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Review of radiation dose estimates in digital breast tomosynthesis relative to those in two-view full-field digital mammography

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Abstract

We examined how radiation dose levels in digital breast tomosynthesis (DBT) differ from those used in 2-view full-field digital mammography (FFDM).

Acquisition parameter settings and information on the average absorbed dose to the glandular tissues within the breasts were reviewed based on clinical studies that evaluated DBT and FFDM. Dose ratios (D_{DBT}/D_{FFDM}) were derived from imaging protocols, which included tomosynthesis in 1- or 2-views alone, and as an adjunct technique to FFDM.

Stand-alone DBT was associated with a much lower to a slightly higher radiation dose compared to that of comparable FFDM units, as summarized in dose ratio ranges of 0.34–1.0 for 1-view DBT, and 0.68 –1.17 for 2-view DBT. One of the lowest reported dose estimates was obtained using a photon-counting DBT unit (avg. 0.70 mGy/scan; range: 0.28–1.26 mGy). Breast doses for DBT combined with FFDM are summarized in dose ratio ranges of 1.03–1.5 for 1-view DBT plus FFDM, and 2.0–2.23 for 2-view DBT plus FFDM. In the latter of these settings, the dose was reduced by ~45% when 2D-views, reconstructed from the DBT images (“synthetic 2D images”), were used as a substitute for FFDM.

Stand-alone DBT operated at lower to slightly higher radiation doses in comparison to FFDM. For DBT combined with FFDM, radiation doses were elevated, at maximum by a factor ~2 1/4 of that of FFDM alone. In this setting, a replacement of FFDM with synthetic 2D-views reduced the

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breast dose approximately by half, which has substantial implications for population screening programs.

Keywords

Digital breast tomosynthesis; Full-field digital mammography; Radiation doses to the breast

Introduction

Digital breast tomosynthesis (DBT) has been shown to improve mammographic accuracy [1–5] and has emerged as a feasible replacement or adjunct technology to full-field digital mammography (FFDM). DBT reconstruction results in pseudo-tomographic images with partial blurring of features outside the selected plane, resulting in a significant reduction of the overlapping tissue effect present in conventional mammography. DBT is increasingly being used as a diagnostic imaging device, is used for screening in some settings in North America and is also being evaluated for population-based screening programs in many countries. Initial results from screening trials have been promising. Increase in breast cancer detection rates of 10%–53% has been achieved often at recall rates reduced by 20% –59% relative to FFDM [1,6–10]. The additional breast cancers have been found in patients of different ages and breast density types, implying a potentially broad role for DBT. A high proportion of the DBT-detected cancers have been reported to be invasive carcinomas, which also indicates a potential impact for DBT in mammography screening.

In DBT, the X-ray tube rotates over a limited angular range and a low dose exposure of the compressed breast is acquired every few degrees. The average absorbed dose to the glandular tissues (AGD) is the summation of absorbed doses in the fibro-glandular tissue of the breast from all the multiple low-dose projection images. The concept of low-dose imaging in tomosynthesis has been made feasible due to the development of digital detectors with rapid read-out capabilities, high dose efficiency (high detector quantum efficiency; DQE) and low noise. The projection images become clinically useful as the reconstructed image information is additive. Tomosynthesis imaging includes multiple parameters that may influence the resulting breast dose. The angular range and number of exposures acquired during a scan are specific to the design of a system and thus these parameters are the same across acquisitions for a particular unit. Different manufacturers of DBT units have adopted quite different settings for these parameters, which are also associated with the detector type used and its design, and whether it is stationary or movable. Typically, the number of images acquired ranges from approximately 10 to 25, whereas the angle ranges from about 10 to 50° [11]. The tube loading, voltage and, in some cases, the anode/filter combination are, as in mammography, parameters, which are specific for the individual breast. In clinical units, these parameters are determined by the automatic exposure control (AEC) according to the characteristics of the imaged breast (e.g. breast thickness, glandular composition) so they will vary between acquisitions. In early clinical tomosynthesis studies, before AEC was implemented, the radiographer set these parameters manually using a technique chart. In DBT, the dosimetric effects of using different combinations of acquisition parameters are relatively well known [12–15]. As the female breast is a

