Normalized Glandular Dose Coefficients for Digital Breast Tomosynthesis with the Chinese Detailed Breast Models

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Abstract

Objective: The increasing incidence of breast cancer among Chinese women has necessitated the utilization of breast X-ray screening, which carries radiation risk. This work aims to provide a dosimetry protocol for the Chinese female population, to replace the traditional standard that utilizes simplified breast models, for the accurate estimation of patients' mean glandular dose undergoing digital breast tomosynthesis (DBT).

Approach: We have constructed the first set of Chinese female detailed breast models with their representative breast parameters. Considering backscatter radiation and computational efficiency, we improved the combination of these models and the Chinese reference adult female whole-body voxel phantom. The image acquisition for four commercial DBT systems, which are widely employed in China, was simulated using the Monte Carlo method to obtain the normalized glandular dose coefficients of DBT (D_{gN}^{DBT}) and glandular depth dose (Dgdepz) for different breast characteristics and X-ray spectra.

Main results: We calculated a series of D_{gN}^{DBT} for breasts with different percentage mass glandularity (5%, 25%, 50%, 75%, and 100%) and compressed breast thicknesses (2cm, 3cm, 4cm, 5cm, 6cm, 7cm), at various tube potentials (25kV, 28kV, 30kV, 32kV, 35kV, and 49kV) and target/filter combinations (W/Rh, W/Al, Mo/Mo, Rh/Rh, Rh/Ag). The parameter dependence of breast characteristics and beam conditions on D_{gN}^{DBT} of detailed breast models was investigated. The D_{gN}^{DBT} results were 14.6% - 51.0% lower than those of the traditional dosimetry standard in China. The difference in D_{gN}^{DBT} was mainly due to the decrease in the depth of the main energy deposition area caused by glandular distribution along the depth direction.

Significance: The results obtained in this work could be employed for the improvement of breast dosimetry in China, and provide more detailed information about risk assessment in DBT.

Full Text

Preamble

Title: Normalized Glandular Dose Coefficients for Digital Breast Tomosynthesis with the Chinese Detailed Breast Models

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Abstract

Objective: The increasing incidence of breast cancer among Chinese women has necessitated the utilization of breast X-ray screening, which carries inherent radiation risks. This work aims to provide a dosimetry protocol specifically for the Chinese female population to replace the traditional standard that utilizes simplified breast models, enabling more accurate estimation of patients' mean glandular dose (MGD) during digital breast tomosynthesis (DBT).

Approach: We constructed the first set of Chinese female detailed breast models with representative breast parameters. Considering backscatter radiation and computational efficiency, we improved the combination of these models with the Chinese reference adult female whole-body voxel phantom (CRAF). The image acquisition for four commercial DBT systems widely employed in China was simulated using the Monte Carlo method to obtain normalized glandular dose coefficients ($D_{gN_{DBT}}$) for different breast characteristics and beam conditions, as well as glandular depth dose ($D_g^{dep}(z)$) for breasts with varying percentage mass glandularity.

Main Results: We calculated a series of $D_{gN_{DBT}}$ values for glandularity levels of 5%, 25%, 50%, 75%, and 100% and compressed breast thicknesses (CBT) of 2 cm, 3 cm, 4 cm, 5 cm, 6 cm, and 7 cm, at various tube potentials (25 kV, 28 kV, 30 kV, 32 kV, 35 kV, and 49 kV) and target/filter combinations (W/Rh, W/Al, Mo/Mo, Rh/Rh, Rh/Ag). The parameter dependence of breast characteristics and beam conditions on $D_{gN_{DBT}}$ was investigated. The $D_{gN_{DBT}}$ values obtained from detailed breast models were mainly lower than those from the traditional dosimetry standard in China, with differences ranging from 14.6% to 51.0%. This discrepancy arises from the decrease in the depth of the main energy deposition area caused by glandular distribution along the depth direction.

Significance: The results obtained in this work could be employed to improve breast dosimetry in China and provide more detailed information for risk assessment during DBT examinations.

Keywords: digital breast tomosynthesis, normalized glandular dose coefficients, detailed breast model, Monte Carlo simulation

1. Introduction

Breast cancer is the most common cancer among women in China, with over 400,000 cases annually [?]. The primary screening method for breast cancer is digital mammography. An improved version of mammography, digital breast tomosynthesis (DBT), which offers 'pseudo-3D' information and more accurate screening results, is gaining popularity in China [?, ?]. The radiation effects of DBT on patients need to be thoroughly investigated. Meanwhile, ICRP Report 103 has revised the tissue weighting factor for breasts from 0.05 to 0.12 [?], making radiation-induced breast cancer risk a critical consideration for the Chinese female population in breast X-ray imaging, especially for DBT.

