Smart Lenses Developed with High-Strength and Shape Memory Gels

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Most of lenses embedded in optical devices used today are as hard as a glass and not deformable. Therefore, it is needed to move the positions of the lenses in focusing and zooming. Actual optical devices sometimes become complex and large. Here we improve Double Network gel lens and newly propose deformable lens system by virtue of high-strength, transparent and transformable hydrogels. Shape-Memory gels are applied to the deformable lens systems. The focal length of DN gel lens was controlled by the degree of swelling of gels. In the deformable lens systems a water layer is sandwiched between two gel sheets to compose a variable focus lens. By changing the pressure of the water layer, the radius of convex curvature of the gel sheet surface can be controlled, and the focal length of the lens can be adjusted. Further, the SMG lens can memorize its shape, so that the focal length can be fixed. The DNG and SMG lenses bring new possibilities to develop actuated gel lenses, which are simple and small, but highly functionalized. [DOI: 10.1380/ejssnt.2012.243]

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I. INTRODUCTION

All the creations on the earth consist of a soft tissue containing much water. For example, while the water contents of vitreous body and crystalline lens of human eyes are 99% and 66%, they provide clear image without breaking under compression stress. Since the natural soft tissues in human body are perfect, it is difficult to make artificial substitute. Indeed, artificial lens which is developed as an alternative to real crystalline lens of human body is much harder than real one, thus, difficult to be deformed. This property will bring many problems, such as the difficulty of the adjustment of focus distance and, even worse, secondary cataract. The artificial lens for human eyes has been already developed by silicone. Since the silicone lens does not contain enough water, the friction coefficient is high. This is the reason why the accumulation of proteins is occurred. Besides, any materials and water cannot penetrate the silicone lens unlike the real one. For these reasons, the current artificial lens does not have enough biocompatibility.

In our previous research, Double Network (DN) gel lens is proposed as trial manufacture in order to make biocompatible artificial lens [2, 5]. The characteristic of non-toxicity of DN gels is already confirmed, since DN gels is used as test beds for cell culture [6–8]. DN gels has high-strength hydrogels, which has two polymer networks in gels. One polymer component is hard and brittle network, called 1st gels. The other is soft and ductile network, called 2nd network gels. As a first step of making DN gels, the 1st gels is made by electrolyte polymer, then, the 1st gel is soaked in 2nd gels solution containing neutral polymer. The structure of DN gels is Interpenetrating Polymer Networks. The schematic of DN gels is shown in Fig. 1.
FIG. 2: The schematic of Shape Memory Gel (SMG): The main chain of SMG is made by flexible and crystalline monomer. The property of crystalline monomer is depending on temperature, that is, it can be flexible by heating and it can keep the shape by cooling.

In this study, the DN gel lens is improved by controlling the swelling of water to keep effective shape for working as lens, and a varifocal lens system is newly proposed. For the varifocal lens system, shape memory gels is used to keep original shape. Shape memory gels (SMG) is covalently-bonded copolymerized gels consisting of flexible polymers and crystalline polymers [1, 4]. The covalent bonding of two kinds of polymers makes main chains, and main chains have side chains due to the crystalline polymers. The side chains behave like crystalline in lower temperature, while behave like amorphous in higher temperature, which is the key characteristics of shape memory as shown in Fig. 2. Indeed, SMG is like plastic plate at room temperature, while Young’s modulus of SMG is suddenly decreased at higher temperature than 50°C. The ability of the varifocal lens system was examined by maximizing and minimizing alphabets in this study, which is obligatory for lens system. This system can be used repeatable.