radiosensitive organ and because tomosynthesis has been introduced into the screening setting, the radiation absorbed dose to the breast is of special concern. Diagnostic Reference levels (DRLs) were introduced by the International Commission on Radiological Protection (ICRP) as a practical guidance in the management of patient doses in radiology [16,17]. In North America, FDA standards are outlined in the Mammography Quality Standard Act (MQSA), which set a breast dose restriction of 3 mGy per acquisition of the American College of Radiology (ACR) phantom [18]. To ensure that patient doses in tomosynthesis are within established recommendations or limits, similar absorbed dose levels should be pursued as is currently used in FFDM, although this should not compromise any benefit in clinical performance.

The purpose of this paper is to review and summarize absorbed doses reported in clinical studies using DBT and FFDM and describe the dose contribution from DBT relative that from FFDM.

Materials and methods

Review of Dose Settings and Dose Estimates

A literature search was performed in reports of clinical studies on breast cancer detection comparing tomosynthesis and full-field digital mammography (FFDM), and which included absorbed dose estimates at FFDM and DBT using equipment developed by different manufacturers and thus of various designs (PubMed search: April 2008 to August 2014; literature search was performed by TS). Information was extracted on how patient-specific acquisition parameters were set and how dose was estimated, if reported. Based on the given information, dose ratios (D_{DBT}/D_{FFDM}) were estimated from examined imaging protocols, which included DBT performed in one and two views as a replacement or as an adjunct technique to FFDM. D_{FFDM} always includes the dose from the two views of the complete FFDM examination. The dose from the cranio-caudal view is assumed to be equal to that of the mediolateral oblique view when performed on the same imaging technique.

Results

DBT Systems

There were 17 papers found that matched the literature search criteria. These included the use of five different types of DBT units (from GE HealthCare, Siemens, Xcounter, Sectra and Hologic; see appendix for a description of their design). The studies were almost exclusively performed in an experimental or early clinical application setting. All DBT systems were of investigational design (i.e. prototype units) except one that was a clinical unit, the Hologic Selenia Dimensions. The DBT systems were often compared with the same FFDM systems (or platforms) that they originally were developed from, except in a few studies where other mammography systems were either partially [19,20] or exclusively used [21–23]. Automatic exposure control (AEC) was only implemented in two types of DBT systems; the Sectra unit (now Philips) and the Hologic Selenia Dimensions. In the other DBT systems the acquisition parameters were set manually for each patient.

Acquisition Parameter Settings and Dose Constraints

If automatic exposure control (AEC) was incorporated into the DBT system, it was used to determine the acquisition parameters and thus set the dose (method i). If not, a manual breast thickness-dependent technique chart was used to set the acquisition parameters, which ensured that the breast dose in DBT was within a specific limit or the same as that of FFDM by being based on:

- **i.** Acquisition parameters associated with system-specific AGD values [24] within acceptance limits proposed by the European Guidelines for Quality Assurance in Breast Cancer Screening and Diagnosis for screen-film mammography [25].
- **ii.** Anode/filter combination and tube voltage determined by the AEC of the FFDM unit; using the same total mAs in DBT and FFDM, which result in the same dose within 10% [12,14].
- **iii.** Acquisition parameters derived from a matched dose calibration with an ionizing chamber of the DBT and FFDM systems, resulting in equal doses (L. Niklason, personal communication, September 2014).

Methods for Estimating the Average Absorbed Dose to the Glandular Tissues

When average glandular dose (AGD) was reported it was estimated for:

1. A ‘standard breast’ according to American College of Radiology (ACR) technical standard [26] using the Nuclear Associates phantom model 18–220; which approximates a 45 mm compressed breast of 50%/50% glandular/adipose composition, and using conversion coefficients [26,27]. In one case, FFDM dose was estimated using software provided by the National Centre for the Coordination of Physics in Mammography (NCCPM) [28,29].
2. Examined breasts, using the methods by Dance et al. [12], or ACR [30], which uses the model developed by Wu et al. [31,32] as a basis for breast dosimetry. These methods are integrated into clinical systems.

