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Development and evaluation of 3D-printed tumor palpation models for surgical training and patient education

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Abstract

Breast cancer screening is implemented as part of governmental healthcare policy in many countries. While breast imaging tests contribute to reducing mortality, some breast cancers may emerge between these screenings. Consequently, it is crucial for women to be vigilant about any changes in their breasts to facilitate the early detection of breast cancer. Recently, the application of 3-dimensional printing technology in the medical field has expanded, including uses in medical imaging and surgical training. In this study, we developed 3D-printed palpation models for breast tumor detection and surveyed seven surgeons specializing in breast care to evaluate the usability of the models. As a result of the survey, we created a model that obtained a maximum mean rating of 7.1 (maximum rating 10, minimum rating 3) on the item 'How accurately does the model simulate the feel of a real tumor?' on a scale from 1 to 10. Although there is some variation in the average value, through this study, we found that it is possible to create a model that is quite close to the actual tumor depending on the materials and shape of the models. Our findings demonstrated the potential use of personalized models both in medical trainee and patient education.

Keywords Breast cancer, 3D printing technology, Palpations models, Tumor detection, Medical education

Background

Breast cancer is the most common cancer among females worldwide, exerting a considerable medical, social, and economic impacts [1, 2]. Previous studies have demonstrated that screening mammography significantly

contributes to reducing breast cancer mortality [3], leading to its adoption as a governmental healthcare policy in Japan. The current breast cancer screening policy in Japan recommends mammography every two years for women aged 40 and above. However, despite these measures, some breast cancers are detected between scheduled screening examinations, known as interval breast cancers [4], highlighting the limitations of current screening programs. For this reason, it is vital for individuals to regularly monitor changes in their breasts, fostering breast awareness, to aid in the early detection of breast cancer. This approach complements screening programs by addressing gaps in detection and emphasizing the importance of personal vigilance in breast health maintenance [5].

Educating the public on breast health is essential for raising breast awareness, with silicone breast palpation simulators and models frequently employed towards

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this end [6]. Furthermore, numerous studies have underscored the effectiveness of breast palpation models in medical student education [7, 8]. Recent studies have demonstrated the efficacy of 3D-printed models for medical training purposes across various specialties. For instance, Kiesel et al. (2022) developed a 3D-printed model of the female pelvis for hands-on training of gynecological examination, which showed significant improvement in students' satisfaction and knowledge gain [9]. Similarly, Bertolini et al. (2024) reported on the effectiveness of a 3D-printed simulator for transcatheter edge-to-edge repair of the tricuspid valve, highlighting its potential in enhancing medical training for complex procedures [10]. However, the high cost of these models precludes their widespread distribution to patients. Additionally, the uniformity of existing models fails to accurately reflect the diverse characteristics and masses found in different individuals' breasts.

Recent advancements in 3-dimensional printing technology have broadened its application within the medical field, encompassing areas such as medical imaging and surgical training. For example, Sheha (2019) et al. [11] detailed their use of a 3D printer to fabricate models from CT images of a patient's spine before sarcoma surgery, aiding in understanding the lesion's anatomy and facilitating preoperative planning. Hanisch (2020) et al. [12] used models created by a 3D printer based on actual patient data, for surgical training of dental students, and found them to be as just as good as conventional

typodont models. The study also pointed out that the use of a 3D printer provides more realistic surgical training.

Building on these findings, we developed 3D-printed palpation models of breast tumors and surveyed surgeons specializing in breast care to assess the models' utility. This study presents the survey findings, discusses the recommended modeling methods based on surgeons' feedback, and explores the models' potential benefits for medical and patient education.