The widely accepted quantity for breast dosimetry protocols is the mean glandular dose (D_g), which reflects the high radiosensitivity of glandular tissue [?]. The breast dosimetry protocol in China follows the simple breast model proposed by Dance et al. [?, ?]. This model consists of a central region with a uniform mixture of glandular and adipose tissues and a peripheral 5 mm thick 'subcutaneous adipose region.' However, this simple model cannot represent the real anatomical structure inside a breast. It is widely agreed that using simplified homogeneous models instead of heterogeneous breast models can lead to overestimation of D_g [?]. Researchers have attempted to obtain breast parameters that affect D_g, including skin thickness [?, ?, ?], subcutaneous adipose layer thickness [?], and glandular distribution [?, ?, ?], through high-resolution clinical dedicated breast computed tomography (DBCT) images in recent years. The literature verifies that to achieve accurate estimation of D_g, more accurate characteristics of the breast need to be considered in breast dosimetry protocols.

Anatomical parameters of the breast vary significantly among different races [?]. These differences in anatomical characteristics may result in inaccurate estimations of D_g received by patients. Previous studies have shown that using a human phantom based on Caucasian characteristics rather than Chinese characteristics can result in more than 50% difference in D_g with the same irradiation pattern [?, ?]. The breast volume of Caucasians, African Americans, and Hispanics is larger than that of Asians, and Caucasian women's breasts are relatively denser than those of Asian women.

Even though several heterogeneous breast models have been constructed for the development of breast dosimetry, they are mainly based on the breast characteristics of Western women [?, ?]. For instance, based on breast metrics examined through DBCT data in America [?], Hernandez constructed a breast model enclosed by a 1.5 mm skin layer as a half-elliptical shape using three elliptic radii. Glandular fraction values were assigned to each contoured region using a fitted Gaussian distribution [?]. Meanwhile, Tucciariello created a new voxel model that considered heterogeneous glandular distribution [?]. To characterize the amount and distribution of glandular tissue in patient breasts during compression, 88 DBCT datasets were acquired from a medical center in the Netherlands for clinical trials [?]. These distributions along three directions were used to define the internal tissue distributions for the cranio-caudal (CC) and medio-lateral-oblique (MLO) models developed. However, there is no literature on dosimetry research specifically for Chinese women's breast characteristics. Therefore, it is crucial to establish breast dosimetry suitable for Chinese women to ensure accurate dose estimation.

In previous work, we conducted a retrospective review based on clinical mammography data of Chinese women, in which we statistically analyzed the anatomical parameters of Chinese women. These parameters differ in breast volume, typical glandular fraction, and subcutaneous adipose thickness compared to those of Western women. Based on these representative breast parameters, we developed the first set of detailed breast models for Chinese females and used these models to calculate D_{gN} coefficients, which have been adopted by the Chinese specification for testing of quality control in X-ray mammography [?].

In this work, we aim to calculate the normalized glandular dose coefficients ($D_{gN_{DBT}}$) for four commercial DBT devices, which are the main foreign DBT manufacturers in China, and analyze the parameter dependence of breast characteristics and beam conditions on $D_{gN_{DBT}}$ when considering the detailed structure inside the breast. Meanwhile, we compared the $D_{gN_{DBT}}$ values between the traditional and improved breast dosimetry protocols for the Chinese female population and analyzed the reasons for the differences based on the dose distribution along the depth direction of the simple and detailed breast models.

2.1. The Improved Dosimetry Protocol for DBT

$D_{gN_{DBT}}$, as the most essential quantity for estimating patient D_g, was calculated for each combination of equipment geometry, X-ray spectrum, and breast model using Monte Carlo (MC) simulations. These values, expressed in mGy/mGy, represent the ratio of D_g (in mGy) to incident air kerma (K_{air}) (in mGy) at the reference point without considering backscatter. The reference point was positioned along the central axis of the upper surface of the breast, at a distance of 4 cm from the edge of the detector closest to the chest wall. For each spectrum and target/filter combination, HVL can be calculated using MC simulation [?] and expressed as the aluminum thickness with equivalent attenuation properties.

D_g is greatly affected by the depth of major energy deposition in the glandular tissue. MC simulations have demonstrated that the dose distribution during mammography exhibits a high degree of heterogeneity [?, ?]. The deposited dose in nearly 40% of glandular voxels exceeded the D_g within the breast model with 4 cm compressed breast thickness (CBT) and 50% glandularity [?]. To investigate the difference in $D_{gN_{DBT}}$ between breast models with different glandular distributions, an alternative dose metric called glandular depth dose ($D_g^{dep}(z)$) has been suggested [?, ?]. $D_g^{dep}(z)$ provides more detailed information about the distribution of radiation dose along the depth direction, especially in areas with dense glandular tissue. Specifically, $D_g^{dep}(z)$ is defined as the glandular dose deposited in a specific slice at depth z.

