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DEVELOPMENT OF BREAST PHANTOM FOR CLINICAL SIMULATION AND EDUCATIONAL PURPOSES

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ABSTRACT

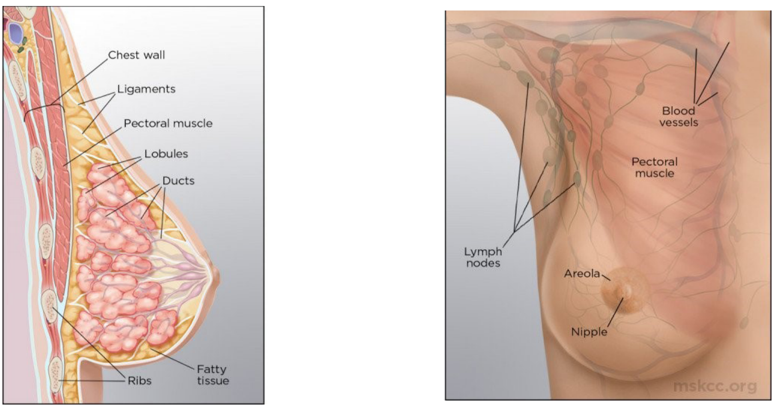
The development of a breast phantom for clinical and educational purposes is critical to providing a realistic and standardized model for training healthcare personnel in breast examination procedures, image interpretation, quality control, and procedure skills. Many current phantoms tend to fall short in providing realistic stiffness and acoustic attenuation. A gelatin-water mixture was used to make a tissue-like breast phantom. Gelatin was chosen for its biocompatibility, non-toxicity, and ability to replicate the mechanical and radiological properties of human soft tissue. Following the phantom's fabrication, Computed Tomography (CT) imaging was used to calculate its Hounsfield units (HU), a measure of tissue density in comparison to water. The resulting HU value was then utilized to determine the phantom's Relative Electron Density (RED), which is an important metric in determining if the phantom is suitable as a proxy for human tissue. The phantom's computed RED value of 1.012 ± 0.036 is within the tolerance range of the typical RED of human breast tissue (0.976), with a 3.6% margin of error. This error percentage is due to the difficulties in correctly reproducing the varied makeup of human breast tissue, which includes a complex blend of glandular, fatty, and connective components. Despite this, the breast phantom has potential as a replacement for real human breast tissue, making it useful in research, clinical practice, education, and quality assurance. This study contributes to Sustainable Development Goal 3: Good Health and Well-being by developing technology and strategies for early detection and treatment of breast cancer. By improving the accuracy of breast imaging technology, this work adds to the larger goal of guaranteeing healthy lives and fostering well-being of people.

Keywords: breast phantom, computed tomography, Hounsfield units, relative electron density, Tissue

INTRODUCTION

Breast cancer is a major global health concern, with millions of women diagnosed each year. Early detection through screening programs, particularly mammography, is crucial for increasing survival rates and lowering the illness burden (Wilkinson & Gathani, 2022). However, the effectiveness of these screening programs is strongly reliant on the quality and accuracy of the imaging technology employed. The use of breast phantoms for quality assurance, calibration, and training is critical in maintaining high breast cancer screening standards (Annemari, 2017).

The anatomy of the human breast is extraordinarily complex, with specialized glandular, adipose, and connective tissues working together to generate this glandular organ (Johnson & Cutler, 2016). These components include lobules, ducts, and fibrous tissues, as shown in Figure 1, all of which must be adequately represented in phantoms to ensure realistic simulations for training and quality control (Gul, 2018).



(a) (b)

Figure 1: (a) A hemi section of the human female breast (b) An anterior view of the human female breast (Jesinger, 2014)

Breast phantoms perform a crucial function in biomedical investigation, simulating optimized biological tissue to assess diagnostic imaging, therapeutic apparatus efficacy, and medical interventions in a controlled setting devoid of jeopardy to animal or human entities (McGarry *et al*., 2020). Breast phantom development has advanced significantly, with researchers focused on producing more realistic stiffness and acoustic attenuation (Bliznakova, 2020; Agbenorku *et al*., 2011) to function in the assessments of the imaging efficacy and dosage parameters of the scanners (Sarno *et al*., 2023). Tissue mimicking phantoms function as a surrogate for the human anatomy in instances where it is unfeasible or essential to subject the individual to radiation. They are formulated for X-ray diagnostics to cultivate, refine, and ensure quality assurance for both established and emergent imaging systems, such as full-field digital mammography, digital tomosynthesis, and computed tomography (CT) (Vasilev *et al*., 2023; Grosso *et al*., 2017). Phantoms designed to mimic the anatomical and radiological properties of breast tissue, such as the heterogeneous multimodal anthropomorphic breast phantom, show excellent agreement with natural breast tissue in terms of mass attenuation coefficients and electron density (Marashdeh & Abdulkarim, 2023; Saleh *et al*., 2023).

