Article

Thermoresponsiveness of Carboxylated Polyallylamines Induced by Divalent Counterions as Ionic Effectors

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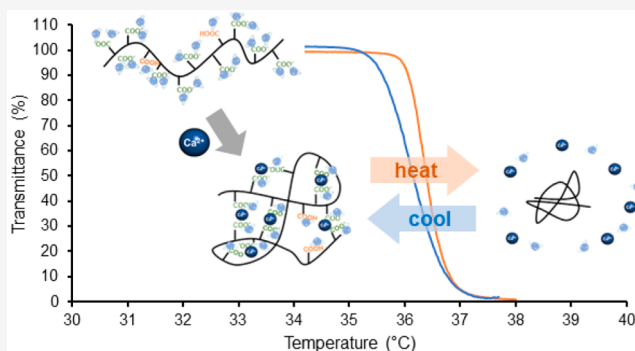
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ABSTRACT: We describe novel ionic effector-induced lower critical solution temperature (LCST)-type thermoresponsive polymers in an aqueous system. Carboxylated polyallylamines (carboxylated PAAs) are conjugates between polyallylamine and various carboxylic anhydrides possessing six-membered rings such as phthalic anhydride and 1-cyclohexene-1,2-dicarboxylic anhydride. These polymers showed LCST-type thermoresponsiveness in the presence of divalent metal ions (Ca^{2+}, Mg^{2+}, or Sr^{2+}) in aqueous media, where a reversible phase transition between soluble and insoluble states was observed with a change in the temperature, although these polymers did not show thermoresponsiveness without divalent ions or with monovalent ions (Li^+, Na^+, or K^+). The cloud points of the carboxylated PAAs could be

precisely controlled by not only salt concentration, pH, salt species, and side-chain structures but also the mixing ratio of different salt species.

INTRODUCTION

Thermoresponsive polymers exhibit a change in their physicochemical properties with temperature,[1−10] in which the control of intermolecular interactions between polymer and solvent or polymer plays a significant role in designing thermoresponsiveness for polymers. Thermoresponsive polymers can be induced by switching the polymer–polymer and polymer–solvent intermolecular interactions at specific temperatures, that is, lower or upper critical solution temperatures (LCST or UCST).[11−14] Poly(N-isopropylacrylamide) (PNIPAM),[1−5] poly(vinyl ether),[6−8] and poly(N-vinyl isobutyramide)[9−11] are representative thermoresponsive polymers with an LCST in aqueous media. Below the LCST, water molecules interact with the hydrophilic moieties of polymers such as amide groups or polyether via hydrogen bonding. The hydrogen bonding between polymer and water molecules weakens above the LCST because of the enthalpic stabilization of water molecules, leading to precipitation of polymers from the aqueous phase.

A novel strategy for providing and regulating thermoresponsiveness to polymer species has been recently developed based on ternary systems by adding effectors to polymer and solvent systems.[2,15,16] In the ternary systems, organic molecules that can interact with polymers and regulate their solubility in the solvents are added as effectors, leading to the a posteriori acquisition of thermoresponsiveness for nonthermoresponsive polymers. As a representative, polymers with urea groups at side chains are insoluble in nonpolar organic solvents because of strong intermolecular hydrogen bonding

among polymers, whereas the addition of various organic molecules with hydrogen-bonding capability provided a thermoresponsive soluble−insoluble phase transition for the polymers.[2,17] In addition, charge transfer complex formation between polymer and effector causing solvation can provide a posteriori acquisition of thermoresponsiveness of polymers.[16,18] These effector-induced thermoresponsive polymers occur in organic solvent systems, but they are not limited to organic solvent systems and have also been reported in aqueous systems. The combination of water-insoluble hydrophobic polymers having bulky adamantyl groups at the side chain and cyclodextrin exhibits effector-induced thermoresponsiveness in an aqueous medium through the inclusion of the adamantyl groups in the cyclodextrin.[19−21] The supramolecular interaction between an adamantyl group and cyclodextrin weakens at increased temperature, leading to dissociation of the inclusion by cyclodextrin and precipitation of the hydrophobic polymers. Also, the ionic effector system in aqueous media has been reported for USCT-type thermoresponsiveness of poly(N,N-dimethylaminoethyl methacrylate) with trivalent metal hexacyano anions such as $[Co(CN)_6]^{3-}$,
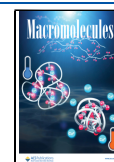
$[Fe(CN)_6]^{3-}$, $[Cr(CN)_6]^{3-}$, and $[Fe(CN)_6]^{3-}$ due to the electrostatic interaction between the anionic counterion and the cationic polyelectrolyte.[22−24] Thus, several examples based on effector-induced thermoresponsive polymers have been reported on the combination of polymer and organic small molecules.