Estimated dose ratios (D_{DBT}/D_{FFDM})

In the one-view DBT studies, dose ratios (D_{DBT}/D_{FFDM}) ranged from 0.34 to 1.0 (Table 1A), whereas in the studies of two-view DBT, the dose ratios ranged from 0.68 to 1.17. When DBT was combined with FFDM, the absorbed dose levels for the tomosynthesis acquisition for *one-view* DBT combined with FFDM ranged from 1.03 to 1.50 of that of FFDM. This absorbed dose ratio range was partially influenced by whether two FFDM views were used together with the DBT view or only a single FFDM view (e.g. DBT_{MLO} + $FFDM_{CC}$); the lowest value in that range (1.03) was from the latter. For *two-view* DBT added to FFDM, the dose ratio (D_{DBT}/D_{FFDM}) ranged from 2.0 to 2.23. In this setting, the breast dose was reduced by 45% when synthetic 2D-views (reconstructed from information acquired during DBT) were used as a substitute for FFDM, as shown in the recent study by Skaane et al. [6] (Table 1B).

Discussion and Conclusion

Evidence on the clinical performance of DBT is rapidly growing, as is the clinical application of this new technology for imaging the breast. This necessitates careful consideration of potential radiation safety issues. Absorbed dose levels for DBT and FFDM in clinical studies (2008–2014) were therefore reviewed and summarized in terms of the relative dose contribution from DBT to that of FFDM. The dose estimates indicate that when tomosynthesis was used as a stand-alone technique, in one or in two views, it resulted in generally similar (slightly lower to a slightly higher) dose to the breast as from FFDM units. For a combined setting of 2-view DBT and FFDM using a commercial unit with dual functionality of acquiring *both* DBT and FFDM images, the DBT dose levels were substantially higher by a factor up to ~2 1/4 that of FFDM alone. However, replacing FFDM with synthetic 2D-views (reconstructed from the DBT acquisitions) reduced the dose approximately by half to a level that was roughly comparable to that of FFDM. An alternative approach to achieve reduced doses was when DBT mediolateral-oblique (MLO) view was used combined with FFDM cranio-caudal (CC) view, which for a clinical unit delivered a total dose to the breast that was similar to (1.03 times) that of FFDM.

As tomosynthesis is increasingly being used, it is relevant to address if performing it in one-view alone is sufficient in terms of accuracy, or if both the MLO and CC views are necessary. It is also important to determine if tomosynthesis should be used as a standalone imaging technique or as an adjunct technique to FFDM. The answer to these questions will have considerable impact on breast-absorbed doses. Because of the limited sampling at tomosynthesis, it does not provide a complete 3D representation of the breast volume. At present, the use of both DBT views, as well as using DBT adjunct to FFDM, has been shown to be beneficial in terms of breast cancer detection in comparison to 1-view DBT for DBT units of various designs [5,19,33,34]. In a recent study, a 2-view DBT acquisition was shown to provide twice the sensitivity- and overall accuracy gain in comparison to 1-view DBT acquisition [33]. Another study [19] found significantly improved breast cancer detection for 2-view DBT over FFDM, when evaluated as a standalone technique, while 1-view DBT only yielded a comparable accuracy to that of FFDM. There are probably multiple reasons for this [34,35]. Considering these accuracy increments in relation to the slight increase in absorbed dose relative to FFDM (such as, by 17% the most, which was partially influenced by the relatively low FFDM dose at the Sectra Mamea system, Table A1), the benefits could outweigh potential risks of late effects of radiation [36]. However, preliminary results of experimental studies need to be examined in larger, preferably randomized or comparative, trials to provide more robust evidence from a clinical setting. Moreover, the gain in accuracy must be balanced with other factors associated with the clinical efficiency of the technique, such as case-review time and examination costs, which both might increase with the number of images acquired.