Gelatin composites exhibit dielectric characteristics remarkably similar to those of breast tissues' dielectric properties and are sufficiently stable to endure for a duration of up to eight (8) weeks (Hess, Liu & Pott, 2022; Islam *et al*., 2018). Gelatin-based breast phantoms have clinical applications that extend beyond training and calibration. These phantoms are particularly useful for refining imaging techniques like mammography since they allow researchers to investigate the impact of breast compression on image quality and patient comfort (Dahal *et al*., 2018). This is especially crucial for increasing mammography accuracy, reducing the need for repeat screenings, and minimizing patient discomfort throughout the procedure (Salem *et al*., 2023).

Breast phantoms need to mimic the acoustic and mechanical properties of real breast tissue for applications like ultrasound and CT imaging, and elastography. Existing phantoms often lack realistic stiffness and acoustic attenuation. Improved tissue-mimicking materials are required (Ng, Kuo, & Lin, 2021). The study aimed to create customizable and cost-effective three-dimensional tissue-mimicking breast phantoms to enhance early breast cancer detection and reduce mortality rates. This initiative supports Sustainable Development Goal 3: Good Health and Well-Being, with the ultimate objective of improving clinical outcomes and saving lives through advanced breast imaging technologies for women of all ages.

MATERIALS AND METHODS

The demography

Breast size is influenced by various factors, including genetics, weight, hormonal changes, and lifestyle, and can fluctuate over time. There is clinical variation in breast measurements among a large group of young West Africa adolescent female (Agbenorku *et al*., 2011). The study employed the average breast size measurements for young West African adolescent females established in a study conducted by Agbenorku *et al*., 2011. Distance from the midline in the xiphoid area to the left and right nipple were 10.94 cm and 10.84 cm respectively.

Fabrication of Breast Phantom

The breast phantom was developed by dissolving 40 g of gelatin powder in 650 ml of water at room temperature. The liquid was thoroughly mixed and heated until the gelatin dissolved entirely, resulting in a homogeneous solution. This solution was then placed into clear condoms that were sealed and fashioned to simulate the anatomical anatomy of the breast. Figures 2 (a) and (b) exhibit the gelatin and water mixture in a mixing dish, as well as the transfer of the cooled solution into a transparent condom.

(a) (b)

Figure 2: (a) A mixture of gelatin and water (b) Gelatin solution in a condom

Computed Tomography Imaging of the Breast Phantom

After fabrication, the breast phantom underwent imaging using a Siemens SOMATOM Definition Flash computed tomography (CT) machine, as shown in **Figure 3**. This dual-source CT scanner was selected for its capability to produce rapid, high-resolution cross-sectional images with minimal motion artifacts and reduced radiation doses. The CT system's high spatial resolution was essential for capturing fine anatomical details. The phantom was evaluated quantitatively in CT by comparing Hounsfield units (HUs) with actual breast tissue. The CT images were taken five times to confirm that the results were consistent and reliable. Scanning was carried out using the following exposure parameters: voltage (70 kVp), current (200 mA), and exposure period (50 ms). The collected pictures were exported to DICOM format, and the Hounsfield Unit (HU) values were determined. The average HU value of 12 was established across several sections of the phantom, giving a foundation for comparing its relative electron density to real breast tissue.

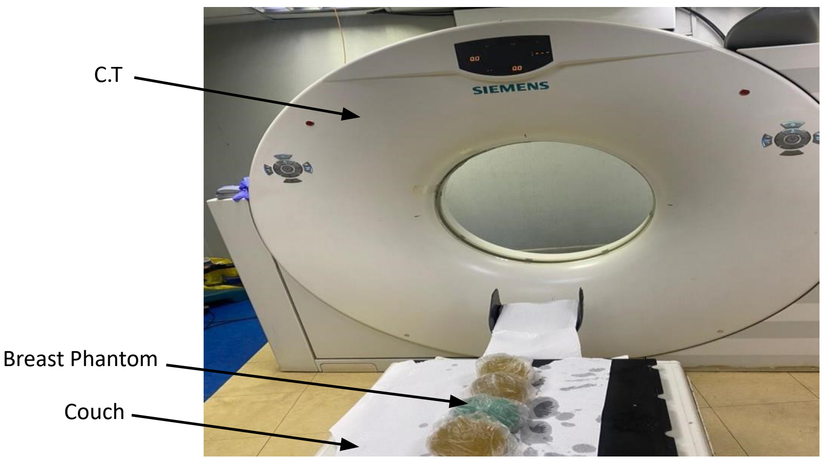


Figure 3: A setup for scanning the fabricated breast phantoms

Calculation of Relative Electron Density of the Phantom

The relative electron density (RED) of the breast phantom was computed using the HU values from the CT images. HU values were converted to RED using Equation 1.

$$RED = \frac{HU}{1000} + 1 \quad \text{(Thomas, 1999)} \qquad \text{Eqn 1}$$

This equation uses the linear relationship between HU values and relative electron density in CT imaging. The estimated RED values indicate the phantom's electron density relative to that of water, which is critical for determining its tissue-equivalent qualities for use in breast imaging research and training.

