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Original paper

Evaluation of a breast software model for 2D and 3D X-ray imaging studies of the breast

Yanka Baneva [a], Kristina Bliznakova [b,*], Lesley Cockmartin [c], Stoyko Marinov [b], Ivan Buliev [b], Giovanni Mettivier [d], Hilde Bosmans [c], Paolo Russo [d], Nicholas Marshall [c], Zhivko Bliznakov [b]

[a] Department of Physics and Biophysics, Medical University of Varna, Varna, Bulgaria
[b] Laboratory of Computer Simulations in Medicine, Technical University of Varna, Varna 9010, Bulgaria
[c] Medical Imaging Research Center, Department of Radiology, University Hospitals Leuven, Herestraat 49, 3000 Leuven, Belgium
[d] Università di Napoli Federico II, Dipartimento di Fisica "Ettore Pancini", and INFN Sezione di Napoli, Napoli, Italy

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ABSTRACT

Introduction: In X-ray imaging, test objects reproducing breast anatomy characteristics are realized to optimize issues such as image processing or reconstruction, lesion detection performance, image quality and radiation induced detriment. Recently, a physical phantom with a structured background has been introduced for both 2D mammography and breast tomosynthesis. A software version of this phantom and a few related versions are now available and a comparison between these 3D software phantoms and the physical phantom will be presented.
Methods: The software breast phantom simulates a semi-cylindrical container filled with spherical beads of different diameters. Four computational breast phantoms were generated with a dedicated software application and for two of these, physical phantoms are also available and they are used for the side by side comparison. Planar projections in mammography and tomosynthesis were simulated under identical incident air kerma conditions. Tomosynthesis slices were reconstructed with an in-house developed reconstruction software. In addition to a visual comparison, parameters like fractal dimension, power law exponent β and second order statistics (skewness, kurtosis) of planar projections and tomosynthesis reconstructed images were compared.
Results: Visually, an excellent agreement between simulated and real planar and tomosynthesis images is observed. The comparison shows also an overall very good agreement between parameters evaluated from simulated and experimental images.
Conclusion: The computational breast phantoms showed a close match with their physical versions. The detailed mathematical analysis of the images confirms the agreement between real and simulated 2D mammography and tomosynthesis images. The software phantom is ready for optimization purpose and extrapolation of the phantom to other breast imaging techniques.
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1. Introduction

Physical and computational phantoms are essential for the development, optimization, and evaluation of modern X-ray imaging systems. Modern breast imaging techniques can be two-dimensional (digital mammography, dual energy and contrast-enhanced mammography, the advanced monochromatic and phase-contrast imaging [1–4]) or three-dimensional (tomosynthesis and breast CT [5–13]). For all these techniques, it is important that both physical and software phantoms reproduce the breast characteristics for the study of particular aspects of the imaging chain such as image processing or reconstruction, lesion detection performance, image quality and radiation induced detriment. In most cases, physical breast phantoms are manufactured from a homogeneous mixture and this may result in a lack of realistic 2D and 3D image representation. While many groups work at a 3D anthropomorphic phantom [14–28], there is not yet a consensus on a particular multi-purpose phantom. The degree of realism of the glandular structure is also variable and inserting lesion like objects remains a challenge. On top of this, physical phantoms may be expensive, especially if different breast models have to be foreseen.

These are some of the reasons that lead to the introduction of computational phantoms and their use in virtual experiments in X-ray imaging. The best computational phantoms allow detailed modelling of the 3D structures of the breast and produce image

* Corresponding author.
E-mail address: kristina.bliznakova@tu-varna.bg (K. Bliznakova).

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characteristics similar to these produced by radiation of real breasts. Assessment of agreement between simulated and real images has been done with fractal dimension and the power law exponent β of the logarithmic power spectrum of mammographic projection images, as well as other parameters such as first order, second order or higher order statistical parameters.

One worked-out example is the UPenn breast phantom that was designed as a software phantom and later realized for physical measurements of 2D mammography and breast tomosynthesis [14–16,21]. Another physical phantom has been introduced by Cockmartin et al. [29] which produces a structured background and was tested for both 2D mammography and breast tomosynthesis [30–32]. This physical breast phantom is based on the work of Gang et al. [33], where it is shown that equal volumes of differently sized acrylic spheres provide a fractal dimension of 3 as well as a power law exponent β equal to 3. The phantom consists of acrylic spheres placed in an acrylic container filled either with air or with water. The phantom images showed power law exponents in the range of the exponents measured in patient data [31].

