Physical properties of polyvinyl alcohol (PVAL) gel materials as phantoms for mammography

Franca Oyiwoja Okoh1, Mohd Fahmi Mohd Yusof2, (a), Norlaili Ahmad Kabir3, Siti Nor Azizah Abdullah4

1,3,4School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia.
2School of Health Sciences, Universiti Sains Malaysia, 16150 Kelantan, Malaysia.

Abstract. This study evaluates the possibility of using polyvinyl alcohol (PVAL) composites as phantom material to simulate different densities of breast tissue for mammography based on their elastic properties. Three categories of PVAL gels were prepared by freezing and thawing 10 % water based PVAL (PVAL), ethanol and water based PVAL (PVAL/E) and a blend of PVAL with graphite powder (PVAL/G) solutions to mimic various breast densities. Young’s modulus (YM) of all samples was evaluated by puncture test using the texture analyser. The results recorded ranged from 0.93 to 4.79 kPa for all samples. The results indicate that the PVAL based phantoms examined could be used to simulate fatty and dense breast tissues based on the values of their densities and YM.

1. Introduction

Phantom materials in medical physics works are used to simulate the physical, mechanical and radiological properties of the human soft tissues of specific organs. Young’s modulus (YM) is a measure of the stiffness of materials and this parameter has been used as the measure of the elasticity of soft tissues [1,2]. This study focused on the development of compressible phantoms suitable for mammography. During mammography imaging, breast compressions are required to reduce breast thickness, limit the radiation dose and increasing the image quality. Although compression of the female breast is critical during mammography, none of the available standard mammographic phantoms have been similarly compressible [3]. Furthermore, commercial tissue mimicking phantoms constitute a very small range of tissue structures and they can have anatomical defects. Besides, their high cost makes it impossible for them to be used routinely as training tools. The evolution of compressible mammographic phantoms would promote the understanding of tissue deformation and verify related models.

Several studies were conducted on the characterization of biomechanical properties of soft tissues such as breast that do not have active mechanical functions but could be subject to mechanical activities like compression during mammography examination [4,5]. Different methods have been employed in the study of YM by many researchers that used the indentation technique where specimens were indented and the force-displacement slope was converted to the tissues YM [2,5,6]. The elasticity and radiological properties of solid gel samples made from 5 to 20 % PVAL concentration in equal amount of ethanol and water solution had been studied in previous works [3,7]. These were conducted by the mean of mechanical testing modalities to perform compression of samples between parallel plates while
evaluating YM values at different strain levels. The results indicated that the YM of the PVAL gels ranged between 20 and 220 kPa at 15% strain level, increasing with PVAL concentrations. These values are similar to the YM of normal and cancerous breast tissue, respectively. Their result also revealed that the linear attenuation coefficients of these gels range from 0.76 to 0.86 cm\(^{-1}\) at 17.5 keV consistent with published values of breast tissue at this energy, 0.8–0.9 cm\(^{-1}\). In our earlier study, the mass attenuation coefficients of 5 to 20 % water based PVAL solid gel samples and found them suitable for use to mimic various categories of breast tissue based on the Breast Imaging and Recording Data System (BIRADS) classification [8]. A Texture Analyser is a texture measurement system that moves in vertical directions to compress or stretch samples. It is commonly used to carry out compression, extension, puncture and rheology test in industrial food and pharmaceutical samples [9]. This study employed the use of the texture analyser to investigate the YM of PVAL composites that could mimic different categories of breast tissues based on their mass densities.

2. Methodology

2.1. Fabrication of gel samples

The PVAL granules used for this research was purchased from Sigma – Aldrich, St. Louis, MO, US. It has an average molecular weight of 85,000 – 124000 and 99+ % degree of hydrolysis. The method of preparation of the PVAL gels was in line with previous studies [3,7,8,10]. The concentration of PVAL solution used throughout this study was 10 wt %. Three categories of PVAL gels were prepared to mimic various breast densities: Water based PVAL (PVAL), ethanol and water based PVAL (PVAL/E) and a blend of PVAL with graphite powder (PVAL/G). The PVAL solution was prepared by dissolving the pre-determined amount of PVAL granules in deionised water (DI) at 90°C. The mixture was stirred continuously during heating with a magnetic stirring bar for at least 2 hours until the entire granules dissolved in water. Ethanol solution (50 %) and graphite powder (4 %) were separately added to 10 % PVAL solution to prepare PVAL/E and PVAL/G solutions respectively. The heating process was carried out in a closed system to avoid loss of liquid. The solutions were allowed to cool down at room temperature for approximately 2 hours. This process allowed the trapped air bubbles in the solution to be eliminated. The PVAL solutions were poured into cylindrical plastic moulds of known volume (height = 20 mm, diameter = 20 mm) and placed in a freezer at approximate temperature of -26°C. The gels were frozen for 12 hours and thawed at room temperature for another 12 hours to obtain solid gels. Six replicates were formed for each type of the PVAL composites evaluated: PVAL, PVAL/E and PVAL/G. Three of each type underwent 1 FTC while the remaining 3 underwent 2 FTCs.