To better understand the contribution of each voxel slice of the detailed breast model to D_g, we use a physical quantity: normalized deposited energy in glandular tissue at slice depth z, $E_{gN}(z)$, which can be calculated by the following equation:

$$E_{gN}(z) = \frac{D_g^{dep}(z) \cdot f_g(z)}{m_g(z)} \quad (1)$$

where $m_g(z)$ is the glandular mass at slice depth z, and $f_g(z)$ is a function that represents the distribution of glandular mass along the depth direction.

In traditional dosimetry, the D_{gN} coefficients measure the D_g undergoing mammography equivalently as multiplication results of the factors g, c, and s in Dance's equation [?, ?, ?]. The g-factor is a dose conversion factor calculated under different spectra with reference to the breast model with 50% glandularity at different CBT. The c-factor and s-factor adjust for a different X-ray spectrum than Mo/Mo target/filter and a different glandularity than 50%, respectively. The relative differences Δ of $D_{gN_{DBT}}$ between the improved and traditional breast dosimetry can be calculated by:

$$\Delta = \frac{gcsT - D_{gN_{DBT}}}{D_{gN_{DBT}}} \times 100\% \quad (2)$$

where g, c, s, T and $D_{gN_{DBT}}$ are the conversion factors under the same breast characteristics and beam conditions, corresponding to the traditional dosimetry standard and this work, respectively.

2.2. The Detailed Breast Model and the Improved Combination with CRAF

In previous work, we identified typical parameters of the breast, including external parameters such as the base diameter of the breast and the distance from the nipple to the chest wall, as well as skin thickness and subcutaneous adipose thickness [?, ?]. Based on the assumptions of Bakic et al. [?] and Mahr et al. [?] regarding the anatomical growth of lactiferous ducts and glandular tissue in the fibroglandular region, we altered the glandular distribution by randomly sampling adipose lobules to replace glandular tissue. This allowed us to closely approximate the glandular distribution of our target breast model to that observed clinically. Meanwhile, the percentage of glandular tissue and CBT of our target models were typical parameters selected from clinical statistics reported for Chinese women [?].

According to these representative breast parameters, we developed the first set of detailed breast models for Chinese females. Table 1 lists the voxel size of models with different glandularity and CBT. Each voxel represents a unique tissue type. As the CBT decreases, the size of the voxel in the depth direction becomes smaller to ensure the completeness of detail in breast models. These models included four breast regions: skin, adipose tissue region (subcutaneous adipose, posterior adipose, and Cooper's ligaments), fibroglandular region (intraglandular adipose, glandular tissue, lactiferous ducts, and lobules), and nipple region (lactiferous sinus and adipose). The skin thickness was set to 1.45 mm. The subcutaneous adipose layer thickness was set to 4 mm near the nipple and slightly more than 4 mm near the chest wall. The fibroglandular region is the central region in the breast model, excluding the skin, subcutaneous adipose layer, and posterior adipose layer, similar to the central region in the simple breast model of the traditional standard.

We constructed detailed breast models with glandularity levels of 5%, 25%, 50%, 75%, and 100%. Glandularity is a physical quantity that indicates the proportion of glandular tissue, and it can be expressed as percentage volume or percentage mass glandularity. The percentage mass glandularity (P_g^M) is calculated by:

$$P_g^M = \frac{m_g}{M_{fg}} \times 100\% \quad (3)$$

where m_g is the mass of glandular tissue and M_{fg} is the total mass of the fibroglandular region. The percentage volume glandularity (P_g^V) is calculated by:

$$P_g^V = \frac{V_g}{V_{br}} \times 100\% \quad (4)$$

where V_g is the volume of glandular tissue, and V_{br} is the volume of the breast model. The P_g^V values for models with 5%, 25%, 50%, 75%, and 100% P_g^M are 1.6%, 8.2%, 16.6%, 25.4%, and 34.4%, respectively. In the fibroglandular region, the model with 5% P_g^M contained only lactiferous ducts and intraglandular adipose tissue, while the model with 100% P_g^M contained only glandular tissue. Models with different glandularity were constructed by altering the number of adipose globules whose central points were uniformly sampled within the fibroglandular region.

Vertical slices of each breast model with different glandularity were deformed to compress these models to 2 cm, 3 cm, 4 cm, 5 cm, 6 cm, and 7 cm in the CC view, resulting in 30 compressed breast models for dose estimation in DBT. The compression algorithm divides the breast model into skin, adipose tissue region, and fibroglandular tissue region, and calculates the elasticity parameters of the breast tissues based on ultrasound velocity measurements and tissue densities. The algorithm compresses each vertical slice of the breast tissue separately using the elastic modulus of the corresponding tissue region and determines the amount of compression based on the strain, which is calculated from the change in thickness of the breast tissue. The algorithm preserves the volume of the breast during compression, as biological materials are considered incompressible, and also considers the original dimensions and thicknesses of the breast model to calculate the final compressed dimensions [?]. The detailed breast models, in which glandular tissue tends to be more concentrated in the central part of the sagittal plane, have different glandular distributions from those of the simple model.

