

Development of a methodology for the rapid production of low-cost breast models for self-diagnosis training

Błażej Gabryszewski^{1*}, Alicja Majewska², Aleksander Wawrzyniak¹,
Magdalena Żukowska¹, Emilia Smolarek¹, Filip Górski¹ 

¹ Faculty of Mechanical Engineering, Poznan University of Technology, Piotrowo 3, 61-138 Poznań, Poland

² Faculty of Medicine, Nicolaus Copernicus University in Toruń- Ludwik Rydygier Collegium Medicum in Bydgoszcz Jagiellońska 13/15, 85-067 Bydgoszcz, Poland

* Corresponding author's e-mail: blazejgab@gmail.com

ABSTRACT

This study presents a rapid and cost-effective methodology for manufacturing glandular breast models intended for health education purposes. The main objective was to assess a hybrid fabrication approach that combines additive manufacturing with vacuum polymer casting in terms of its capability to reproduce the complex internal architecture of heterogeneously dense breast tissue for medical training applications. The proposed method enables realistic representation of glandular tissue, adipose tissue, and cancerous lesions. The external geometry of the model was acquired using 3D scanning of the human torso, whereas the internal anatomical structures and pathological changes were reconstructed through segmentation of medical imaging data. Subsequent stages included the fabrication of 3D-printed molds and the selection of silicone materials suitable for reproducing the anatomical characteristics of breast tissue. The final product was manufactured using a complex assembly process. This involved the use of castings produced in separate molds, the order of which is crucial in terms of the stability and accuracy of the process. The components possess different mechanical properties, which better reflects the glandular breast anatomy. Qualitative evaluation demonstrated that the developed approach successfully replicates heterogeneously dense breast tissue, accurately reflecting the spatial distribution of glandular and adipose components. The proposed methodology therefore constitutes an accessible and anatomically realistic alternative to commercially available training phantoms, offering valuable support for patient education and breast self-examination training.

Keywords: breast cancer, self-diagnosis, anatomical models, 3D printing, vacuum casting.

INTRODUCTION

Breast cancer remains the most frequently diagnosed malignancy among women worldwide, representing a significant challenge for global public health. According to the Global Cancer Observatory, approximately 2.3 million new cases and over 660,000 deaths were recorded in 2022 [1]. In Poland, the 2023 National Cancer Registry data indicates that breast cancer accounts for 22.6% of all female cancer diagnoses and 14.6% of cancer-related deaths [2]. The high mortality rates associated with late-stage

diagnosis underscore the critical importance of early detection strategies [3–5].

The foundation of early detection lies in organized screening programs, such as mammography, which should be complemented by regular breast self-examination (BSE). Although its clinical efficacy is sometimes debated, BSE remains a basic tool for increasing „breast awareness,” allowing women to detect interval cancers between screenings [6]. However, the effectiveness of BSE training is strictly dependent on the quality of didactic tools. As emphasized in recent literature, many educational programs fail not because of a lack

of interest, but due to the unavailability of high-quality simulators that allow for the distinction between normal glandular structures and pathological masses [7,8].

Current commercial breast phantoms, while widely used, exhibit significant limitations. Research indicates that many available models are in a way that prevents expensive for mass implementation in public health campaigns [8]. More importantly, from a structural perspective, these phantoms often lack anatomical realism. Most commercial models consist of a uniform silicone mass representing only adipose tissue, failing to simulate the complex, heterogeneously dense glandular architecture characteristic of many patients.

Additive manufacturing (AM) has emerged as a transformative force in personalized medicine. As described by Górski (2025), the development of computer-aided design for 3D printable medical devices allows for the creation of complex, anatomically shaped tools tailored to specific clinical needs [9]. While AM is extensively utilized for surgical planning and the production of individualized pre-surgery supplies, as seen in maxillofacial reconstructions, its application in developing soft-tissue educational phantoms is still developing [10].

The synergy of low-budget manufacturing methods, specifically the combination of 3D printing and vacuum silicone casting, offers a promising yet under-researched pathway for medical simulation. Żukowska et al. (2019) demonstrated a methodology for low-cost rapid manufacturing of anatomical models that successfully imitate the material properties of soft tissues [11]. Despite these advancements, there is a noteworthy research gap regarding a standardized, accessible workflow that integrates 3D scanning, medical imaging segmentation (DICOM), and multi-material casting to replicate the BI-RADS (Breast Imaging-Reporting and Data System) classifications in phantoms. Existing studies predominantly focus on either cost-prohibitive professional simulators or elementary AM models, leaving a deficit of accessible phantoms that combine high anatomical fidelity with a diverse range of pathological features for mass public health education.

