Suitability of 3D printing materials for printing anthropomorphic phantoms: A simulation study

Nikolay Dukov\textsuperscript{1}, Elica Encheva\textsuperscript{1,2} and Kristina Bliznakova\textsuperscript{1,a}

\textsuperscript{1} Medical University “Prof. Dr. Paraskev Stoyanov”, Varna, Bulgaria
\textsuperscript{2} University Hospital “St. Marina”, Varna, Bulgaria
\textsuperscript{a}E-mail: kristina.bliznakova@mu-varna.bg

Abstract. The use of anthropomorphic phantoms finds an increased application in the last years. From their use in virtual studies to assessment of new imaging technologies and reconstruction algorithms. The current study proposes a resource saving approach, in terms of time and money for assessing the creation of an anthropomorphic model by means of 3D printing. A four component object consisting of segmentations of adipose, gland, skin and lesion tissues was created from an MRI image set. From the resulting object two computational breast models were created – one with the elemental composition of the real breast tissues and a second one with the elemental composition of the low cost 3D printing materials planned to be used for the phantom manufacturing. Then, an in-house developed software was used to generate mammography images, which were subjected to both visual assessment and profile comparison. In this study we used nylon and acrylonitrile butadiene styrene 3D printing materials to represent the x-ray properties of the different breast tissues. The results showed that these 3D materials well represent the x-ray absorption characteristics of both glandular, adipose and skin tissues, while further investigation on suitable materials for representing the lesion characteristics is needed.

1. Introduction

Anthropomorphic phantoms are a valuable tool, which has been increasingly used during the last years in carrying out virtual studies dedicated to assess the efficiency of a given treatment, the development and optimization of new medical technologies, as well as assessment of new algorithms for image reconstruction. In the field of breast imaging, anthropomorphic phantoms may be used for quality control procedures, as well as for optimisation of existing, emerging and performance testing of novel imaging techniques. In general, the anthropomorphic breast phantoms may be classified into computational and physical phantoms [1, 2]. The computational phantoms are created by applying a wide range of techniques such as constructive solid geometry, tomographic, non-uniform rational B-splines, polygon-mesh, and hybrid techniques to model the breast as accurate as possible, with all anatomical variations which arise during its development as well as between individuals [3-7]. Physical anthropomorphic phantoms could be produced by molding techniques, 3D printing and low cost paper-based approaches. Among them, 3D printing technologies provide an excellent opportunity to create realistic models of the breast by using a number of printing materials with physical and x-ray characteristics similar to these of human tissues. Although, there is a substantial advancement in 3D technologies and the creation of new 3D printing materials, the number of 3D printing materials which satisfy the requirements for radiological similarity with breast tissue data is still limited, especially for representing lesion tissue [2]. Furthermore, the process of creating a physical x-ray anthropomorphic phantom is lengthily, even with 3D printing technologies. Traditionally, this is an iterative process that involves 3D printing with a given material/materials, scanning at an x-ray facility and evaluating the...
results for suitability. However, making use of software tools for virtual studies to assess the appropriateness of a given 3D printing material for the physical production of x-ray anthropomorphic phantoms can greatly reduce the time and costs involved.

The purpose of this study is to define whether the available low cost 3D printing materials used with fused deposition modelling (FDM) printing technique, are suitable for the production of a four component breast anthropomorphic phantom dedicated to x-ray imaging studies. The study is entirely original and will result in a developed methodology for studying different 3D printing materials, to be used with other 3D printing materials and anthropomorphic phantoms.

2. Materials and methods

An overview of the proposed approach for exploring the possibilities for production of anthropomorphic breast phantoms with low cost 3D printing materials is shown in figure 1. Shortly described, the source of the anthropomorphic phantom is from MRI breast imaging. The tomographic data are then segmented into four breast tissues: adipose, gland, skin and lesion. The obtained segmentation data is then combined into one three-dimensional object. Based on that object two matrices are created with: a) a matrix with the elemental composition of the real breast tissues and b) a matrix with the elemental composition of the 3D printing materials that are planned to be used in printing the physical anthropomorphic breast model. Finally, a comparison of the obtained simulated mammography images is performed.

**Figure 1.** Overview of the approach to define whether specific 3D printing materials are suitable for the production of four component anthropomorphic phantom dedicated to x-ray breast imaging.

2.1. Patient data

For the creation of the breast phantom a set of breast MRI images from T1-weighted scan were used. The image set consists of images with voxel size of 0.70mm x 0.70mm x 0.80 mm of real patient diagnosed with breast cancer. The scanning was carried out with GE Signa HDxt 1.5 T MRI scanner and with contrast agent present, while the scanning sequence was axial multi-phase VIBRANT (3-phase).
This retrospective study was approved by the Ethics Committee of Medical University of Varna (Approval number 102/22.04.2021).

