Development of a Fast Response Molecular Recognition Ion Gating Membrane

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Common synthetic membrane pores are always open and cannot control the membrane transport properties by themselves. The molecular recognition gate membrane is a more sophisticated device; the membrane can automatically maintain a specific substance concentration, prevent toxic substance leakage, or transfer chemical signals. Important properties in producing a molecular recognition gating function are molecular sensitivity, flux change, and response time for pore opening and closing.

Hydrogel is a well-known material because of its unique feature of volume change, some gels being able to reversibly phase change as a result of chemical[1] or ion signals.[2] Gating membranes using stimuli-responsive hydrogel have been reported. These gates act in response to changes in temperature, ionic strength,[3] electric current,[4] or pH.[5,6] A glucose recognition gating system has also been reported;[7] however, the gating effect and response speed were found to be unsatisfactory. The usual cross-linked gel needs a long time for the volume change because of poor water diffusivity in the gel. In addition, molecule diffusivity in polymers is limited by cross-linking because the cross-linking restricts the chain mobility and results in poor diffusivity.[8] To overcome this, we have employed a linear polymer chain to generate a faster volume change.

In this study, we have made a molecular recognition ion gating membrane using thermosensitive linear polymer with a crown ether receptor. The concept of this ion gate membrane is schematically illustrated in Figure 1. *N*-isopropylacrylamide (NIPAM), a thermosensitive polymer, exhibits a dramatic gating effect due to gel swelling, and the crown ether receptor allows ionic molecular sensing. NIPAM has a lower critical solution temperature (LCST), and when the receptor captures a specific ion, the LCST can be shifted.[2] The polymer chain attached to an ion guest−host complex behaves like an ionic polymer chain, thereby resulting in the LCST changing to a higher temperature due to the osmotic pressure. As a consequence, the gel can isothermally phase change as the result of a specific ion signal at a temperature between the two LCSTs. The linear NIPAM polymer with a pendant crown ether was fixed on the pore surface of a porous substrate. This type of polymer is suitable for making a molecular recognition gate membrane because the gel itself can recognize the chemical signal and the linear polymer may show very fast sensing and high gating properties. Ca^{2+} or Ba^{2+} ions
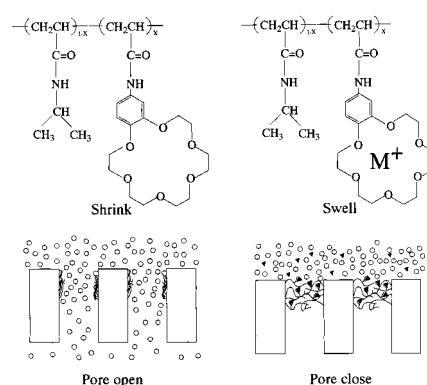

Figure 1. Schematic representation of the gating system using a porous membrane having thermosensitive gel and molecular recognition receptors on the pore surface. When the crown ether host captures specific metal ions, the grafted polymer swells in the pores and closes the pores. When metal ions are removed from the crown ether host, the polymer shrinks and the pores open.

were chosen as the test substance because ions are important for chemical signals in biomembranes.

Synthesis of benzo[18]crown-6-acrylamide (BCAm) is reported elsewhere.[9,10] NIPAM was used after purifying by reprecipitation in benzene. Porous polyethylene (HDPE) film was used as the porous substrate. The HDPE substrate of 110 μm in thickness, 0.2 μm in pore size, was supplied by 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.[12,13] Plasma-made polymer radicals form mainly on a porous substrate surface; however, a small number of radicals form inside the substrate.[13] The radicals formed inside the substrate can be utilized as an initiator for post-graft polymerization.[12,13] Thus, linear-grafted copolymer attached to the pore surface will be formed in the porous substrate pores, as illustrated in Figure 1. The argon plasma power and treatment period were fixed at 10 W and 60 s, respectively. The plasma-treated substrate was in contact with air for 60 min, and then in contact 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.

The grafted polymer formation profile in the substrate was measured by the microscopic FT-IR mapping method. The membrane sample was sliced with a microtome, and the sliced

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(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. *Adv. Polym. Sci.* **1993**, *110*, 49.
(3) Ito, Y.; Nishi, S.; Park, Y. S.; Imanishi, Y. *Macromolecules* **1997**, *30*, 5856.
(4) Kwon, I. C.; Bae, Y. H.; Kim, S. W. *Nature* **1991**, *354*, 291.
(5) Ito, Y.; Inaba, M.; Chung, D. J.; Imanishi, Y. *Macromolecules* **1992**, *25*, 7313.
(6) Mika, A. M.; Childs, R. F.; Dickson, J. M.; McCarry, B. E.; Gagnon, D. R. *J. Membr. Sci.* **1995**, *108*, 37.
(7) Ishihara, K.; Kobayashi, M.; Shionohara, I. *Macromol. Chem. Rapid Commun.* **1983**, *4*, 327.
(8) Yamaguchi, T.; Tominaga, A.; Nakao, S.; Kimura, S. *AIChE J.* **1996**, *42*, 892.