To address this gap, this study focuses on the methodological assessment of a hybrid manufacturing process. The primary objective is to evaluate the effectiveness of integrating additive manufacturing and vacuum casting in replicating the intricate internal structures of heterogeneously

dense breast tissue. By validating this low-cost approach, the research aim is to provide a scalable solution for improving the quality of breast self-examination training tools.

MATERIALS AND METHODS

Concept of model development

The concept for this project was initiated following consultations with the International Federation of Medical Students' Associations (IFMSA) Poland, which highlighted a significant shortage of high-quality yet affordable training materials for campaigns promoting breast health awareness. Addressing these educational needs, the primary objective of this project was to develop breast models that accurately replicate the tactile and anatomical characteristics of glandular and adipose tissues. The process was divided into four major stages:

- Data acquisition – involving 3D scanning for external geometry and medical imaging for internal structures (glandular tissue and cancerous lesions).
- Digital modeling – anatomical segmentation and design of the casting molds.
- Production – 3D printing of the molds and vacuum silicone casting.
- Validation – clinical expert verification and empirical testing by users.

Each stage was optimized to balance anatomical accuracy with cost-effectiveness and reproducibility. The workflow is illustrated in the flow-chart in Figure 1.

Anatomical data collection and imaging segmentation

The external surface geometry was acquired using an EinScan Pro 2X handheld 3D scanner (Shining 3D, Hangzhou, China). Data collection was performed based on a group of three volunteers from the research team, which ensured controlled conditions and full compliance with internal safety and privacy protocols. To maintain the highest ethical standards, all participants provided written informed consent for the use of their anonymized topographical data for research purposes. The scans were performed in a seated position with the arms elevated,

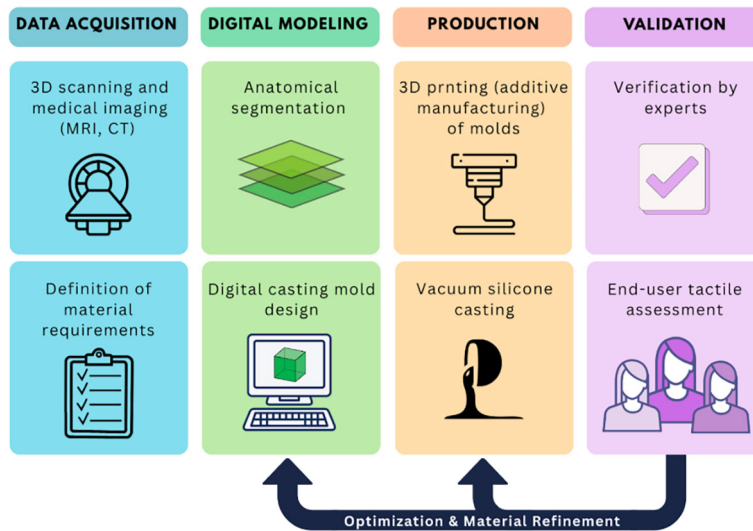


Figure 1. Project methodology diagram

reflecting the recommended posture for clinical breast self-examination (BSE) [12]. This specific posture allowed for the accurate capture of the breast's external morphology under the influence of gravity, ensuring high anatomical fidelity of the resulting phantoms (Figure 2). The scanning process generated a point cloud, which was converted into a mesh grid using EinScan Software V3.0. The 'Unwatertight' conversion option was selected to preserve the integrity of the raw data. The resulting digital model was then manually inspected to identify and correct artifacts from the automatic conversion process. These steps were necessary to prepare the geometry for designing the casting mold.

To complement the external geometry with internal structures – specifically the glandular tissue and cancerous lesions – DICOM data from clinical MRI and CT scans were used. This

data was obtained from the Prof. Franciszek Łukaszczyk Oncology Center in Bydgoszcz. The internal anatomy was reconstructed using InVesalius software. Manual thresholding and mask-based segmentation enabled the isolation of internal features of interest (Figure 3) [13].

Digital modeling and mold design

Before starting the mold design process, all anatomical data sets had undergone multi-stage digital processing to correct geometric inaccuracies resulting from scanning and segmentation. In the case of the external geometry of the breast, special attention was paid to cleaning the scan and reconstructing the surface, as the raw 3D scan contained image noise, local distortions, and incomplete areas typical of manual surface scanning.