2.2. Segmentation and phantom construction
In order to separate the four tissue types of interest for x-ray imaging: adipose, gland, skin and lesion, a segmentation procedure was developed in Matlab R2020a and performed on the MRI image set. The procedure is semi-automatic and starts with the DICOM images from the set, followed by a set of thresholding and morphological operations, and a reviewing process from a medical doctor with expertise in the field of medical imaging for removing residual artifacts. After a region of interest is chosen (ROI), the skin is segmented followed by the glandular tissue and the tumor tissue. Then the three components are assembled together into one object.

With the purpose of segmenting the adipose tissue a mask covering the whole breast is first generated. This mask is then subtracted with a mask representing the previously created object from the segmentations of the skin, gland and lesion tissues. This results in an “adipose mask”, which is used for the segmentation of the adipose tissue.

Finally, the adipose tissue is added to the previously created three component object, now resulting in a four component object comprised of adipose, gland, skin and lesion tissues.

2.3. Computational models
Two computational breast models were created based on the four component object: one model, corresponding to the elemental composition of the skin, gland, adipose and tumor tissues (CBM1) and a second model with suggested 3D printing material substitutes for the four tissues (CBM2). The elemental composition for CBM1 and CBM2 are shown in table 1. Data for the elemental composition of the real breast tissues and the 3D printing materials were taken from [8]. The 3D printing materials were acrylonitrile butadiene styrene (ABS) and nylon for approximating the radiological properties of adipose and the rest of the three tissues, respectively. Their choice is based on the investigation of the radiological properties of the different materials for the purposes of creating 3D anthropomorphic phantoms [8].

Table 1. Elemental composition and materials used for the two breast computational models CBM1 and CBM2.

| Tissue  | CBM1 Elemental composition | 3D printing material | CBM2 Elemental composition |
|---------|---------------------------|----------------------|---------------------------|
| Adipose | H: 0.112, C: 0.619, N: 0.017, O: 0.251, P: 0.001 | ABS                  | H: 0.075, C: 0.855, N: 0.053, O: 0.016, S: 0.001 |
| Gland   | H: 0.102, C: 0.184, N: 0.032, O: 0.677, P: 0.005 | Nylon                | H: 0.099, C: 0.626, N: 0.119, O: 0.156 |
| Skin    | H: 0.098, C: 0.178, N: 0.050, O: 0.667, P: 0.007 | Nylon                | H: 0.099, C: 0.626, N: 0.119, O: 0.156 |
| Lesion  | H: 0.102, C: 0.184 | Nylon                | H: 0.099, C: 0.626 |
As can be seen from table 1, for the purpose of mimicking the different breast tissues, for the breast model CBM2, two materials are considered - Nylon and ABS, which are available for fuse deposition modelling printers (FDM). Thus, resulting in a simulation of a manufactured breast model of a printing procedure with two materials.

2.4. Simulation

For the purposes of the simulation study a dedicated in-house developed software was used [9, 10]. This software tool allows simulation of several x-ray imaging acquisition geometries such as radiography, limited tomography, as well as circular and helical computed tomography. The tool is comprised of two basic modules: a) Module for computational modelling of phantoms, which includes solid geometry and voxel based approaches; b) Module for modelling radiological images, which includes different geometries such as isocentric and partial isocentric rotational geometries, as well as radiography and mammography. The main parameters of the simulated geometry are the distances from the source to the center of rotation and to the detector (SID, SDD), as well as the length of the gantry acquisition arc and the angle step, including imaging and beam parameters.

The two created models were used with an x-ray simulations of a mammography setup, with the modelled geometry shown in figure 2. Specifically, in our simulation, the x-ray tube and the detector were placed on a distance SDD set to 800 mm, while the distances SID was 650 mm. The simulated projection images were modelled with a pixel size of 100 µm and the incident fan beam energy was set to 19 keV. Noise modelling was not concerned in this simulation study.

![Figure 2](image)

**Figure 2.** Modelled geometry for the simulation of x-ray images. SDD is the source to detector distance, while SID is the source to isocenter distance.

The generated x-ray images are line-integral images, presenting the $\mu(x, y, z)dl$ in the Beer’s law:
\[ I = I_0 \exp \left( - \int_\ell \mu(x, y, z) dl \right) \]  

where \( \mu(x,y,z) \) is the spatially dependent linear attenuation coefficient, \( \ell \) is the path length through the object and \( I_0 \) is the intensity of radiation at the source segment that emits to the area of the detector, taken equal for all viewing angles.

2.5. Comparison
The comparison of the resulting simulations of models CBM1 and CBM2 was performed by means of comparison of line profiles taken through the generated planar mammography images as well as by means of visual assessment.

