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# Evaluation of the effect of silicone breast inserts on X-ray mammography and breast tomosynthesis images: A Monte Carlo simulation study

A. Daskalaki [a,*], K. Bliznakova [b], N. Pallikarakis [a]

[a] *Department of Medical Physics, School of Medicine, University of Patras, Patras, Greece*
[b] *Department of Medical Electronics, Technical University of Varna, Varna, Bulgaria*

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ABSTRACT

*Purpose:* Breast augmentation is one of the most popular cosmetic surgeries worldwide. The aim of this study is to investigate the effect of breast implant insertion on the detectability and visibility of lesions on mammography and breast tomosynthesis (BT) images.

*Materials and methods:* Three software phantoms, composed of a homogeneous background with embedded silicone gel structures, and two types of breast abnormalities, microcalcifications (µCs) and masses, were generated. Two X-ray breast imaging modalities were simulated: mammography and BT with six incident monochromatic X-ray beams with energies in the interval between 20 and 30 keV. Projection images were generated using an in-house developed Monte Carlo simulator. The detectability of mammographic findings adjacent to the implant material and the influence of the incident beam energy and implant thickness on the feature detection were studied.

*Results:* It was found that implants thicker than 26 mm for the case of mammography and 14 mm for the case of BT obscured the visibility of underlying structures. Although BT demonstrated a lack of contrast, this modality was able to visualize µCs under considerable depths of implant. Increasing the incident beam energy led to better visualization of small µCs, while in the case of breast masses, their detectability was limited.

*Conclusions:* Silicone gel implants introduce a limitation in the image quality of mammograms resulting in low detectability of features. In addition, silicone gel implants obscure partially or totally parts of the image, depending on the size and the thickness of the implant as well the energy of the X-rays used.


## Introduction

Breast cancer screening and diagnosis are the primary aim of the X-ray mammography and breast tomosynthesis (BT). Patients with silicone gel implants should be treated with an alternative way regarding the dose limits, the incident beam energy and the acquisition protocols. However, prostheses used for breast reconstruction and augmentation contain a material with higher atomic number (Z) compared to the breast tissue, and this may affect the image quality and the dose distribution within the breast.

There are several types of breast implants used for breast augmentation and reconstruction in plastic surgery. Depending on the filler material, the breast implants are divided into saline, silicone, and composite. The saline implant has an elastomer silicone shell filled with sterile saline solution. The silicone implant has an elastomer silicone shell filled with viscous silicone gel, while the alternative composition implants feature miscellaneous fillers, such as soy oil and polypropylene string. This work focuses on silicone implants, due to their wide acceptance from the medical community and the problems they introduce to diagnostic imaging [1–3]. Specifically, silicone implants are filled with viscous silicone gel and covered with silicone polymer. Silicone gel, used for breast implants, is a synthetic material inert containing 38% silicon (Si) usually in the form of a silicone tetramer (polydimethylsiloxane) with chemical composition: $CH_3[Si(CH_3)_2O]_4Si(CH_3)_3$ that has an effective atomic number of 10.37, a density of 0.97 g/cc and a volume ranging between 90 cc and 800 cc.

Several characteristics of silicone gel implants and the techniques of their placement affect the X-ray based imaging of the breast. The presence of silicone gel-filled implants interferes with standard mammography, since silicone is a radiopaque material. The physical presence of the implant compresses fat and glandular tissues

* Corresponding author. Department of Medical Physics, School of Medicine, University of Patras, 26500, Rio, Patras, Greece. Tel.: +30 2610 997702; fax: +30 2610 992496.
*E-mail address:* dasnatasa@gmail.com (A. Daskalaki).

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increasing the density of the breasts, which frequently lacks the contrast needed to detect subtle early features associated with breast cancer [4]. This means that in the case of implant insertion more tissue may be imaged in a smaller space, which causes superposition of structures, resulting in poorer image quality. Since silicone filled implants have a low X-ray transmission in the region of the implant, the detection of small masses in the breast is reduced [5,6]. As a result, breast lesions near the silicone gel implant require special mammography procedures for their detection [7]. Moreover, silicone gel implants obscure portions of the breast on mammography images [8,9]. It has been estimated that about 25% of the breast tissue is not visible in the presence of silicone gel implants on mammography images [10]. Studies taking into account the visualized mammography breast tissue area before and after augmentation mammoplasty indicate a reduction of measurable tissue area in the range of 15%–44% depending on the imaging procedure and the positioning [11]. Anterior breast tissue was visualized better with displacement mammography, while compression mammography indicated better results for the posterior breast tissue.

