Super-hydrophilic silicone hydrogels composed of interpenetrating polymer networks with phospholipid polymer

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Novel silicone hydrogel materials with extremely hydrophilic surfaces were synthesized from two polymer components. Silicone networks prepared from bis(trimethylsilyloxy)methylsilyl propylglycerol methacrylate (SiMA) and hydrophilic networks prepared by the polymerization of 2-methacryloyloxyethyl phosphorylcholine (MPC) in poly(SiMA) networks were used to construct an interpenetrating polymer network (IPN) structure. Random copolymerization of SiMA and MPC was also carried out to obtain control hydrogel samples. The obtained IPN hydrogel materials had highly hydrophilic surfaces in addition to good transparency, mechanical properties. Further, they showed good oxygen permeability because of the presence of the SiMA unit and good resistance to protein adsorption because of the presence of the MPC unit. Results of x-ray photoelectron spectroscopic analysis and microscopic FT-IR spectroscopy revealed that the superhydrophilicity of the IPN hydrogels was due to the surface concentration of the MPC units. The IPN hydrogel was confirmed to be suitable for the fabrication of soft contact lenses.

1. INTRODUCTION

Today, the number of people wearing contact lenses in the world is between 125 and 140 million [1]. However, several studies have indicated that approximately 50% of contact-lens wearers show some clinical symptoms [2]. Contact-lens wearers run the risk of contracting diseases mainly because of tear protein adsorption on the lenses or because of certain surface properties of the lenses [3]. In order to reduce this risk, many researchers have attempted to develop lenses with hydrophilic surfaces that are resistant to protein adsorption.

It has been reported that the phospholipid polymers synthesized from 2-methacryloyloxyethyl phosphorylcholine (MPC; Fig. 1(a)), which is a methacrylate with a phosphorylcholine group, and other vinyl compounds have biologically inert and extremely hydrophilic surfaces [4,5]. Over the last 15 years, several studies have been performed on the surface modification of artificial vessels [6], artificial hip joints [7], and diagnostic devices [8] by using MPC polymers; some of the surface-modified products have also been put to practical use. MPC polymer gels for use in the fabrication of contact lenses were synthesized and characterized [9]. Commercial MPC polymers used in the fabrication of contact lenses are the copolymers of MPC and 2-hydroxyethyl methacrylate (HEMA) prepared using small amounts of crosslinkers. Contact lenses fabricated from MPC polymer gel had excellent resistance to protein adsorption and have better hydrophilic surfaces than conventional HEMA-based contact lenses; however, these lenses suffer from mechanical weakness and low oxygen permeability [10, 11]. Bis(trimethylsilyloxy)methylsilyl propylglycerol methacrylate (SiMA; Fig. 1(b)) is the principal compound used for enhancing the oxygen permeability and improving the mechanical properties of commercial silicone-based hydrogel lenses [12].

The purpose of this study is to use SiMA and MPC to synthesize novel silicone-based hydrogel materials that have the properties of both the starting materials. Copolymerization is generally employed to combine two polymer units, but the incompatibility of SiMA units with MPC units might lead to the formation of opaque hydrogels because of microphase separation. Interpenetrating polymer networks (IPNs), which are combinations of two or more polymer networks that are synthesized in juxtaposition, can be used to address this problem. The entanglement of two cross-linked polymers leads to the development of forced miscibility in contrast to the usual incompatible blends obtained by other means; the resulting products have good dimensional stability. In this study, we synthesized a copolymer and an IPN composed of poly(SiMA) and poly(MPC) chains and compared their properties to assess their suitability for the fabrication of soft contact lenses.

Fig.1 Chemical structures of (a) MPC and (b) SiMA
2. EXPERIMENTS

2.1 Preparation of hybrid gel

2.1.1 Preparation of poly(SiMA-co-MPC)

SiMA and MPC (total monomer concentration: 2.0 M) were dissolved in isopropyl alcohol (IPA); to the solution, the crosslinker triethyleneglycol dimethacrylate (TEGDMA; concentration: 3 mol% with respect to monomer) and the photoinitiator 2,2-dimethoxy-2-phenylacetophenone (DMPA; concentration: 3 mol% with respect to monomer) were added. The mixture was poured then into a mold made by clamping together two poly(ethylene terephthalate) (PET) plates using a 200-μm thick PET sheet as a spacer. The mold was irradiated with UV light for 30 min. The sample was then extracted from the mold and immersed in a mixture of IPA/water (50/50 by volume) for at least 1 day in order to ensure complete removal of the unreacted compounds. The samples thus prepared were cut into disks of diameter 10 mm. The obtained copolymer materials were noted in MPC weight ratio such as SiMA-co-MPC(10), SiMA-co-MPC(19), SiMA-co-MPC(29) and SiMA-co-MPC(39).

