Design and Manufacture of Polyvinyl Chloride (PVC) Tissue Mimicking Material for Needle Insertion

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Abstract
The polyvinyl chloride (PVC) tissue-mimicking material for needle insertion was manufactured and evaluated. Factorial design of experiment was conducted by changing three factors – the ratio of softener and PVC polymer solution, the mass fraction of mineral oil, and the mass fraction of micro-sized glass beads – to study the indentation hardness, compression elastic modulus and friction and cutting forces in needle insertion of 12 types of soft PVC material. The indentation hardness of the soft PVC material ranged from 5 to 50. The elastic modulus of the soft PVC material was from 6 to 45 kPa between 0-0.15 strain. The friction and cutting force during needle insertion also had large ranges, which were from 0.005 to 0.086 N/mm and 0.04 to 0.36 N respectively. The analysis of variance showed that the ratio of softener and PVC polymer solution had the most significant effect on all of the four properties of the PVC material. The percentage of mineral oil also had statistical significance on these four properties. The glass beads only had effect on the needle insertion cutting force. A nonlinear regression model was applied to find relationships among mechanical properties and the significant factors. The $R^2$ values of the regression analysis results were all larger than 0.9. Four properties of a PVC tissue-mimicking material can be designed to desired values based on these relationships.

Keywords: Tissue Mimicking Material, PVC, Hardness, Elastic Modulus, Needle Insertion

1 Introduction

Tissue mimicking materials are widely used in clinical simulators, medical research, and soft robotics. Within clinical simulators, materials that simulate the properties of real biological tissue are critical to make simulators more realistic for surgeons, nurses and caregivers to practice and learn their clinical skills (Liu et al., 2003; Domuracki et al., 2009; Srinivasan et al., 2006; and Dankelman 2008). In medical research, tissue mimicking materials play an important role as the idealized tissue models

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to design and test clinical tools, methods, and systems, achieving more repeatable results in experiments than real tissue due to their stability, consistency, and uniform properties (Culjat et al., 2010; Cao et al., 2013; and Yoshida et al., 2012). For example, the geometrical designs of needle tips can be evaluated more thoroughly by the consistent results obtained from the use of tissue mimicking materials (Wang et al., 2014).

Tissue mimicking materials can be divided into two general groups: biopolymers and chemically synthesized polymers (Chen and Shih, 2013). Agar, agarose, gelatin and gellan gum are commonly used biopolymers. They tend to contain a high mass fraction of water (>80%) making them similar in many respects to soft biological tissues. However, biopolymers are not stable for long term use because of the evaporation of their water content and eventual bacterial growth (Pogue and Patterson, 2006). Examples of chemically synthesized polymers include polyvinyl alcohol (PVA), polymerized siloxanes (silicone), and polyvinyl chloride (PVC). Compared to biopolymers, these types of polymers are more stable and durable (Spirou et al., 2005 and Wang et al., 2014). However, the lack of water in most chemically synthesized polymers often makes them less similar to tissues, particularly in needle insertion (Hungr et al., 2012).

Needle insertion is one of the most common medical procedures (van Gerwen et al., 2012 and Abolhassani et al., 2007). Tissue mimicking materials have been used to achieve more consistent experimental results in studies of the needle tip design, deflection of needle and deformation of tissue during needle insertion, and many other clinical procedures using needles. Gellan gum (Asadian et al., 2010), agar (Wan et al., 2005), gelatin (Roesthuis et al., 2011), and silicone (Wang et al., 2014) have been used as the tissue-mimicking materials to study the needle insertion. Besides these materials, PVC has been shown to be a suitable and widely used material for needle insertion research in soft tissue because of its optical transparency and appropriate haptic and mechanical properties. A brief survey of the literature reveals many studies that have effectively used PVC to test a variety of needle insertion models. Using the PVC as tissue-mimicking material, Haddadi et al. (2011) evaluated a dynamic model for bevel-tip needle deflection, Podder et al. (2005) studied the effect of needle tip geometry on the needle insertion force and deflection, McGill et al. (2012) investigated the effect of needle insertion speed on the needle deflection, Misra et al. (2010) built a mechanics based model for robotic needle steering, Reed et al. (2009) studied a rotational dynamic model, and DiMaio et al. (2003) estimated the force distribution along the needle shaft and compared the force from the model. The above studies show the important role of PVC in needle insertion research. To improve the performance of PVC material in needle insertion experiments, the composition of this material can and should be designed, which become one of the goals of this research.