All the effects which come along with implant presence on diagnostic breast imaging in correlation with their high percent of usage indicate further investigation on this issue. The objective of this work is to investigate further the effect of the silicone gel insertion on the image quality of mammography and BT images considering different energies and dose levels. Moreover, this study evaluates the detectability of both high and low contrast features on simulated images in the presence of silicone gel implants of different thicknesses at beam energies in the interval of 20–30 keV. For this purpose, three software phantoms with silicone gel prosthesis were designed and used for X-ray imaging simulations. X-ray transport and images of these phantoms were generated in a mammographic and BT mode, using the validated in-house developed software XRayImagingSimulator [12,13]. X-ray mammography and BT imaging processes were modeled and simulated with incident energies as well as dose limits modified in a way to implement constant incident photon fluence for all the simulations. Six monochromatic X-ray beams with energies in the interval of 20–30 keV were simulated, resulting in entrance surface exposure (ESE) in the range of 1.83–4.32 mGy for the first and third phantom and 3.59–8.47 mGy for the second phantom. The visibility of breast masses and the detection of μCs under different silicone base thicknesses were evaluated versus the incident beam energy and the type of the X-ray imaging technique (mammography and BT).

## Materials and methods

The three different software phantoms dedicated for silicone gel implant breast imaging were designed using the abovementioned in-house developed software. The first one has a step-wedge geometry, the second one has a helical form, while the third is a breast-like phantom. The first two phantoms were designed with escalating geometries in order to be able to investigate the effects of different silicone thicknesses in a single imaging phantom. The first one has silicone inserts reaching a thickness of 36 mm, while the second one gives the ability to investigate higher thicknesses of silicone up to 49 mm in more detail. In addition, the third phantom was designed to yield a more realistic illustration of breast implant insertion. Breast abnormalities, i.e. microcalcifications ($CaCO_3$) and low-contrast features (breast masses) with nominal densities of 2.8 g/cm$^3$ and 1.011 g/cm$^3$, respectively, were simulated and inserted near the silicone gel based implant material. These phantoms were the basic tools in investigating the effect of silicone gel implants on the image quality and breast lesion detection under different imaging conditions.

### *Software phantoms*

#### *Step-wedge phantom*

A phantom, shown in Fig. 1a, was designed using 18 adjacent cuboids and modeled from a silicone gel ($CH_3[Si(CH_3)O]_4Si(CH_3)_3$), with a thickness in the range of 2 mm–36 mm, forming a step-wedge (geometry). The step-wedge phantom was placed in a $50 \times 100 \times 40$ mm$^3$ homogeneous block, filled with a mixture of 50% adipose and 50% glandular tissue with a density of 0.982 g/cm$^3$ [14]. A $CaCO_3$ sphere with a radius of 0.2 mm was placed at a distance of 2 mm under each cuboid. The phantom was converted to a voxel-based one, whereas – for time consuming reasons – a voxel size of 200 μm was chosen along each direction.

#### *Snail phantom*

A snail phantom, shown in Fig. 1b, was created consisting of 49 adjacent $2 \times 2$ mm silicone gel cuboids (representing the implant) with thicknesses ranging from 1 mm to 49 mm. In addition, 49 spheres, simulated as $CaCO_3$ with a radius of 0.2 mm, were placed at a distance of 1 mm under each implant cuboid. Modeled lesions and implants were inserted within a homogeneous block with a size of $18 \times 18 \times 54$ mm$^3$ simulated as a mixture of 50% adipose and 50% glandular tissue. In this phantom the thickest implant material is placed at the center in contrast to the previous step-wedge one, where the thickest implant is placed at the right side of the phantom. Similar to the previous phantom, the snail phantom was converted to a voxel-based one with a voxel size of 100 μm along each direction.

#### *Phantom with a realistic implant shape*

A rectangular slab phantom with a realistic shape and composition mimicking a silicone gel implant was designed as shown in Fig. 1c. The phantom with dimensions of $50 \times 100 \times 45$ mm$^3$ was composed of a homogeneous mixture of material simulating 50% adipose tissue and 50% glandular tissue. The implant was modeled in the form of a semi-ellipsoid with dimensions of $20 \times 46 \times 20$ mm$^3$ filled with silicone gel. Two clusters of μCs, each one consisting of six $CaCO_3$ spheres with radii of 0.138 mm and 0.4 mm, respectively, and a set of three water spheres with radii of 1 mm, 1.5 mm and 2 mm, respectively, were inserted within the base material.

### *X-ray imaging simulation*

X-ray projection images from the developed software phantoms were simulated with the Monte Carlo module of the XRayImagingSimulator, at different incident energies between 20 keV and 30 keV.

#### *Simulated imaging protocols*

The mammography simulation included generation of six mammography images from each phantom with source to object plane and source to detector distances of 600 mm and 650 mm, respectively. The incident photon flux was $5 \times 10^5$ photons/pixel, while the detector response was not simulated. For the simulation study with the step-wedge and the phantom with the realistic implant shape, projection images with a size of 770 pixels × 770 pixels and a pixel dimension of 140 μm × 140 μm were generated. For the simulation study with the snail phantom, the images were with a size of 400 pixels × 400 pixels and pixel dimensions of 100 μm × 100 μm, generated at a source to detector distance of 660 mm.

Breast tomosynthesis protocol included generation of projection images in an isocentric mode, with the X-ray source and the detector rotating around the phantom contrariwise. The acquisition parameters, i.e. distances, image size and resolution, the total photon flux as well as the incident beam energies, were kept the same. Specifically, for the step-wedge phantom, 31 projection images