2.1.2 Preparation of poly(SiMA-ipn-MPC)

SiMA, TEGDMA (1 wt% with respect to SiMA) and DMPA (1 wt% with respect to SiMA) were mixed. The mixture was gelated in the manner described previously and thoroughly dried at 60 °C for 1 day. Subsequently, the samples were immersed in the MPC–IPA solutions of various concentrations (1.0 M, 1.5 M, 2.0 M and 2.5 M) containing TEGDMA (3 mol% with respect to MPC) and DMPA (3 mol% with respect to MPC) for 1 day and allowed to swell to equilibrium at ambient temperature. The swollen samples were irradiated with UV light, as previously described, and the IPN structures were synthesized. The obtained IPN materials were noted in MPC weight ratio such as SiMA-ipn-MPC(13), SiMA-ipn-MPC(19), SiMA-ipn-MPC(30) and SiMA-ipn-MPC(45).

2.2 Characterization

2.2.1 Measurement of optical transparency

The optical transparencies of the hydrogels swollen in distilled water were measured using a UV spectrometer (V-560, JASCO, Tokyo, Japan). For reference, the transmittance of the commercially available soft contact lens 1-DAY ACUVUE® were also measured. The transparency of the hydrogels calculated by using Lambert’s equation was found to correspond to a thickness of 100 μm.

2.2.2 Measurement of equilibrium water content

The equilibrium water content (EWC) in the hydrogels was calculated by using the following equation:

\[ EWC(\%) = \frac{W_{\text{swell}} - W_{\text{dry}}}{W_{\text{swell}}} \times 100 \]

where, \( W_{\text{swell}} \) is the weight of the hydrogels swollen in distilled water, and \( W_{\text{dry}} \) is the dry weight of hydrogels.

2.2.3 Measurement of static water contact angle

The captive-bubble method (Fig.2) was used to measure the static water contact angles (SCAs). The air-contact angles of the hydrogels in distilled water were measured (CA-W, Kyowa, Saitama, Tokyo), and the SCAs were calculated by subtracting these air contact angles from 180°.

2.2.4 X-ray photoelectron spectroscopy

X-ray photoelectron spectroscopy (XPS: AXIS-His 165, Shimadzu/Kratos, Kyoto, Japan) was used to study the distribution of MPC units in the hydrogels. The presence of the MPC units was confirmed from the absorbance of the \(-\text{O}(-\text{O})\text{O}(-\text{O})\) moiety at 966 cm\(^{-1}\). For these measurements, 5-mm-thick samples were prepared in the manner described previously.

2.2.5 Microscopic infrared spectroscopy

Microscopic FT-IR spectroscopy (JY-4000 and FT/IR-6300, JASCO, Tokyo, Japan) was used to study the distribution of MPC units in the hydrogels. The presence of the MPC units was confirmed from the absorbance of the \(-\text{O}(-\text{O})\text{O}(-\text{O})\) moiety at 966 cm\(^{-1}\). For these measurements, 5-mm-thick samples were prepared in the manner described previously.

2.2.6 Evaluation of mechanical properties

The elasticity of the hydrogels was evaluated by means of the compression test (STA-1150, AND, Tokyo, Japan). Cylindrical samples (diameter: 10 mm; thickness: 5 mm) were compressed at a cross-head speed of 1 mm/min by a probe (diameter: 12 mm) at 25 °C (n = 8).

2.2.7 Measurement of oxygen permeability

The oxygen permeability (Dk) of the hydrogels was determined by using the electrochemical method. A rod-shaped electrode was inserted into a cylindrical cell filled with 2 mL of the electrolyte—0.5 M aqueous KOH solution (Fig.3). Cathode was in contact with the pure water surrounding the sample. The measured values of Dk are expressed in terms of barriers, which represent the volume of oxygen transmitted (10\(^{-11}\) cm\(^3\)) in the standard state per s and cm\(^2\).