II. EXPERIMENTAL

A. Synthesis of the DN gels and Fabrication of the DN gel lens

For the 1st networks of DN gels, 2-acrylamido-2-methyl-1-propane sulfonic acid sodium salt (NaAMPS, SIGMA-ALDRICH CHEMIE GmbH, Japan) monomer (50 wt.% solution in water) was used to make polymer. N,N’-methylenebisacrylamide (MBAA, Wako Pure Chemical Industries ltd., Japan) was used as a crosslinker and -keto glutaric acid (-keto, Wako Pure Chemical Industries ltd., Japan) was used as an initiator. The NaAMPS concentration in aqueous pregel solution was 1 M, and the MBAA and -keto concentrations were 4 mol% and 0.01 mol%. For the 2nd networks of DN gels, dimethyacrylamide (DMAAm, TOKYO CHEMICAL INDUSTRY CO., LTD., Japan) monomer was used to make polymer. MBAA and -keto are also used. The DMAAm concentration in aqueous pregel solution was 1 M, and the MBAA and -keto concentrations were 0.02 mol% and 0.1 mol%. Precise protocol to make DN gels plate is described our previous paper [2].

DN gel lens were made by sandwiching the pregel solution between two plano-concave lenses under UV irradiation as described our previous paper [2]. Well-formed DN gels lens was made in this study, as shown in Fig. 3. In order to keep the focal length of lens, it is important to control degrees of swelling, which is affected by solvent and storage solution. Eight types of combinations for minimizing the degree of swelling were examined as shown in Table I. Solvent 1 means the solvent for 1st pregel solution, solvent 2 means as the same for 2nd gel, and the DN gel lens is stored in Storage solution. These gels were measured water content ratio by Moisture Analyzer MS-70 (A&D CO., LTD., Japan).

B. Synthesis of the SMG and Fabrication of the varifocal gel lens system

For synthesis of SMG, Stearyl Acrylate (SA, Wako Pure Chemical Industries ltd., Japan) monomer was used as a crystal component of SMG. DMAAm monomer was used as a hydrophilic flexible component of SMG. SA and DMAAm will make main chain by covalent bonding. The ratio of SA to DMAAm was 1:3 in molar concentration. MBAA was used as a crosslinker, Benzophenone (Wako Pure Chemical Industries ltd., Japan) was used as a photo initiator. For the preparation of the SMG, SA and DMAAm monomers concentration in aqueous pregel solution was 1 M in total, the concentrations of MBAA and Benzophenone were 0.05 mol% and 0.1 mol%. The solution was stirred well and the bubbling of nitrogen gas was performed for several tens of minutes to remove oxygen gas from the solution. Then, the solution was poured into the parallel-glasses mold, which sandwiched a silicon spacer of 1 mm in thickness between two pieces of glass plates, and it was irradiated by UV lamp for about 9 hours, and then a SMG films were prepared.

A deformable lens system is proposed by virtue of high-strength, transparent and transformable hydrogels. The concept of the varifocal gel lens is quite simple, which is shown in Fig. 4. In this system, a water layer is sandwiched between two gel sheets. By changing the pressure of the water layer, the radius of convex curvature of the gel sheet surface can be controlled, and the focal length of the lens can be adjusted. SMG were used as two gels sheets. The schematic of the varifocal gel lens system is shown in Fig. 5, which is named Gel Shape-Transformable Yield-
TABLE I: The condition of solvent for synthesizing DN gels: The water content ratio and degree of swelling of gels were affected by the combinations of solvents and preservative solution.

| No. | Solvent 1   | Solvent 2   | Storage solution | Water content ratio (%) | Degree of swelling (%) |
|-----|-------------|-------------|-------------------|------------------------|------------------------|
| 1   | pure water  | pure water  | pure water        | 91.1                   | 116                    |
| 2   | pure water  | pure water  | saline             | 85.9                   | 109                    |
| 3   | pure water  | saline      | pure water        | 87.8                   | 116                    |
| 4   | pure water  | saline      | saline             | 89.1                   | 117                    |
| 5   | saline      | pure water  | pure water        | 86.8                   | 113                    |
| 6   | saline      | pure water  | saline             | 85.0                   | 110                    |
| 7   | saline      | saline      | pure water        | 90.5                   | 120                    |
| 8   | saline      | saline      | saline             | 88.5                   | 117                    |

FIG. 4: The concept of the varifocal gel lens system: The focus length is adjusted by draining and filling the water. The condition (a) and (b) are corresponding to Fig.7.

FIG. 5: The schematic of varifocal gel lens system: The fluids is poured between two gel films.