Methods

Development of breast tumor palpation models using 3-dimensional printing technology

Initially, 3D geometry data, with a 15 mm diameter sphere, embedded at the bottom of a 20 mm cube, was generated using 3D-CAD software, ZW3D2023 (ZWSOFT CO., LTD.) (Fig. 1). The inside of the sphere was filled with support material AR-S1 (KEYENCE CORPORATION). We used the AGILISTA-3200 (KEYENCE CORPORATION) for 3D printing, which employs Material Jetting technology. This printer offers high-resolution capabilities (minimum layer thickness of 15 μm) and the ability to print with multiple materials simultaneously, allowing us to create models with varying properties in a single print job. On the other hand, the cube was printed using AR-G1L (KEYENCE CORPORATION) and its wall thicknesses were varied to be 0.5 mm, 1.0 mm, and 1.5 mm, resulting in three distinct models designated as Models A, B, and C,

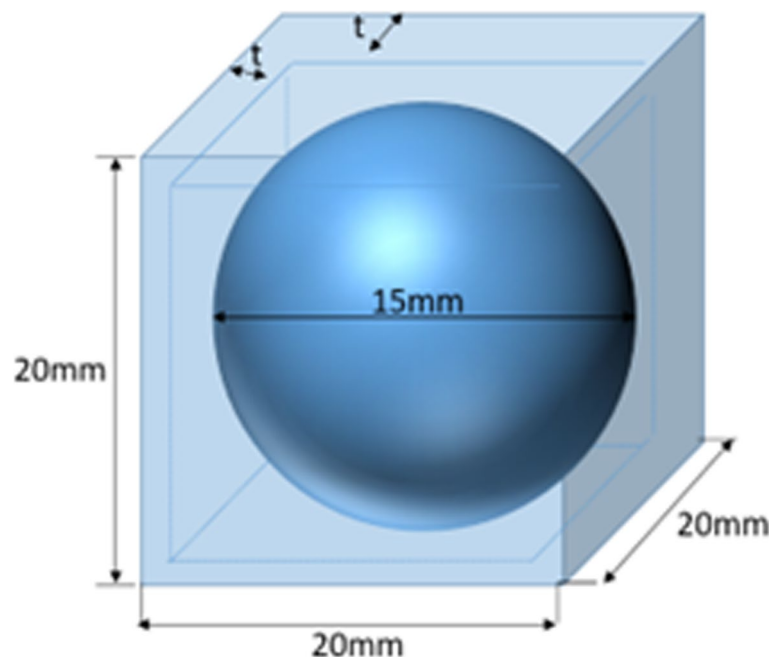


Fig. 1 An overall view of the 3D data and the variability in “t.”

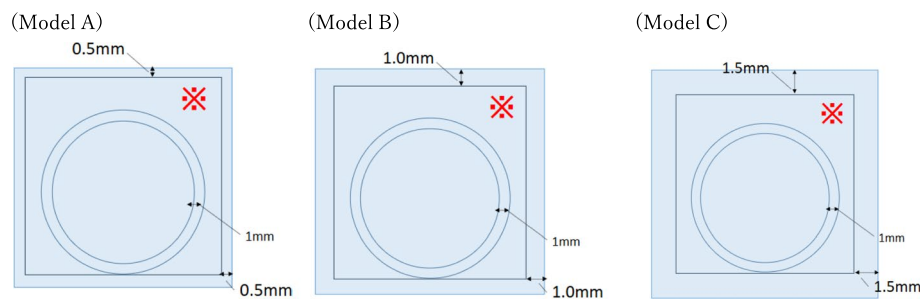


Fig. 2 The cube's central cross-section and the support material filling ("X")

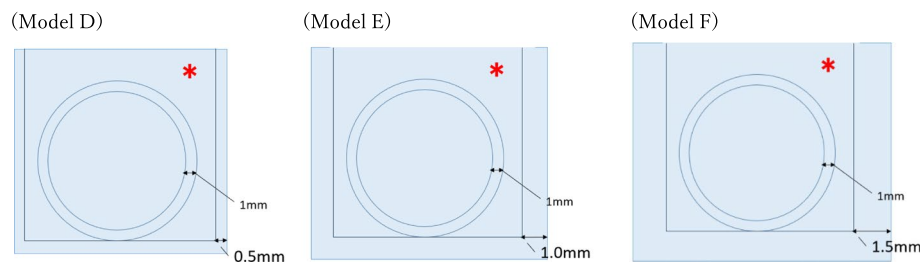


Fig. 3 The cube's central cross-section and the urethane gel filling ("*")