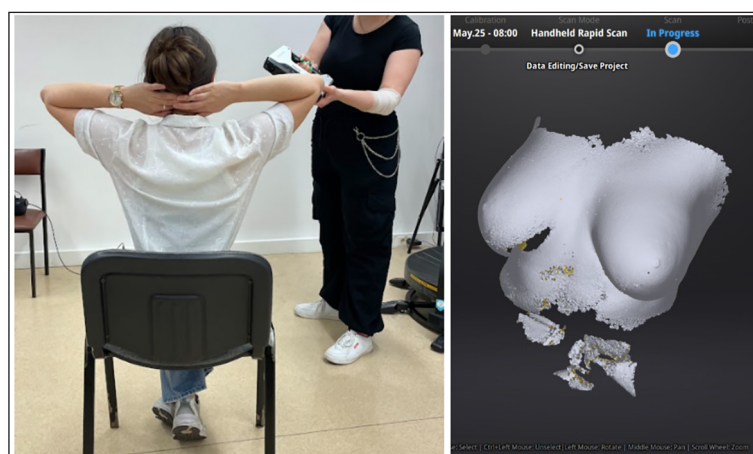


Figure 2. Illustrative photo showing the scanning process

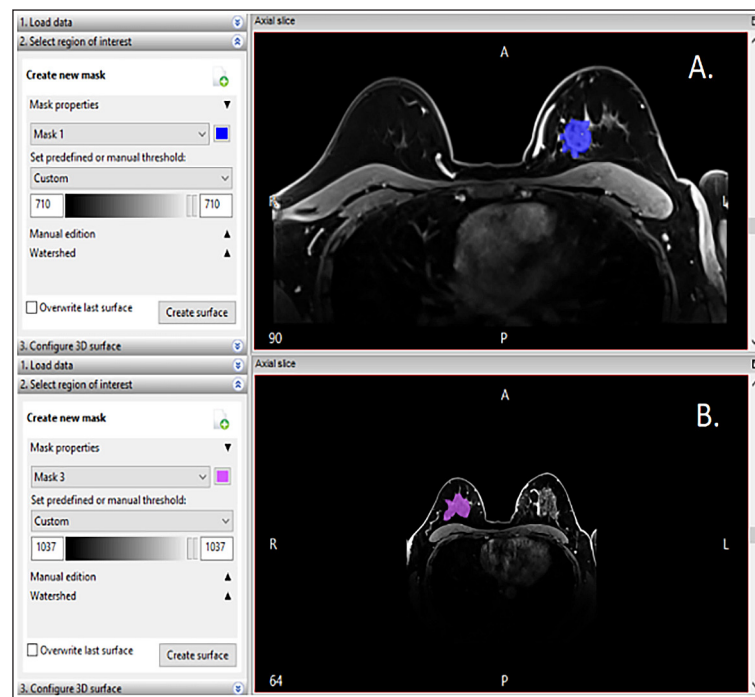


Figure 3. Masks applied in the segmentation process – neoplastic change (A), gland (B)

The pre-processing stage included the removal of scanning artifacts, the elimination of non-manifold elements, the correction of local mesh defects, and the reconstruction of missing surface fragments. For the external breast model part, the main goal was to achieve a completely waterproof geometry suitable for mold design and casting.

The models of glandular tissue and tumor, obtained through the segmentation of medical images, were also refined to eliminate unconnected mesh fragments and irregular triangulation artifacts resulting from manual segmentation. The tools available in GOM Inspect 2017 were used for mesh separation, reconstruction, hole close, and controlled surface smoothing. The smoothing process was applied locally and globally to reduce sharp transitions and irregularities while preserving the original anatomical shape and dimensional accuracy of the structures.

After refining the mesh, the models were verified in Bambu Studio slicer software to assess geometric integrity and additive manufacturing possibilities. This step allowed for early detection of potential problems related to mesh errors, wall thickness, or structural inconsistencies before proceeding with mold design.

The casting molds were designed separately for three elements: the external breast shell, the glandular tissue, and the tumor. STL mesh files were converted into solid models using

Autodesk Meshmixer and Autodesk Inventor 2024 with the Mesh Enabler plug-in. This allowed for precise wall thickness control at 5 mm and the integration of technical elements like vent channels and sprues.

A special mold configuration was developed to enable the production of realistic, full-volume internal structures. Two-piece molds were designed for the glandular tissue and tumor to facilitate the removal of complex geometries from the mold. In contrast, the breast shell mold consisted of a single outer shell designed to accommodate the internal components during the final stage of casting. The outer mold used to produce skin-like silicone layer was used as a base to create the breast shell mold by scaling it to 70% of its original size.

