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## Molecular Recognition Ion Gating Membranes

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A novel molecular recognition gating membrane was developed. The device facilitates to make a new process showing biomembrane-like systematic functions. The membrane is a porous thin film, and the pores rapidly open and close in response to specific ion signals. Grafted polymer composing of N-isopropylacrylamide (NIPAM) and benzo[18]crown-6 pendent copolymer was fixed onto the surface of the membrane pores. The membrane pores close when the membrane comes in contact with aqueous solution containing  $K^+$ ,  $Sr^{2+}$ ,  $Ba^{2+}$  or  $Pb^{2+}$ , but  $Na^+$ ,  $Li^+$  or  $Ca^{2+}$  ion did not affect the pore closure. The response time is very rapid and reversible, and the pores close within 30 seconds.

### Introduction

Synthetic membrane pores are always open unlike biomembranes. Biomembranes have ion gates and channels, and the system leads to controlling chemical concentration, energy transduction, signal transfer or multi functional complicated systems. Synthetic membranes in next generation should have similar systematic functions to facilitate novel processes.

Hydrogel is a well-known material because of its unique feature of volume transition, and some gels can reversibly phase transit by chemical or ion signals <sup>1,2</sup>. Some molecular recognized gating systems for glucose <sup>3</sup> were also reported, however, the gating effect and speed were not satisfactory.

In this study, we have successfully made a molecular recognized gating membrane using thermosensitive gel with molecular recognized receptor. The concept of this gate membrane is schematically illustrated in Figure 1. <sup>4</sup> The NIPAM, thermosensitive polymer, exhibits dramatic gating effect due to gel swelling and receptor exhibits molecular sensing. The NIPAM has a lower critical solution temperature (LCST), and when the receptor captures a specific substance, the LCST can be shifted due to hydrophilicity change. As a result, the gel can isothermally phase transit by the chemical signal.  $K^+$  or  $Ba^{2+}$  ions were chosen as the specific substance because ions are important for chemical signals in biomembranes.

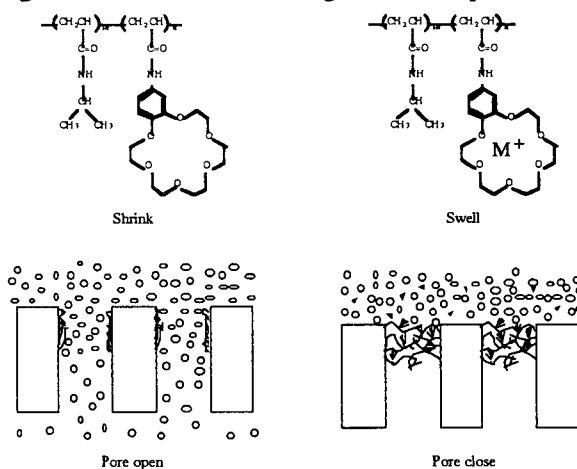


Figure 1. Schematic representative of the gating system using porous membrane having thermosensitive gel and crown ether pendent copolymer on the pore surface.

### Experimental

Synthesis of benzo[18]crown-6-acrylamide (BCAm) is reported elsewhere<sup>5</sup>. Porous polyethylene (HDPE) film, the substrate of 110  $\mu\text{m}$  in thickness, 0.2  $\mu\text{m}$  in pore size, was supplied from Asahi Chemical CO LTD.

Plasma-graft polymerization was employed to fix a linear NIPAM-BCAm copolymer on the pore surface. The grafted polymer is a linear polymer because it grows from a polymer radical formed on a trunk-polymer. Although plasma treatment is well known as a surface modification technique, grafted polymer can be formed inside the porous substrate by controlling the polymerization conditions.<sup>6,7</sup> Plasma-made polymer radicals form mainly on a porous substrate surface, however, a small number of radicals form inside the substrate.<sup>7</sup> The radicals formed inside the substrate can be utilized as an initiator for post-graft polymerization.<sup>6,7</sup> Thus, linear-grafted copolymer attached to the pore surface will be formed in the porous substrate pores, as illustrated in Figure 1. Argon plasma power and treatment period were fixed at 10 W and 60 seconds, respectively. The plasma treated substrate was contacted with air for 60 minutes, and then contacted with monomer solution at 80 °C. For monomer solution, a mixture of NIPAM, BCAM and water solution was emulsified with sodium dodecyl sulfate (SDS). The SDS and total monomer concentrations in solution were fixed at 4 and 5 wt%, respectively. The weight percentage of BCAM in the total monomer was 15 wt%.