Typically, soft PVC materials are made by combining a PVC polymer solution and its softener diethyl hexyl adipate, then heating the combination to a certain temperature. Components of the soft PVC material can be adjusted to design the new material with desired properties. For instance, the mass ratio between the softener and PVC polymer solution determine the hardness of the soft PVC material. By adjusting this ratio, the hardness of the soft PVC material can be changed to simulate the mechanical properties of different tissues (Hungr et al., 2012). Similar to other chemically synthesize polymers, PVC does not have fluid inside, which causes the friction force in needle insertion procedure to not feel biologically realistic (Hungr et al., 2012). To make the soft PVC material more similar to real tissue in this regard, a lubricating agent can be added into the PVC sample to simulate the interstitial fluids of tissue. Wang et al. (2014) used mineral oil as such lubrication agent in silicone-based tissue mimicking materials and conducted needle insertion tests. With the addition of mineral oil, the hardness, elastic modulus, and friction forces of silicone were observed to have obvious changes (Wang et al., 2014). The friction force decreased with the increase of oil percentage in the silicone material. In this study, mineral oil is added to the soft PVC material as a lubricant to decrease the friction force of the needle insertion. In needle insertion, ultrasound imaging is common to monitor and guide the motion of the needle. The original PVC material looks very different than tissue because of its lack of speckle formation. Scattering agents, such as the micro-sized glass beads,
can be added to PVC to form what clinicians look for when observing ultrasound images. Micro-sized glass beads can be added into the material to increase the scattering effect, making the PVC more realistic in ultrasound imaging, while still preserving the overall optical clarity of the material. This paper presents the design and manufacture of soft PVC materials with different composition and tests their mechanical and needle insertion properties.

In this study, a design of experiment was used to evaluate the effects of three factors – (1) the ratio between softener and PVC polymer solution, (2) the mass fraction of mineral oil, and (3) the mass fraction of the micro-sized glass beads – on the properties of soft PVC material. The Shore hardness was measured with a durometer and converted to an elastic modulus. Stress-strain curves were obtained from compression tests to calculate and validate the elastic modulus. Finally, needle insertion tests were conducted to measure the friction force and cutting force during needle insertion. According to the results of the statistical analysis, the significance of the three factors was clarified. A regression model for each material property was developed to get the quantitative relationship between the mass fraction of the components and the material properties. With the regression equations, a material can be designed to have any combination of desired properties by adjusting the three factors in this paper.

2 Materials and Methods

2.1 Manufacture of the Soft PVC Material

The soft polyvinyl chloride (PVC) is a non-toxic plastic commonly used for making soft parts (Spirou et al, 2005). Its molecular formula is \((C_2H_3Cl)_n\). It is made by mixing the PVC polymer solution and its softener diethyl hexyl adipate together, heating to a high temperature for vulcanizing, and cooling to a lower temperature (usually around room temperature) to cure. In this paper, the PVC polymer solution and softener are both from M-F Manufacturing (Ft. Worth, TX). The mixture of the PVC polymer solution and the plastic softener is a white opaque solution. After the mixture is heated to a high temperature over 100°C, the monomers in the solution will polymerize and become transparent (Spirou et al, 2005). To adjust the properties of the PVC, white mineral oil (W.S. Dodge Oil, Maywood, CA) and 50 μm glass beads (Comco, Burbank, CA) were added and mixed uniformly. For this research, the mixed PVC solution was heated by a heat plate to 150°C and stirred by a magnetic stirrer. The material cannot be heated too long, because over heating may burn the material and change its properties. After the mixture turned transparent, it was moved to a vacuum chamber to remove the bubbles inside the liquid. Finally, the liquid mixture was poured into cylindrical molds (44 mm in diameter) and cooled to room temperature to obtain soft PVC samples conformed the desired shape. For each material, the PVC sample 50 mm in length was used for needle insertion experiments and three sample 20 mm in length were used for other property tests (shown in Figure 1). The size of the sample is determined according to ASTM D2240-05 and ASTM E111 standards.

