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Fabrication of Spiropyran-functionalized Photochromic Hydrogel Lenses

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Abstract

Poly(hydroxyethyl methacrylate)-based hydrogels were surface-functionalized with spiropyran (SP) derivatives to obtain photochromic contact lenses. The contact lens reversibly changes from colorless to purple as response to UV light since colorless ring-closed SP state converts to purple ring-opened merocyanine (MC) state under UV light irradiation. The purple contact lens emits red light at 640 nm. Importantly, the presence of SP segments did not significantly affect the equilibrium water content (EWC) of the lens. SP-functionalized hydrogel lenses may find potential applications in developing light-adaptive ophthalmic materials.

Keywords: Spiropyran, Hydrogel, HEMA, Photochromic.

1. Introduction

Hydrogels are three-dimensional polymers capable of containing a large percentage of water similar to body tissues. Its biocompatibility makes it suitable for various biomedical applications such as drug delivery and scaffold for tissue engineering[1]. Especially, hydrogels have been used as contact lenses for vision correction, cosmetic purposes and ocular drug delivery[2,3]. Wichterle's work on the synthesis of poly(hydroxyethyl methacrylate) (PHEMA)-based hydrogels led to the invention of the first soft contact lenses[4]. Polymerization of HEMA produced a comfortable and water-absorbing hydrogel exhibiting a water swollen structure with good transparency, making it the traditional material for soft contact lens.

Recently, smart hydrogels have been developed with properties controllable by external stimuli such as temperature, pH, light and others. In particular, light is an attractive option since it can be controlled both spatially and temporally with great precision and convenience[5]. Various light-responsive materials such as azobenzene, bisthienylethene, phenoxyquinone and spiropyran (SP) have been studied. Among these materials, spiropyran (SP) and its derivatives have attracted great attention because of their facile synthesis and of the observable difference between their isomers[6]. The photochromicity of SP originates from the cleavage of the spiro C-O bond and subsequent formation of the planar merocyanine (MC) configuration upon UV light irradiation[7]. The colorless SP state transforms to a purple MC upon UV-light irradiation, but reverse-transformation to SP state occurs with visible light irradiation[8]. This makes SP derivatives ideal for use in optical memory devices, sensors, drug delivery, data storage and bioimaging technology[9-11].

In this study, photochromic hydrogel contact lenses were prepared by using SP derivatives. Pre-formed P(HEMA) hydrogels were surface-modified with SP derivatives via esterification reactions (Fig 1). Absorbance, emission and water content of the resulting hydrogels were investigated. The hydrogels exhibited an excellent photochromic property with specific light irradiation.

2. Materials and Methods

2.1. Chemicals and Equipment

2-Hydroxyethyl methacrylate (HEMA) was purchased

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from Junsei (Japan), ethylene glycol dimethacrylate (EGDMA), Azobisisobutyronitrile (AIBN), 4-dimethylaminopyridine (DMAP) were purchased from Sigma-Aldrich. N,N-dicyclohexylcarbodiimide (DCC) was purchased from GL Biochem. Carboxylic acid derivative of spiropyran (SP-COOH) was synthesized according to previously reported procedures[10]. Dimethylformamide (DMF) and other reagents were analytical grade and used without further purification. The absorption spectra of the hydrogel lenses were measured at a wavelength range of 285-750 nm, in triplicate, with a Shimadzu, UV-1650PC (Japan) spectrophotometer. The ^{1}H-NMR spectra were recorded using JEOL JNM-AL300 (Japan). The emission spectra were measured with Hitachi F-7000 fluorescence spectrophotometer (Japan). The hydrogels were illuminated with UV-light at 365 nm (UV-Model LV, France; 8 mW cm^{-2}) or with white LED (SM400-1, Korea; 48 W).