Previous research has indicated that, based on the simple breast model, beam condition (target/filter combination, beam HVL) and breast characteristics (CBT and glandularity) are the main influencing factors of $D_{gN_{DBT}}$, besides the tomosynthesis system specifications [?]. To investigate the difference in $D_{gN_{DBT}}$ between the detailed breast models and simple breast models, we constructed a series of homogeneous breast models with 4 cm CBT and 25%, 50%, 75%, and 100% P_g^M by uniformly sampling the glandular voxels in the central part.

We combined the compressed breast model with the Chinese reference adult female whole-body voxel phantom (CRAF) in our previous work to account for backscatter radiation from the female body. However, this reduced computational efficiency of MC simulation due to millions of voxels in CRAF. To enhance the efficiency and accuracy of MC simulation, we improved the geometric construction of CRAF in the simulation. According to the breast position in the female body, CRAF was rotated and cropped while retaining the major organs and tissues that provide backscattered particles. During the construction of the imaging geometry, the nipple of the breast model was aligned with the nipple of CRAF. CRAF and the cropped CRAF model are illustrated in Figure 1 [Figure 1: see original paper].

Figure 1. (a) The 3D display of the CRAF model, where the pink region represents the breast organ in CRAF. (b) The improved method to combine the breast model and CRAF. The major organs, including the heart, lung, and posterior muscle of the breast, were reserved, and the body tissue away from the breast was removed. The breast organ in CRAF is replaced by the detailed breast model.

Table 1. The voxel size of detailed breast models with different glandularity and CBT

CBT (cm)	P_g^M (%)	Voxel size (mm × mm × mm)
2	5, 25, 50, 75, 100	0.2 × 0.2 × 0.050
3	5, 25, 50, 75, 100	0.2 × 0.2 × 0.070
4	5, 25, 50, 75, 100	0.2 × 0.2 × 0.087
5	5, 25, 50, 75, 100	0.2 × 0.2 × 0.103
6	5, 25, 50, 75, 100	0.2 × 0.2 × 0.119
7	5, 25, 50, 75, 100	0.2 × 0.2 × 0.129

2.3. Irradiation Geometries

The simulation geometry used to calculate two quantities—D_g and $D_g^{dep}(z)$—is shown in Figure 2 Figure 2: see original paper. The geometry consists of an X-ray tube and a series of geometry components. The X-ray tube has an X-ray source and a filter employed for energy spectrum hardening below it. During the scanning process, the source and filter rotate together around the center of rotation along the orbit. The geometry components include a compression paddle, a breast model, a support paddle, and an image receptor, which are aligned with the chest wall plane. The compression paddle is constructed from polycarbonate, while the support paddle is composed of carbon fiber. There is an air gap between the support paddle and the image receptor. The position of the compression paddle, which is placed on top of the breast model, changes with the CBT. An isotropic particle emission at a cone angle that covers the image receptor edge was set up. We constructed four commercial scanning geometries, with device parameters listed in Table 2 .

To simulate K_{air}, the breast model and the support paddle were eliminated, and a cylindrical air-filled ionization chamber (15 mm radius, 10 mm height) was positioned at the breast entrance plane [**?**, **?**]. The compression paddle was elevated to 40 cm above the ionization chamber's upper plane to reduce scattered radiation from the paddle [**?**]. Air filled the world in all simulations. The simulation geometry is displayed in Figure 2(b).

Table 2. Manufacturer's device imaging parameters

Parameter	Siemens Mammomat Inspiration	Hologic Selenia Dimensions	GE Seno-Claire	GE Senographe Pristina
Anode target/filter combination	W/Rh 50 m	W/Al 700 m	Mo/Mo 30 m, Rh/Rh 25 m	Mo/Mo 30 m, Rh/Ag 50 m
Scan angle, $\Delta\alpha$ (°)	50 (i.e., $±$25)	25 (i.e., $±$12.5)	15 (i.e., $±$7.5)	25 (i.e., $±$12.5)
Number of projections, N	-	-	-	-
Distance source to detector (DSD) (mm)	-	-	-	-
Distance detector to rotation (DDR) (mm)	-	-	-	-
Distance of air gap (DAG) (mm)	-	-	-	-
Detector field (mm × mm)	240 × 300	239 × 306	240 × 286	240 × 290
Compression paddle material	Polycarbonate	Polycarbonate	Polycarbonate	Polycarbonate

Parameter	Siemens Mammomat Inspiration	Hologic Selenia Dimensions	GE Seno-Claire	GE Senographe Pristina
Compression paddle thickness (mm)	-	-	-	-
Carbon fiber support paddle thickness (mm)	-	-	-	-

Figure 2. The irradiation geometry to measure (a) glandular dose and (b) K_{air}

2.4. Monte Carlo Simulation

A previous MC computer program for mammography dosimetry was modified to calculate D_g for DBT using the Geant4 (version 10.6) simulation toolkit [?]. The irradiation geometries were described in detail in Section 2.3. The validation of the mammography dosimetric program can be found in reference [?]. A simple breast model with 4 cm CBT and 50% P_g^M was constructed using voxels to validate the modification of the X-ray tube rotation angle. This model had a uniform distribution of voxels labeled glandular and adipose in the central part. Four different spectra (Mo/Mo 25 kV, Rh/Rh 29 kV, W/Rh 34 kV, and W/Ag 40 kV) were used to irradiate this model for projections from 0° to 30° with 5° increments.