![Figure 1: Samples of soft PVC.](image-url)
2.2 Design of Experiment

A factorial design of experiment was established to investigate effects of the amount of components on the properties of the soft PVC material (Montgomery, 2008). The three factors in the factorial design of experiment were the mass ratio between softener and PVC polymer solution \( R_{SP} \), the mass fraction of the mineral \( w_o \), and the presence or absence of glass beads \( w_g \). The \( R_{SP} \) is known to have a significant effect on properties of PVC. Therefore, in this experiment, the factor of \( R_{SP} \) was given at three levels: 0, 0.5 and 1. The other two factors were given two levels. Soft PVC with different \( w_o \) have been manufactured before this research and it has been seen that the highest \( w_o \) at which the oil does not leak after curing is 5%. The two levels of \( w_o \) were chosen to be 0 and 5%. If \( w_g \) was too high, the glass beads would precipitate during PVC manufacturing. Two levels of the \( w_g \) were chosen to be 0 and 1%. The factors and levels of the design of experiment were listed in Table 1. The results of the experiments were analyzed with Minitab® (Minitab Inc., State College, PA). Experiments were replicated for 3 times for every sample.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Low</th>
<th>Middle</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{SP} )</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>( w_o )</td>
<td>0</td>
<td>-</td>
<td>5%</td>
</tr>
<tr>
<td>( w_g )</td>
<td>0</td>
<td>-</td>
<td>1%</td>
</tr>
</tbody>
</table>

*Table 1: Values of each factor at different levels*

2.3 Indentation Test for Measurement of the Hardness

Durometers are commonly used to measure the hardness of soft materials like rubber (ASTM Standard D2240-05). A Type 000-S durometer with a sphere surface indenter was used to measure the hardness of the soft PVC, as shown in Figure 2. The durometer was mounted to a linear actuator (Model HLD60, Moog Animatics, Milpitas, CA) to control its movement and position. After the indenter contacted the sample surface, the actuator drove the durometer to move down with a distance of 5 mm to make the durometer plate touch the surface of the sample, and the reading on the dial was recorded as the hardness of the sample. The results of the hardness tests can be converted to a measure of the elastic modulus via:

\[
E = \frac{3(1-\nu^2) \cdot F}{4\sqrt{R \cdot h^{\frac{3}{2}}}}
\]  

where \( \nu \) is Poisson’s ratio, \( F \) is the spring force of the durometer, \( R \) is the radius of the sphere indenter and \( h \) is the indentation depth (Chen and Shih, 2013). The soft PVC material was assumed to be incompressible. Its Poisson’s ratio was assumed to be 0.49 via the results of Naylor (1974). According to American Society for Testing and Materials (ASTM) Standard D2240-05, \( F \) and \( h \) can be calculated with:

\[
F = 0.01756 \cdot H + 0.167
\]

\[
h = 0.005 \left(1 - \frac{H}{100}\right)
\]

where 0.005 is the extension length of the indenter and 100 is the maximum dial reading.
2.4 Compression Test for Measurement of the Elastic Modulus

Compression tests are usually made on PVC to obtain the stress-strain curves (Hungr et al., 2012; Mehrabian and Samania, 2009) and measure the elastic modulus. As shown in Figure 3, a custom compression test setup was built to compress the PVC specimen. An aluminum plate was mounted on a linear actuator while a sample of the same size and shape as was used during the hardness testing was placed on top of a piezoelectric dynamometer (Model 9273, Kistler, Winterthur, Switzerland). During the test, the aluminum plate was driven by the actuator to compress the sample at the speed of 0.5 mm/s. The force exerted on the sample was measured by the dynamometer. For the 20 mm sample height, the sample is compressed by 9 mm with the maximum engineering strain of 0.45. To get an elastic modulus, the part of the curve for the lower strains (<15%) was used by making a linear fit to get the slope, which is the representative elastic modulus of the sample. Each PVC material has three samples. The average of the results of these three samples was used as the elastic modulus of the material. The elastic modulus measured by compression test was compared with that obtained with indenter hardness measurement.