As shown (Table A1), estimates on absorbed doses to the breast in DBT were lower to comparable to FFDM in the 1-view setting as well as in the 2-view setting, although, the lowest dose levels were achieved in studies of 1-view DBT. These results indicate that it is possible to use similar dose levels as FFDM in both these imaging protocols. It does not exclude the fact that significant dose savings might be achieved by acquiring fewer views or

scans, but rather reflects the approach chosen by the manufacturer and/or the investigator. Presumably, the general aim of the studies has been to use equivalent (or lower) absorbed dose levels to what is typically used in FFDM. As a consequence, when 1-view DBT has been the primary modality under investigation, similar total dose per examination has usually been used compared to that of FFDM [5,21,22,37]. Thereby, to a certain degree these may also have been adapted to dose levels typically used at a clinical center where a study was conducted. Dose levels are known to vary between clinics (e.g. DRLs are typically country or region specific), systems used [38] and, also, their provided image quality may vary [39], both because of radiologists' preference and due to differences in the breast characteristics of the population. An example of this is the study by Wallis et al. [19], where patients were examined both in England and in Sweden, with an average breast dose per DBT scan that was relatively about 17% higher in England than in Sweden (avg. 0.82 mGy and 0.70 mGy, respectively). For the patients examined at FFDM, the resulting average breast dose was 50% higher in England than in Sweden (avg. 1.2 and 0.6 mGy, respectively). The DBT units in England and Sweden were the same, while the FFDM units were from different manufacturers (GE and Sectra), which contributed to the dose discrepancy.

As expected when performing multiple acquisitions of the breast, as for 2-view tomosynthesis together with 2-view FFDM, the total dose increased (Table 1B, dose ratio range: 2.0–2.2). FFDM is the current reference standard for detection of calcifications. Therefore, the concept of synthetic 2D images was introduced as a potential replacement to FFDM in the combined setting. The 2D images are generated using an algorithm applied to the tomosynthesis data set. These synthetic 2D images are intended to help limit the absorbed dose to the breast, maintain the accuracy of FFDM for detection of calcifications and potentially ease the comparison to prior years' screening images. Other manufacturers of tomosynthesis units have developed methods with the same purpose [40]. In a screening-trial including 12 621 patients [6], replacing the FFDM views with synthetic 2D-views was associated with a decreased absorbed dose level by ~45% when compared to the combined setting of DBT and FFDM resulting in a slightly higher dose than using FFDM alone (~19%). It should be noted that this relative increase might be explained by a drop of the FFDM dose when setting the AEC of the clinical unit as it acquires both DBT and FFDM images, rather than being an actual increase of DBT dose.

It should also be noted that the DBT dose estimates for a standard breast (Teerstra et al.: D_{DBT}: 1.74 mGy Michell et al.: D_{DBT}: 1.6 6 –1.90 mGy) performed according to the American College of Radiology technical standard [26] were well below the MQSA limit of 3 mGy. When accounting for study-specific AGD estimates based on patient examinations, which were only reported in a limited number of studies, the values presented for photon-counting units were particularly low. In the study by Wallis et al. [19] the average dose per DBT scan was as low as 0.7 mGy (range: 0.28–1.42 mGy). The dose-efficiency of the detector (DQE) is important in tomosynthesis systems because the exposure to the detector per projection is at least an order of magnitude lower than that in FFDM. Photon-counting detectors do not exhibit electronic noise, and the technique rejects nearly all scattered radiation, which allow the use of low patient doses without sacrificing image quality. Therefore, photon-counting detectors are promising and warrant further research.

In other clinical studies, the DBT units operated at comparable to slightly higher doses than that of FFDM. In some studies, the acquisition parameters were set based on the AEC at FFDM. When evaluating stand-alone 1-view DBT, the same anode/filter combination and tube voltage was used as in FFDM, while the tube-current exposure time product was double that of a single FFDM view. It has been shown by Sechopoulos et al. [41] that for a complete, standard tomosynthesis acquisition, the variation in D_{DBT} is less than 10% compared to the resulting D_{FFDM} for the same imaging conditions, and varies mainly with breast thickness and size. As such, in these studies, the doses from tomosynthesis acquired in 1-view were the same as for 2-view FFDM within 10%. In the studies by Gennaro et al. [21,22] and Thibault et al. [42], the AGD levels were within acceptance limits proposed by European Guidelines for Quality Assurance in Breast Cancer Screening and Diagnosis [25] for standard screen-film mammography in two views.

