DESIGN AND APPLICATION OF A THREE-DIMENSIONAL PRINTED ANTHROPOMORPHIC BREAST PHANTOM IN MAMMOGRAPHY - A REVIEW ARTICLE

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Abstract: Although mammography serves as a key screening tool for early breast anomaly detection, its reliance on ionizing radiation requires dose minimization without compromising image integrity. The advent of 3D printing has enabled the creation of breast phantoms that closely replicate diverse tissue types, offering a valuable platform for refining mammographic techniques. This review consolidates existing research concerning the fabrication, structural design, and practical uses of these 3D-printed phantoms, specifically focusing on their capacity to replicate anatomical structures, physical tissue properties, and radiological characteristics. During the summer of 2026, English-language studies published between January 2016 and May 2026 were sourced through a search of the PubMed and Scopus databases. The review evaluated studies involving 3D printed anthropomorphic breast phantoms for mammography, applying predefined inclusion and exclusion criteria from the study. Eight studies met the criteria, illustrating diverse strategies for the design of these phantoms. The phantoms successfully reproduced anatomical structures, tissue attenuation properties, and radiographic textures. The modular design allowed insertion of lesions, microcalcifications, and iodine objects, improving the assessment of lesion detectability and system performance. Integration with observer models enabled objective assessment of image quality and prediction of human observer performance. 3D printed anthropomorphic breast phantoms provide a reliable, reproducible, and flexible platform for technical evaluation of mammography systems and dose optimization. Continued refinement of materials and modeling techniques will further improve tissue realism and diagnostic relevance.
Keywords: mammography, breast, 3D printing, anthropomorphic phantom

1. INTRODUCTION

Mammography is a commonly utilized imaging tool in clinical care for the timely detection and characterization of breast tissue changes and represents a key diagnostic tool in modern healthcare for breast cancer screening (Fico et al., 2023). Advances in mammographic technology are essential to preserving diagnostic reliability while lowering radiation levels, as ensuring high image quality while controlling radiation dose is crucial to ensure that the merits of these techniques exceed their potential hazards. However, the utilization of ionizing radiation in clinical trials presents ethical and logistical challenges, such as increased risk to patients and substantial time burden and resources (Graff, 2016).