Additive manufacturing

The casting molds were fabricated via fused filament fabrication (FFF) additive manufacturing using Bambu Lab P1S printer with polylactic acid (PLA) filament (Figure 4). Slicing was performed in Bambu Studio with the following parameters: 15% cubic infill, a 0.2 mm layer height, and support structures enabled. Nozzle and bed temperatures were maintained at 210 °C and 60 °C, respectively [14]. The time required to print the casting molds was:

- Mold of the breast – 3 hours and 43 minutes,
- Gland – 3 hours and 36 minutes,
- Tumor – 14 minutes.

Post-processing included the manual removal of supports and thorough sanding of the inner mold surfaces to minimize stair-stepping effects. This step was essential to ensure that these textures would not transfer to the silicone cast.

Silicone casting procedure

The selection of silicone materials followed a targeted, multi-stage research and development methodology tailored to each functional component of the phantom. This iterative process was governed by distinct haptic and engineering to achieve an optimal balance between soft-tissue compliance and manufacturing process stability.

To determine the most realistic breast core consistency that mimics adipose tissue, a preliminary study phase was conducted, comprising eight separate iterations. In iterations 1–3, a pilot group consisting of 10 volunteers (aged 20–60) conducted blind tactile comparisons between the prototype of mixtures silicones with modifiers in varying proportions and the commercially available NAGOR breast implant, the Impleo Smooth (GCA, UK), which served as a reference for realistic tissue resistance. In this phase, standard, very soft silicones such as Ecoflex™ 00-10 and Ecoflex™ 00-20 (Smooth-On, USA) without modifiers were tested, but they were rejected due to excessive hardness or unnatural elasticity that did not correspond to the fat matrix model. Subsequent iterations (4–8) focused on optimizing processing characteristics such as viscosity, pot life, and demolding stability by introducing tactile softeners. Highly modified formulations, as well as gel-like systems such as Eco-Gel Silicone (Smooth-On, USA), were evaluated but discarded

because they resulted in excessive leakage of material (modifier syneresis), a complete loss of structural cohesion, or fluid-like behavior during casting. Ultimately, the hybrid matrix of Dragon Skin™ 10 M mixed with the Slacker™ tactile modifier (Smooth-On, USA) in a strict 1:0.71:1 ratio (Part B : Slacker : Part A) was selected for its superior manufacturing reliability and precise replication of healthy tissue density.

Developing the internal glandular structures required six iterations of prototyping to ensure adequate anatomical accuracy. The evaluation, conducted by the same group of volunteers, focused primarily on achieving a distinct tactile contrast between the surrounding adipose tissue and the glands. Unmodified preparations with higher hardness, such as pure Dragon Skin™ 10 (1:0:1), were rejected due to excessive stiffness, which masked smaller internal nodules during palpation. In contrast, preparations based on Sorta-Clear™ 12 mixed with Slacker in high proportions (1:0.75:1) were rejected because the material became structurally unstable. Optimal haptic and mechanical response was achieved by using Dragon Skin™ 10 mixed with Slacker™ in a customized ratio of 1:0.5:1, which provided the characteristic elasticity of fibro-glandular tissue necessary for effective palpation training.

For the simulated pathological lesions, four iterations were performed to guarantee clinical validity. Various silicone configurations were presented for evaluation to the Head of the Breast Cancer and Reconstructive Surgery Department at the Oncology Center in Bydgoszcz. Based on large clinical experience in palpating malignant breast tumors, the primary requirement was a high mechanical contrast coupled with rigid, well-defined geometric boundaries [15]. Softer polymer compositions, including Ecoflex™ 00-30 and Sorta-Clear™ 12, failed to provide sufficient

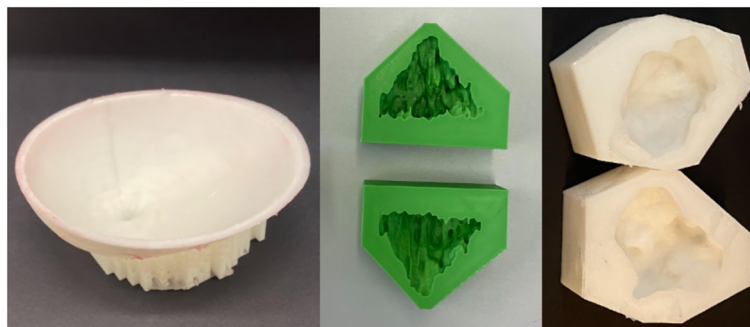


Figure 4. Mold of the breast (left), gland (center), and tumor (right)

tactile distinctness against the surrounding matrix and were immediately rejected by the clinical expert. Consequently, Sorta-Clear™ 37 (Smooth-On, USA) was selected as the ideal representation of solid, rigid neoplastic nodules.

