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Original paper

Homogeneous vs. patient specific breast models for Monte Carlo evaluation of mean glandular dose in mammography

A. Sarno[a], G. Mettivier[a,*], F. Di Lillo[a], K. Bliznakova[b], I. Sechopoulos[c], P. Russo[a]

[a] Dipartimento di Fisica "Ettore Pancini", Università di Napoli Federico II & INFN Sez. di Napoli, I-80126 Napoli, Italy
[b] Laboratory of Computer Simulations in Medicine, Technical University of Varna, Varna, Bulgaria
[c] Department of Radiology and Nuclear Medicine, Radboud University Medical Centre and Dutch Expert Centre for Screening (LRCB), Nijmegen, Netherlands

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ABSTRACT

Purpose: To compare, via Monte Carlo simulations, homogeneous and non-homogenous breast models adopted for mean glandular dose (MGD) estimates in mammography vs. patient specific digital breast phantoms.
Methods: We developed a GEANT4 Monte Carlo code simulating four homogenous cylindrical breast models featured as follows: (1) semi-cylindrical section enveloped in a 5-mm adipose layer; (2) semi-elliptical section with a 4-mm thick skin; (3) semi-cylindrical section with a 1.45-mm skin layer; (4) semi-cylindrical section in a 1.45-mm skin layer and 2-mm subcutaneous adipose layer. Twenty patient specific digital breast phantoms produced from a dedicated CT scanner were assumed as reference in the comparison. We simulated two spectra produced from two anode/filter combinations. An additional digital breast phantom was produced via *BreastSimulator* software.
Results: With reference to the results for patient-specific breast phantoms and for W/Al spectra, models #1 and #3 showed higher MGD values by about 1% (ranges [–33%; +28%] and [−31%; +30%], respectively), while for model #4 it was 2% lower (range [−34%; +26%]) and for model #2 –11% (range [−39%; +14%]), on average. On the other hand, for W/Rh spectra, models #1 and #4 showed lower MGD values by 2% and 1%, while for model #2 and #3 it was 14% and 8% lower, respectively (ranges [−43%; +13%] and [−41%; +21%]). The simulation with the digital breast phantom produced with *BreastSimulator* showed a MGD overestimation of +33%.
Conclusions: The homogeneous breast models led to maximum MGD underestimation and overestimation of 43% and 28%, respectively, when compared to patient specific breast phantoms derived from clinical CT scans.

1. Introduction

The dose reference parameter in 2D mammography is the mean glandular dose (MGD) [1], i.e. the dose, on average, to the glandular tissue of the breast undergoing the exam. Following several protocols worldwide [2–5], the MGD is estimated from measurement of the air kerma at the entrance skin surface of the compressed breast, multiplied by suitable conversion coefficients: the normalized glandular dose (DgN) coefficients [6,7] or the set of (g, c, s) coefficients [8,9]. These coefficients depend on the beam characteristics, as well as on the breast anatomy, such as the compressed thickness and the glandular fraction. Both DgN and (g, c, s) coefficients are computed via Monte Carlo (MC) simulations where the breast is suitably modelled. In the current protocols (see the review in Ref. [5]), the breast is represented as a cylinder with a semi-circular or semi-ellipsoidal section, made of a homogeneous mixture of glandular and adipose tissue enveloped in a layer mimicking the skin. These models replicate neither the real breast shape nor the heterogeneous texture of the glandular tissue. However, the glandular tissue in the breast departs from the nipple and is mainly located in the central part of the organ, surrounded by the adipose tissue: this layer may partially shield the inner radiosensitive tissue. Dance et al. [10] showed that the location of the gland within the breast could bring to MGD differences as large as 48%, pointing out the lack of 3D digital breast models with a realistic glandular tissue distribution for a proper dose calculation. Modern 3D breast imaging techniques – such as computed tomography dedicated to the breast (BCT) [11–14] – allowed producing patient-like digital breast models, which reflect the breast anatomical characteristics for a more accurate MGD calculation [15]. Both Sechopoulos et al. [16] and Hernandez et al. [17] studied the influence of the homogeneous assumption on the calculated MGD. They produced digital compressed breast phantoms from high-resolution 3D images of breasts acquired via BCT scanners. These digital phantoms

* Corresponding author.
E-mail address: mettivier@na.infn.it (G. Mettivier).

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presented a heterogeneous glandular distribution, which mimicked that of real breasts. In addition, they generated homogeneous breast phantoms by substituting the heterogeneous tissue with a homogeneous one with the same glandular fraction. Via MC simulations, they found out that the MGD calculated with the so-modelled homogenous digital breast phantoms was about 30% higher, on average, with respect to the corresponding heterogeneous digital breast phantoms. In addition, in Ref. [16] the ratio between the MGD evaluated with the homogeneous and the heterogeneous models was comprised in the range 2.17 and 0.84, so indicating a maximum overestimation and underestimation of 117% and 16%, respectively, for the studied cohort. In any case, the models adopted in protocols for MGD estimates in mammography do not reproduce any real breast and present skin thicknesses and compositions, which differ from the homogeneous digital phantoms used in Refs. [16,17]. Indeed, the skin thickness and its composition have a huge impact on the MGD estimates, and the thicker is the skin, the lower is the dose to the gland, for the photon energies usually used in mammography [18,19]. While the digital phantoms derived from BCT images presented a skin thickness of 1.5 mm [17], the model proposed in Ref. [8] for the (g, c, s) calculation had a 5-mm thick skin made of adipose tissue. On the other hand, in Ref. [6] the skin had a thickness of 4 mm. These differences in skin thickness as well as the breast shapes and dimensions may partially compensate for the MGD overestimation caused by the homogeneous assumption. In this respect we also note that the skin thickness may not be constant on the surface of the breast [18].