2.2.8 Measurement of in vitro protein adsorption

The in vitro adsorption of single proteins by hydrogels in a phosphate buffered saline (PBS) environment was investigated. First, the samples swollen in PBS were immersed in 4.5-mg/mL bovine serum albumin (BSA) at...
37 °C for 15 min. Subsequently, they were rinsed in 30 mL PBS and then immersed in 1-wt% sodium dodecyl sulfate (SDS); the adsorbed protein was completely desorbed by sonication for 30 min [13]. A protein assay kit (Micro BCA™ protein assay reagent kit, #23235, Pierce, Rockford, IL, USA) was used to determine the amount of protein desorbed into the SDS solution with the help of an absorptiometer (Wallac 1420 ARVO sx, Perkin Elmer). For comparison, ACUVUE OASYS® was also subjected to the protein adsorption test.

3. RESULTS AND DISCUSSION

3.1 Optical properties of the hydrogels

Fig. 4 shows the difference in the transparencies of the obtained hydrogels. Interestingly, while the transparencies of the SiMA-co-MPC hydrogels increased with the MPC content, those of the SiMA-ipn-MPC hydrogels were independent of the MPC content. Table 1 shows the transmittance of each hydrogel at 500 nm. From this result, we concluded that more than 80% of visible light was transmitted by all the SiMA-ipn-MPC hydrogels. The difference in the transparencies of the hydrogels was probably because of the differences in their structures. In the case of the SiMA-ipn-MPC hydrogels, entanglement of the two cross-linked polymers led to forced miscibility, which resulted in the observed transparency.

3.2 Surface hydrophilicity

Fig. 5 and 6 show the dependence of the EWC and SCA on the MPC content (wt%). The EWC increased with the MPC content in both types of hydrogels. However, while the SCA of the SiMA-ipn-MPC hydrogels decreased drastically with an increase in the MPC content, that of the SiMA-co-MPC hydrogels was relatively constant. It was found during the measurement that no air bubbles were adsorbed on the surfaces of SiMA-ipn-MPC(30) and SiMA-ipn-MPC(45); hence, the SCAs of these two samples were recorded as 0°. This was a direct indication of the superhydrophilicity of these hydrogels. The difference in the surface hydrophilicities of the hydrogels was related to the difference in surface compositions of the MPC units synthesized by the hybridization method.

Fig. 7 shows the dependence of the EWC and SCA on the MPC content (wt%). The EWC increased with the MPC content in both types of hydrogels. However, while the SCA of the SiMA-ipn-MPC hydrogels decreased drastically with an increase in the MPC content, that of the SiMA-co-MPC hydrogels was relatively constant. It was found during the measurement that no air bubbles were adsorbed on the surfaces of SiMA-ipn-MPC(30) and SiMA-ipn-MPC(45); hence, the SCAs of these two samples were recorded as 0°. This was a direct indication of the superhydrophilicity of these hydrogels. The difference in the surface hydrophilicities of the hydrogels was related to the difference in surface compositions of the MPC units synthesized by the hybridization method.

Table 1 Transmittance of the hydrogels at 500 nm.

<table>
<thead>
<tr>
<th>Transmittance (%)</th>
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<tbody>
<tr>
<td>at 500 nm</td>
<td>at 500 nm</td>
</tr>
<tr>
<td>SIMA-co-MPC(10)</td>
<td>63.4</td>
</tr>
<tr>
<td>SIMA-co-MPC(19)</td>
<td>88.9</td>
</tr>
<tr>
<td>SIMA-co-MPC(20)</td>
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<tr>
<td>SIMA-co-MPC(20)</td>
<td>99.7</td>
</tr>
<tr>
<td>SIMA-co-MPC(30)</td>
<td>98.9</td>
</tr>
<tr>
<td>Acuvue OASYS®</td>
<td>97.8</td>
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</tbody>
</table>

Fig. 8 shows the dependence of the EWC and SCA on the MPC content (wt%). The EWC increased with the MPC content in both types of hydrogels. However, while the SCA of the SiMA-ipn-MPC hydrogels decreased drastically with an increase in the MPC content, that of the SiMA-co-MPC hydrogels was relatively constant. It was found during the measurement that no air bubbles were adsorbed on the surfaces of SiMA-ipn-MPC(30) and SiMA-ipn-MPC(45); hence, the SCAs of these two samples were recorded as 0°. This was a direct indication of the superhydrophilicity of these hydrogels. The difference in the surface hydrophilicities of the hydrogels was related to the difference in surface compositions of the MPC units synthesized by the hybridization method.