There are limitations in the present review; the most important one being that the summarized estimates were based on limited reported information and most studies did not describe how the dose estimates vary for different patients (breast types) within the study population. A majority of the studies were conducted without AEC, which is important to characterize on a given DBT system. In a phantom-based study [41], large variations were found in dose-dependence with regards to breast density and thickness. Dose estimates were generally higher for FFDM than for DBT in dense breasts (glandular fractions above 50%) of thicknesses greater than 40 mm. For fatty breasts (glandular fractions below 50%) of thicknesses lower than 40 mm the doses were higher for DBT. According to recent quantitative analysis of breast densities, glandular fractions above 50% are rarely, if ever, encountered in the clinic [43]. However, due to recent advances in technology, the *overall AGD* for a combined setting of DBT and FFDM was found *similar* to that of FFDM just a few years earlier on previous FFDM systems. A recent study [44] examined dose variations in 149 patients using the same type of DBT unit as in the previously described phantom-based study, and found similar results in dose-dependence of breast density and thickness. The mean AGD *per acquisition* for the whole study population was 6.7% higher for DBT than for FFDM, but this difference varies considerably for breasts of varying thickness and density. The dose difference for the complete examinations e.g. DBT_{MLO} + $FFDM_{CC}$ in comparison to FFDM alone was only 3% (Table 1B). The results are system-specific and influenced by the settings of the AEC. Therefore, it would desirable to perform similar studies on clinical DBT systems of other designs.

Finally, it should be acknowledged that the estimates presented in our review do not account for local dose distributions in the breast. DBT as well as FFDM are performed using low energy X-rays. As a consequence, the variation in dose in different regions of the same breast during one acquisition can vary substantially with depth of the tissue [45]. These factors are relevant to consider when interpreting the results.

The main conclusion of this review is that tomosynthesis as a stand-alone technique, in one- as well as in two views, can be accomplished at lower or slightly higher absorbed doses than FFDM. When DBT was combined with FFDM, the dose levels were approximately doubled, with more variability in delivered breast doses noted. However, in the context of technologic advances in this field this corresponds to a dose that is similar to that from FFDM just a few

years earlier on previous FFDM systems [46]. For this adjunct setting, a replacement of FFDM with synthetic 2D-views can reduce the breast dose approximately by half, which may have substantial implications for population screening programs, and is immediately relevant to planning large-scale screening evaluations. It should be noted though that because most of the DBT units were investigational types (e.g. at an early clinical testing stage), work in dose optimization and strategies as such might have been limited at the time when several of the studies were performed. Therefore, the dose might often have been set at a higher level than required, to ensure that image quality was not compromised. Manufacturers are now progressively developing clinical systems, with optimized AEC, with approximately the same dose per acquisition of a single DBT view as a single FFDM view, as seen in several studies in this review. DBT is still under a steady development phase and important results from screening trials on interval cancer rates and outcomes are yet to be published, so our report on radiation doses should be considered in that context. While the benefit of a clinically appropriate X-ray imaging exam might outweigh the risk, efforts should nonetheless be made to minimize this risk by reducing unnecessary exposure to ionizing radiation. Therefore, it is also essential to underline that optimization in breast dosimetryand other refinements in DBT technology and image reconstruction have the potential to offer additional dose savings, and are worthy of further research to ensure that adoption of DBT into routine practice is underpinned by minimization of absorbed doses to the breast. Ongoing and new studies of DBT in the screening setting in particular should monitor and report absorbed dose levels to inform future breast screening practice and policy.

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Appendix

Table A1

A description of different DBT and FFDM (SFM) systems used in clinical studies. The Siemens and GE systems were based on a stationary detector design, while the others systems used moving detectors. The DBT systems by Xcounter, Sectra (Philips) and GE used iterative reconstruction methods, while the other systems used filtered-back projection methods.