2.5 Needle Insertion Experiments

Needle insertion experiments were used to assess friction and cutting forces. The experimental setup of needle insertion is shown in Figure 4. An 18 gauge stainless steel solid trocar (1.01 mm diameter) with 15° bevel angle three-plane diamond tip was used as the needle inserted into the PVC.
In the solid needle insertion procedure, when the needle tip was inside the sample, the axial force is the sum of cutting force at the tip and friction force on the surface of the needle rod. After the needle tip is penetrated out of the sample, only the friction force remains on the needle, thus accounting for the remaining force measured. Subtracting the friction force after penetration from the force at the penetrating point, the cutting force can be obtained. The needle was fixed to a custom designed needle holder that was mounted to a stack of linear stages in parallel and inserted in the axial direction of the PVC sample. Two linear stages (Model 200cri, Siskiyou Instrument, Grants Pass, Oregon, USA) were used to drive the needle to insert into the PVC sample with the same speed in the same direction—the combination of the two stages in parallel allowed the distance over which the needle is moved to be longer. The other linear stage (Model 100cri, Siskiyou Instrument, Grants Pass, Oregon, USA) was used to adjust the position of the needle. Another piezoelectric dynamometer (Model 9256, Kistler, Winterthur, Switzerland) was used to measure the force during the needle insertion. The cylindrical PVC sample (44 mm in diameter and 50 mm in length) was secured by a holder on top of the dynamometer. The insertion speed was 0.7 mm/s and the insertion distance was 70 mm. For each sample, the insertion was repeated for 6 times along a concentric circle of the cylinder by rotating the sample 60° between each run. In each insertion, after the needle reached the farthest position, it was retracted and advanced for three cycles to test the friction force during cyclic insertion.

![Experimental setup of the needle insertion tests.](image)

3 Results and Discussions

3.1 Hardness

The hardness of the PVC samples with different composition is shown in Figure 5. These PVC samples were soft with hardness below 50. The factor of $R_{SP}$ was observed to have the most significant effect on the hardness of the PVC. PVC samples with larger $R_{SP}$ have lower hardnesses. The sample with $R_{SP}$ of 0 has a Shore 00 hardness 5 times greater than that with $R_{SP}$ of 1. The addition of mineral oil also lowered the hardness by 10% to 40%. The influence of the 50 μm glass beads on the hardness was not seen to be as significant as the other two factors.
The hardness of different composition materials measured by durometer is shown in Figure 5. The elastic moduli calculated from the hardness data were also affected by the value of $R_{SP}$ most significantly. With the same value of $R_{SP}$ and $w_g$, samples that contained mineral oil had smaller elastic moduli than those without mineral oil. The 50 μm glass beads showed no clear effect on the elastic modulus of the PVC material.

![Figure 5: The hardness of different composition materials measured by durometer.](image)

The elastic moduli calculated from the shore hardness with Equations (1)-(3) are shown in Figure 6. Similar to the hardness, the elastic moduli obtained from the hardness data were also affected by the value of $R_{SP}$ most significantly. With the same value of $R_{SP}$ and $w_g$, samples that contained mineral oil had smaller elastic moduli than those without mineral oil. The 50 μm glass beads showed no clear effect on the elastic modulus of the PVC material.

![Figure 6: The elastic modulus calculated from the Shore hardness test.](image)