Fig. 5 Water content and surface hydrophilicities of SiMA-co-MPC.

Fig. 6 Water content and surface hydrophilicities of SiMA-ipn-MPC.

The presence of phosphorous is strong evidence of the presence of the polar phospholipids group. Fig. 7 shows results of the XPS measurements. The P/Si ratio in the SiMA-ipn-MPC hydrogels increased drastically with the MPC content, unlike that in the SiMA-co-MPC hydrogels. This increase did not correspond to the theoretical values. This indicated that the MPC units in the SiMA-ipn-MPC hydrogels were enriched at the surface.

Fig. 7 Surface composition of phosphorous determined from the XPS spectra. The broken line represents the value calculated from the bulk composition of the hydrogels.

Fig. 8 Microscopic FT-IR image of the distribution of MPC units in the hydrogels.

Fig. 8 shows the microscopic FT-IR images of the MPC unit in the hydrogels. From these images, it can be observed that the MPC unit was located in the SiMA-co-MPC hydrogels homogeneously. On the other hand, the MPC unit introduced into the SiMA-ipn-MPC hydrogels showed surface condensation and gradient in bulk material. This result also indicates that the superhydrophilicity of the hydrogel surfaces was due to the surface condensation of the MPC units.
3.3 Mechanical properties of the hydrogels

Table 2 shows the Young’s modulus of the hydrogels. While SiMA-co-MPC hydrogels had a low Young’s modulus, SiMA-ipn-MPC hydrogels had high Young’s modulus. This is the distinct structural characteristic of these hydrogels. This observation implies that the elasticity of the SiMA-ipn-MPC hydrogels can be controlled by adjusting the mechanical properties of the SiMA gel.

<table>
<thead>
<tr>
<th>Hydrogel</th>
<th>Young’s modulus (MPa)</th>
<th>Equilibrium water content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiMA-co-MPC(10)</td>
<td>10</td>
<td>16.0</td>
</tr>
<tr>
<td>SiMA-co-MPC(19)</td>
<td>8</td>
<td>32.1</td>
</tr>
<tr>
<td>SiMA-co-MPC(28)</td>
<td>8</td>
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<td>SiMA-ipn-MPC(10)</td>
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<tr>
<td>SiMA-ipn-MPC(30)</td>
<td>40</td>
<td>29.7</td>
</tr>
</tbody>
</table>

3.4 Oxygen permeability

Generally, the oxygen permeability of conventional hydrogel lenses increases with the EWC because oxygen is transported by dissolution in water. However, the oxygen permeability of silicone hydrogel lenses decreases with an increase in the EWC because oxygen also dissolves directly into the silicone component. Fig.9 shows the results of the oxygen permeability measurements. The oxygen permeabilities of the two types of hydrogels synthesized in this study were as high as those of commercial silicone hydrogels, and they decreased with an increase in the EWC. This indicates that the high oxygen permeability of the SiMA units is independent of the hybridization method.

![Fig.9 Change in the oxygen permeability of hydrogels with the water content.](image)

3.5 Protein adsorption

Fig.10 shows the results of the protein adsorption test. The surfaces of all the hydrogel samples synthesized in this study had better resistance to protein adsorption than do those of commercially available soft contact lenses. Moreover, the amount of adsorbed protein decreased because of the large number of MPC units in the hydrogels. This means that the resistance shown by the MPC units to protein adsorption independent of the hybridization method.

4. CONCLUSION

We synthesized hybrid silicone hydrogels composed of SiMA and MPC by two methods—copolymerization and construction of the IPN structures. The obtained IPN hydrogels had high optical transparency and good surface hydrophilicity. Further, they had good mechanical properties and oxygen permeabilities because of the SiMA unit and excellent resistance to protein adsorption because of the MPC units. XPS and microscopic FT-IR analysis revealed that the superhydrophilicity of the IPN hydrogel surface was because of the surface enrichment of the MPC units. On the basis of these results, the IPN hydrogels composed of SiMA and MPC were confirmed to be suitable for the fabrication of continuous-wear soft contact lenses.

Acknowledgement

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Reference


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