Herein, we describe ionic effector-induced LCST-type thermoresponsive polymers in aqueous media as a novel type of effector-induced thermoresponsive polymer. The polymer prepared from the reaction of polyallylamine (PAA) and carboxylic anhydrides (carboxylated PAAs) shows LCST-type phase transition behavior in aqueous media containing divalent metal ions (Ca^{2+}, Mg^{2+}, or Sr^{2+}) as effector ions (Scheme 1).

Scheme 1. Thermoresponsiveness of Carboxylated Polyallylamine (PAA) Induced by Divalent Counterions
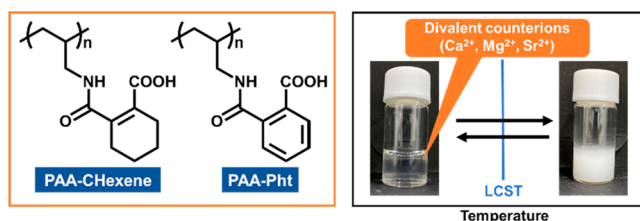
From the evaluation of the effects of the concentration of Ca^{2+} ion and polymer as well as pH at the cloud points, it was found that divalent metal ions induced the conformational change of carboxylated PAA, resulting in aggregation with dehydration

and Ca^{2+} release at a certain temperature with an increase in temperature. As introduced above, the conventional effector-induced LCST-type thermoresponsiveness has used a small organic molecule as an effector, but the system with metal ions has never been reported as far as we know. The critical advantage of this system is the easy design of their thermoresponsiveness by changing ionic species and their mixture. We believe that this type of thermoresponsive polymer using an ionic effector will allow the flexible design of thermoresponsive polymers in aqueous media.

■ RESULTS AND DISCUSSION

A conjugation reaction between poly(allylamine hydrochloride) (PAA-HCl) and phthalic anhydride was performed in carbonate buffer (pH 9.5) to prepare carboxylated water-soluble polymer (PAA-Pht). From the ^1H NMR spectra of the obtained PAA-Pht and original PAA, the methylene peak of the side chain in the original PAA ($\delta \approx 2.6$ ppm) shifted to $\delta \approx 3.4$ ppm after the reaction because of amide linkage formation, indicating that the conjugation reaction between PAA-HCl and phthalic anhydride proceeded (Figure 1a). The primary amines of PAA were almost completely converted to carboxylates because the original peak ($\delta \approx 2.6$ ppm) disappeared. From an acid−base titration (Figure S1), the apparent pK_a of PAA-Pht was estimated to be ∼5.9.

It was found that the PAA-Pht shows thermoresponsive properties in the presence of specific ionic species as a third component in water. The thermoresponsive property of PAA-Pht was evaluated from the change in transmittance at 500 nm
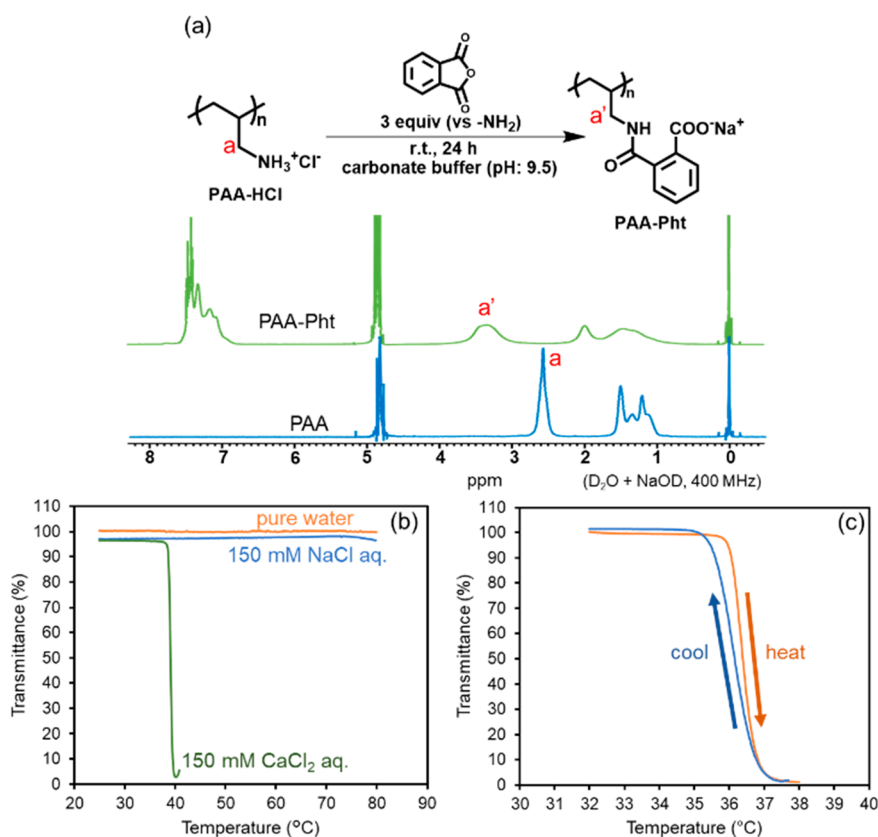