Statistical analysis

The accuracy of the fabricated breast phantom was assessed by comparing its measured Relative Electron Density (RED) to the standard RED of human breast tissue. To quantify the deviation between these values percentage error was used as a statistical analysis tool. This method was chosen for its effectiveness in providing a clear measure of accuracy. The percentage error formula is given as:

$$\text{RE} = \pm \frac{Measured\ value - Standard\ value}{Standard\ Value} \times 100\% \quad \text{(Park \& Stefanski, 1998)} \qquad \text{Eqn 2}$$

Where the standard relative electron density of human breast has a value of 0.976 (Buang *et al*., 2022)

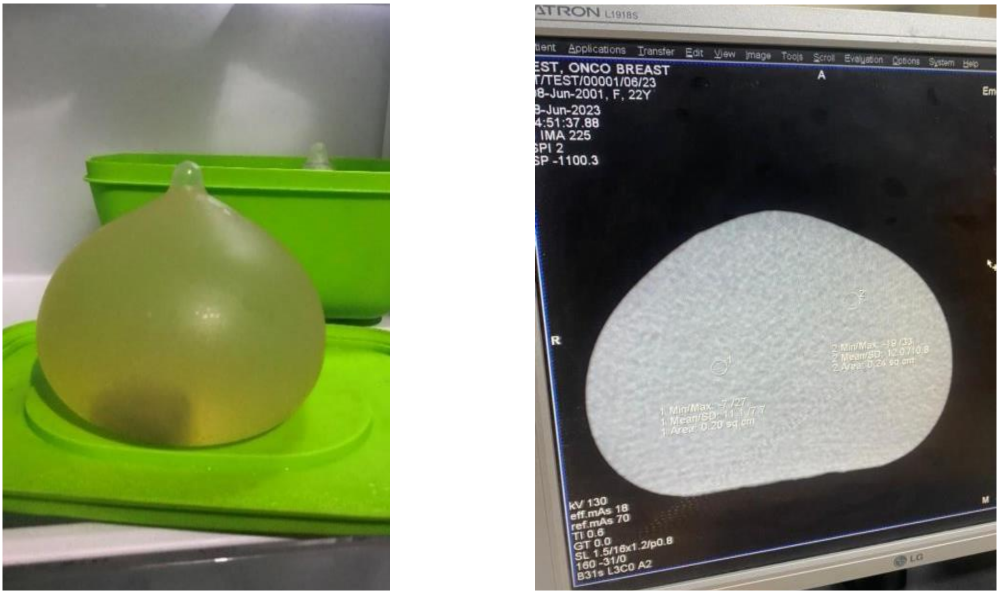
This statistical approach was applied to verify whether the fabricated breast phantom could accurately replicate the properties of human breast tissue in clinical imaging settings.

Volume of the designed breast phantom

The accurate volume calculation of the breast phantom is critical for providing realistic simulations in medical imaging and radiation therapy. The volume of the phantom was determined using the water displacement method. The initial water level in a measuring cylinder was recorded, followed by the final water level after immersing the phantom. The volume of the planned phantom was determined as Equation 3 for simulations validation.

Volume of Phantom= Final Water level - Initial Water level Eqn 3

RESULTS



(a) (b)

Figure 4: (a) A fabricated breast phantom and (b) A CT scan image of the fabricated phantom

A cost-effective breast phantom was successfully developed to mimic the tissue properties of human breast tissue when subjected to computed tomography imaging. Figure 4(a) illustrates the developed breast phantom, whereas Figure 4(b) illustrates the CT scan image corresponding to the phantom. The anatomical configuration of the phantom, as represented in Figure 4, closely resemble that of an actual human breast. The relative electron density (RED) of the developed breast phantom was determined using the HU value derived from the CT imaging. The HU value recorded for the developed phantom was 12. Consequently, the RED was computed to be 1.012 with a percentage error of 3.6%. The volumetric measurement of the breast phantom was measured at 650 ml, which is consistent with the typical volumetric range for human breasts ranging from 500–700 ml (Sindi *et al*.,2019; Campaigne *et al*., 1979). This volumetric precision significantly enhances the applicability of the phantom for both imaging and therapeutic purposes**.**