Dosimetry quantities, glandular dose and K_{air}, were estimated by independent MC simulations. Only photons were considered in the simulations (cut-off energy of 10 eV, cut-off length of 0.1 mm). All secondary electrons were regarded as deposited locally. The number of photons simulated for D_g was between 10^8 and 10^9, depending on the parameters of input models (i.e., breast glandularity and CBT). The statistical uncertainty for glandular dose and K_{air} was reduced to less than 1%. The simulations were conducted using an Intel® Xeon® CPU E5-2680@2.3 GHz. The computational time required to process 10^8 photons using a single core was several hours. On the basis of ensuring simulation accuracy, the calculation speed has been greatly improved. To ensure the statistical uncertainty for $D_g^{dep}(z)$ at all depths reached less than 1%, the number of photons simulated for $D_g^{dep}(z)$ was set to 1.3×10^{10}. Python (v. 3.9) [?] scripts were written to generate input files and shell scripts for simulation automation.

The properties of adipose, glandular, and skin tissues, including their composition and density, were obtained from ICRU Report 46 [?]. Values for Cooper's ligament tissue in the detailed breast model were not specifically provided by ICRU, so the density and element composition of Cooper's ligament tissue were substituted by those of muscular fibrous tissue [?].

Polychromatic X-ray spectra acquired from the spectral models of Boone et al. [?] and Hernandez et al. [?] were simulated. Simulations were conducted to cover typical parameters available in clinical systems using various tube potentials (25 kV, 28 kV, 30 kV, 32 kV, 35 kV, and 49 kV) and target/filter combinations (W/Rh, W/Al, Mo/Mo, Rh/Rh, Rh/Ag). The polychromatic spectra exhibited an energy resolution of 0.5 keV. The heeling effect was not implemented.

3.1. Validation of Simulation Methods

In Figure 3 [Figure 3: see original paper], the t-factors reported in Dance et al. [?], which capture the variation in D_{gN} due to non-zero projection angles of an X-ray source, are compared with those generated using the MC code employed in this study for four spectra and projection angles α ranging from 0° to 30°. The results are consistent with the data obtained from Dance et al., with all data differing within 3%. The largest difference occurs at the largest angle. The main reason for this variation is the construction method for the simple model. In Dance's approach, the energy deposited in the adipose and glandular tissues in the central region of the simple breast model is calculated based on the probability of interaction between the two tissues. However, in this work, the energy deposited in glandular tissue can be obtained directly because adipose and glandular tissues are separated in the voxel model utilized.

Figure 3. Comparison between the validated results and Dance's data.

3.2. Improved Computational Efficiency and Accuracy Considering Backscatter

Table 3 lists the MC simulation computation time and differences for three combinations under the same irradiation parameters and breast model: breast without CRAF, CRAF+breast, and CRAF+breast (improved). The results without considering backscattering were 2.4% lower than those considering body backscattering. This is because posterior adipose exists in the model itself, which provides a portion of backscatter dose to the glandular tissue. However, the presence of CRAF still makes the simulation results more accurate. Compared with the combination method using the complete female body, which wasted considerable computational time on unnecessary organ voxels for particle transport [?], the improved method adopted in this paper retains only the main body and organs that produce backscatter particles for glandular tissue. This results in a significant improvement (about 40 times) in computation speed while ensuring computational accuracy, allowing us to simulate a large number of particles in a short period (several hours) and reduce dose statistical errors.

Table 3. Computation time and result difference (compared to the improved combination) of the three model combinations

Combination	Particles	Computation time (h)	Difference (%)
Breast only	1×10^8	-	-2.4%
CRAF+breast	5×10^6	-	-
CRAF+breast (improved)	1×10^8	-	-

3.3. Normalized Glandular Dose – $D_{gN_{DBT}}$

3.3.1. Parameter Dependence of Breast Characteristics and Beam Conditions on $D_{gN_{DBT}}$

The dependence of various model parameters on $D_{gN_{DBT}}$ needs to be investigated based on the detailed breast model. In the simulation, four breast models with different CBTs (4 cm and 5 cm) and P_g^M (25% and 50%) were adopted for irradiation. We calculated the HVL for the energy spectra at different tube voltages and two target/filter combinations of Mo/Mo and W/Rh, and found a good linear relationship between HVL and $D_{gN_{DBT}}$. Linear regression analysis showed high consistency ($R^2 > 0.999$) and low residual error (within 1×10^{-3}) for Mo/Mo (Figure 4 Figure 4: see original paper), and good consistency ($R^2 > 0.95$) and moderate residual error (within 4×10^{-3}) for W/Rh (Figure 4(b)).