2.2. Synthesis of Photochromic P(HEMA) Contact Lenses

HEMA monomer was purified through vacuum distillation before polymerization. P(HEMA) contact lens was prepared by dissolving 0.04 g of EGDMA and a small amount of AIBN in 9.92 g of HEMA. After 30 min of sonication, the solution was injected to polypropylene contact lens molds and oven-dried at 80°C for at least 4 hrs. The contact lenses were removed from the molds, soaked in distilled water to remove unreacted monomers and initiators, and further oven-dried at 40°C for at least 5 hrs. The contact lenses were immersed in DMF containing SP-COOH, DMAP and DCC at 0°C to RT. Finally, they were washed with ethanol and distilled water for 24 hrs to remove excess reactants.[12]

2.3. Measurement of Equilibrium Water Content (EWC)

$$\% \ EWC = (W_w - W_d)/W_w \times 100 \quad (1)$$

where W_w and W_d are the masses of the fully hydrated and dry lenses, respectively.[13] The water content of the lenses was measured gravimetrically. The lenses were soaked in distilled water for 24 hrs at room temperature. Before weighing, excess water on the surface of the lens were removed by placing the lens on clean, dry Kimtech wipes, folding the wipes over the lens and lightly pressing them. After drying inside the oven at 50°C for 24 hrs, the dried lens was weighed. This was repeated for five samples and %EWC was calculated using Eq. 1.

3. Results and Discussion

Conventional P(HEMA) hydrogel lens is made by polymerizing HEMA with ethylene glycol dimethacry-

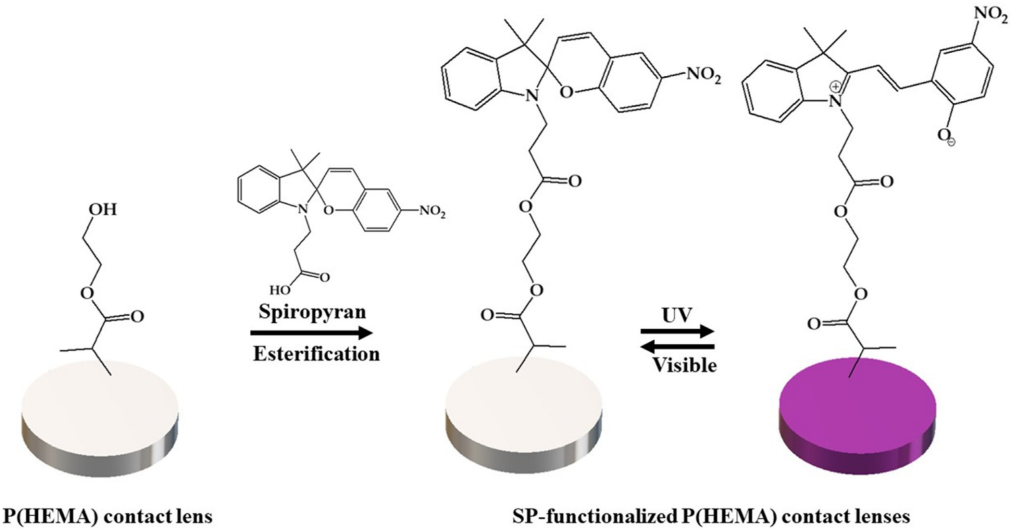

Fig. 1. Schematic representation of development of photochromic hydrogel contact lenses functionalized with spiropyran.

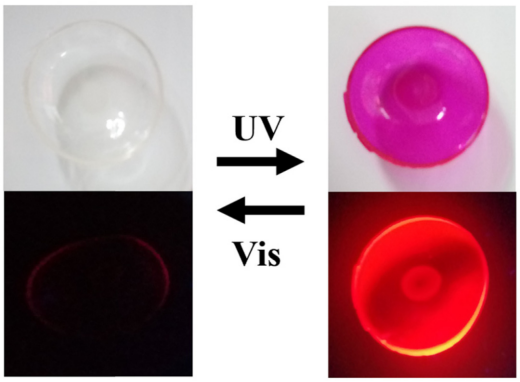

Fig. 2. (a) Photographs (top) and (b) fluorescence images (bottom) of spiropyran-functionalized hydrogel lenses before and after UV irradiation at 365 nm for 3 min.

late (EGDMA) as crosslinker and azobisisobutyronitrile (AIBN) as the radical initiator. The resulting polymer contains hydroxyl groups available for functionalization. SP-COOH containing carboxylic acid groups was embedded onto the contact lens via esterification between the -OH group of P(HEMA) and the -COOH moiety of SP-COOH[10]. This produced a photochromic hydrogel lens that changes from colorless to purple upon absorption of UV light (Fig. 1 and 2). The presence of SP units on the lens surface was confirmed by the strong absorbance in the 200 to 380 nm UV range. By means of Beer's Law linear regression at 338 nm based on the calibration curve of free SP having a concentration range of 0.1-0.4 mM, the amount of SP on the surface of the lens was determined to be 0.0935± 0.006 μmol/cm^2.

