**Porous Tubular PVA Hydrogels: Preparation and Assessment**

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**ABSTRACT**

Hydrogels have been used in related biomedical fields, and their pore size and structure are an important investigation emphasis in relative studies. Hydrogels with different pore sizes have different applications. This study aims to examine the pore size and porosity of the polyvinyl alcohol (PVA) tubular hydrogels. Sodium chloride (NaCl) with different concentrations serves as the porogen while polyvinylpyrrolidone (PVP) serves as the surfactant. PVA is made into tubular hydrogels via a freeze-thaw method and the cross-linking with glutaraldehyde. The hydrogels are then processed with an ultrasonic vibration in order to remove the residual solvents and the porogens, in order to obtain tubular PVA hydrogels with an interconnected porous structure. The test results indicate that the porosity and pore size of the PVA hydrogels significantly increase as a result of the uses of a porogen. Excessive NaCl as a porogen damages the porous structure of hydrogels, which in turn decreases the porosity and pore size of the hydrogels.

**INTRODUCTION**

Hydrogel has been applied to related biomedical fields because it has a high swelling, maintains a great deal of moisture, and possesses appropriate
The porous structure of the hydrogel thus becomes an important research topic in the field of tissue engineering. Different porous structures are correlated with the cell attachments, growth, and hyperplasia, which in turn results in differences in the applications of hydrogels [3, 4]. Biocompatible and nontoxic macromolecules are common materials to make hydrogels in order to meet the requirements of biological tissues, such as PVA, chitosan, and alginate. PVA is a water-soluble polymer that is biocompatible, non-toxic, and biodegradable, and has been commonly used in the tissue engineering field. The molecular chains of PVA contain a great amount of hydroxyl, which easily incurs the presence of intramolecular hydrogen bonds. Therefore, PVA is hydrophilic [5, 6, 7]. PVA hydrogels require cross-linking to improve their mechanical properties and to extend their degradation time. Physical cross-linking and chemical cross-linking are two common methods used to process PVA hydrogels. The chemical cross-linking uses glutaraldehyde or borax as chemical cross-linking agents, while the physical cross-linking uses the freeze-thaw method to improve the intramolecular hydrogen bond of PVA hydrogel. Furthermore, different freeze-thaw cycles determine the dense degree of their porous structures [8, 9]. This study aims to create PVA hydrogels with intercommunicated porous structure. Different concentration of nonionic polymer compounds, including PVP and NaCl, are used as porogens. Finally, the porous structure, pore size, and porosity of the PVA hydrogels are assessed and analyzed.

EXPERIMENTAL

Materials

Polyvinyl alcohol (PVA, Mw146,000-186,000, 99+% hydrolyzed) is purchased from Sigma-Aldrich, U.S.A. Polyvinylpyrrolidone (PVP, average mol wt 360,000) is purchased from Sigma-Aldrich, U.S.A. Sodium chloride (NaCl, Choneye Pure Chemicals Co., Ltd., Japan) is reagent grade. Glutaraldehyde (GA, 25% aq. soin.) is purchased from Alfa Aesar, U.S.A.

Experimental Procedure

First, 44.5 ml of deionized water is heated to 115 °C, after which 5.5 g of PVA powder is added. The blend is heated and stirred for 4 hours in order to form an 11 wt% of PVA solution. Next, 1g of PVP is dissolved in 49 ml of deionized water in order to form the surfactant. 0, 0.2, 0.25 or 0.33 g/ml of NaCl solid particles are respectively dissolved in the surfactant to form four porogens. The control group is made without porogens, and four experimental groups are denoted as N0, N0.2, N0.25, and N0.33 where the letter refers to NaCl and the number refers to the concentration of NaCl. Samples are as indicated in Table 1. Afterwards, different blends are injected via a barrel syringe into a tubular mold that has a 6-mm outer diameter and a 4.4-mm inner diameter. The tubular mold is equipped with a stainless steel mandrel with a 3-mm diameter in its center. The whole set is frozen in a refrigerator at -20 °C for 20 hours, and is then thawed at room temperature for 4 hours while the mandrel is removed. The freeze-thaw cycles have been repeated six times, and the hollow tubular hydrogels are then obtained. The hydrogels are crosslinked with 1.5 % glutaraldehyde solution for 1 hour, and then washed in an
ultrasonic vibration for another hour in order to remove the residual glutaraldehyde solution and porogens. Finally, the tubular PVA hydrogels with a thickness of 0.49 mm are yielded.

Table 1. The denotation of different PVA hydrogels.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Sample control group</th>
<th>N0</th>
<th>N0.2</th>
<th>N0.25</th>
<th>N0.33</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVA (wt%)</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>PVP (wt%)</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NaCl (g/ml)</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.25</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Scanning Electron Microscopy (SEM)

An SEM is used to observe the surface and cross-section of the tubular PVA hydrogels. Before this measurement, samples are frozen by using liquid nitrogen and then broken via a brittle fracture for the observation of their cross-sections. Samples are freeze dried, and affixed to the stage of the instrument by using carbon visco. A vacuum evaporator is used to coat a thin layer of gold for 30 seconds, after which the samples are placed in high vacuum SEM and photographed.

Porosity and Pore Size Analyses

A stereomicroscope (SZ-CTV, OLYMPUS, Taiwan, ROC) and the Image Pro Plus (Media Cybernetics, US) are used to measure and compute the porosity and pore size of the samples for analyses and discussion.