respectively. The interiors defined by these walls were filled either with support material (Fig. 2). In addition, the 3D geometry data of a similar cube with one face removed was generated using the same methodology, and models were created with the thickness of the cube walls varied to 0.5 mm, 1.0 mm, and 1.5 mm, with the interior filled with urethane gel, designated as Models D, E, and F (Fig. 3). As a result, we generated a total of six models based on the combinations of three wall thicknesses and two types of fillers (Fig. 4). The urethane gel used was "Human skin gel (Hardness 0)" (EXSEAL CO, LTD.).

Questionnaire survey

To evaluate the models, a questionnaire comprising the following four items was developed.

- Q1. How accurately does the model simulate the feel of a real tumor? (1 = not at all, 10 = about the same as the real one)
- Q2. How would you rate the tumor's firmness? (1 = too soft, 5 = just right, 10 = too hard)
- Q3. How would you rate the firmness of the tissue surrounding the tumor? (1 = too soft, 5 = just right, 10 = too hard)
- Q4. An additional section was provided for comments.



Fig. 4 A completed model example (Fig. 2A, 0.5 mm thickness and support material filling)

Participants were required to rate questions Q1 to Q3 on a scale from 1 to 10. If the model's wall thickness prevented their fingers from reaching the tumor, making evaluation difficult, they were instructed to mark their

response as “N/A.” Question 4 allowed for free comments. Palpation was conducted either with the index finger alone or by applying pressure with both the thumb and index finger. The responses to the questionnaire were analyzed using a Mann-Whitney U test, with specific comparisons made between different support materials and wall thicknesses to evaluate how accurately the models simulate real tumor characteristics. All statistical analyses were performed using R version 4.1.2. *P*-values less than 0.05 were considered to indicate statistical significance.

Results

Seven surgeons, all specializing in breast care, were invited to palpate each model, followed by participation in a questionnaire survey. The cohort of surgeons comprised two with over 30 years of clinical experience, one with over 20 years, three with more than 10 years, and one with less than 10 years of experience. The questionnaire data were collected and analyzed, yielding the following findings. Regarding Q4, which was intended for free-text responses, we did not receive any comments from the participants.

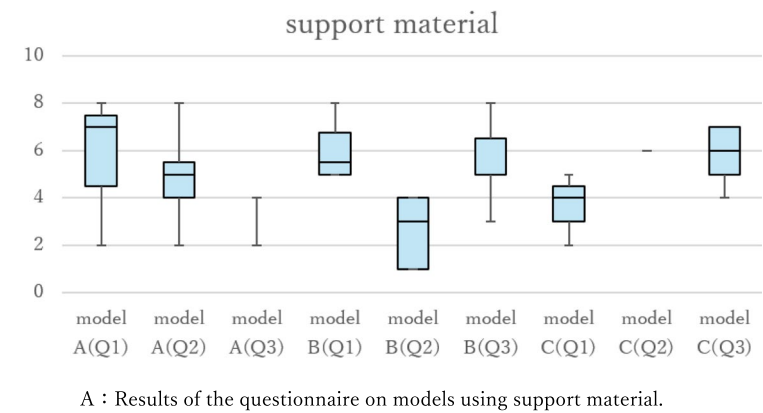
Analysis of support material models

In Q1, palpation models garnered mean scores of 5.9, 6.0, and 3.7 for Models A, B, and C respectively, with median

