



Published in final edited form as:

Polymer (Guildf). 2014 May 13; 55(10): 2325–2331. doi:10.1016/j.polymer.2014.03.062.

RAFT polymerization of temperature- and salt-responsive block copolymers as reversible hydrogels

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Abstract

Reversible-addition fragmentation chain transfer (RAFT) polymerization enabled the synthesis of novel, stimuli-responsive, AB and ABA block copolymers. The B block contained oligo(ethylene glycol) methyl ether methacrylate (OEG) and was permanently hydrophilic in the conditions examined. The A block consisted of diethylene glycol methyl ether methacrylate (DEG) and [2-(methacryloyloxy)ethyl]trimethylammonium chloride (TMA). The A block displayed both salt- and temperature-response with lower critical solution temperatures (LCSTs) dependent on the molar content of TMA and the presence of salt. Higher TMA content in the AB diblock copolymers increased the critical micelle temperatures (CMT) in HPLC-grade water due to an increased hydrophilicity of the A block. Upon addition of 0.9 wt% NaCl, the CMTs of poly(OEG-*b*-DEG₉₅TMA₅) decreased from 50 °C to 36 °C due to screening of electrostatic repulsion between the TMA units. ABA triblock copolymers displayed excellent hydrogel properties with salt- and temperature-dependent gel points. TMA incorporation in the A block increased the gel points for all triblock copolymers, and salt-response increased with higher TMA composition in the A block. For example, poly(DEG₉₈TMA₂-*b*-OEG-*b*-DEG₉₈TMA₂) formed a hydrogel at 40 °C in HPLC-grade water and 26 °C in 0.9 wt% NaCl aqueous solution. These salt- and temperature-responsive AB diblock and ABA triblock copolymers find applications as drug delivery vehicles, adhesives, and hydrogels.

Keywords

RAFT polymerization; Hydrogels; Stimuli-responsive

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1. Introduction

Stimuli-responsive macromolecules are an important area of advanced materials wherein the polymer properties change upon a response to different environmental conditions [1]. Various stimuli are widely investigated in the earlier literature including temperature, pH, salt, light, and analyte concentrations [2]. Stimuli-responsive polymeric materials find a broad range of applications including drug delivery vehicles [3], sensors [4], hydrogels [5], and smart surfaces [6]. Temperature-responsive macromolecules are widely reported as stimuli-responsive for biomedical applications with a target-temperature response near physiological body temperature (37 °C) [7]. Polymer families that display temperature-responsive properties include polyacrylamides [8], polyacrylates [9], polymethacrylates [10,11], polyoxazolines [12], polyethers [13], and polypeptides [14]. Polymers that display lower critical solution temperatures (LCSTs) exhibit unique solubility properties in water, and as defined, the polymer is soluble in water below the LCST, but upon heating above the LCST, the polymer becomes water-insoluble and precipitates [15].

Poly(*n*-isopropyl acrylamide) (PNIPAM) is the most widely studied LCST polymer due to an ideal LCST of 32 °C for biological applications [16]. The advent of controlled radical polymerization enabled the design and synthesis of poly(NIPAM)-containing block copolymers. For example, McCormick et al. [17] generated poly(-dimethyl acrylamide-*b*-*n*-isopropyl acrylamide) and poly(dimethyl acrylamide-*b*-*n*-isopropyl acrylamide-*b*-dimethyl acrylamide) block copolymers utilizing reversible addition-fragmentation chain transfer (RAFT) polymerization, and they demonstrated temperature-responsive micellization due to the poly(NIPAM) block. Acrylate and methacrylate polymers with LCST behavior recently received significant attention. De and Sumerlin [18] synthesized poly(diethylene ethyl ether acrylate) (PDEGA) random and block copolymers with dimethyl acrylamide as a hydrophilic comonomer. The LCST behavior of the random copolymers linearly depended on the mol% incorporation of dimethyl acrylamide; LCSTs ranged from ~10 °C to 90 °C and the LCSTs increased with dimethyl acrylamide incorporation. The poly(DEGA-*b*-dimethyl acrylamide) diblock copolymers displayed thermoresponsive micellization behavior.

Oligoethylene glycol methacrylate monomers have received significant attention recently in the literature [10,19]. The length of the oligoethylene glycol side chain dramatically impacts LCST behavior [20,21]. Longer ether side chains result in higher LCSTs due to enhanced hydrophilicity of the polymer. These macromolecules display LCST behavior due to the interplay between the hydrophobic polymer backbone and the hydrogen bonding of the ether units to water [10]. Poly(diethylene glycol methyl ether methacrylate) homopolymer with two ethylene glycol repeat units exhibits an LCST of 26 °C [22], and various researchers reported a broad range of block copolymers and random copolymers. Random copolymers containing hydrophilic monomers such as OEG [22], 2-dimethylaminoethyl methacrylate (DMA) [23], or methacrylic acid [23] enabled the tuning of the LCST. Multiple researchers examined poly(DEG-*b*-DMA) diblock copolymers for their temperature- and pH-responsive micellization behavior [24,25]. Müller et al. [26] synthesized DEG and DMA star block copolymers with a DMA core and DEG shell. These triblock copolymers displayed pH-responsive and thermoresponsive hydrogel behavior. Lutz and coworkers also examined

DEG-containing covalently crosslinked hydrogels [11] and physically crosslinked hydrogels [27]. The covalently crosslinked hydrogels deswelled upon heating above the LCST of DEG, and the DEG-containing star block copolymers exhibited thermoresponsive gelation.