Figure 1. ^1H NMR spectra of PAA-Pht (a, top) and original PAA (a, bottom); changes in the transmittance of PAA-Pht in acidic solution containing no salt, NaCl, CaCl$_2$ (150 mM) (pH 5.2, 4.0 mg/mL) heating by 1 °C/min (b); changes in the transmittance of PAA-Pht in acidic solution containing CaCl$_2$ (150 mM) (pH 5.2, 4.0 mg/mL) heating and cooling by 0.1 °C/min (c).
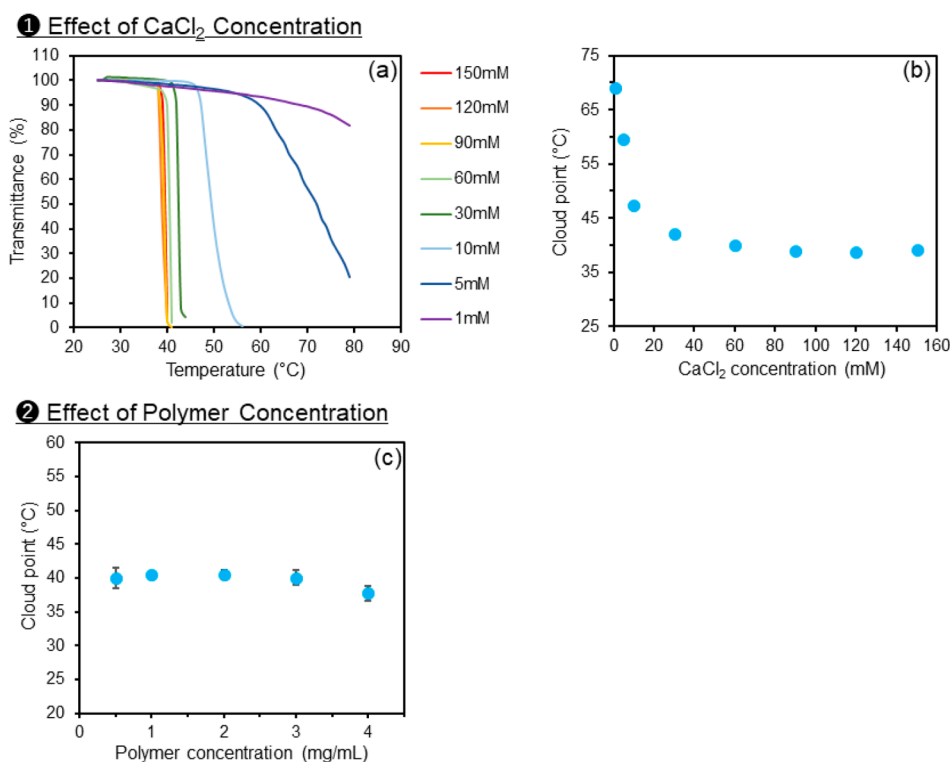
Figure 2. Changes in the transmittance of PAA-Pht in an acidic solution with varying $CaCl_2$ concentration (0.1, 1, 5, 10, 30, 60, 90, 120, and 150 mM) (pH 5.2, 4.0 mg/mL) (a). Plots of cloud points against $CaCl_2$ concentration (b) and polymer concentration (c) (pH 5.2, 150 mM $CaCl_2$ aq) ($n = 4$).

with an increase in temperature for the PAA-Pht aqueous solution. PAA-Pht in deionized water or alkaline metal salts (LiCl, NaCl, or KCl) solution remained transparent from 25 to 80 °C (Figures 1b). Interestingly, the PAA-Pht aqueous solutions with alkaline earth metal ions (Ca^{2+}) showed a steep decrease in the transmittance against an increase in temperature (Figures 1b and S2), indicating that the PAA-Pht in the presence of alkaline earth metal ions (Ca^{2+}) exhibits an LCST-type thermoresponsive property. Also, the cloud points of PAA-Pht in the presence of Ca^{2+} were independent of counteranion species in salts ($CaCl_2$, $CaBr_2$, or $Ca(NO_3)_2$) (Figure S2). The cloud point, which is defined as the temperature when the transmittance reached 90% (90%T), was observed at ~36.1 °C under the heating process (Figure 1c). Furthermore, this change in transmittance with temperature change was almost reversible, and the cloud point determined in the cooling process was 35.7 °C (Figure 1c). In addition, the thermoresponsiveness of PAA-Pht in $CaCl_2$ aqueous solution ($CaCl_2$: 150 mM) was observed even in the presence of NaCl with varying concentrations, and there was a negligible effect of Na^+ ions on the cloud points of PAA-Pht aqueous solutions with Ca^{2+} ions (Figure S3). This suggests the importance of the presence of Ca^{2+} ions for the thermoresponsiveness of PAA-Pht.

