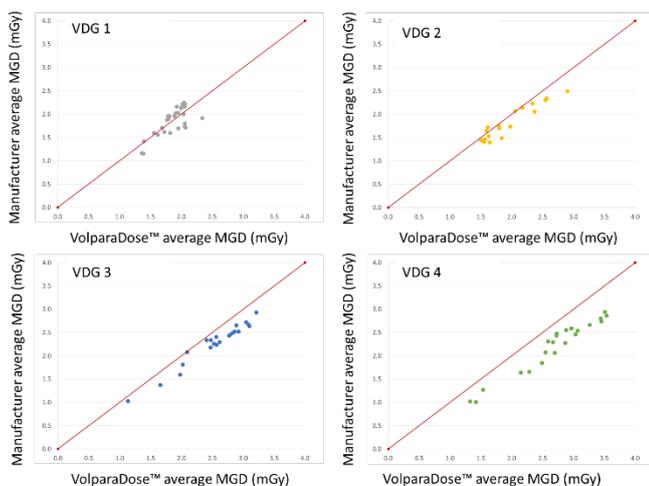


Figure 3: Comparison of manufacturer A and VolparaDose estimates of average MGD according to BI-RADS (VDG) breast density categories.

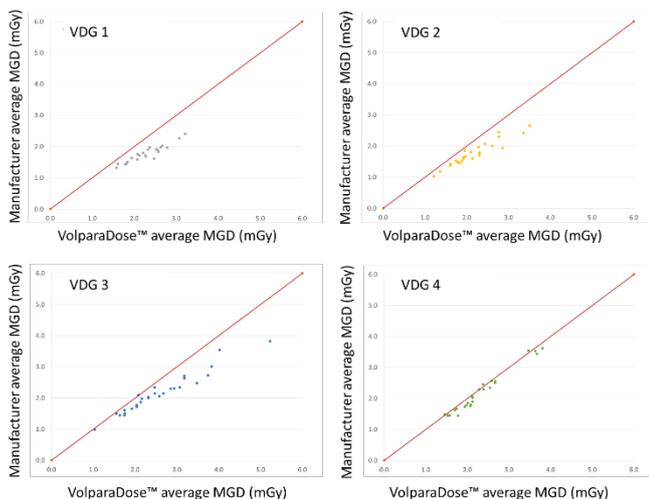


Figure 4: Comparison of manufacturer B and VolparaDose estimates of average MGD according to BI-RADS (VDG) breast density categories.

Figure 5 highlights the benefits of using a standard algorithm, which takes into account patients' actual breast densities, for MGD comparisons across X-ray systems. This example shows two X-ray machines that imaged similar

populations of patients. However, the manufacturer-reported doses show an 8.2% increase from X1 to Y2 (1.46 to 1.58 mGy), whereas the patient-specific one reveals a 22.2% increase (1.49 v 1.82 mGy).

Vendor	X1	Y2
Number of Images	992	1010
Number of Studies	250	260
Number of Unique Patients	250	260
Mean Studies per Day	22.7	18.6
Median Patient Age	54	60
Median Fibroglandular Tissue Volume (cm ³)	45.7	49.8
Median Volumetric Breast Density (%)	6.8	6.3
Median Breast Volume (cm ³)	775	785
VDG 1 (%)	31.2	29.6
VDG 2 (%)	24.0	31.5
VDG 3 (%)	31.2	21.2
VDG 4 (%)	13.6	17.7
Mean VDG	2.3	2.3
Median Breast Thickness (mm)	62.0	58.5
Median Contact Area (mm ²)	9235	8685
Median Mean Manufacturer MGD per image (mGy)	1.46	1.58
Median VolparaDose (mGy)	1.49	1.82
Median Compression Force (H)	77.5	61.2
Median Pressure Applied (kPa)	8.7	8.5
Median Paddle Tilt Angle (degrees)	1.14	1.43

Figure 5: Example screenshot of VolparaDose results for two different manufacturers accessed via the VolparaAnalytics dashboard. These machines screened populations with similar breasts (volumetric breast density and breast volume), yet Y2 had higher average MGD values as estimated by the manufacturer, and even higher still by VolparaDose.

VolparaDose™ Deployment

VolparaDose is very easy to implement and there are several options for deployment:

- VolparaDoseRT can be purchased as an add-on module to VolparaDensity and allows the radiologist or technician to view the average MGD per image on the Secondary Capture Image (see Figure 6). Similarly to the breast density results, the patient-specific average MGD per image can also be integrated into patient letters, either via the Secondary Capture Image, or from a Mammography CAD SR, with compatible reporting systems.
- VolparaDoseSR allows MGD measurements to be integrated into DICOM-compatible dose tracking systems for a patient-specific cumulative dose history for each woman.
- For quality assurance activities, the minimum, median, and maximum MGD values can be viewed on the VolparaAnalytics dashboard for each mammography unit and operator. These values can also be directly compared with the manufacturer-reported MGD values.



Figure 6: VolparaDoseRT allows a personalized estimate of average MGD per image to be displayed alongside the volumetric breast density results on the Secondary Capture Image.

VolparaDose is compatible with all major mammography systems, as well as digital breast tomosynthesis systems. It is important to note that, in addition to the DICOM tags required by VolparaDensity, VolparaDose requires an accurate entrance dose estimate from the manufacturer to be present in the image header information. Some systems may not have been configured to put these values into the DICOM header.

Please contact us for enquiries regarding VolparaDose compatibility with X-ray systems at your facility.

Conclusion

Patient-specific dose reporting in mammography is now possible, and allows for more consistent dose information to be provided to women. Moreover, standardized dose estimations enable meaningful comparisons of radiation doses between machines, to help identify potential opportunities for improved quality control.

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FOR A DEMONSTRATION

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