Study	Studies on DBT systems of various designs (2008–2014)						C (S
	Manufacturer	DBT unit (FFDM platform or clinical unit)	AEC	Detector technology/ Conversion of X-rays	Number of projections	Angular range (°)	
Gennaro et al. 2010 [21]Gennaro et al. 2013 [22]Thibault et al. 2013 [42]	GE*	Senographe DS	No	CsI, amorphous silicon/Indirect	15	40	Se Se

Study	Studies on DBT systems of various designs (2008–2014)						C (S
	Manufacturer	DBT unit (FFDM platform or clinical unit)	AEC	Detector technology/ Conversion of X-rays	Number of projections	Angular range (°)	
Thibault et al. 2013 [42]							Se
Svahn et al. 2010 [5] Svahn et al. 2012 [37]	Siemens*	Novation^{DR}	No	Amorphous selenium/Direct	25	50	M
Svane et al. 2010 [23]	Xcounter	Xmamo – 3T	No	48 parallel detector elements/ Photon-counting	26	26	Fl Sl 3I Se Se Sl M
Wallis et al. 2012 [19] Zanca et al. 2012 [20]	Sectra (Philips)	MicroDose	Yes	Multislit (Si)/Photon-counting	21	11	M Se Se
Good et al. 2008 [47] [a] Gur et al., 2009 [48] [a] Teerstra et al. 2010 [49] Rafferty et al. 2013 [50] Rafferty et al. 2014 [33]	Hologic	Selenia	No	Amorphous selenium/Direct	11	15	– – Se Se Se
Michell et al. 2012 [29] [b] Waldherr et al. 2013 [51] Skaane et al. 2014 [6] Shin et al. 2014 [44]	Hologic	Selenia Dimension	s Yes	Amorphous selenium/Direct	15	15	Se D

[a] In the studies by Good et al. [47] and Gur et al. [48] there was no specific information on the model/name of DBT or FFDM system(s) used, but technicalities of the DBT unit was the same as for the Hologic investigational unit based on the Selenia platform.

[b] In the study by Waldherr et al. [51] the system had similar technical description as the clinical unit, but the model/name was not presented.

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Table 1A

Summary of methods used for estimating or constraining the radiation doses at a specific level and the estimated dose ratios (D_{DBT}/D_{FFDM}). The studies account for DBT systems used in clinical studies reported in 2008–2014 on breast cancer detection evaluating digital breast tomosynthesis (DBT) (A) as stand-alone imaging technique and (B) adjunct to full-field digital mammography (FFDM), in one or in two views, in comparison to FFDM. A dose ratio of 1.00 means that the glandular dose at the DBT imaging protocol was equal to that of the complete conventional mammography examination, whereas above or below 1.00 indicates a higher or lower glandular radiation dose to the breast, respectively.