Polymers containing ionic groups commonly display a response to salt since added salt triggers a change in solubility or polymer conformation [28]. For example, polyelectrolytes display an extended conformation in dilute salt-free solutions due to electrostatic repulsion in the polymer backbone, commonly termed the polyelectrolyte effect [29]. The addition of salt to the solution effectively screens the electrostatic repulsions in the polymer backbone, reducing both intra- and intermolecular repulsion and allowing the polyelectrolyte to adopt a less extended coil-like configurations in solution [30]. More importantly, addition of salt reduces counterion dominated osmotic pressure, destabilizing the homogeneous phase. As a result of this, salt triggerable polymers display salt-dependent solubility where the addition of salt induces precipitation [31]. Tuning solubility of polymers through salt concentration enables the generation of a broad range of materials suitable for biomedical and hygiene applications. Bunyard et al. [32] examined the salt response of ammonium-containing polycaprolactones, and they demonstrated the impact of salt concentration, salt identity, and ionic content in the polymer on the salt-triggered solubility of the cationic polycaprolactones.

We report herein the synthesis and characterization of salt- and temperature-responsive diblock and triblock copolymers through the incorporation of hydrophilic and ionic monomers, which impart polymeric LCST and salt-triggerable behavior. We set out to develop associating polymeric systems, which could be tuned to respond to a range of conditions relevant to contact with or use within the body. RAFT polymerization enabled the well-defined synthesis of AB diblock and ABA triblock copolymers using monofunctional or difunctional trithiocarbonate chain transfer agents. The B block was hydrophilic while the A block displayed both salt- and temperature-responsive character dependent on the relative incorporation of DEG and TMA groups. Dynamic light scattering probed the micellization behavior of the AB diblock copolymers with a focus on their temperature-response and salt-response. Solution rheological studies using temperature ramp experiments probed the hydrogel behavior of the ABA triblock copolymers and elucidated the sol–gel transition (gel point) for all triblock copolymers. These salt- and temperature-responsive block copolymers are candidates for drug delivery, adhesive, and hydrogel applications.

2. Experimental section

2.1. Materials

Oligo(ethylene glycol) methyl ether methacrylate (OEG) (485 g/mol) and diethylene glycol methyl ether methacrylate (DEG) (95%) were obtained from Sigma–Aldrich, and inhibitor was removed using a neutral alumina column prior to polymerization. [2-(methacryloyloxy)ethyl]trimethylammonium chloride (80 wt% in water) (TMA) was purchased from Sigma–Aldrich and used as received. 4,4'-Azobis(4-cyanopentanoic acid) (V-501) (>98%) was obtained from Sigma–Aldrich and recrystallized from methanol. 4-Cyano-4-(ethylsulfanylthiocarbonylsulfanyl)pentanoic acid (CEP) [33] and 1,6-bis(4-cyano-4-(ethylsulfanylthiocarbonylsulfanyl)pentanoic acid)hexane diamide (dCEP) were

synthesized according to previous literature procedures. HPLC grade water (pH = 7.0) and other solvents were purchased from Spectrum Chemical and used as received. All other reagents were purchased from Sigma–Aldrich and used as received.

2.2. Analytical methods

Aqueous SEC was performed using a ternary mixture of 54/23/23 v/v/v water/methanol/ acetic acid with 0.1 M sodium acetate as the eluant. The aqueous SEC instrumentation consisted of a Waters 1515 isocratic HPLC pump, a Waters 717plus autosampler, two Waters ultrahydrogel linear columns, one Waters ultrahydrogel 250 column, a Wyatt MiniDAWN light scattering (LS) detector, and a Waters 2414 refractive index (RI) detector operating at a flow rate of 0.8 mL/min. Poly(OEG) and poly(DEG) displayed dn/dc values of 0.1156 mL/g and 0.1267 mL/g, respectively, in the aqueous SEC solvent. The dn/dc values for all block copolymers were estimated at 0.12 mL/g to enable calculation of absolute molecular weights. Dynamic light scattering was performed using a Malvern Zetasizer Nano and enabled the determination of the critical micellization temperature. Polymer solutions (1 mg/mL in pure water or 0.9 wt% NaCl in water) were subjected to a temperature step protocol (2 °C/step from 4 °C to 50 °C) and the hydrodynamic diameters were measured after a 5 min equilibration at each step. The critical micellization temperature was attributed to the temperature step where the polymers exhibited a shift in their hydrodynamic diameters from unimers (<10 nm) to micelles (>20 nm). Solution rheology using a TA Instruments DHR-2 strain-controlled rheometer with a 2° 40 mm cone and Peltier plate geometry directly probed hydrogel formation and overall gel strengths. Polymer solutions (25 wt% polymer in pure water or 0.9 wt% NaCl in water) were subjected to temperature sweep experiments using 1% oscillatory strains at 1 Hz with a heating rate of 0.5 °C/min from 4 °C to 50 °C. The approximate gel point was determined using the TA Instruments TRIOS package and was defined as the crossover point of the storage and loss moduli. Complementary techniques will be described below in more detail.