The outer skin layer was optimized through three iterations. While initial prototypes utilized complex, multi-layer silicone configurations combining Ecoflex™ 00-20 and Eco-Gel reinforced with gauze, tactile feedback from the volunteer group indicated that a simplified single-layer skin design was sufficient. Because the underlying breast core already exhibited identical mechanical compliance, the secondary base layer was redundant. Eliminating this multi-material setup significantly streamlined the manufacturing workflow without compromising the external haptic realism of the final phantom.

After testing each iteration, it was decided to use the following silicones for the individual components:

- Pathological lesion: Sorta Clear™ 37 (Shore A 37) was used because of hardness, providing the necessary mechanical contrast against the softer surrounding tissues (Figure 5).
- Glandular tissue: Dragon Skin™ Medium 10 was modified with Slacker™ in a 1:0,71:1 ratio to achieve consistency representative of the mammary gland (Shore Hardness 000-40) (Figure 6).
- Adipose tissue (core): Ecoflex™ GEL (Smooth-On, USA) (Shore Hardness 000-35) was used to mimic the soft breast fat, filling the remaining volume of the phantom.
- Skin layer: Dragon Skin™ Medium 10 was modified with Slacker™ in a 1:0,66:1 ratio and tinted with a sun-colored pigment. By using different proportions of Slacker™ than for glandular tissue, Shore Hardness of skin layer was 000-35.
- Nipple: Dragon Skin™ Very Fast 10 (Smooth-On, USA) (Shore Hardness A-10) was used with a red pigment to differentiate the anatomical detail of the areola complex.

The phantom was produced using a two-stage casting process. First the glandular tissue and the pathological lesions were cast in proper two-part molds. Once these structures were ready, they were positioned in the single-part breast shell mold. Specifically, the pathological lesions were placed in the upper outer quadrant of the breast, reflecting epidemiological data on the most

frequent localization of cancerous lesions [16]. Then it was filled with silicone representing the adipose tissue. To eliminate air bubbles, all silicone mixtures were degassed in a vacuum chamber prior to pouring. A curing period of 24 hours at room temperature was applied for all silicone elements at each stage of the process.

Validation and user testing

The validation of the developed phantom was conducted in two stages: an initial core material assessment and a final functional evaluation involving experts and end-users.

Stage 1: Core material validation

In the first phase, a core model made of Ecoflex™ 00-10 (Smooth-On, USA) was evaluated by a group of 10 female volunteers (aged 20–60 years). This age range was chosen to ensure that the material could be evaluated in relation to different natural tissue densities. Participants compared the prototype and a commercially available breast prosthesis NAGOR Impleo Smooth (GC Aesthetics, Ireland) relative to their own breasts. The evaluation focused on hardness, compressibility, and tactile resistance.

Stage 2: Expert evaluation and functional testing

The final version of the phantom was validated by educators from a non-governmental organization (IFMSA-Poland) specializing in breast self-examination training. These specialists rated the phantom's educational utility and its ability to represent realistic anatomy including glandular tissue.

The respondents were asked to perform a self-examination procedure on a phantom, i.e., a visual examination. This is followed by a palpation examination, which involves carefully examining each breast with the fingertips of the three middle fingers using one of three techniques. The first technique involves concentric movements that begin by tracing a large circle along the circumference of the breast. The fingers then move spirally toward the nipple, making small, circular motions. The second technique involves radial movements, in which the breast is mentally divided into a clock face, and the examination is performed by moving the fingers from the nipple to the outer edges of the breast, tracing small circles as they go. The final technique involves

up-and-down movements, where the breast is divided into vertical strips along which the fingers move alternately up and down, simultaneously tracing small circles.

After the physical examination, participants completed a structured questionnaire. The assessment was based on a 5-point Likert scale: 1 – very poor, 2 – poor, 3 – neutral, 4 – good, 5 – very good. The specific questions asked of the evaluators are summarized in Table 1.

Subsequently a functional palpation assessment was conducted with a group of 20 female participants. Their task was to locate the tumors within the model. This procedure was designed to verify if the mechanical contrast between the glandular tissue and the pathological lesions was sufficient for correct identification. The successful localization of the lesions by the participants confirmed the phantom's effectiveness as a tool for breast self-examination education.

RESULTS

Production results

Final materials

The fabrication process resulted in a multi-material anatomical breast phantom. The primary mold, 3D printed from PLA using a Bambu Lab P1S, provided a shell that allowed for high-fidelity silicone casting. The final model contains four silicone components.