DISCUSSIONS

The existing investigation centers on the formulation of an economical breast phantom intended for the purposes of testing, assessment, and strategic planning in the realms of radiotherapy and minimally invasive medical interventions. The fabricated phantom demonstrates compatibility with CT imaging modalities. The CT imaging results reveal that the phantom closely emulates breast tissue predominantly characterized by fibroglandular composition. In the context of CT imaging, the breast phantom exhibited a wholly homogeneous profile, which is deemed adequate for localization assessments and neoplasm detection. The fabricated homogeneous breast phantom closely mimics normal breast tissue, with significant implications for clinical research and education. The comparison of the phantom's radiographic appearance to that of real breast tissue in CT demonstrates its effectiveness as a surrogate for clinical simulations. The phantom's realistic imaging characteristics underscore its potential as a valuable tool in medical imaging education, offering practitioners and students a platform to enhance their skills in interpreting imaging findings accurately. This can lead to improved resolution and quality of radiographic images, contributing to better diagnostic outcomes.

The study achieved a RED measurement of 1.012 for the generated breast phantom, accompanied by a 3.6% margin of error in comparison to the electron density of actual breast tissue as reported by Buang *et al*., (2022). This finding is comparable to other significant research endeavours within the domain. For instance, Cannatà *et al*., (2021) developed a gelatin-based breast phantom while taking into account its dielectric and mechanical characteristics. Beyond the primary emphasis of this study, which was centered on the relative electron density of the employed material, the dielectric and mechanical attributes of the material render it an exceptionally effective breast surrogate (Cannatà *et al*., 2021). This study strikes a balance between cost-effectiveness and accuracy, offering a respectable level of precision with a moderate error rate. The methods used in the study are accessible and practical for a wide range of research and clinical settings, making the phantom both useful and affordable while maintaining a good level of accuracy.

Future research endeavours may focus on the incorporation of additional materials into the gelatin phantom with the objective of simulating various breast tissues, including adipose tissue. Furthermore, the fabricated breast phantom could be evaluated using alternative imaging techniques such as mammography, ultrasound, and magnetic resonance imaging (MRI), which are routinely employed in breast screening, to assess the extent to which the phantom accurately replicates actual breast tissue when subjected to these imaging modalities. Nonetheless, the breast phantom developed in the present investigation demonstrates a favourable comparison to prior studies conducted by Ruschin *et al*., (2016), who concentrated on the creation of a multipurpose breast phantom intended for applications in CT, MRI, and ultrasound, specifically for radiotherapy and minimally invasive procedures. The HU value reported by Ruschin *et al*., (2016) was established at 24, in contrast to the value of 12 derived from this study. Employing the HU value determined by Ruschin *et al*., (2016), the relative electron density of their phantom was calculated to be 1.024, which is slightly higher than the value of 1.012 that was obtained in this research. The constructed phantom's RED (1.012) is similar to that of standard human breast tissue (0.976), which is a noteworthy achievement. This closeness is critical for assuring the phantom's accuracy in CT simulations, as it has a direct impact on X-ray attenuation and, as a result, the quality of radiographic images produced.

LIMITATION

The human breast is a complex organ with a diverse composition, as seen in Figure 1. However, the homogeneous breast phantom fabricated may not fully convey the intricacies of breast tissue characteristics, limiting the findings' applicability to all clinical circumstances.

DELIMITATION

The breast phantom was created specifically to portray ladies with breast sizes ranging from 550 to 750 cc. The study employed the average breast size measurements for young West African, this range was chosen to target a specific portion of the population, ensuring that the phantom accurately represents the breast sizes usually encountered in this group. By focusing on this volume range, the scientists hope to improve the phantom's accuracy and relevance for diagnostic purposes, resulting in better diagnostic tools and patient outcomes.

CONCLUSION

Cost-effective three-dimensional tissue-mimicking breast phantoms was successfully developed to accurately imitate actual female breast tissue, with a relative electron density of 1.012 ± 0.036 and a minimum error rate of 3.6%. The electron density of the phantom is nearly identical to that of genuine human breast tissue (0.976), indicating that it is a reliable alternative for clinical research, education, and quality control in breast imaging. Given the limitations of using genuine human breast tissue, particularly the use of ionizing radiation, this phantom offers a useful alternative. This study advances breast imaging technologies and helps to achieve Sustainable Development Goal 3: Good Health and Well-Being by improving the accuracy and accessibility of imaging techniques for early detection and treatment of breast cancer.

RECOMMENDATION

The research suggests a promising direction for future investigations by recommending the development of heterogeneous breast phantoms. This recommendation aims to create phantoms that can accurately mimic the diverse internal cellular composition of human breast tissue, enhancing realism in clinical and educational purposes. Implementing these recommendations could significantly advance the effectiveness of breast phantom technology in medical imaging such as magnetic resonance imaging training, quality assurance, and for research purpose.

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