3.2 Elastic Modulus

Figure 7 shows the typical stress-strain curve of the compression tests. In the beginning, the stress increased with the strain almost linearly. After the strain exceeded approximately 0.15, the stress began to increase with the strain nonlinearly. To get the elastic modulus in the elastic region of the material, the measured stress data with strain below 0.15 were used. Figure 8 shows the elastic modulus (all below 50 kPa) of each soft PVC sample obtained from compression tests. The elastic modulus decreased with the increase of $R_{SP}$. Among the three factors of the components in soft PVC material, the $R_{SP}$ had the most significant effect on the elastic modulus. The elastic moduli of the soft PVC materials with $R_{SP}$ of 0 (all below 10 kPa) were about 5 times larger than those with $R_{SP}$ of 1. The PVC with mineral oil tended to have smaller elastic moduli than those without mineral oil. The 50 μm glass beads also lowered the elastic modulus of the material. For each PVC sample, the elastic modulus obtained by compression tests was close to that calculated using the Shore hardness, though the compression tests typically yielded slightly smaller values and had a correspondingly smaller variation within the measured modulus. The influence of the 50 μm glass beads on the elastic
modulus was different between these two methods. The data of the elastic modulus calculated from shore hardness showed no effect of glass beads on the elastic modulus. However, based on the elastic modulus measured in compression tests, the glass beads seemed to lower (about 5%) the elastic modulus of the PVC. The elastic moduli of PVC samples are from 6 to 45 kPa, which is similar to tissue mimicking material such as silicone (21.3 kPa) and real tissue like liver (11 kPa) (Wang et al, 2014).

![Figure 7](image1.png)

**Figure 7:** The stress-strain curve of the PVC sample with $R_{SP}$ of 1, $w_o$ of 0, $w_g$ of 0.

![Figure 8](image2.png)

**Figure 8:** The elastic modulus of each soft PVC material obtained from the compression test.

### 3.3 Friction and Cutting Forces in Needle Insertion

The typical force along the axial direction of the six insertions in one sample is shown in Figure 9. This force profile is similar to that of the silicone (Wang et al, 2014). The force data of the six insertions were consistent. Seven regions are identified in the force profile. In Region I, the needle was inserted into the sample and punched out. In Regions II, IV and VI, the needle was retracted by 20 mm with the tip outside the sample. In Regions III, V and VII, the needle was driven forward by 20 mm after retraction. In Region I, there are four observable phases in the force profile. In Phase I, the needle tip indented the sample surface and caused the sample to deform. In Phase II, the needle tip cut into the sample and the insertion force dropped slightly because of the fracture of the PVC material. In Phase III, the insertion force consisted of the summation of the cutting force and the friction force. In Phase IV, the needle tip punched out of the sample. The force in Phase IV was only attributable to the friction force on the needle surface. Since the contact surface between the surface of the needle and sample was constant, the force within this period remained the same. The difference between the peak force in Phase III and the friction force in Phase IV was thus the cutting force. In Regions II, IV and VI, the force was the friction force in the opposite direction of Region I, while in
Regions III, V and VII, the force was the friction in the same direction as region I. Therefore, the friction force in Regions II, IV and VI is negative. The friction force in Regions II, IV and VI was almost the same. The same group trend of similar friction forces was seen in Regions III, V and VII. This phenomenon showed that the material can resist destruction wrought by friction, and thus retained its properties well.

The average force of Phase IV in Region I was used to compare the friction force of the needle insertion in different PVC materials. To preclude the error in sample length, the friction force per unit length was used to compare the difference between the different PVC materials. The cutting force was obtained by subtracting the friction force in Phase IV from the peak insertion force in Phase III. The friction force per length and the cutting force are shown in Figures 10 and 11. The friction force was influenced by the value of $R_{SP}$ significantly. The mineral oil had an important effect on the friction force. PVC materials with mineral oil had 50% lower friction force than those without mineral oil. The influence of glass beads on the friction force was not clear. The friction force of needle in PVC samples is from 0.005 to 0.086 N/mm. Wang et al (2014) measured the needle insertion friction force in silicone with a 1.01 mm diameter needle. The friction force of the silicone is 0.01-0.1 N/mm. It’s similar to the friction force of needle insertion in PVC samples. Except for silicone, the needle insertion friction force in PVC is also similar to that in real tissue, such as liver and muscle (Wang et al 2014, Kataoka et al 2001).

**Figure 9:** Force of the six insertions into the PVC sample with $R_{SP}$ of 0.5, $w_o$ of 0, $w_g$ of 1%.

**Figure 10:** Friction force per length in needle insertion of different PVC materials.
The influence of $R_{SP}$ on the cutting force was also very significant. According to the mean of the data in every PVC material, the effect of the mineral oil and glass beads on the cutting force was not clearly established.