- Adipose tissue (core) made of 170 g Ecoflex™ GEL
- Glandular tissue made of 28 g Dragon Skin™ 10 MEDIUM and 10 g Slacker™
- Pathological lesion made of 5 g SORTA-Clear™ 37

- Skin layer made of 76 g Dragon Skin™ 10 MEDIUM and 25 g Slacker™
- Nipple made of 10 g Dragon Skin™ Very Fast and 1.3 g Slacker™

Model parts

The individual properties of these components, alongside their visual representation after the casting and curing process, are described in detail below to illustrate the achieved anatomical fidelity.

For simulating tumors, Sorta Clear™ 37 was selected because of its high mechanical contrast and rigidity, which accurately mimics the tactile properties of a solid tumor. The material's hardness was validated by clinical experts to ensure it provides a distinct „lump” sensation when palpated through softer surrounding layers (Figure 5).

The glandular tissue was fabricated using Dragon Skin™ Medium 10 modified with Slacker™ in a 1:0.71:1 ratio, resulting in a Shore Hardness of 000-40. This specific formulation replicates the elastic modulus of fibroglandular structures, providing the „intermediate” resistance necessary for advanced palpation training (Figure 6).

The phantom's core, representing adipose tissue, was cast using Ecoflex™ GEL (Shore Hardness 000-35) to replicate the soft, compliant consistency of breast fat. This ultra-soft material fills the remaining volume of the phantom, allowing the internal structures to move and respond realistically under pressure.

The external layer combines a pigmented skin membrane - Dragon Skin™ Medium 10 with Slacker™ (1:0.66:1 ratio, Shore 000-35) and a distinct nipple-areola complex made of Dragon Skin™ Very Fast 10 without hardness reducing modifier (Shore A 10). This multi-material approach ensures realistic surface friction during

Table 1. Table containing questions, rating scales, and assessment results

Question	Rating scale	Score
1. Visual realism of the phantom (color, surface texture, and overall appearance).	1 - very unrealistic; 2 - unrealistic; 3 - hard to say; 4 - realistic; 5 - very realistic	4.2
2. Tactile realism of the base material representing adipose and healthy breast tissue.	1 - very unrealistic; 2 - unrealistic; 3- hard to say; 4 - realistic; 5 - very realistic	4.5
3. Tactile contrast and distinctness between healthy tissue and internal glandular structures.	1 - very unrealistic; 2 - unrealistic; 3- hard to say; 4 - realistic; 5 - very realistic	4.6
4. Realism of the shape, hardness, and mobility of the embedded tumor lesions.	1 - very unrealistic; 2 - unrealistic; 3 - hard to say; 4 - realistic; 5 - very realistic	4.7
5. Ease of detecting lesions during the correct medical self-examination procedure.	1 - very unrealistic; 2 - unrealistic; 3 - hard to say; 4 - realistic; 5 - very realistic	4.8
6. Overall educational utility of the model for self-diagnosis training.	1 - very poor; 2 - poor; 3 - hard to say; 4 - good; 5 - very good	4.9



Figure 5. Cast tumor

examination and provides the necessary visual and tactile markers for the nipple-areola complex.

Visual assessment

The iterative design process highlighted that maintaining correct technological and mechanical parameters is insufficient if the visual presentation fails to evoke a realistic clinical experience. Initial prototype testing revealed that the early model did not meet the necessary aesthetic and visual requirements primarily due to overly bright and non-realistic. Expert feedback underscored that these visual deficiencies significantly hindered the perceived fidelity of the simulator. This finding emphasizes that the visual attributes of a medical phantom are critical factors directly influencing user reception and the overall psychological

engagement, independent of structural accuracy. The final high-fidelity model was refined to transition from a simplified, perfectly symmetrical geometry with uniform pigmentation to a natural, asymmetrical form captured via 3D scanning, complete with a detailed nipple-areola complex and realistic skin pigmentation. Visual assessments confirmed that adopting a highly authentic, 'human-like' representation significantly lowers the psychological barrier for users, thereby increasing training reliability and engagement. Furthermore, the updated design allows for precise adjustments of skin tones. This capacity for multi-ethnic representation enhances the inclusivity of the training tools, which serves as a fundamental factor in improving social perception and the effectiveness of public health education programs across diverse communities.