Figure 4. $D_{gN_{DBT}}$ values calculated for (a) Mo/Mo and (b) W/Rh target/filter combinations, and their linear fit (continuous lines) at varying beam HVL.

Figure 5 [Figure 5: see original paper] shows the relationship between $D_{gN_{DBT}}$ and glandularity for different CBTs and the target/filter combination of W/Rh at 28 kVp. $D_{gN_{DBT}}$ values generally decrease as P_g^M increases from 25% to 100%. However, we also observe an unexpected result: the model with 5% glandularity has a lower $D_{gN_{DBT}}$ than the model with 25% P_g^M. This result contradicts findings from the literature based on simple breast models [?, ?]. We will discuss possible reasons for this discrepancy in the following section.

Figure 5. $D_{gN_{DBT}}$ values change with P_g^M for different CBTs and the target/filter combination of W/Rh at 28 kVp.

We examined the relationship between $D_{gN_{DBT}}$ and CBT for different tube voltages by setting the P_g^M of the breast models to 25%. These data were fitted with the bi-exponential function proposed by Sobol and Wu (1997), which describes the relationship between $D_{gN_{DBT}}$ and CBT. Regression analysis shows that this function accurately modeled our data (Figure 6 [Figure 6: see original paper]), with high goodness of fit ($R^2 > 0.99$) and low residual error (within 4×10^{-3}).

Figure 6. $D_{gN_{DBT}}$ values calculated for W/Rh target/filter combination and bi-exponential fit (continuous lines) at varying CBT.

3.3.2. $D_{gN_{DBT}}$ Tabulation for Commercial Devices

For the DBT devices widely used in China, Tables A1-A5 in Appendix A list the $D_{gN_{DBT}}$ values for different target/filter combinations, HVL, CBT, and P_g^M. As illustrated in Table 1, the imaging geometry parameters of GE SenoClaire and GE Senographe Pristina are almost equal. The difference in $D_{gN_{DBT}}$ for Mo/Mo target filtration between these two devices is within 0.5% while the target/filter combination is Mo/Mo. The data in Table A3 can be used for dose estimation of Mo/Mo target filtration for both devices. The data results from other devices are significantly influenced by the target/filter combination when HVL, CBT, and P_g^M parameters are fixed. These coefficients can also be applied to estimate the D_g for breasts with corresponding P_g^M.

3.4. Glandular Depth Dose – $D_g^{dep}(z)$

We performed simulations on detailed breast models and simple breast models with different P_g^M values of 25%, 50%, 75%, and 100%. Each model had the same CBT of 4 cm. The glandular tissue in detailed models was not uniformly distributed along the depth direction, as shown in Figure 7 Figure 7: see original paper. We used a W/Rh 28 kV beam to irradiate these breast models and calculated the normalized $D_g^{dep}(z)$ for each model. Figure 7(b) compares the normalized $D_g^{dep}(z)$ curves for detailed models and shows the relative error of these four models during the MC simulation at the top-right corner. The linear attenuation coefficients of the models depend on glandularity. As glandularity increases, so does the linear attenuation coefficient, because the density and equivalent attenuation coefficient of glandular tissue are larger than those of adipose tissue. Figure 7(c) shows the $E_{gN}(z)$ comparison between detailed models and simple models. It can be observed that for a simple model, most of the deposited energy in glandular tissue is concentrated in the upper surface of the central region, but for detailed models, the main energy deposition area is concentrated between the breast depth of about 1 cm and 2 cm. The greatest discrepancy in $E_{gN}(z)$ between the detailed and simple breast models is found near the breast surface and is primarily associated with depth variations of $f_g(z)$. When considering detailed breast models with varying glandularity, the main energy deposition area depicted in Figure 7(c) is marginally shallower than the depth associated with the highest concentration of $f_g(z)$ as a result of the X-ray beam's exponential attenuation.

Figure 7. (a) The glandular fraction along the z direction of detailed breast models and simple breast models. (b) The normalized $D_g^{dep}(z)$ curves of detailed breast models with different P_g^M: 25%, 50%, 75%, and 100%. (c) $E_{gN}(z)$ of detailed breast models and simple models.

3.5. Literature Comparison

As demonstrated in Section 3.3.1, a strong linear correlation exists between $D_{gN_{DBT}}$ and HVL. By fitting the available data, we calculated $D_{gN_{DBT}}$ values for other HVLs and compared them with $D_{gN_{DBT}}$ values obtained by multiplying $gcsT$ as provided by Dance. The relative differences Δ ranged from 18.6% to 51.0%, as summarized by CBTs and X-ray spectra. When CBT and glandularity remain constant, Δ increases with HVL because a higher HVL beam is more penetrating. Figure 8 [Figure 8: see original paper] illustrates the $D_{gN_{DBT}}$ results for varying CBT and glandularity. As CBT increases and glandularity decreases, the corresponding points progressively deviate from the identity line. This indicates that Δ decreases with increasing glandularity and increases with increasing CBT. The highest Δ value is observed for the breast model with 7 cm CBT and 5% glandularity.