RESULTS AND DISCUSSION

SEM of Tubular PVA Hydrogels

The SEM images of the surface and cross section of the control group are shown in Figure 1. The pure PVA hydrogels without any porogens exhibit a dense surface as indicated in Figure 1 (A). After the freeze-thaw process, the hydrogels...
start to have interconnected porous structure over their surface and in its interior. Increasing the freeze-thaw cycles improves the intra-molecular hydrogen bond, which in turn results in a denser structure. According to the SEM image of the control group with a high magnification of 1000×, the hydrogels have surface and cross-section that are close to smooth, and there are no significant pores in their interior, as seen in Figure 1 (B). N0 exhibits an incomplete porous structure over the surface and cross-section of the hydrogels as indicated in Figure 1 (C, D). PVP can be efficiently distributed and dissolved in water. After the evenly-blended PVA/PVP hydrogels are processed with multiple freeze-thaw cycles, PVA molecular chains construct a firm three-dimensional network structure. The subsequent ultrasonic vibration does not have a significant influence on PVA molecular chains. In addition, the PVP molecules that are distributed in the hydrogel are highly hydrophilic, and the removal of PVP molecules thus results in a porous structure with evenly distributed small-size pores over the surface and interior of N0. NaCl has been commonly used in the preparation of porous hydrogels. Hydrogels are subjected to a high moisture loss during the defrosting process. After six freeze-thaw cycles, the NaCl that has been dissolved and evenly disturbed in the hydrogel starts to be separated out and then distributed over the surface of the hydrogels. The NaCl is then removed as a result of cleansing, which causes a larger pore size over the surface and the cross-section of N0.2, as indicated in Figure 1 (E, F). The surface is no longer dense and smooth, followed by the appearance of a great amount of pores. These pores are evenly distributed and interconnected, and provide the hydrogels with a sponge structure. The increasing concentration of NaCl solution changes the interconnected morphology exhibited on the surface and cross-section of N0.25, as indicated in Figure 1 (G, H). Inorganic salts are dissociated in water, which causes the presence of hydronium. Hydronium demonstrates a hydration capacity when they are jointed with water molecules. When PVA is blended with a high concentration of NaCl as the porogen, the dehydration agglomeration occurs in some PVA, and thereby prevents an even distribution of porogen and PVA. As a result, the porous structure of hydrogel is damaged, which is exemplified by the diminished pore size and the uneven distribution of pores. According to N0.33 as seen in Figure 1 (I, J), a 0.33 g/ml NaCl porogen causes a limited amount of pores that are in the form as sunk huge holes, as indicated by the arrows. These large-size pores are presumed to be the result of the agglomeration of PVA. In addition, there are barely porous structures observed from the interior of the hydrogels, indicating that these large-size pores fail to construct an interconnected structure in the interior, and appear to be a pure damage to the surface structure.
3.2 Porosity of Tubular PVA Hydrogels

![Figure 2](image)

**Figure 2.** Porosity of tubular PVA hydrogels as related to different concentrations of porogens.

Figure 2 shows the porosity of PVA hydrogels as related to the concentrations of porogens. After six freeze-thaw cycles, the control group still has a compact porous structure that makes the surface of the hydrogels to be close to smooth, and thus the control group has a porosity of 0. N0 has a porosity of 38%. N0.2 that is made of 0.2 g/ml NaCl porogen has a great amount of NaCl being separated out during the thawing process. An ultrasonic vibration then removes the NaCl. N0.2 thus has a porosity that is beyond 50% and an interconnected porous structure, which indicates a better porous structure. However, increasing NaCl concentration to 0.25 g/ml causes a 40% decrease in the porosity of N0.25. The main cause is that the excessive NaCl leads to the agglomeration of PVA, which damages the formation of pores. In contrast, 0.33 g/ml NaCl porogen improves the porosity of N0.33. However, the increase in pore area is ascribed to the sunk, non-interconnected large-size pores, and this increase in porosity is not satisfactory.

**Pore Size of Tubular PVA Hydrogels**

Figure 3 shows the pore size of the tubular PVA hydrogels as related to different concentrations of porogens. N0 has 60% of pores (0-1 µm²) and 37% of pores (1-10 µm²). The combination of 0.2 g/ml NaCl porogen increases the pore size of N0.2. The amount of pores with a size of 0-1 µm² is decreased, the amount of pores of 1-10 µm² is increased to 35%, while some pores have a size between 10-40 µm², and the amount of pore (beyond 40 µm²) is approximate 5%. In addition, when the NaCl concentration is 0.25 or 0.33 g/ml, the hydrogels (N0.25 and N0.33) have more than 70% of pores that are 0-1 µm², and less than 30% of pores that are 1-10 µm², and barely no pores that are beyond 10 µm². These results are ascribed to the fact that excessive amount of NaCl results in non-interconnected crevices and dents in the surface structure, and the shortage of a complete porous structure prevents the pore size measurement of these hydrogels.
CONCLUSION

This study successfully uses PVA/NaCl mixtures as porogens, and forms the tubular PVA hydrogels with an interconnected porous structure. The pure PVA hydrogels have a dense and smooth morphology as a result of 6 freeze-thaw cycles. The use of porogens provides the hydrogels with interconnected porous structure over their surface and cross-sections. In particular, the combination of 0.2 g/ml NaCl porogen results in a porosity above 50 %, and there are 15 % of pores that have a pore size of beyond 10 µm². NO.2 is the hydrogels that have the optimal porous structure. However, the porous structure of hydrogels is then damaged as a result of the increasing NaCl concentration, and causes the non-interconnected dents and crevices. The combination of 0.33 g/ml NaCl porogen causes the porosity of hydrogels to decrease by 30 %, and more than 70 % of pores have a size of 0-1 µm². In sum, a NaCl concentration that is beyond 0.25 g/ml is unfavorable to the formation of tubular PVA hydrogels.

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REFERENCES