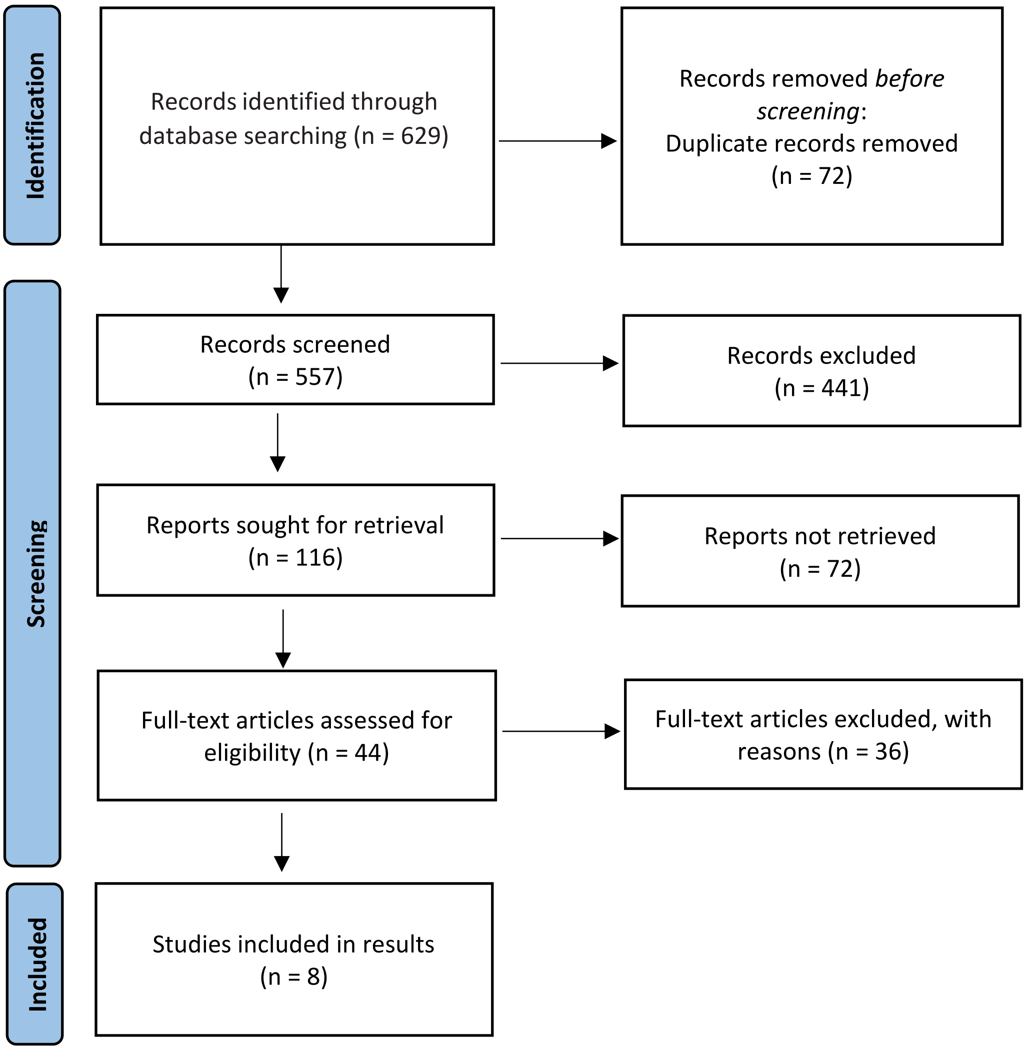
Consistent with the mandate to minimize radiation exposure, physical phantoms serve as substitutes for breast tissue when evaluating new mammography systems and conducting routine quality control of existing equipment. Nevertheless, most are constructed from homogeneous materials and fail to replicate the anatomical complexity of the human breast (Badal, Clark, & Ghammraoui, 2018). Commercial phantoms are widely used to simulate breast tissue, tissue, yet they lack the realistic physical attributes of genuine tissue and often prove inadequate for diagnostic purposes. As they are meant for general use and can rarely be customized, it is necessary to develop tissue-equivalent phantoms with customized properties and dimensions, with 3D printing enabling more complex and anatomically realistic models, improving dose optimization in mammography systems (Kiarashi et al., 2015), (Bliznakova, 2020). Realistic and accurate simulation of breast anatomy involves imitating the external shapes, as well as the different tissues and pathological changes for all types of breasts. Realistic and accurate simulation of breast anatomy requires encompassing both external morphology and internal tissue architecture, along with pathological variations across different breast types. The properties of the modeled structures are determined by the selected tissue-equivalent materials, including their elemental composition, physical density, and effective atomic number (Sarno et al., 2023).

This review seeks to evaluate and integrate available findings on the design, fabrication, and application of 3D-printed anthropomorphic breast phantoms for mammography, emphasizing their capability to simulate anatomical structures, tissue characteristics, and radiological properties.

2. MATERIALS AND METHODS

This review compiles the current scientific literature on the design and application of 3D-printed anthropomorphic breast phantoms in mammography. Searches were aimed at studies whose titles or keywords included the terms "breast phantom," "3D printing," and "mammography." A search of the PubMed and Scopus databases was conducted in the summer of 2026, covering literature, spanning the period from January 2016 to May 2026. The review was confined to articles written in English. Eligibility criteria were defined to include studies focusing on breast phantoms intended for mammographic imaging and fabricated using 3D printing techniques. Studies were excluded if they involved purely numerical phantom simulations or phantoms developed for imaging modalities other than mammography. In addition, reports, abstracts, study protocols, conference proceedings, case reports, review articles, and qualitative studies did not meet the criteria and were therefore excluded. Following the screening phase, eight studies remained eligible and formed the basis of this review (Figure 1).

Figure 1. Flowchart of a selection of studies for the review



Source: Page, M.J., 2021.

3. RESULTS

The eight studies comprising this review are summarized in Table 1. Having each satisfied the predefined inclusion criteria, these studies collectively reflect diverse methodologies for the design and production of 3D-printed anthropomorphic breast phantoms for mammography.