Costs and accessibility

The economic evaluation focused on the materials required to produce the anatomical phantom. The total cost of the silicones used for a single model was €20.07. This unit cost was determined based on the pricing of „Trial Size Units” (0.91 kg packages) as of January 2026. Specifically, it comprises €10.72 for Ecoflex™ GEL (170 g used), €6.43 for Dragon Skin™ 10 MEDIUM (104 g), €0.60 for Dragon Skin™ FX/Very Fast (10 g), €2.50 for Slacker™ tactile mutator (36.3 g), and €0.38 for SORTA-Clear™ 37 (5 g). The price should include the production of casting molds, the cost of which must be considered in terms of mass production. Only negligible mold degradation was noted. The mold is estimated

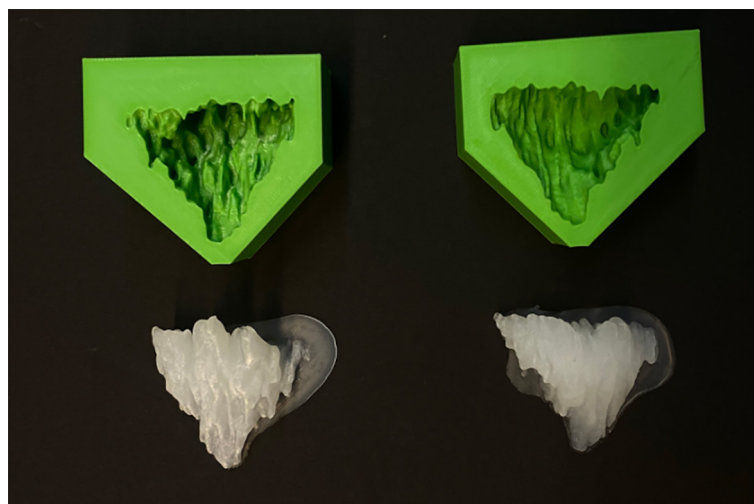


Figure 6. Cast gland

to withstand approximately 50–100 consecutive casting cycles without structural damage [17]. It is precisely this characteristic of casting molds that makes it difficult to estimate the costs they will generate. The production of one set of casting molds costs €7.10. This figure accounts for all internal and external components, including the adipose tissue, glandular structures, pathological lesions and skin layer.

Compared to a commercially available breast model for self examination training priced at €241,12, which represents only an adipose-like structure and pathological lesions, the developed solution offers a significant financial advantage. The material expenditure for the proposed phantom is approximately 12 times lower than the retail price of commercial phantom currently available on the market. It should be noted that the cost calculation for the prototype focuses only on material consumption and does not account for labor wages or other operational overheads that are included in the pricing of commercial products. Nevertheless, the economic advantage remains significantly high, as the proposed method allows for the production of a more anatomically advanced trainer at a much lower price.

Anatomical fidelity and educational advantage

The inclusion of glandular tissue allows for a more realistic simulation of the breast's internal architecture (Figure 7). This is particularly crucial for younger women, who typically have higher breast density [18]. Commercial models,

which often represent only adipose tissue with pathological lesions, may lead to a lack of awareness or a misconception regarding how a tumor presents when surrounded by dense structures. The phantom creates a more challenging and authentic tactile environment. It teaches users to distinguish between normal physiological irregularities and suspicious lesions. While the phantom serves as a tool for breast self-examination education, it is designed to build awareness and does not replace professional diagnostic procedures such as breast ultrasound or mammography.

The model, as evaluated by experts, received mixed scores across various features. Visual appearance (Q1) received an average score of 4.2/5, while the tactile realism of the healthy tissue simulation (Q2) was highly rated at 4.5/5. Participants noted that direct pressure without the use of procedures provided a good initial sense of tissue compliance. The use of breast self-examination techniques significantly improved their ability to accurately map the boundaries of internal structures.

The tactile contrast between healthy tissue and simulated pathologies (Q3) received a rating of 4.6/5, and the realism of the embedded tumors (Q4) achieved an average rating of 4.7/5. Importantly, when using the correct self-examination protocol, the ease of detecting lesions (Q5) was rated 4.8/5, and 100% of participants successfully located all hidden nodules. The overall educational value of the low-cost model (Q6) received an exceptional rating of 4.9/5, confirming the validity of the proposed rapid manufacturing methodology.