scores of 7.0, 5.5, and 4.0. The highest scores were 8 for Models A and B, and 5 for Model C, while the lowest scores were 2 for Models A and C, and 5 for Model B. Model B received one N/A response for Q1 and two for Q2, and Model C had six N/A responses for Q2 and two for Q3, with Model A having no N/A responses. The Mann-Whitney U test, detailed in Fig. 5B, evaluated the questionnaire responses for each model, indicating no statistical significance between Models A and B (Q1 *p*=0.8988), a possible trend towards significance between Models A and C (Q1 *p*=0.0540), and a statistically significant difference between Models B and C (Q1 *p*=0.0052). For Q3, statistically significant differences were found between Models A and B (*p*=0.0048) and A and C (*p*=0.0108), but not between Models B and C (*p*=0.6578). Due to the N/A responses, Q2 was not applicable for statistical comparison between Models A and B or B and C.

Analysis of urethane gel models

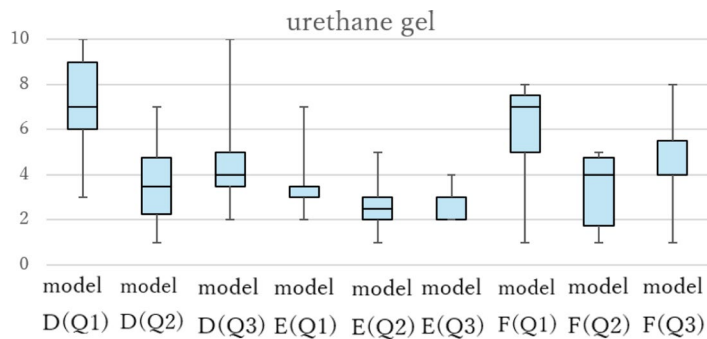
Following the assessment of support material models, the analysis of urethane gel models was conducted as depicted in Fig. 6A. In Q1, models D, E, and F achieved average values of 7.1, 3.6, and 5.9 respectively, with median values corresponding to 7.0, 3.0, and 7.0. The maximum ratings given were 10 for Model D, 7 for Model E, and 3 for Model F, with the minimum ratings being 3,



support material			
	A vs B	A vs C	B vs C
Q1	0.8988	0.054	0.0052
Q2	0.0568	N/A	N/A
Q3	0.0048	0.0108	0.6578

B : Comparison by Mann-Whitney U tests of each questionnaire item on models using support material

Fig. 5 **A** Results of the questionnaire on models using support material. **B** Comparison by Mann-Whitney U tests of each questionnaire item on models using support material



A : Results of questionnaire on models using urethan gel.

urethane gel			
	D vs E	D vs F	E vs F
Q1	0.0077	0.3572	0.068
Q2	0.3605	0.7089	0.3632
Q3	0.088	0.912	0.052

B : Comparison by Mann-Whitney U tests of each questionnaire item on models using urethan

Fig. 6 **A** Results of questionnaire on models using urethan gel. **B** Comparison by Mann-Whitney U tests of each questionnaire item on models using urethan gel

2, and 1 for each respective model. Each model had one instance where Q2 was marked as N/A by a participant. Mann-Whitney U tests were performed to compare responses for each model, with the results displayed in Fig. 6B. The analysis revealed a statistical significant difference between Models D and E for Q1 ($p=0.0077$), but no statistical significant difference was observed between Models D and F ($p=0.3572$) or E and F ($p=0.0680$) for the same question. For Q3, the results indicated a marginal trend towards significance between Models E and F ($p=0.0520$), while the other comparisons showed no statistically significant differences. As with the support material models, Q2 comparisons were not applicable due to N/A responses. These results complement the earlier findings from the support material model analysis, providing further insights into the palpation models' effectiveness using urethane gel.

Discussion

The evaluation of palpation models by seven experienced breast care surgeons revealed discernible differences in the perception of model fidelity based on material and design in this study. The analysis showed that models constructed with urethane gel generally received higher mean and median scores compared to those using support material, with Model D attaining

the highest mean score of 7.1. Notably, the wall thickness appeared to be a critical factor in the realism of the models; thinner walls tended to be associated with higher ratings of similarity to actual tumors. However, there was a trade-off between thinness and durability, underscoring the need for careful optimization of wall thickness. These findings are crucial as we consider the practical application and potential benefits of these models in medical training and patient education.