![Figure 1](image_url). The fabricated PVAL composites test samples of (a) PVAL-G (b) PVAL and (c) PVAL-E samples.
2.2. Physical and Mechanical testing of gel samples

The mass density, $\rho$ of each sample was calculated as the ratio of mass to volume (g/cm$^3$). The mass and volume of each sample were measured using the electronic balance and displacement method respectively. The values of 3 replicates for each sample were averaged and taken to attain a high measurement accuracy to the nearest 0.01 g/cm$^3$.

To characterize tissue or material stiffness, the mechanical property of PVAL composites were studied through the puncture test. Specifically, the Young’s modulus (YM) was evaluated. The puncture test was carried out using the texture analyser (Model TA. XT. Plus Texture Analyzer, UK) with a 5 kg load cell. The fabricated gel samples were maintained at room temperature 24 hours prior to the test. In this test, the resistance of material to an applied force was measured. A sample was placed in the mechanical testing machine and force was applied, the aluminium probe (12.6 mm diameter) was compressed into the sample to a penetration depth of 8 mm at crosshead speed of 0.5 mm/s. This experiment was carried out on PVAL, PVAL/E and PVAL/G samples that underwent 1 and 2 FTCs to measure the YM and the effect of force on sample type and stiffness.

Young’s modulus is given by:

$$E = \frac{\delta \varepsilon}{\sigma}$$

with $\sigma = F/A$ (Force/cross sectional Area) and $\varepsilon = \Delta l/l$ (Changes in the length/original length). The cross-sectional area of cylindrical objects is $A = \pi r^2$ where $r$ is the radius of the cylinder. The force-distance data was collected from TA system and YM calculated using equation 1.

3. Results and Discussion

The evaluated mean densities of the PVAL gel samples is summarised in Table 1. The result revealed that all the PVAL samples have densities approximately equal to the density of water (1.0 g/cm$^3$) with PVAL/E having the least density of 0.952 ± 0.011 g/cm$^3$ and PVAL/G having the highest density of 1.081 ± 0.02 g/cm$^3$. The addition of graphite powder which has a density of 2.0 g/cm$^3$ increased the density of PVAL/G to higher than 1.0 g/cm$^3$ while ethanol solution ($\rho = 0.78$ g/cm$^3$) reduced the density below water. The nearness of the mass densities of evaluated PVAL composites to the density of water and breast tissue (1.02 g/cm$^3$) suggests that the samples possess water/tissue equivalent properties which makes it suitable for use and breast phantom material.

Table 1. The calculated average mass density of fabricated PVAL gel samples by using the gravimetric method

| Sample | Mean Density ± SD |
|--------|-------------------|
| PVAL   | 1.056 ± 0.002     |
| PVAL/E | 0.952 ± 0.011     |
| PVAL/G | 1.081 ± 0.02      |

Figure 2 shows the calculated YM (a) and Force applied (b) for PVAL, PVAL/E and PVAL/G samples that underwent 1 and 2 FTCs. The value of YM obtained for all samples ranged from 0.93 to 4.79 kPa with PVAL (1 FTC) and PVAL/G (2 FTC) recording the least and highest YM respectively. The results confirm the linear relationship that exist between force and YM. Stiffer samples required higher force to push the aluminium probe through the samples hence recoded higher YM, the reverse was the case for less stiff samples. This is because graphite powder fills the void spaces in the PVAL/G matrix thereby making the gel more compact and requiring more force to plunge through. For all categories of samples examined, the force and YM increased with an increase in the number of FTCs as expected.
There is a notable disagreement between our measured YM and those of [3]. Nevertheless, our results are close to the results obtained by [2] who measured YM of agar and gelatine and obtained 5.6 – 12.2 kPa. Our results also agree with the values of YM achieved by [5] when they measured the YM of 168 breast tissue specimens in vitro and obtained 3.25 and 3.24 kPa for adipose and fibro glandular tissues respectively. Furthermore, in vivo measurements by [11,12] covers a range of 1.0 to 20.0 kPa and 2.0 to 37.0 kPa for adipose and fibro glandular tissues respectively. This can be associated with the fact that different authors used various strain levels, inconsistent sample geometry and different measurement methods. It should be remembered that differences in the YM of different tissues can span an extremely large dynamic range of elasticity [4] so even with large errors, differential diagnosis based on elasticity imaging may still be useful. In line with previous studies, the result of this study indicates that all gel samples studied could simulate different categories of breast tissue based on their density.

4. Conclusion
This study focused on the measurement of the physical and mechanical properties of PVAL- based solid gel as breast tissue equivalent material. The densities of the fabricated PVAL gel phantoms showed close resemblance to those of water and breast tissue based on AAPM, ICRU-44 1989. The YM obtained in this experiment for all samples ranged from 0.93 to 4.79 kPa. The results indicate that the PVAL based phantoms examined could be used to simulate fatty and dense breast tissue based on the values of their densities and YM.

Figure 2. Calculated (a) Young’s Modulus and (b) Applied Force of the PVAL, PVAL/E and PVAL/G that underwent 1 and 2 FTCs.
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