Cloud points of PAA-Pht aqueous solutions were evaluated in acid aqueous solutions containing various concentrations of $CaCl_2$ (Figure 2a). The cloud point of the PAA-Pht aqueous solution gradually decreased with increasing $CaCl_2$ concentration from 0.01 to 30 mM, and then, the cloud point became almost constant at ~39 °C in higher $CaCl_2$ concentration (>30 mM) (Figure 2b). The results supported that LCST-type thermoresponsiveness of PAA-Pht aqueous solution was a

Ca^{2+}-ion-induced phase transition. In this experiment, the amounts of Ca^{2+} ions in the precipitated polymers were also calculated from the difference between the original Ca^{2+} concentration and Ca^{2+} concentration in the supernatants quantified by using a Ca^{2+}-ion-selective electrode. The difference from the original concentration with Ca^{2+} concentration in the supernatant was negligible, demonstrating that the precipitated polymers above the cloud points did not include Ca^{2+} ions. That is, Ca^{2+} ions were released with the phase transition of PAA-Pht to the supernatants. These results indicate that the Ca^{2+}-ion-induced thermoresponsive phase transition of PAA-Pht is accompanied not only by dehydration but also by Ca^{2+} ion release with the protonation of carboxylate from the polymers. The dehydration and Ca^{2+} ion release are thermodynamic advantages because of an increase in entropy.

It is possible that Ca^{2+} promotes the intramolecular interaction of polymers because the thermoresponsive phase transition of PAA-Pht is not induced by monovalent Na^+ but by divalent Ca^{2+} (Figure 1b). When the thermoresponsive property of PAA-Pht was triggered by intermolecular interaction between different polymer chains through divalent ions, the polymer concentration affects the cloud points; that is, the cloud point may be decreased with increasing polymer concentration. The effect of polymer concentration on the cloud point of the PAA-Pht aqueous solution was evaluated at a fixed concentration of $CaCl_2$ (150 mM). There was no dependence of the cloud points of PAA-Pht on the polymer concentration in the evaluated concentration range (Figure 2c). Therefore, it is expected that the Ca^{2+}-ion-induced thermoresponsive phase transition is caused by intramolecular interaction of the polymer with divalent Ca^{2+} rather than
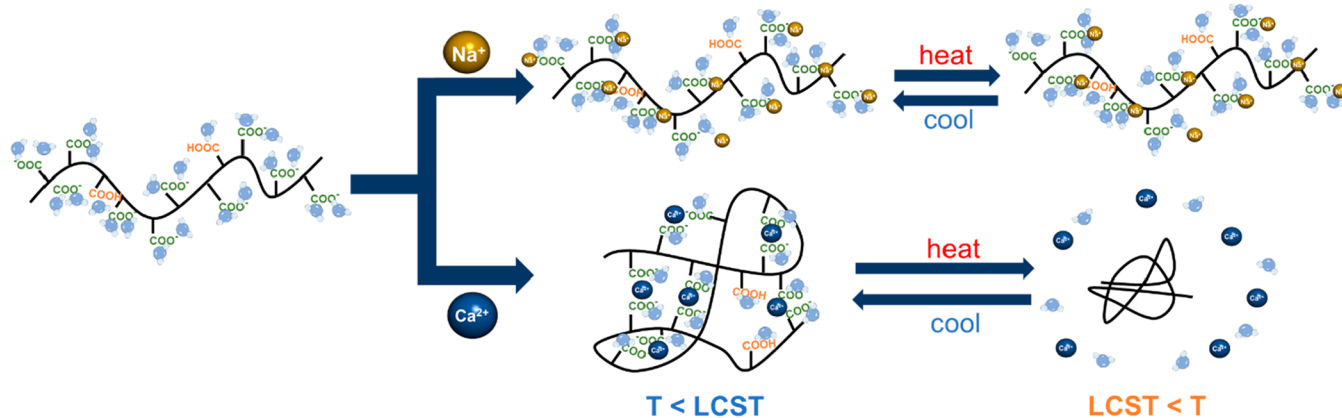
Figure 3. Schematic image of the thermoresponsive mechanism of PAA-Pht with divalent counterions.
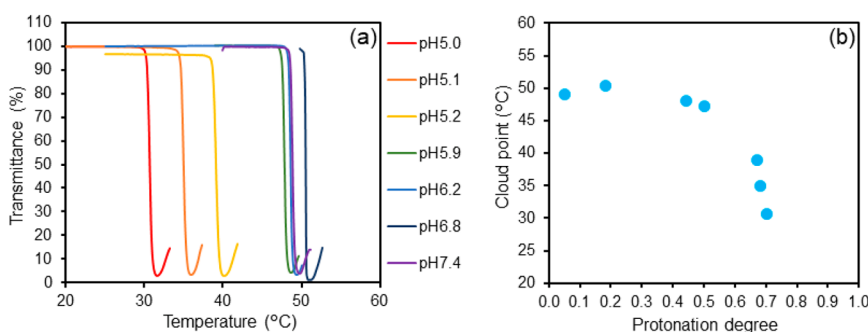