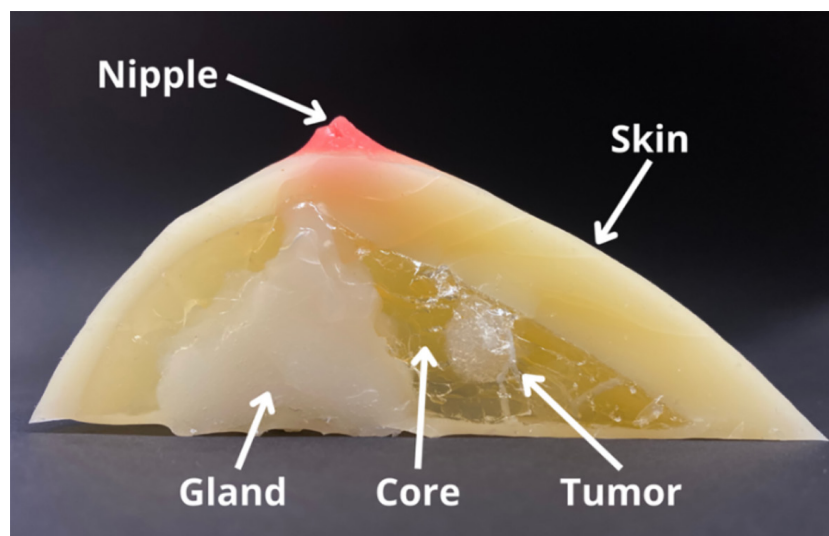


Figure 7. Cross-section of a breast phantom with visible structures

Empirical validation and feedback

During the final user testing, all of the 20 participants in the age group 20–30 years old successfully located the pathological lesions through palpation. This confirmed that the mechanical contrast between the layers was effectively chosen for detection. Educators from the NGO highlighted that the presence of the glandular tissue makes the simulation more realistic and better prepares users for the actual feeling of a clinical breast examination. Participants noted that finding the tumors required more focus because of the presence of the glandular tissue. However, this was a positive feature, as it forced a more careful examination technique.

Limitations

Despite the promising results, this study has several limitations that should be acknowledged:

- **Morphological variety of lesions:** The phantom utilized a single pathological lesion shape. While the geometry was selected to represent a specific type of breast cancer, it does not represent the diversity of clinical presentations found in real patients.
- **Tissue property calibration:** Establishing precise target mechanical parameters for silicone elastomers remains challenging. This is due to the difficulties in performing *in vivo* testing on human breast tissue and the fact that post-mortem tissues undergo significant changes in elasticity and firmness, making them less reliable.
- **Sample size:** The functional validation was conducted on a relatively small group of 15 to 20 people. Future studies should involve a larger and more diverse population to provide more statistically robust data on the phantom's educational effectiveness.
- **External layer:** While the current skin layer was improved during the process, future work should focus on developing a more advanced material to better simulate the complex properties and texture of the human skin.

CONCLUSIONS

The integration of FFF additive manufacturing and silicone casting proved to be a effective approach in order to recreate the complex internal structure of human breast tissue. Throughout the iterative prototyping and material calibration

phases, a primary focus was placed on ensuring that the final workflow would be a stable, predictable, and repeatable manufacturing process. This systematic approach to prototyping made it possible to fine-tune the material blends so that the final phantom delivers a realistic tactile response, directly meeting the practical demands of medical educators while remaining fully feasible for production using accessible workshop techniques.

By strategically combining various silicone formulations, the resulting model successfully achieves the distinct mechanical contrast necessary to differentiate between normal physiological anatomy and pathological lesions during manual palpation. Introducing a distinct layer for glandular tissue represents a major step forward in anatomical realism, addressing a frequent shortcoming of uniform commercial simulators which often fail to prepare trainees, especially younger women with higher breast density, for the actual feel of dense tissue structures.

Furthermore, the economic and practical evaluation confirms that this hybrid methodology offers a scalable and accessible alternative to high-cost educational tools. While the custom-made molds show negligible wear and are capable of withstanding dozens of casting cycles, the direct material cost for a single advanced phantom remains roughly twelve times lower than the retail price of less realistic commercial options. Ultimately, the fact that all participants in the user testing successfully identified the hidden tumors confirms that the model functions effectively as a reliable, high-fidelity tactile trainer. From a manufacturing process perspective, centering the core component in the mold designed for the skin layer proved problematic. This resulted in an uneven and uncontrolled distribution of the outer layer, thereby affecting the model's proper functioning. Future research should address the design of a mold for a thin-walled model that ensures the intended uneven distribution of material in the outer shell. Developing such a mold will improve the quality of the model by increasing the realism of the phantom. Despite the need for improvements in mold design, as well as possibility to refine the skin texture and expand the variety of tumor geometries, this project establishes a robust and repeatable framework for the low-cost manufacturing of soft-tissue medical simulators, opening practical pathways for widespread public health campaigns and breast cancer awareness programs.

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