This work aimed at comparing the homogeneous breast models usually adopted for MGD estimates, with patient specific digital breast phantoms, which reflect both the anatomy and glandular tissue distribution of real breasts. These patient specific digital phantoms were obtained from segmented 3D images of the uncompressed breast acquired via a commercial BCT scanner and digitally compressed via a suitable mechanical model. In addition, a digital breast phantom was developed via *BreastSimulator* software package [20], for a preliminary investigation of its adoption in breast dosimetry in addition to breast imaging investigations.

2. Materials and Methods

2.1. MC code

A MC code for MGD calculation in X-ray breast imaging was developed and presented in previous papers [19,21–24]. It is based on GEANT4 ver. 10.00 toolkit and adopts the standard physics list Option4. The default photon threshold cutoffs were used, and photoelectric, coherent and incoherent scatter photon interactions were simulated. Due to the low influence on the MGD calculation [19,21], the electrons were not tracked, but supposed to release energy at the generated location. The composition of the simulated breast tissues was that proposed in Ref. [1]; for water and PMMA the compositions indicated in the NIST database were used.

2.2. Homogeneous breast models

We investigated four homogeneous breast models with the following characteristics: Model #1, a cylinder with a semi-circular section with a radius of 8 cm and a 0.5-cm-thick adipose layer surrounding the radiosensitive breast tissue; Model #2, a cylinder with a semi-elliptical section with minor semi-axis – connecting the nipple to the chest – of 8 cm and the major axis of 18 cm and with 0.4-cm thick skin; Model #3, a cylinder with a semi-circular cross section with a radius of 10 cm and with 0.145-cm thick skin; Model #4, a cylinder with a semi-circular cross section with a radius of 10 cm and with 0.145-cm thick skin and 2-mm subcutaneous adipose layer. The inner portions of the four models were made of a homogeneous mixture of glandular and adipose tissue. The model #1 reflects the breast geometry proposed in Ref. [8] and the model #2 the one in Ref. [6].

Table 1
Homogeneous breast models investigated within this work.

Model	Breast section	Skin layer (mm)	Adipose layer (mm)	References
#1	Semi-circular; Radius = 8.0 cm	0.00	5.00	[8]
#2	Semi-ellipsoidal; Minor semi-axis (chest-to-nipple) = 8.0 cm, Major axis = 18.0 cm	4.00	0.00	[6]
#3	Semi-circular; Radius = 10.0	1.45	0.00	[18,19]
#4	Semi-circular; Radius = 10.0	1.45	2.00	[19,25]

However, literature [25] and recent research studies conducted with BCT scanners [18,26] showed that the skin thickness is lower than that proposed in Ref. [8] (5 mm) and in Ref. [6] (4 mm). The thickness of the skin layer was between 0.5 mm and 2.0 mm, and the subcutaneous adipose layer [25] was not visible in 3D images of the breast. Huang et al. [18], with a relatively large cohort of imaged breasts, showed that the breast skin presents an average thickness of 1.45 mm, much less than the thickness adopted in Refs. [6,8]. Shi et al. [26] reached similar results (1.44 mm of average thickness) with an independent patient cohort. For this reasons, in this study, we investigated also the models #3 and #4 described above. Table 1 summarizes the specifications of the homogeneous breast models investigated in this paper. The breast thickness and glandular fraction by mass were selected on the basis of the characteristics of the compared patient specific breast.

2.3. BreastSimulator

BreastSimulator is a modular software package for breast imaging research [20]. It is composed by the following four main modules: 1) Breast Modeling Module for generating 3D breast models; 2) Breast Compression Module for compressing digital breast models; 3) Image Generation Module for analytically generating synthetic projection images; 4) Visualization Module composed of a set of utilities to visualize 2D and 3D breast images. The module 1 permits to create digital breast phantoms with a selected composition. The simulated breasts' features include the breast shape, the duct system, the Cooper's ligaments, the pectoralis muscle, the skin and the lymphatic and blood systems; in addition, breast lesions can be added [27]. The user can increase the complexity of the breast model by including any of such features and by increasing their number or size. Mettivier et al. [27] showed a first validation of this software vs. real 3D breast images in terms of anatomical noise in a previous work.

BreastSimulator's module 2 permits to simulate the mechanical compression (based on the algorithm described in Ref. [28]) of the 3D uncompressed breast models. The 3D breast images (whose voxels are classified in adipose tissue, glandular tissue and skin tissue) are divided into model elements each consisting of 27 voxels. They are connected via springs, having uniform and isotropic linear modulus of elasticity. The software permits to classify the voxels on the basis of their content [29]. The tissue was considered as incompressible; hence, the breast volume does not change during the compression. The Young's modulus for the skin, the adipose tissue and the glandular tissue were set to 88 kPa, 1 kPa and 10 kPa, respectively [30].

2.4. Digital breast phantom via BreastSimulator

A digital breast phantom was generated via the *BreastSimulator* software, for MGD calculation and comparison to patient specific digital breast phantom (Fig. 1). Its glandular fraction by mass was 16% and it was compressed, via the module 2 of *BreastSimulator*, in order to have a compressed breast thickness of 68.6 mm. The dimension of the voxels was $0.245 \times 0.245 \times 0.245\ mm^3$. Differently from the homogeneous