A. Studies comparing DBT only *versus* FFDM.

	Study	Dose ascertainment and/or dose estimate (see Methods)	Reported information on absorbed dose	Dose ratio estimation (D_{DBT}/D_{FFDM})	Absorbed dose ratio (D_{DBT}/D_{FFDM})
One-view DBT	Gennaro et al. 2010	ii	DBT dose was within that of 2-view SFM. D_{FFDM} was not presented.	–	–
	Svahn et al. 2010, 2012	iii	Double the tube current-exposure time product was used of a single 2D-image dose, using the same tube voltage and anode/filter combination	$\sim\frac{0.9-1.0}{1.0}$	~0.9–1.0
	Svane et al. 2011	–	DBT dose was 63% of the double 2D-image dose	$\sim\frac{0.63}{1.00}$	0.63[a]
	Wallis et al. 2012	i, 2	Average dose: DBT: 0.7 mGy/exposure (0.28–1.42 mGy, Sweden), 0.82 mGy/exposure (0.40–1.26 mGy, England).	$\frac{0.70\text{mGy}}{2\text{views}\times 0.60\text{mGy}}=0.58$	0.34–0.58
			FFDM: 0.6 mGy/exposure (0.2–1.9 mGy, Sweden, Sectra Mamea system)	$\frac{0.82\text{mGy}}{2\text{views}\times 1.20\text{mGy}}=0.34$	
			1.2 mGy/exposure (0.7–2.4 mGy, England, GE system)		
	Zanca et al. 2012	i, 2	See Wallis et al.	See Wallis et al.	(0.34–0.58)[b]
	Waldherr et al. 2013	i	DBT dose/acquisition ~ that of an FFDM image	$\sim\frac{1.0}{2.0}$	~0.5
	Thibault et al. 2013	ii	DBT dose was within that of 2-view SFM. D_{FFDM} was not presented. D_{DBT} range: 1.9–7 mGy	–	–
	Dose ratio range:				0.34–1.0
Two-view DBT	Good et al. 2008	iv	DBT dose/acquisition ~ that of an FFDM view. Average breast dose: ~2 mGy/view	$\sim\frac{2\text{views}\times 2\text{mGy}}{2\text{views}\times 2\text{mGy}}=1.0$	~1.0

A. Studies comparing DBT only *versus* FFDM.

Study	Dose ascertainment and/or dose estimate (see Methods)	Reported information on absorbed dose	Dose ratio estimation (D_{DBT}/D_{FFDM})	Absorbed dose ratio (D_{DBT}/D_{FFDM})
Gur et al. 2009	iv	DBT dose/acquisition ~ that of a mammogram	$\sim\frac{1.0}{1.0}$	~1.0
Teertstra et al. 2010	iv, 1	Average glandular dose: DBT: 1.74 mGy FFDM: 1.70 mGy	$\frac{1.74\text{mGy}}{1.70\text{mGy}}=1.02$	1.02
Wallis et al. 2012	i, 2	Average dose: DBT: 0.7 mGy/exposure (0.28–1.42 mGy, Sweden), 0.82 mGy/exposure (0.40–1.26 mGy, England).	$\frac{2\text{views}\times 0.82\text{mGy}}{2\text{views}\times 1.20\text{mGy}}=0.68$	0.68–1.17
		FFDM: 0.6 mGy/exposure (0.2–1.9 mGy, Sweden, Sectra Mamea system)	$\frac{2\text{views}\times 0.70\text{mGy}}{2\text{views}\times 0.60\text{mGy}}=1.17$	
		1.2 mGy/exposure (0.7–2.4 mGy, England, GE system)		
Zanca et al. 2012	i, 2	See Wallis et al.	See Wallis et al.	(0.68–1.17)[b]
Dose ratio range:				0.68–1.17

[a] In this study there was 7 different mammography systems used, of which 5 were FFDM units and 2 were SFM units. Therefore, the dose ratio is only a rough estimate of the dose contribution from DBT relative that of FFDM. If the two SFM units had a relatively higher impact on the dose contribution than the FFDM units, the true dose ratio could be lower, and if vice versa was the case, then the dose ratio could be somewhat higher.

[b] This study was based on the same patient images as Wallis et al. 2012 [19]. Hence, it resulted in the same dose ratios and is not included in the overall dose ratio range.

Table 1B

Absorbed dose ratios (D_{DBT}/D_{FFDM}) and DBT systems used in clinical studies comparing DBT in one or in two views as an adjunct to mammography *versus* mammography only. D_{DBT} represents the total dose of the complete examination, so in this case, D_{DBT} includes the glandular dose estimates for the DBT acquisitions and the adjunct mammography acquisitions.