3. Results
Figure 3 shows the created software breast model from the breast MRI data. Figure 3a shows a selected slice from the originally created 3D breast model (before any tissue assignment), while figure 3b shows the three-dimensional visualisation of the whole original computational breast phantom.

![Figure 3](image1)

\textbf{Figure 3}. Created software breast phantom from MRI data – a) a slice from the breast phantom, b) three dimension visualisation.

![Figure 4](image2)

\textbf{Figure 4}. Results from the x-ray simulations of the created software breast phantom from MRI data – a) x-ray simulation with elemental composition corresponding to adipose, gland, skin and lesion...
tissues (CBM1), b) x-ray simulation with elemental composition corresponding to 3D printing material substitutes for the four tissues: adipose, gland, skin and lesion tissues (CBM2). The red arrow indicates the horizontal position of the plot profiles shown in figure 5.

Figure 4 visually depicts the results from the x-ray simulations of the two breast matrices – elemental composition of breast tissues (CBM1) and elemental composition of suggested 3D printing material substitutes (CBM2).

Figure 5 shows the line profiles taken through the x-ray simulated projections depicted in figure 4. The line profiles in both images are taken horizontally and at the same position. In figure 4, the red arrow on the left next to figure 4a, indicates the position at which the horizontal profile lines were drawn. The visual representation of the numerical data obtained from the line profiles of both x-ray projections are combined into a single figure (figure 5), for better visualization assessment and comparison.

![Figure 5. Profiles, taken horizontally from end to end in the middle of the images shown in figure 4.](image)

4. Discussion
This work tackles the issue of creating anthropomorphic breast phantoms for x-ray imaging studies with widely available and affordable 3D printing materials for FDM printers. As such task is cumbersome, time consuming and expensive we opt for a computerized solution by utilizing computational models of the breast model candidate for 3D printing and x-ray simulation techniques. The proposed approach can quickly show if the 3D materials to be used in printing physical models for radiological purpose are suitable and thus this will result in reduced costs.

The chosen breast MRI image set is from a patient with rather large mammary glands, which provides a good opportunity, due to the size, for assessment of the x-ray characteristics of the tissues of interest and the considered tissue substitutes.

We opted for a semi-automatic segmentation of the tissues, as even if the segmentation procedure was fully automated, close collaboration with a medical doctor with expertise in the field is necessary as well as thorough evaluation, which is not the focus of this study. The segmentation and construction
procedures described in section 2.2 resulted in a breast model with similar shape to a real breast shape, as seen from figure 3. Furthermore, the distribution of the breast glandular tissue as well as the skin after segmentation appear similar to the distribution of these tissues in real patient images [11-14].

The x-ray simulation of the first computational breast model (CBM1), displayed in figure 4a, showed that the lesion is well differentiated from the rest of the tissues. The rest of the tissues (adipose, gland and skin) also show expectable visual characteristics and the projection image is considered to be realistic. Performing x-ray simulation on the second computational model (CBM2), which considers 3D printing materials (shown in figure 4b) shows that in the projected image the tumor is not well differentiated from the rest of the tissues. The rest of the tissues (adipose, gland and skin), however were evaluated to appear realistically on the simulated x-ray image.

The comparison of profiles (shown in figure 5), taken across the simulated planar images (figure 4) shows a relatively good match with a maximum difference of 15% between the line-integral images. Although, the first model (CBM1) exhibits slightly higher grey values compared to the second (CBM2), the profile patterns of both models follow the same trend. The comparison also indicates that in the projection image of the breast phantom with the 3D printed materials (CBM2), the lesion structure is not well represented. This can be observed on the graph where an increase of grey values to 0.45 for the tissue composition (CBM1) in figure 5 (the red arrow in figure 5 indicates the position) stemming from the influence of the tumor formation. In the case of 3D printing materials composition (CBM2) however, similar increase in that position is not prominent, indicating that the material used for the tumor formation does not exhibit desirable characteristics. Thus, another 3D printed material is needed to adequately represent the radiological properties of the breast lesions. Such a material might be polylactic acid or nylon mixed with a 3D material with higher density.

5. Conclusions
The current study tested through modelling and simulations, the performance of two widely available 3D printed materials for FDM: ABS and nylon to “manufacture” breast phantoms for x-ray imaging purposes. The results showed that the use of nylon and ABS is appropriate for the development of anthropomorphic models and that these 3D printing substitutes well represent the absorption characteristics of glandular and adipose tissues, while in the case of tumor representation, there is a need for further exploration of new materials with suitable such characteristics. Through a simulation study of 3D materials and their comparison by means of subjective and objective evaluation with the x-ray behaviour of real breast tissues, this approach turns out to reduce the cost and time related to manufacturing of anthropomorphic x-ray breast phantoms. Future work concerns testing of more 3D materials and manufacturing the physical version of these models.

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