(9) Ungaro, R.; El Haj, B.; Smid, J. *J. Am. Chem. Soc.* **1976**, 5198.
(10) Yagi, K.; Ruitz, J. A.; Sanchez, M. C. *Macromol. Chem. Rapid Commun.* **1980**, *1*, 263.
(11) Suzuki, M.; Kishida, A.; Iwata, H.; Ikada, Y. *Macromolecules* **1986**, *19*, 1804.
(12) Yamaguchi, T.; Nakao, S.; Kimura, S. *Macromolecules* **1991**, *24*, 5522.
(13) Yamaguchi, T.; Nakao, S.; Kimura, S. *J. Polym. Sci., Polym. Chem. Ed.* **1996**, *34*, 1203.
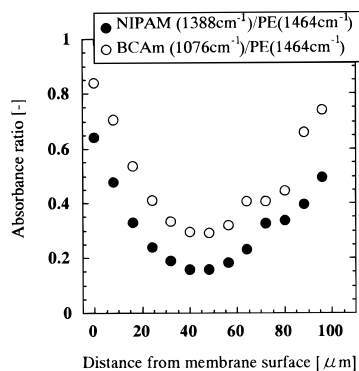
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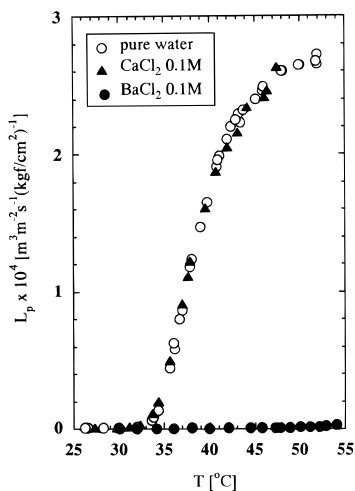**Figure 2.** Grafted polymer formation profile in the substrate.

Figure 3. Temperature dependence of the solution permeability coefficient for water containing different ions through the PE-g-NIPAM/BCAm membrane. Effective membrane area was 13.2 cm^2, and the feed flow rate was 500 mL/minute. The applied pressure was maintained between 0.3 and 0.5 kgf/cm^2. The permeability coefficient, L_p was used instead of solution flux to correct for the applied pressure difference and the temperature dependence of solution viscosity. The permeability coefficient was corrected based on the viscosity of water at 20 °C.

sample was scanned by FT-IR. Spectra were collected each step of 10 μm or less across in the direction of the membrane thickness. The aperture size of each measurement was 10 × 50 μm. Poly-(NIPAM), poly(BCAm), and polyethylene had characteristic peaks at 1388, 1076, and 1464 cm^{-1}, respectively. The height ratio of each characteristic peak to the polyethylene substrate peak corresponds to the grafted polymer composition. Figure 2 shows the profile of the FT-IR absorbance ratio of the NIPAM or BCAm peak to the polyethylene peak in the membrane. The absorbance ratio was plotted against the distance from the membrane surface. The graph shows that NIPAM−BCAm grafted copolymer was formed inside the substrate as has been observed in previous studies using different monomers.[12,13] Both sides of the surface have a higher graft amount because monomers can diffuse from both surfaces, the graft amount decreasing with the increase in the distance from both surfaces. The graph also shows 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 3. Pure water and water containing ions were used as the feed. For an aqueous solution of CaCl$_2$, the temperature dependence of the solution permeability was almost the same as for pure water. However, for BaCl$_2$, the temperature dependence was significantly different from that of pure water. The dependence agrees well with the
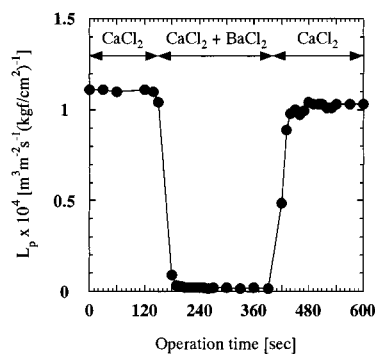

Figure 4. Solution permeability coefficient change in response to the Ba^{2+} signal. Aqueous solutions containing 0.1 M CaCl$_2$ and 0.09 M CaCl$_2$ with 0.01 M BaCl$_2$ ions were prepared, and the solutions were supplied to the membrane alternately. The solution temperature, the feed flow rate, and the applied pressure were kept at 38 °C, 500 mL/minute and 0.3 kgf/cm^2, respectively.

stability constants of the crown ether complexes with ions.[14,15] Ba^{2+} has a high stability constant, 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 BaCl$_2$, 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 4. When 0.1 M CaCl$_2$ 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$_2$ and 0.01 M BaCl$_2$ 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^{2+}. The crown ether has a high stability constant for complexing with Ba^{2+}, and thus the Ba^{2+} 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 s. 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 cross-linked thermosensitive gels is more than 10 min or hours;[5,16] thus, the present gate system shows a faster response. The rate-determining step for the usual cross-linked 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.

When the feed solution was changed to an aqueous solution of 0.1 M CaCl$_2$ from the aqueous solution containing 0.09 M CaCl$_2$ and 0.01 M BaCl$_2$, Ba^{2+} was easily removed from the crown ether, the gel was shrunk, and the pores were opened. This response was also prompt, the initial flux being recovered within 30 s. Again, the decomposition rate of the complex and ion and water diffusivity in the gel were fast, and the quick gating system could be reversibly operated. The membrane showed reproducible and durable gating properties throughout our experiments.

(14) Izatt, R. M.; Bradshaw, J. S.; Nielsen, S. A.; Lamb, J. D.; Christensen, J. J. *Chem. Rev.* **1985**, *85*, 271.
(15) Kopolow, S.; Hogen Esch, T. E.; Smid, J. *Macromolecules* **1973**, *6*, 133.
(16) Yoshida, R.; Uchida, K.; Kaneko, Y.; Sakai, K.; Kikuchi, A.; Sakurai, Y.; Okano, T. *Nature* **1995**, *374*, 240.