The SP-modified lenses become purple upon irradiation with UV light at 365 nm for three minutes. The purple lens exhibits strong absorbance in the visible region, with a peak at around 544 nm, corresponding to the conversion of SP state to the MC form (Fig. 3). This is accompanied by the appearance of a strong red fluorescence emission at around 640 nm (excited at 348 nm) as shown in Fig. 4. Importantly, the purple color of lenses disappears gradually and emission intensity at 640 nm significantly decreases when exposed to visible light emitting diode (LED). This result indicates a reversible conversion from the purple MC form to the colorless SP form in the hydrogel states.

The equilibrium water content (EWC) is an important parameter in the contact lens since it represents the abil-

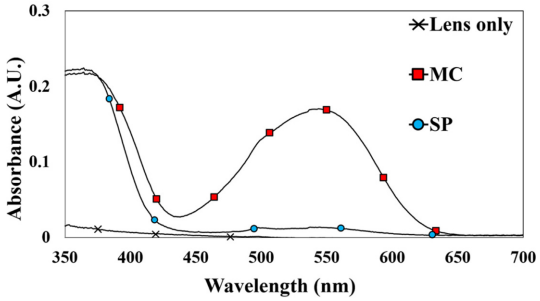

Fig. 3. Absorption spectra of the pristine and spiropyran-conjugated contact lens before and after 365 nm UV irradiation for 3 min.

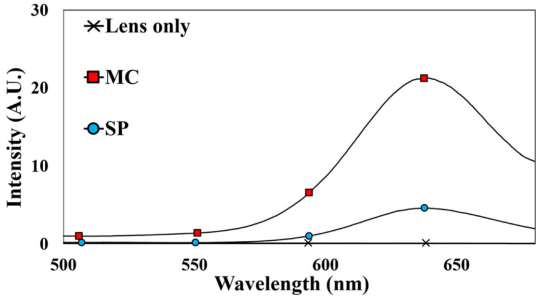

Fig. 4. FL emission spectra (EW = 348 nm) of the pristine and spiropyran-conjugated contact lens before and after 365 nm UV irradiation for 3 min.

Table 1. EWC (%) of the hydrogel lenses

Hydrogels	Water Content (%)
P(HEMA)	38.24 ± 0.43
P(HEMA) with SP	39.27 ± 1.97

Data are means±SD (n =5)

ity of the contact lens to retain water and serves as an indication of its clinical behavior. The usual EWC of hydrogel lenses is >38%, which contributes to their softness.[14] The surface conjugation of SP did not affect the ability of the lens to bind water. The equilibrium water content (EWC) of the SP-conjugated contact lenses is 39.27±1.97%. This result is not significantly different from the water content of the pristine contact lens (Table 1), as the amount of attached SP was too small.

One of most important aspects of synthesizing SP-based photochromic materials is the effectiveness of their response to external stimuli. When the hydrogels were prepared by a copolymerization process using SP

monomer, the SP segment is captured in small pores in the hydrogel network. The entrapped compounds are prevented from interconverting between the SP and MC states, and thus their photochromic ability is lost. One practical strategy to obtain efficient structural conversion of SPs is the surface-immobilization of SP derivatives onto the hydrogels.[15] Herein, we functionalized SPs onto the surface of pre-formed hydrogels to allow the large free volume to SP segments, and the successful photochromic ability was obtained. Furthermore, photochromic process of the hydrogel could be performed at least five times.

4. Conclusions

The results presented here show the novel synthesis of a photochromic hydrogel contact lens. P(HEMA)-based hydrogel was firstly synthesized and the subsequent surface-modification with SP derivatives yielded the photochromic contact lens. The resulting contact lens changes from colorless to purple upon UV-light irradiation. The contact lenses exhibited reversible color change with exposure to visible light. Notably, the equilibrium water content of the lenses was preserved. The facile method of preparing photochromic hydrogel lenses described herein could be a significant contribution in the development of light-adaptive ophthalmic materials.

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