Table 1. Characteristics of eligible studies

Publication	Research objectives	Materials and methods	Results	Conclusion
Badal et al., 2018	To design a simple and reproducible method for designing 3D printed breast phantoms that replicate attenuation profiles from real	Open-source software was used to convert raw mammograms into 3D mesh models encoding pixel-wise attenuation, which were printed using	Printed phantoms produced X-ray images with good structural agreement with the corresponding original mammograms, and the materials showed	The methodology enables the reproducible fabrication of anatomically realistic 3D breast phantoms and

	mammograms.	various 3D printing systems.	measurable differences in attenuation characteristics among different printing technologies.	demonstrates their potential for evaluating mammography system performance.
Balta et al., 2018	To examine the feasibility of a task-based framework for assessment that merges an anthropomorphic breast phantom with a mathematical observer model.	Images of the two gold disk sizes were acquired using two mammography systems at different doses and analyzed by model observers and human readers. Performance correlations between human and model observers were assessed on processed and unprocessed regions of interest.	Both model and human detectability rose with higher radiation doses, yielding robust correlations ($r^2 \approx 0.79$–0.93 across various systems and disk sizes). Predicted observer performance closely matched actual human outcomes, with no meaningful differences observed, and image processing did not measurably influence signal detection.	The framework has shown potential, indicating that objective assessment of image quality is feasible, yet continued improvement of the phantom and investigation of additional model observers is recommended.
Bermúdez et al., 2023	To present a novel 3D mammographic phantom for equipment quality assessment, quantification of breast glandular tissue proportion, and simulation of microcalcifications as lesion analogues.	The phantom is modularly designed with an attenuation field matrix, built-in microcalcifications and a spatial resolution test object. Tests were performed by measuring contrast, noise, spatial resolution and calibrating the intensity to the proportion of glandular tissue.	Microcalcification detection proved reliable at a level of 95.4% and 68.3%. Successful calibration of intensity to glandularity was performed for a compressed 4 cm breast.	The proposed 3D phantom is competitive with commercial models according to standard accreditation criteria, and its modularity and distribution of inserts enable the provision of reference values for tissue and lesions, and the efficient evaluation of the performance of mammography systems.
Boita et al., 2021	To validate an image modification algorithm that adjusts mammograms to appear as if they were taken with different technical factors, using realistic mammograms of 3D printed breast phantoms.	Five 3D printed breast phantoms were acquired on two digital mammography systems under original and modified acquisition conditions. Algorithm-generated images were compared to real targets, and relative percentage errors were determined.	The simulated images closely matched the target images, with low relative error rates across all metrics.	The validated algorithm accurately simulates changes in technical factors and can support studies that evaluate how acquisition settings affect cancer detection using clinical mammograms.
Ikejimba et al., 2017	To create a fast and inexpensive approach for creating realistic phantoms that are	After digital modeling, the phantom was divided into fatty and glandular zones, with the latter generated	P1 and P2 parchment papers showed attenuation similar to fat, whereas ink-loaded	This study introduces an affordable and accessible