Figure 4. Changes in the transmittance of PAA-Pht in an acidic solution with $CaCl_2$ (150 mM) (pH 5.0, 5.1, 5.2, 5.9, 6.2, 6.8, and 7.4; 4.0 mg/mL) (a). Plots of cloud points against protonation degrees (b). The protonation degrees were determined by acid–base titration (Figure S1).

intermolecular interaction among polymer chains. From these results, the possible mechanism of appearance of the thermoresponsive property in the PAA-Pht in the aqueous media containing divalent metal cations is as follows. Intramolecular interaction of two carboxylate anions with divalent metal ions within polymer molecules could cause a polymer conformational change to a compact form like a coil-to-globule conformational change resulting in ease of aggregation of the polymer. Increasing temperature above the LCST, the carboxylated PAA with compact form could induce the phase transition accompanied by Ca^{2+} ion release and dehydration (Figure 3).

It is expected that the apparent affinity between PAA-Pht and Ca^{2+} can be regulated by the pH of the aqueous medium because of pH-dependent protonation of carboxylate anions in PAA-Pht. The change in transmittance with a temperature increase of the PAA-Pht aqueous solution containing 150 mM $CaCl_2$ was evaluated at varying pH conditions (Figure 4a), and the cloud points at varying pHs were then plotted against the protonation degree determined by acid–base titration (Figure 4b). At a protonation degree of PAA-Pht of less than 0.5, the cloud points were almost constant regardless of the protonation degree. However, a further increase of the protonation degree from 0.5 induced a drastic drop in the cloud points (Figure 4b). In the titration curve (protonation degree vs pH) of PAA-Pht in the absence of Ca^{2+} (Figure S1), a discontinuous change was observed at a protonation degree of ~0.6. Such a discontinuous change in the titration curve is often observed in the titration of weak polyelectrolytes. Typical examples are polypeptides such as poly(L-glutamic acid)[25,26] and poly(L-lysine)[26,27] exhibiting a pH-dependent helix–coil

transition and the observed discontinuous change in the titration curve at a pH inducing a conformational transition. In the acid–base titration of PAA-Pht (Figure S1), it seems that the conformational change of the polymer strand from a relatively spread out form to a compact form was induced at a protonation degree of ~0.6 by weakening the electrostatic repulsion in the polymer strand as the pH decreased; that is, the protonation degree increased. The decrease in cloud points at a protonation degree of ~0.5 shown in Figure 4b is considered to be related to the conformational change of the polymer strand because of the decrease in pH. At a protonation degree of less than 0.5, PAA-Pht takes a relatively spread-out conformation and exhibits almost constant cloud points. An increase in the protonation degree to more than 0.6 induces the conformation change to a relatively compact form and provides a decrease in the cloud points, suggesting that the dehydration occurs more easily.

The critical temperature of thermoresponsive polymers can generally be regulated by changing the hydrophilicity of the polymer chains.[28−30] In addition to PAA-Pht, two types of carboxylated PAAs with different side-chain structures were also prepared by the same procedure as for PAA-Pht using 1-cyclohexene-1,2-dicarboxylic anhydride (PAA-CHexene) or an equimolar mixture of phthalic anhydride and 1-cyclohexene-1,2-dicarboxylic anhydride (PAA-Pht/CHexene) instead of phthalic anhydride. PAA-CHexene and PAA-Pht/CHexen were obtained through almost complete conversion of the amino group in PAA (Figure S5a,b). The Pht and CHexene contents of PAA-Pht/CHexene were determined to be 54% and 46%, respectively (Table S1). It is reported that π electrons can work as a hydrogen acceptor,[31−34] and the

polymer side chains possessing fewer π electrons may lead to a decrease in the cloud point because of an increase in the hydrophobicity of polymers. In the presence of Ca^{2+}, PAA-CHexene and PAA-Pht/CHexene showed the same LCST-type phase transition behavior as PAA-Pht (Figures S6 and S7). Upon comparison of the cloud points at 150 mM $CaCl_2$ for carboxylated PAAs, they were 48.8, 37.8, and 31.8 °C in the order PAA-Pht, PAA-Pht/CHexene, and PAA-CHexene (Figure 5). These results indicate that the phase-transition
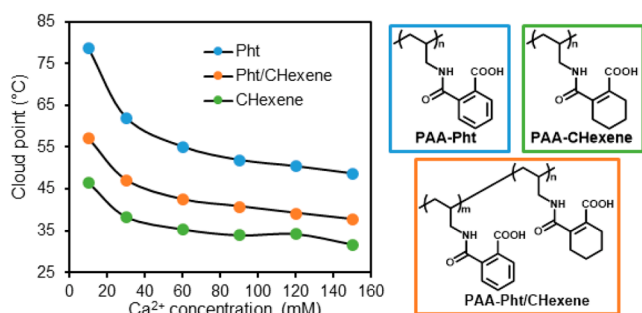