Further development of this phantom are expected based on the improvement of the inserted breast lesions, the improvement of the shape of the beads (non-spherical) and the study of more appropriate material compositions (other than PMMA and water) for the manufacturing of the phantom. For this purpose, a software application called *LUCMFRGen* was developed that allows to create software versions of the physical phantom based on parameters like sizes of the container and the spheres, as well as the material characteristics. In the beginning, the tool was developed for educational applications [34].

Fig. 1. A photo of the physical breast phantom, filled with water.

The purpose of this work was to perform a detailed validation of the *LUCMFRGen* software for applications in mammography and tomosynthesis.

2. Materials and methods

2.1. Physical phantom

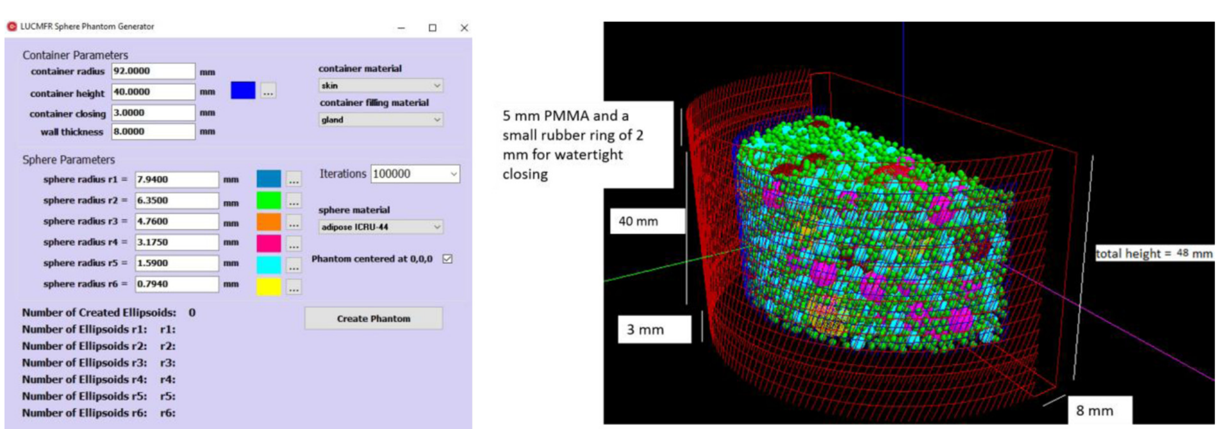
The physical phantom is an acrylic semi-circular container with 48 mm thickness and 200 mm diameter (Fig. 1), representing 60 mm compressed breast thickness [32]. Acrylic spheres with six different diameters were inserted in the container: 15.88 mm, 12.70 mm, 9.52 mm, 6.35 mm, 3.18 mm and 1.85 mm. Compared to Gang's publication [33], spheres with smaller diameters have been added. The total volume of the acrylic spheres of one particular diameter was constant [29]. This phantom is dedicated to testing and optimizing 2D mammography and breast tomosynthesis.

Two such physical phantoms were initially produced: one phantom of acrylic spheres filled with air and one phantom filled with water (Fig. 1).

2.2. Software phantom

In order to create phantoms with different dimensions, volume and content, a dedicated software tool *LUCMFRGen* was designed, implemented and used in this study [34]. The computational model was divided in two main parts - a container and a spheres. The container is modelled as a set of two semi-cylinders and a slab object, approximating the sidewall of the physical model. The software application samples randomly the location of the spherical objects within the internal semi-cylinder, starting from the spheres with largest diameter. The algorithm also verifies that the currently sampled sphere does not have intersection with other spheres. The procedure of generating spheres is time consuming, as their number reaches 29,000 and every new sphere needs to be checked for non-overlapping. The algorithm implements the sphere packing concept for unequal non-overlapping spheres in a container space. Since we use random packing of the generated spheres, the packing density of the spheres is approximately 64%. The software was tested for educational applications in an international course program (Eutempe-Rxmodule 5) [34,35].

For the purposes of this work, four phantoms which have equal container dimensions were created. An example is shown in Fig. 2b and summarized in Table 1.



(a) (b)

Fig. 2. Generation of computational breast phantoms: (a) a screenshot from the *LUCMFRGen* software and (b) generated phantom.

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