Figure 8. Comparison of the estimated $D_{gN_{DBT}}$ values for different CBT and glandularity under the target/filter combination W/Rh 28 kVp of Siemens Mammomat Inspiration. The data of each group with the same CBT correspond to 100%, 75%, 50%, 25%, and 5% P_g^M from left to right. The identity line indicates equal $D_{gN_{DBT}}$ values for the detailed and simple breast models.

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4. Discussion

The high incidence of breast cancer in China necessitates accurate coefficients for glandular dose estimation for Chinese women undergoing breast screening. However, there are significant differences in internal structure between Chinese and Western women [**?**, **?**], and dose estimation for Chinese women is based on dosimetry protocols developed using simple breast models, which may result in overestimation of D_g. Therefore, establishing dosimetry protocols specifically for Chinese women would greatly improve assessment of radiation risk during breast screening and contribute to increasing understanding of racial differences in breast cancer risk.

In this work, we used Geant4 to calculate a series of conversion factors, $D_{gN_{DBT}}$, for four commercial DBT devices based on detailed breast models. The detailed breast models, constructed based on representative breast parameters of the Chinese female population, were combined with CRAF. Previous studies have agreed that beam conditions (target/filter combination, beam HVL) and breast characteristics (CBT and glandularity) are the main factors affecting $D_{gN_{DBT}}$, which were computed using simple breast models. This paper studied the correlation of these factors based on detailed breast models. $D_{gN_{DBT}}$ and HVL still exhibited a good linear relationship, although the detailed structure is heterogeneous. We illustrated that $D_{gN_{DBT}}$ and CBT exhibited a bi-exponential attenuation relationship in detailed breast models, consistent with the findings of Sarno [?] based on simple breast models.

It is worth noting that pressure affects CBT. Excessive pressure can lead to thinning of the breast, which in turn reduces $D_{gN_{DBT}}$. Previous studies showed that $D_{gN_{DBT}}$ and glandularity had a perfect quadratic function relationship and decreased with increasing glandularity [?]. However, the results of this paper indicated that at lower glandularity, $D_{gN_{DBT}}$ increased with ascending glandularity. This difference arises mainly from assumptions made during breast model generation. We assumed that at lower glandularity, glandular tissue mainly exists in the form of lactiferous ducts. Medically, lactiferous ducts are random tree-like structures that grow from the lactiferous sinus at the nipple to the chest wall and are concentrated in the area near the nipple within the breast [?]. When a patient's glandularity increases, adipose tissue in the fibroglandular region is gradually replaced by glandular tissue. Two changes occur that affect D_g. First, the centroid of glandular tissue gradually moves along the nipple-chest direction, meaning the glandular tissue will be closer to the X-ray source and will receive higher glandular dose. Second, the exponential attenuation characteristic of $D_g^{dep}(z)$ makes the D_g obtained by the breast model with 25% P_g^M higher than that obtained by the model with 5% P_g^M. However, in the homogeneous model assumption, the transformation from 5% to 25% P_g^M does not involve gradual replacement of glandular tissue, and the centroid of glandular tissue always remains at the same position. The difference between these two assumptions causes different performance variations of $D_{gN_{DBT}}$ at low glandularity. It is worth mentioning that parameter dependence of breast characteristics and beam conditions on $D_{gN_{DBT}}$, based on breast models with microstructure, has not been documented previously.

In addition, we compared the $D_{gN_{DBT}}$ values of this work with those of the traditional protocol and found differences of about 18.6-51.0%. Caballo et al. [?] compared $D_{gN_{DBT}}$ values of homogeneous models with those of real clinical patients, and the 25% and 75% quartiles of the difference were (26.3%, 56.4%), which are very close to our variation in $D_{gN_{DBT}}$. These comparative data indicate that the detailed breast model we used can approximate clinical patient breast models.

We analyzed the distribution of normalized deposited energy in glandular tissue ($E_{gN}(z)$) along the depth direction for detailed breast models and homogeneous breast models with 4 cm CBT and different glandularity. We found that the main energy deposition region of detailed breast models was located in the upper area with a depth range between 1 cm and 2 cm. This area shifted to a shallower region for simple breast models. The downward trend in the main energy deposition region will inevitably result in a decline in D_g and $D_{gN_{DBT}}$. As CBT increases, the distance between the main energy deposition areas of the detailed and simple breast models also increases, leading to a larger difference in $D_{gN_{DBT}}$ between the models with increasing CBT. Overall, the results of this study indicate that the discrepancy between $D_{gN_{DBT}}$ values obtained from detailed breast models and those from simple models increases with decreasing glandularity, increasing CBT, and increasing beam energy, as also illustrated by Hernandez et al. [?] and Cordeiro de Souza et al. [?]. Meanwhile, $E_{gN}(z)$, as a quantity considering the amount and distribution or location of glandular tissue along the depth direction, contributes to identifying high-risk areas within the breast during screening that require careful examination and monitoring as they are more prone to cancer induction.