Figure 5. Plots of cloud point vs $CaCl_2$ concentration for PAA-Pht, PAA-CHexene, and PAA-Pht/CHexene (Pht: 54%; CHexene: 46%) in an acidic solution (pH 6.1, 4.0 mg/mL).

temperature of carboxylated PAAs in aqueous media could be controlled by side-chain structures. In addition, carboxylated PAAs not only with cyclic spacer structures but also with noncyclic spacer structures exhibited LCST-type thermoresponsiveness in the presence of Ca^{2+} ions. Carboxylated PAAs named PAA-Glu and PAA-MGlu, which were prepared by using glutaric anhydride (Glu) and 3-methylglutaric anhydride (MGlu) (Figure S5c,d), showed significantly high cloud points (PAA-Glu: 83.9 °C; PAA-MGlu: 71.5 °C; Figure S7) compared with carboxylated PAAs with cyclic spacer structures.

The important advantage of this ionic effector concept is that the thermoresponsive property of the carboxylated PAA can be controlled by changing the ionic species. The cloud points of PAA-Pht appeared at 89.9 and 30.9 °C when Mg^{2+} and Sr^{2+} were used as divalent cationic effectors, respectively (Figure 6). This dependency of the cloud point on metal ionic species is probably relevant to the hydration Gibbs energy ($\Delta_{hyd}G$) of the ionic species themselves (the $\Delta_{hyd}G$ values of

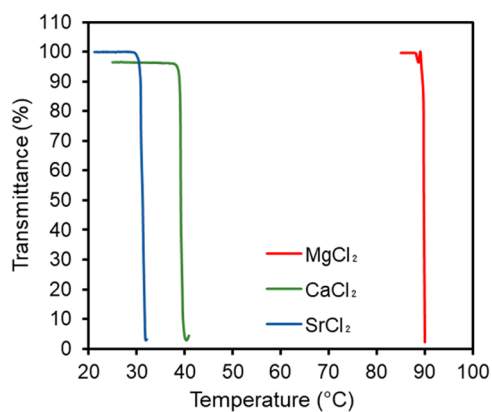**Figure 6.** Changes in the transmittance of PAA-Pht in the acid solution containing various salts ($MgCl_2$, $CaCl_2$, and $SrCl_2$) (pH 5.2, 4.0 mg/mL).

Sr^{2+}, Ca^{2+}, and Mg^{2+} are −1447, −1593, and −1906 kJ/mol, respectively),[35] where $\Delta_{hyd}G$ is the Gibbs energy change of ion species (1 mol) from a gaseous state at 101 kPa to an infinite dilution state when dissolved in water. In other words, the lower the $\Delta_{hyd}G$ value is, the more stable the hydrated state of the ion species is, leading to a higher cloud point. Furthermore, the phase-transition temperature of carboxylated PAA was regulated by the mixing of divalent cationic effectors. In acidic aqueous solutions containing Mg^{2+} and Ca^{2+} with various mole fractions at a fixed total concentration of divalent cations (150 mM), the cloud points of PAA-Pht were linearly increased with increasing mole fraction of Mg^{2+} (Figures 7 and S8), indicating
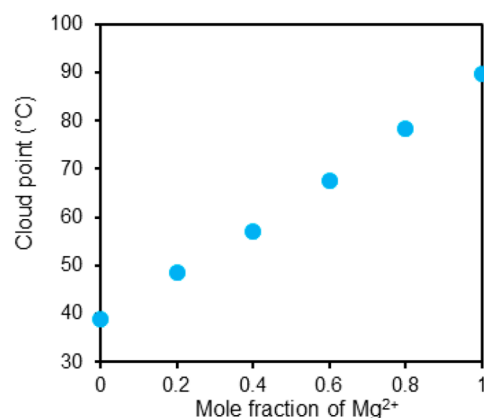

Figure 7. Plots of cloud point vs mole fraction of Mg^{2+} for PAA-Pht in an acidic solution containing $MgCl_2$ and $CaCl_2$ with various mole fractions (pH 5.2, 4.0 mg/mL). The total concentration of $MgCl_2$ and $CaCl_2$ was fixed to be 150 mM.

that the mole fractions of the divalent metal cations interacting with PAA-Pht are almost the same as the mole fractions of the bulk solution. These results indicate that the phase-transition temperature of carboxylated PAA can be controlled by the mole fraction of divalent metal cationic effectors in the aqueous solution.