A feed solution flowed through the feed side of a membrane cell under a fixed operating pressure, and the permeating flux was measured. To check the membrane response time, two feed solutions containing different ions were prepared, and the solutions were maintained at the same temperature. Each solution was alternately supplied to the membrane cell, and the flux change through the membrane was measured by weight. To check molecular weight cut-off (MWCO) curve of the membrane, dextrans were used as the solute and the concentration was measured by TOC.

### Results and Discussion

The grafted polymer formation profile in the substrate was measured by the microscopic FT-IR mapping method. The results show that NIPAM-BCAm grafted copolymer was formed inside the substrate as has been observed in previous studies using different monomers.<sup>6,7</sup> Both sides of the surface have a higher graft amount because monomers can diffuse from both surfaces, the graft amount decreasing with increase in the distance from both surfaces. The results

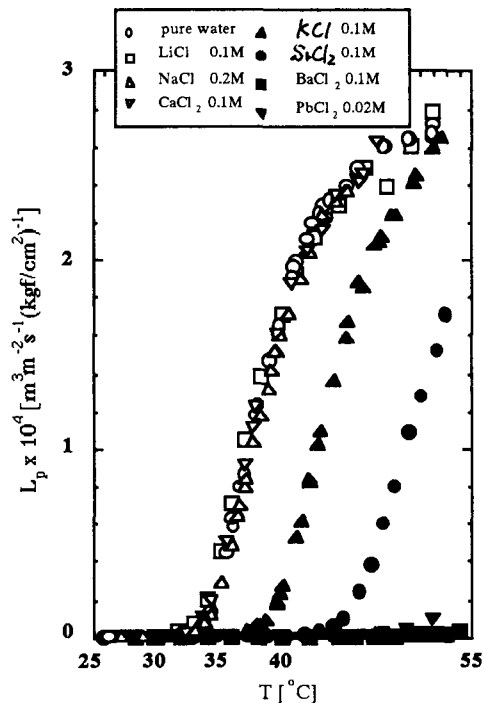


Figure 2. Temperature dependence of solution permeability coefficient containing different ions through PE-g-NIPAM/BCAm membrane.

also show that copolymer composition of the NIPAM-BCAm grafted polymer was almost homogeneous through the membrane.

Poly(NIPAM) has its LCST at 32 °C, the volume being significantly changed by small temperature changes around the LCST. The temperature dependence of the solution permeability coefficient through the membrane is shown in Figure 2. Pure water and water containing ions were used as the feed. For an aqueous solution of LiCl, NaCl or CaCl<sub>2</sub>, the temperature dependence of the solution permeability was almost the same as for pure water. However, for KCl, SrCl<sub>2</sub>, BaCl<sub>2</sub> and PbCl<sub>2</sub> cases, the temperature dependence was significantly different from that of pure water. The dependence agrees well with the stability constants of the crown ether complexes with ions.<sup>8,9</sup> Ba<sup>2+</sup>, K<sup>+</sup>, Sr<sup>2+</sup> and Pb<sup>2+</sup> have high stability constants, and the ion having a higher stability constant is more effectively trapped in the crown ether host. Thus, when the crown ether host was occupied by an ion, the LCST of the polymer changed to a higher temperature, the volume of the gel increased, and the pores closed. Using KCl, SrCl<sub>2</sub>, BaCl<sub>2</sub> and PbCl<sub>2</sub>, the membrane pores closed at the experimental temperature. When a membrane is used at this temperature of around 40 °C, the membrane can recognize specific chemicals and the pores can close. This means that a gating system has been achieved.

The response time for pore opening or closing is shown in Figure 3. When 0.1 M CaCl<sub>2</sub> aqueous solution was supplied to the feed, the membrane pores were open and showed high solution permeability. Then, an aqueous solution containing 0.09 M CaCl<sub>2</sub> and 0.01 M BaCl<sub>2</sub> was supplied to the feed by changing the liquid. The membrane pores suddenly closed and the solution permeability dropped significantly and reached less than one fiftieth of the permeability without Ba<sup>2+</sup>. The crown ether has a high stability constant for complexing with Ba<sup>2+</sup>, and so the Ba<sup>2+</sup> ions are trapped in the crown ether, causing gel swelling to take place. The response time was very short, and when the feed solution was changed the pores closed within 30 seconds. This result shows that both complex formation rate and diffusion rate of ions and water in the gel are very rapid, and these rapid rates produce the fast response gating system. The response time of crosslinked thermosensitive gels is more than 10 minutes or hours; thus, the present gate system shows a faster response. The rate-determining step for the usual crosslinked gel systems is water and substance diffusion in the gel. This gate system has a linear-grafted polymer, and because such a grafted polymer has high mobility, it results in fast diffusion in the gel.