	designed to provide realistic representation and well-suited for implementation in 2D and 3D imaging systems.	through Voronoi segmentation. These regions were then printed layer by layer using inkjet technology, combining three parchment types (P1, P2, P3) with radiopaque ink. Evaluation focused on geometric fidelity, repeatability, and ink reliability.	parchment behaved like glandular tissue. The fabricated phantom yielded printed and simulated images that matched closely, with less than 3% print-to-print ink-signal deviation and overall variability under 1%.	approach for producing anatomically precise breast phantoms, utilizing inkjet printing technology and common, easy-to-source materials.
Rossman et al., 2019	To design a modular breast phantom that enables improved visualization of lesions and calcifications.	The research refines earlier phantom prototypes by utilizing adapted 3D printers to produce structures with smooth fat-to-glandular interfaces, enabled by salt- and nanoparticle-doped materials.	By accommodating a greater diversity of breast tissue densities, this modular phantom achieves superior anatomical accuracy compared to its predecessors. Its insertable components enhance the evaluation of lesion and calcification detectability, while a dedicated uniform area facilitates consistent quality control testing, ensuring a comprehensive assessment of mammography system performance.	Designed with both flexibility and anatomical fidelity in mind, the improved modular breast phantom serves as a reliable and versatile device to improve clinical mammography assessment.
Schopphoven et al., 2019	To establish a 3D-printed fabrication approach for breast phantoms that emphasizes anatomically realistic features and X-ray attenuation properties based on clinical image data.	PolyJet 3D printing and a polypropylene-like material were used for fabrication. Raw clinical image pixel intensities were converted into height data to produce a 3D model, which was then printed and validated while maintaining a uniform setup throughout. The phantom was also tested on five different systems to confirm its interoperability.	The anthropomorphic phantom correlated well with the clinical image in anatomy and attenuation. Automatic exposure control, exposure settings, and post-processing were identical for clinical and phantom imaging.	A 3D printing-based method has been effectively developed to fabricate anatomically realistic breast phantoms intended for mammographic imaging, providing precise anatomical and radiological representations.
Varallo et al., 2022	To create anatomically accurate, compressed 3D printed breast phantoms that are intended for use in digital mammography.	Three breast phantoms were fabricated by FDM 3D printing, using adipose, glandular, and skin tissue simulation materials, based on segmented clinical computed tomography images. Phantoms were imaged at three locations, and anatomical noise was estimated using the β parameter in both modalities.	Phantom images displayed realistic internal textures, accurately mirroring the glandular patterns seen in clinical images. The β values recorded on mammography images ranged from 2.84 to 3.79.	3D printed breast phantoms effectively recreated realistic anatomical features and radiographic textures, exhibiting significant potential for deployment in clinical quality

				control, image quality assessment, and dosimetry studies.

Source: Author

4. DISCUSSIONS

The creation of anthropomorphic breast phantoms via 3D printing represents a significant advance in the field of mammographic diagnostics, enabling the integration of physical-technical and diagnostic evaluation under controlled conditions. Studies conducted by Badal et al. (2018) and Schopphoven et al. (2019) demonstrate that it becomes possible to faithfully reproduce anatomical structures and attenuation profile of real breast tissue with a high level of fidelity, thereby reducing the need for patient exposure to ionizing radiation and enabling standardized evaluation of mammographic system performance. Ikejimba et al. (2017) demonstrated that the utilization of advanced modeling techniques enables rapid and accurate fabrication of phantoms with multilayered structures of glandular and adipose tissue, which further improves the reproducibility and flexibility of phantoms for 3D mammographic evaluation.

Varallo et al. (2022) and Bermúdez et al. (2023) emphasize the importance with the aid of multi-material 3D printing to construct phantoms that not only reflect anatomical features, while simultaneously affording the ability for precise calibration of intensity and glandular structure, assessment of contrast-to-noise ratio and spatial resolution, and simulation of microcalcifications. Such phantoms offer the advantages of modularity and accessibility compared to commercial models, while positioning near the patient's breast, provides reference values that reflect the real relationships of glandular and fat tissue.

The integration of phantoms with mathematical models of the observer, as shown by Balta et al. (2018), represents a significant step towards objective assessment of image quality, together with the means to anticipate perception under different technical imaging conditions. Also, Rossman et al. (2019) show that modular design, including the inserts for lesions, calcifications and iodinated objects, further increases the functionality of phantoms and enables comprehensive evaluation of mammography systems, including lesion detection and identification of microcalcifications. This close synergy between advanced 3D printing techniques and precise modeling of breast anatomy ensures that the developed phantoms represent a reliable, reproducible, and flexible platform for optimizing imaging protocols and validating image processing algorithms. However, despite the obvious advantages, there are limitations that require further optimization, including further refinement of the materials to more realistically simulate heterogeneous tissues, reduce resolution loss, and explore additional observer models for a broader spectrum of image quality assessment applications.

5. CONCLUSIONS

Development of 3D printed anthropomorphic breast phantoms represents a key advance in mammography diagnostics, enabling precise and reproducible simulation of anatomical structures, tissues and lesions, surpassing commercial models in anatomical realism, modularity and adaptation to clinical and research needs. Their application optimizes imaging protocols, system performance assessment, algorithm validation and education, while reducing patient radiation exposure, while further research must improve materials and observer models for more realistic simulation and a wider range of evaluation tasks.

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