■ CONCLUSIONS

Herein, we found a novel type of effector-induced LCST-type thermoresponsive polymer prepared through the reaction between polyallylamine and carboxylic anhydrides possessing a six-membered ring, called carboxylated PAAs. Carboxylated PAAs exhibit thermoresponsiveness in the aqueous media only in the presence of alkaline earth metal ions (Ca^{2+}, Mg^{2+}, and/or Sr^{2+}); they did not show thermoresponsiveness with alkali metal ions (Li^+, Na^+, and/or K^+) and without any salts. In this thermoresponsive system, alkaline earth metal ions behaved as effectors and induced a conformational change of polymers to a compact form with intramolecular cross-linking, leading to dehydration and effector release at a specific temperature. In addition, we demonstrated that thermoresponsive properties could be regulated by pH, ionic species, and hydrophobicity of the side chain. This novel and pioneering thermoresponsive system is expected to be applied to chemical materials such as metal ion sensing devices[36] and nanocarriers for drug delivery systems (DDS).[37−39]

■ EXPERIMENTAL SECTION

Materials. PAA-HCl-3L (M_w = 15000) was provided by NITTOBO (Tokyo, Japan). 1-Cyclohexene-1,2-dicarboxylic anhy-

dride was purchased from Tokyo Chemical Industries (Tokyo, Japan). NaCl, Na_2CO_3, NaOH, LiCl, and phthalic anhydride were purchased from Nacalai Tesque Co. (Kyoto, Japan). $NaHCO_3$ was purchased from Wako Pure Chemical Co., Ltd. (Osaka, Japan). $MgCl_2 \cdot 6H_2O$ and KCl were purchased from Kishida Chemical Co., Ltd. (Osaka, Japan). $SrCl_2 \cdot 6H_2O$ was purchased from Sigma-Aldrich Co. LLC (St. Louis, MO). The dialysis membrane (Spectra/Por membrane) (MWCO, 2 kDa) was purchased from SPECTRUM (USA).

Apparatus. UV−vis spectral measurements were conducted by using a V-550 spectrophotometer (Jasco Ltd., Tokyo, Japan). ^1H NMR spectra were measured by using a 400 MHz FT-NMR apparatus (JNM-LA300 FT-NMR system, JEOL Ltd., Tokyo, Japan). The pH values of aqueous media and the quantity of Ca^{2+} were measured by using a pH/ion meter (F-55, Horiba Ltd., Kyoto, Japan).

Preparation of Carboxylated PAAs. Three different types of carboxylated PAAs that have different types of side-chain structures were synthesized by using the following procedure. PAA-HCl was dissolved in carbonate buffer (pH 9.5) (2.5 mg/mL), and the pH was adjusted to 9.5 by using a 1 M sodium hydroxide aqueous solution. Pht (1093.3 mg, 7.38 mmol) or CHexene (982.2 mg, 6.46 mmol) was added to the PAA aqueous solution three times every hour for the preparation of PAA-Pht or PAA-CHexene, respectively. For PAA-Pht/CHexene, Pht (364.3 mg, 2.46 mmol) and CHexene (374.2 mg, 2.46 mmol) were added to the PAA aqueous solution three times every hour. After adjusting the pH value of the aqueous solution to 9.5, the reaction proceeded for 24 h under gentle stirring. After the addition of 100 equiv of sodium chloride (vs carboxylic acid groups) to the aqueous solution, the polymers were dialyzed to remove free low-molecular-weight compounds and salt species with weakly basic water (pH ≈ 9.5) for 3 days. Then, the dry carboxylated PAAs were obtained by lyophilization.

Thermoresponsive Property of Carboxylated PAAs in the Presence of Various Salts. PAA-Pht was dissolved in aqueous solutions (pH 5.2, 4.0 mg/mL) without or with various salts (LiCl, NaCl, KCl, $MgCl_2$, $CaCl_2$, $CaBr_2$, $Ca(NO_3)_2$, or $SrCl_2$). The polymer solution (2 mL) was placed in UV cells (1 cm × 1 cm), and the transmittance (λ = 500 nm) of the polymer solution was measured from 25 to 80 °C (heating speed: 1 °C/min; data interval: 10 s). The reversible thermoresponsive property of PAA-Pht was also investigated in an aqueous solution containing 150 mM $CaCl_2$ aq (pH 5.2, 4 mg/mL). The transmittance (λ = 500 nm) of the polymer solution was measured from 32 to 38 °C for the heating process and from 38 to 32 °C for the cooling process (heating or cooling speed: 0.1 °C/min; data interval: 10 s).