C. Verification of the Lens systems

Characteristics of the DN gel lens and varifocal gel lens were confirmed by simple experiments. Figure 7 shows the refraction test of the DN gel lens. To visualize the light path of the laser beam, the steam form the boiled water was used. In actual, the DN gel lens was placed above the boiled water and then the refraction test was performed. First, the incident laser beam through the center part of the DN gel lens (a), the laser beam bends at the DN gel lens goes through the acentric part of the lens (b). The scale bar shows 10 mm.

FIG. 6: The real image of the varifocal gel lens: SMG sheets were fixed in the system. The focal length $f$ is controlled by draining and filling water.

FIG. 7: The optical tests of DN gel lens: The laser beam goes straight through the center part of the DN gel lens (a), the laser beam bends at the DN gel lens goes through the acentric part of the lens (b). The scale bar shows 10 mm.
FIG. 8: The confirmation of the focal length: The incident laser beams through the varifocal lens at several distances from the center (a). The focal length $f$ does not depend on the distance from the center at all (b). The focal length $f$ is inversely proportional to the thickness of the varifocal lens, as shown in (c). The Dioptre $1/f$ is approximately proportional to the thickness, which is important for optical devices (d).

FIG. 9: The magnification of the character by the varifocal lens system: The focal length was changed by controlling the water pressure, thus the character was indeed magnified by the lens.

The refraction test. The incident laser beams were passed at several positions from the center, the focal length was measured at each case. The relationship between the focal length $f$ and the thickness of the lens was also calculated. Then the value $1/f$, named Dioptre, was determined as function of the thickness of the lens.

III. RESULTS AND DISCUSSIONS

A. Controlling the Degrees of Swelling

In order to keep the right focal length, it is important to control the swelling of gels. Table 1 shows the water content ratio and the degree of swelling depending on solvents and storage solution. The water content ratios of all the gels were closed to 90%, and the degrees of swelling were closed to 110%. The water content ratio and degree of swelling of No. 2 and No. 6 are smaller than the others, besides, the storage solution is saline. That is nice for controlling the artificial gel lens considering the usage of the lens in human body. Here, No. 2 is chose for DN gel lens, since the Solvent 1 and Solvent 2 are pure water, which is easier to synthesize the DN gels.

B. Evaluation of the lens system

The DN gel lens shown in Fig. 3 was made under the condition of No. 2 solution. In order to examine the ability of the DN gel lens, the laser beam was irradiated to the lens as shown in Fig. 7. The beam went straight through the center part of the lens implies that the lens has a uniform structure. The laser beam bended at acentric part of the lens implying that the lens made from the DN gels also has a good optical power.

Figure 6 shows the varifocal gel lens under the fluids injection state. Water was filled from the fluids inlet. Left picture was natural state and two gels were parallel. The lens worked as biconvex lens under the condition of right picture by filling water. The water was 50° in order to let the SMG film flexible. This system is reversible, and it is possible to keep the shape when the water is cooled under transition temperature of SMG. In this case the focal lengths corresponded to about 15 mm to 50 mm.

The incident laser beams through the several positions from the center of the varifocal gel lens were gathered at a point as shown in Fig. 8(a). As shown in Fig. 8(b) the focal length was observed as a function of the distance by analyzing the digital photos, where the size of the pixel of digital photo corresponded to 0.7 mm. It was found that the focal length did not depend on the distance from the center at all. The result implies that the gel lens is so uniform, that the aberration of the lens is possibly ignored. The relationship between the focal length and the thickness of the lenses was determined as shown in Figs. 8(d, c). It implies that the Dioptre $1/f$ that characterizes the lens was proportional to the thickness. These facts confirmed the gel lens is possibly applied as well as the as optic materials. In actual, the lens system magnifies characters as shown in Fig. 9, implying the system works well as the varifocal gel lens.

IV. CONCLUSION

The biocompatible DN gel lens was developed. The swelling of gels are important for the ability of the lens, which is controlled in this study. The varifocal gel lens system was newly proposed in this study. The SMG give the suitable function to varifocal lens. Each lens has the sufficient function for the crystalline lens, which will be useful for alternatives of human crystalline lens and minimize the optical system in engineering product.

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