	Study	Dose ascertainment and/or dose estimate (see Methods)	Reported information on radiation dose	Dose ratio estimation (D_{DBT}/D_{FFDM})	Absorbed dose ratio (D_{DBT}/D_{FFDM})
One-view DBT	Gennaro et al. 2013	ii	DBT dose was within dose at 2- view SFM. D_{FFDM} was not presented	–	–
	Svahn et al. 2010	iii	Double the tube current- exposure time product was used of a single 2D-image dose, using the same tube voltage and anode/filter combination	$\mathrm{Dose}_{\min}\left(\frac{1\mathrm{view}_{\mathrm{DBT}}+1\mathrm{view}_{\mathrm{FFDM}}}{2\mathrm{view}_{\mathrm{FFDM}}}\right)=\frac{0.9+0.5}{1.0}=1.4$ $\mathrm{Dose}_{\max}\left(\frac{1\mathrm{view}_{\mathrm{DBT}}+1\mathrm{view}_{\mathrm{FFDM}}}{2\mathrm{view}_{\mathrm{FFDM}}}\right)=\frac{1.0+0.5}{1.0}=1.5$	~1.4–1.5
	Thibault et al. 2013	ii	DBT dose was within that of 2- view SFM. D_{FFDM} was not presented. D_{DBT} range: 1.9 –7 mGy	–	–
	Waldherr et al. 2013	i	DBT dose/acquisition ~that of an FFDM image	$\mathrm{Dose}\left(\frac{1\mathrm{view}_{\mathrm{DBT}}+2\mathrm{view}_{\mathrm{FFDM}}}{2\mathrm{view}_{\mathrm{FFDM}}}\right)=\frac{3.0}{2.0}=1.5$	~1.5
	Rafferty et al. 2014	iv	Dose for DBT + FFDM ~ twice that of FFDM	$\mathrm{Dose}\left(\frac{1\mathrm{view}_{\mathrm{DBT}}+2\mathrm{view}_{\mathrm{FFDM}}}{2\mathrm{view}_{\mathrm{FFDM}}}\right)=\frac{3.0}{2.0}=1.5$	~1.5
	Shin et al. 2014	i, 2	The mean average glandular dose: FFDM: 1.63 mGy (0.68–7.41) DBT: 1.74 mGy (0.93–5.02 mGy)	$\mathrm{Dose}\left(\frac{1\mathrm{view}_{\mathrm{DBT}}+1\mathrm{view}_{\mathrm{FFDM}}}{2\mathrm{view}_{\mathrm{FFDM}}}\right)=\frac{1.74+1.63}{1.63+1.63}=1.03$	~1.03
	Dose ratio range:				1.03–1.5
Two-view DBT	Gur et al. 2009	iv	DBT dose/acquisition ~ that of a mammogram	$\sim\frac{2.0}{1.0}$	~2.0
	Michell et al. 2012	iv, 1	FFDM: 1.37–1.57 mGy DBT: 1.66–1.90 mGy SFM dose was not presented	$\mathrm{Dose}_{\min}\left(\frac{2\mathrm{views}(1.37+1.66)\mathrm{mGy}}{2\mathrm{views}\times 1.37\mathrm{mGy}}\right)=2.21$ $\mathrm{Dose}_{\max}\left(\frac{2\mathrm{views}(1.57+1.90)\mathrm{mGy}}{2\mathrm{views}\times 1.57\mathrm{mGy}}\right)=2.21$	2.21

Study	Dose ascertainment and/or dose estimate (see Methods)	Reported information on radiation dose	Dose ratio estimation (D_{DBT}/D_{FFDM})	Absorbed dose ratio (D_{DBT}/D_{FFDM})
Rafferty et al. 2013, 2014	iv	Dose for DBT + FFDM ~ twice that of FFDM	$\sim\frac{2.0}{1.0}$	~2.0
Skaane et al. 2014	i, 2	Average dose (standard deviations): FFDM: 1.58 ± 0.61 DBT + FFDM: 3.52 ± 1.08	$\left(\frac{2\text{views} \times 3.52\text{mGy}}{2\text{views} \times 1.58\text{mGy}}\right) = 2.23$	2.23
Skaane et al. 2014	i, 2	Average dose (standard deviations): FFDM: 1.58 ± 0.61 DBT + synthetic 2D: 1.95 ± 0.58.	$\left(\frac{2\text{views} \times 1.95\text{mGy}}{2\text{views} \times 1.58\text{mGy}}\right) = 1.23$	(1.23)
Dose ratio range:				2.0–2.23