The ion signal can change membrane pore sizes, and we can control membrane MWCO properties by the chemical signal. Figure 4 shows MWCO curve of the PE-g-NIPAM/BCAm membrane with different Ba<sup>2+</sup> concentration

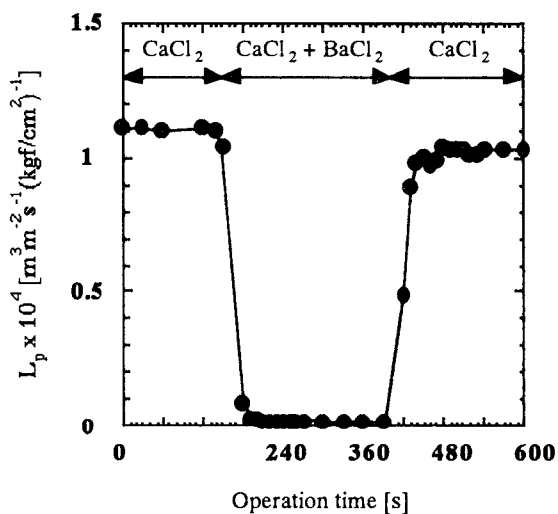


Figure 3. Solution permeability coefficient change in response to Ba<sup>2+</sup> signal.

aqueous solvent. The membrane pore size were measured by observed rejection with dextran having different molecular weight. Solution temperature and dextran concentration were fixed at 38 °C and 90-110 ppm, respectively, and the feed solution was flowed at 500 ml/min. The applied pressure was fixed at 1 kgf/cm<sup>2</sup> except for pure water solvent case. When dextran with pure water was used as the feed solution, lower applied pressure was employed to maintain the same level of flux with 1000 ppm Ba<sup>2+</sup> solvent cases to reduce concentration polarization effect. MWCO curve was shifted to lower molecular weight region with increase in Ba<sup>2+</sup> signal concentration in solution. Thus, the results clearly showed the membrane pore-size can be controlled by specific chemical signal.

This ion gating system can be utilized for many applications like sensors, DDS, artificial organs or new device to transfer chemical signals. When we choose other receptor in gel, we can make a molecular recognized gate system for variety of substances.

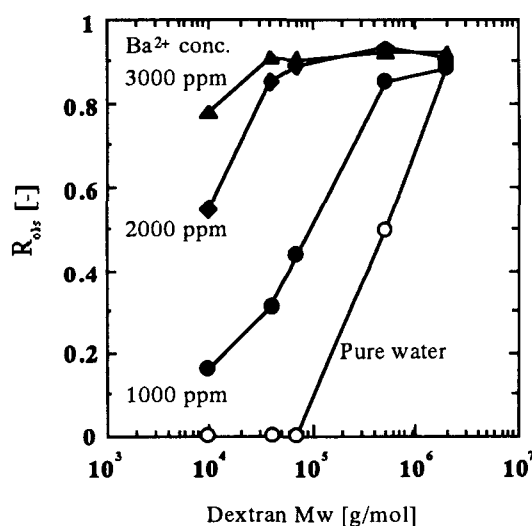


Figure 4. Molecular weight cut-off curves of the ion-gating membrane.

#### References

- 1) Kokufuta, E.; Xhang, Y.-Q.; Tanaka, T. *Nature*, **1991**, *351*, 302.
- 2) Irie, M.; Misumi, Y.; Tanaka, T. *Polymer*, **1993**, *34*, 4531.  
Irie, M. *Advances in Polymer Science*, **1993**, *110*, 49.
- 3) Ishihara, K.; Kobayashi, M.; Shionohara, I. *Macromol. Chem. Rapid Commun.*, **1983**, *4*, 327.
- 4) Yamaguchi, T.; Ito, T.; Sato, T.; Shinbo, T.; Nakao, S., *J. Am. Chem. Soc.*, **1999**, *121*, 4078.
- 5) Ungaro, R.; El Haj, B.; Smid, J. J. *Am. Chem. Soc.*, **1976**, 5198.
- 6) Yamaguchi, T.; Nakao, S.; Kimura, S. *Macromolecules*, **1991**, *24*, 5522.
- 7) Yamaguchi, T.; Nakao, S.; Kimura, S. *J. Polym. Sci., Polym. Chem. Ed*, **1996**, *34*, 1203.
- 8) Izatt, R.M.; Bradshaw, J.S.; Nielsen, S.A.; Lamb, J.D.; Christensen, J.J. *Chem. Rev.*, **1985**, *85*, 271.
- 9) Kopolow, S.; Hogen Esch, T.E.; Smid, J. *Macromolecules*, **1973**, *6*, 133.