![Figure 11: Cutting force in needle insertion of different PVC materials.](image)

### 3.4 Regression Model

The Analysis of Variance (ANOVA) results of the significance of each factor on the hardness, elastic modulus, friction force and cutting force are summarized in Table 2. In statistics, the p-value is a function of the observed sample results (a statistic) that is used for testing a statistical hypothesis. If p value is smaller than 0.01, the result would be considered as statistically significant. The $R_{SP}$ had significant effect on all of the four properties of the PVC material. The $w_o$ also had significant effect on the four properties of the PVC material. The $w_g$ had no significant effect on the hardness and friction force but had a minor effect on the elastic modulus and cutting force. The glass beads were added into the PVC to increase the scattering effect to make the PVC more realistic in ultrasound imaging (the effectiveness of which will be discussed in future publication). The glass beads have no significant effect on the mechanical properties of material.

<table>
<thead>
<tr>
<th>Factor</th>
<th>$p$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hardness ($H$)</td>
</tr>
<tr>
<td>$R_{SP}$</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>$w_o$</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>$w_g$</td>
<td>0.112</td>
</tr>
</tbody>
</table>

**Table 2:** The ANOVA results of the effect of factors on the material properties (*statistically significant)

The regression models of the four properties were developed with the factors that had significant effect on the property. Based on the trend of the results, the nonlinear regression equations describe the relationships between the mechanical properties and significant factors are listed in Table 3. With these equations, the PVC material can be designed to have the similar properties of the tissue by changing the factors of $R_{SP}, w_o$ and $w_g$. The $R^2$ for the four properties are all larger than 0.9.
### Table 3: The regression equations of the hardness, elastic modulus, friction force and cutting force

<table>
<thead>
<tr>
<th>Regression Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H = 50.89 - 63.58 R_{SP} - 65.6 w_o + 21.5 R_{SP}^2$</td>
<td>0.99</td>
</tr>
<tr>
<td>$E (kPa) = 43.66 - 75.33 R_{SP} - 43.92 w_o + 39.56 R_{SP}^2$</td>
<td>0.99</td>
</tr>
<tr>
<td>$F_r (N/mm) = 0.08 - 0.13 R_{SP} - 0.72 w_o + 0.75 R_{SP} w_o + 0.06 R_{SP}^2$</td>
<td>0.97</td>
</tr>
<tr>
<td>$F_r = 0.34 - 0.55 R_{SP} - 2.91 w_o - 11.45 w_g + 3.49 R_{SP} w_o$</td>
<td></td>
</tr>
<tr>
<td>$+ 14.74 R_{SP} w_g + 179.3 w_o w_g - 227.2 R_{SP} w_o w_g + 0.23 R_{SP}^2$</td>
<td>0.91</td>
</tr>
</tbody>
</table>

### 4 Conclusions

This paper investigated the influence of the ratio between softener and polymer solution ($R_{SP}$), the mass fraction of mineral oil ($w_o$), and the mass fraction of glass beads ($w_g$) on the mechanical properties of the PVC material. Based on the results of the ANOVA, $R_{SP}$ had the most significant effect on hardness, elastic modulus, needle insertion friction force, and cutting force of the PVC material. From our observations, the mineral oil could be used to lower the hardness and elastic modulus. It lubricated the needle insertion procedure and reduced the friction force effectively. The glass beads had some influence on the elastic modulus of the material. However, they had no clear effect on the hardness and needle insertion friction force. Since the aim to add glass beads was to enhance the scattering effect of the material and make the PVC close to the real soft tissue in ultrasound imaging, this was a desirable result. Nonlinear regression models of the hardness, elastic modulus, friction force and cutting force were obtained. With these equations, the properties of the PVC material can be designed and fabricated.

### 5 Acknowledgements

This research work is sponsored by the Nation Science Foundation (NSF) Award CMMI 1266063 and the Chinese Scholarship Council.

### 6 References


Mehrabian H and Samania A. Constrained hyperelastic parameters reconstruction of PVA (Polyvinyl Alcohol) phantom undergoing large deformation. In: *Proc. of SPIE*, 2009, 7261: 72612G.


Wang YC, Tai BL, Yu HW and Shih AJ. Silicon-based tissue-mimicking phantom for needle insertion simulation. *Journal of Medical Devices* 2014; 8: 021001.