Effect of Ca^{2+} Ion Concentrations. PAA-Pht was dissolved in an aqueous solution (pH 5.2, 4.0 mg/mL) containing various concentrations of $CaCl_2$ (1, 5, 10, 30, 60, 90, 120, and 150 mM). The polymer solution (2 mL) was placed in UV cells (1 cm × 1 cm). The transmittance (λ = 500 nm) of the polymer solution was measured from 25 to 80 °C (heating speed: 1 °C/min; data interval: 10 s).

Quantitative Analysis of Ca^{2+} Ions Using a Ca^{2+} Ion-Selective Electrode. For preparation of measurement samples, PAA-Pht was dissolved in an aqueous solution (pH 5.2, 4.0 mg/mL) containing various concentrations of $CaCl_2$ (30, 60, 90, 120, and 150 mM). Then, the polymer solutions were heated in a water bath (70 °C) for 20 s following filtration of the suspension with the funnel kept at 60 °C and cooling the filtrate with ice; then 10 μL of NaOH aq (1 M) was added to the filtrate immediately. For the measurement of the Ca^{2+} concentration using a Ca^{2+} ion-selective electrode, first, calibration of the ion meter was performed. Various concentrations of $CaCl_2$ aqueous solutions (30, 60, 90, 120, and 150 mM) (2 mL) were prepared following the ionic strength regulator (600 μL) and NaOH aq (0.1 M)/deionized water (total 28 mL) being added to fix the pH to 7.0 with stirring; then the ion meter was calibrated with gentle stirring. Finally, the Ca^{2+} ion concentrations in the filtrates were measured by using the calibrated ion meter. Various filtered solutions (2 mL) were prepared following the ionic strength regulator (600 μL) and NaOH aq (0.1 M)/deionized water (total 28 mL) were

added to fix the pH to 7.0 with stirring; then the Ca^{2+} concentrations in the sample solutions were measured with gentle stirring.

Effect of Polymer Concentration. PAA-Pht was dissolved in aqueous solutions (pH 5.2) containing $CaCl_2$ (150 mM). In the experiments, the polymer concentrations were 0.5, 1.0, 2.0, 3.0, and 4.0 mg/mL. The polymer solution (2 mL) was placed in UV cells (1 cm × 1 cm). The transmittance (λ = 500 nm) of the polymer solution was measured from 25 to 80 °C (heating speed: 1 °C/min; data interval: 10 s).

Effect of pH. PAA-Pht was dissolved in aqueous solutions (4.0 mg/mL) containing $CaCl_2$ (150 mM), where the pH of the aqueous solution was adjusted to 5.0, 5.1, 5.2, 5.9, 6.2, 6.8, or 7.4. The polymer solution (2 mL) was placed in UV cells (1 cm × 1 cm). The transmittance (λ = 500 nm) of the polymer solution was measured from 25 to 80 °C (heating speed: 1 °C/min; data interval: 10 s).

Effect of Side-Chain Structure. PAA-Pht, PAA-CHexene, and PAA-Pht/CHexene were dissolved in aqueous solutions (pH 6.1, 4.0 mg/mL) containing $CaCl_2$ (150 mM). The polymer solution (2 mL) was placed in UV cells (1 cm × 1 cm). The transmittance (λ = 500 nm) of the polymer solution was measured from 25 to 80 °C (heating speed: 1 °C/min; data interval: 10 s).

Effect of Counterion Species. We attempted to dissolve PAA-Pht in aqueous solutions containing $MgCl_2$, $CaCl_2$, $SrCl_2$, $CuCl_2$, $ZnCl_2$, $NiCl_2$, or $AlCl_3$ at fixed salt concentration (150 mM). The effect of counterion species was evaluated for alkaline earth metal ions (Mg^{2+}, Ca^{2+}, and Sr^{2+}) because PAA-Pht did not dissolve into the aqueous solutions containing divalent transition-metal ions or a trivalent metal ion. Two types of experiments were conducted. For one, PAA-Pht was dissolved in aqueous solutions (pH 5.2, 4.0 mg/mL) containing $MgCl_2$, $CaCl_2$, or $SrCl_2$ (150 mM). For the other, PAA-Pht was dissolved in aqueous solutions containing $MgCl_2$ and $CaCl_2$ with various mole fractions (0, 0.2, 0.4, 0.6, 0.8, or 1). The polymer solution (2 mL) was placed in UV cells (1 cm × 1 cm). The transmittance (λ = 500 nm) of the polymer solution was measured from 25 to 80 °C (heating speed: 1 °C/min; data interval: 10 s).

■ ASSOCIATED CONTENT

ⓈI Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.macromol.2c00795.

> Titration curve of PAA-Pht, the evaluation of cloud points under additional conditions, and ^1H NMR spectra (PDF)

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Notes

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