1. Optimal modeling method

Whether the model was filled with support material or urethane gel, models with thinner walls received higher ratings. However, excessively thin walls may compromise the model's integrity during palpation, posing a risk of breakage. Therefore, it is essential to calibrate wall thickness to balance durability with a realistic palpation experience. When comparing fillers (as shown in Fig. 7), models with urethane gel generally achieved higher maximum and average scores than those with support material, indicating the superior tactile quality of urethane gel. Notably, one respondent rated the Model D as '10', equating it nearly to the real-life palpation experience, suggesting the successful replication of a practical model.

Support material	Model A	5.9
	Model B	6
	Model C	3.7
Urethane gel	Model D	7.1
	Model E	3.6
	Model F	5.9

Fig. 7 Average scores of Q1 by filler material

Nevertheless, this study's limitation lies in the model's cubic shape and 20mm size, which does not emulate the actual breast and cannot be effectively evaluated using palm palpation. Additionally, as all participants were experts in breast care, further analysis by medical students and doctors who are not specialized in breast cancer will be needed.

2. Usefulness of 3D printed palpation models in medical education and patient education

The developed model has potential as an effective training tool for medical students and residents learning breast palpation. Evidence from Pilgrim et al. [7] suggests that hands-on practice with a silicone breast model, coupled with immediate feedback on a female volunteer, is more beneficial than theoretical lectures alone. Similarly, Schubart et al. [8] have found breast palpation simulators to be particularly valuable for medical students with limited clinical experience. Although the advantages of palpation models in medical education are well-established, such models are generally costly and standardized. Our model promises to be cost-effective for educational purposes, with the added advantage of customizable shapes and sizes via computer adjustments, enabling the creation of diverse breast tumor models.

Further, distributing 3D-printed models like those in this study to the general public could potentially advance breast cancer detection. Research by Idrees et al. [13] has demonstrated the effectiveness of breast palpation models for teaching self-examination in India, thereby enhancing breast awareness. In clinical settings, masses that cannot be immediately classified as malignant are often monitored over time.

The capability of 3D printing technology to produce highly individualized models for each patient's mass could lead to more personalized consultation guidelines.

3. Future directions

This study lays the groundwork for several promising research avenues. First, we plan to develop a wider range of models with varying tumor sizes, depths, and textures to more comprehensively simulate the diversity of breast tumors encountered in clinical practice. Second, we aim to conduct a larger-scale evaluation involving not only experienced surgeons but also medical students and residents to assess the models' effectiveness in different stages of medical education. Additionally, we intend to explore the integration of these 3D-printed models with virtual reality (VR) technology, potentially creating a hybrid learning environment that combines tactile feedback with visual guidance. Finally, we will investigate the possibility of customizing models based on individual patient data, which could revolutionize preoperative planning and patient education in breast cancer care.

Conclusion

Our investigation into the production methods of 3D-printed tumor models has demonstrated a clear preference among surgeons for models crafted with urethane gel over those with support material, particularly when the models feature thinner walls. These results highlighted the implication of urethane gel in creating high-fidelity models. Development of new filling materials and optimization of shape will provide more effective models and contribute to medical education as well as the early detection of breast cancer.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s41205-024-00234-x>.

Supplementary Material 1.

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Authors' contributions

H.K. prepared the manuscript, created the 3D-printed palpation models, collected and analyzed the survey data. A.F. oversaw the entire study, designed the research, and interpreted the results. S.F. provided guidance on 3D printing technology and contributed to the study design. R.M., M.K., and H.N. reviewed the manuscript content. H.N. also supervised the entire study. All authors reviewed and approved the final manuscript.

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Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request. Summary statistics and aggregated data are included in this published article and its supplementary information files.

Data availability

Date availability: We share our data in a supplement file.

Declarations**Ethics approval and consent to participate**

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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