The method for defining glandularity in this work is not entirely the same as that employed in other literature [?, ?, ?]. Dance's model includes an outer 5 mm adipose layer and a central glandular region. Initially, the outer 5 mm layer was thought to be skin. However, as researchers' understanding of breast anatomy gradually deepened, it was found that the thickness of the outer skin layer was 1.45 mm and that there was almost no glandular tissue in the subcutaneous adipose layer, which was about 3-4 mm thick. Although it is now widely accepted that the "5 mm skin" view is incorrect, this has created a coincidence that the 5 mm adipose layer in Dance's model can be seen as a combination of skin (1.45 mm) and subcutaneous adipose (3-4 mm). Therefore, when defining P_g^M in this paper, we excluded the skin and subcutaneous adipose layers to make its physical meaning consistent with glandularity in Dance's model [?, ?]. Of course, for comparison with other literature and use in clinical dose calculations, this paper also defines the concept of breast volume density to measure the proportion of glands in the entire breast.

Admittedly, it is necessary to recognize that this study has several limitations. The detailed breast model was mainly developed based on representative breast parameters (including breast shape, CBT, glandularity, skin thickness, subcutaneous adipose thickness, etc.) of Chinese women, but we lacked high-resolution clinical images of Chinese women to obtain more accurate parameter information. Research has indicated that glandular distribution with different types has an important impact on dose conversion coefficients, especially the location of the concentrated area of glandular tissue [?]. In their study of clinical DBCT images, Fedon [?] found that the glandular distribution is not symmetrical along the depth direction, with the center being biased downward in the depth direction. Therefore, obtaining accurate glandular distribution of Chinese women in different age groups is an important direction for future research. In this work, $D_{gN_{DBT}}$ shows an upward trend at lower glandularity. This special result indicates that the growth characteristics of lactiferous ducts also greatly affect the calculation results of $D_{gN_{DBT}}$. The influence of this factor also needs further investigation. It is worth mentioning that these detailed breast models can also provide images with texture. Based on the anthropomorphic characteristics of the detailed breast model, we can investigate the association between image quality and radiation risk in the future and use it to obtain optimal exposure parameters for individualized patients.

5. Conclusion

The present research aimed to provide $D_{gN_{DBT}}$ tabulations for four commercial DBT systems widely used in China. Based on detailed breast models combined with CRAF, the dependence of $D_{gN_{DBT}}$ on various parameters, including beam condition (target/filter combination, beam HVL) and breast characteristics (CBT and glandularity), which had not been documented previously, were investigated. The calculated results deviated by up to 18.6% and 51.0% from data obtained from the traditional dosimetry protocol. Meanwhile, we also proposed a physical quantity, $E_{gN}(z)$, to analyze the difference of $D_{gN_{DBT}}$ in breast models with different glandular distribution and to determine roughly the range of breast depth with high cancer risk. This work makes an important contribution to improving the breast dosimetry protocol of DBT in China. The $D_{gN_{DBT}}$ tabulations obtained in this work provide a powerful tool for the rapid and straightforward assessment of D_g for the Chinese female population undergoing DBT scanning. However, the study still has certain limitations due to the lack of clinical data. Another aspect to explore in the future is obtaining breast characteristics (including glandular distribution, glandularity, and breast size) of Chinese females in different age groups.

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Appendix A

Table A1. Target/filter combination W/Rh of Siemens Mammomat Inspiration

HVL (mmAl)	CBT (cm)	$D_{gN_{DBT}}$ values for different P_g^M
...	...	...

Table A2. Target/filter combination W/Al of Hologic Selenia Dimensions

HVL (mmAl)	CBT (cm)	$D_{gN_{DBT}}$ values for different P_g^M
...	...	...

Table A3. Target/filter combination Mo/Mo of GE SenoClaire and GE Senographe Pristina

HVL (mmAl)	CBT (cm)	$D_{gN_{DBT}}$ values for different P_g^M
...	...	...

Table A4. Target/filter combination Rh/Rh of GE SenoClaire

HVL (mmAl)	CBT (cm)	$D_{gN_{DBT}}$ values for different P_g^M
...	...	...

Table A5. Target/filter combination Rh/Ag of GE Senographe Pristina

HVL (mmAl)	CBT (cm)	$D_{gN_{DBT}}$ values for different P_g^M
...	...	...

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Note: Figure translations are in progress. See original paper for figures.