2.3. Synthesis of poly(OEG) monofunctional macroCTA

A 500-mL, round-bottomed, flask containing OEG (40.10 g, 82.7 mmol), CEP (868 mg, 3.30 mmol), V-501 (184 mg, 0.656 mmol), and DMSO (330 mL) was sparged with argon for 1 h. The resulting yellow solution was heated at 70 °C for 250 min and then dialyzed against water for 3 d (MWCO = 3500 g/mol) to remove solvent and residual monomer. Lyophilization isolated a yellow polymeric oil (M_n = 13,600 g/mol, PDI = 1.04).

2.4. Synthesis of salt- and temperature-responsive diblock copolymers

All diblock copolymers were synthesized according to a similar procedure. The synthesis of poly(OEG-*b*-DEG₉₉TMA₁) follows as a representative example. Poly(OEG) macroCTA (364.0 mg, 0.0268 mmol), DEG (978 μL, 5.30 mmol), TMA (12.5 μL, 0.0532 mmol), V-501 (3.74 mg, 0.0133 mmol), and DMF (10.268 mL) were added to a 25-mL, round-bottomed flask with a magnetic stir bar. The resulting yellow solution was sparged with argon for 15 min and subsequently heated at 70 °C for 6 h. The polymer solution was dialyzed against water (MWCO = 3500 g/mol) and then subsequently lyophilized to obtain the diblock copolymer (M_n = 39.4 kg/mol, PDI = 1.03).

2.5. Synthesis of poly(OEG) difunctional macroCTA

The following example demonstrates the synthesis of a difunctional poly(OEG) macroCTA. OEG (0.995 g, 2.05 mmol), dCEP (8.34 mg, 0.0137 mmol), V-501 (1.54 mg, 0.00549 mmol), and DMSO (8.247 mL) were added to a 25-mL, round-bottomed, flask with a magnetic stir bar. The resulting solution was sparged with argon for 30 min and then heated at 70 °C for 220 min. The polymer solution was dialyzed against water (MWCO = 3500 g/mol) and lyophilized to obtain a yellow oil (Aqueous SEC: $M_n = 74.6$ kg/mol, PDI = 1.01).

2.6. Synthesis of salt- and temperature-responsive triblock copolymers

A representative procedure to prepare poly(DEG_xTMA_y-*b*-OEG-*b*-DEG_xTMA_y) triblock copolymers containing a feed of 3 mol% TMA into the outer block follows. DEG (2.89 mL, 15.7 mmol), TMA (114 μL, 0.439 mmol), poly(OEG) macroCTA (523.9 mg, $M_n = 64.9$ kg/mol), and DMF (15.99 mL) were added to a 25-mL, round-bottomed, flask with magnetic stir bar. The resulting solution was sparged with argon for 30 min and subsequently heated at 70 °C for 7 h. The polymer solution was dialyzed against water (MWCO = 3500 g/mol) at 4 °C and lyophilized to obtain a slightly yellow polymer (Aqueous SEC: $M_n = 230$ kg/mol, PDI = 1.19).

3. Results and discussion

3.1. Polymer synthesis

Block copolymers containing a hydrophilic block and a salt- and temperature-responsive block enabled the examination of critical micellization temperatures and hydrogel formation. An OEG block acted as a biocompatible, hydrophilic block, and a random copolymer of DEG and TMA served as the salt- and temperature-responsive block. DEG homopolymers display an LCST of ~26 °C [22] and the incorporation of TMA was hypothesized to increase the LCST behavior to near body temperature and also enabling a salt-response. RAFT polymerization readily enabled the preparation of salt- and temperature-responsive diblock and triblock copolymers as shown in Scheme 1. A monofunctional trithiocarbonate CTA, CEP, mediated the polymerization of OEG to synthesize a well-defined poly(OEG) macroCTA ($M_n = 13.6$ kg/mol, PDI = 1.04). Subsequent chain extension with a mixture of DEG and TMA created the desired salt- and temperature-responsive diblock copolymers. Fig. 1 exemplifies the aqueous SEC analysis of the poly(OEG) macroCTA, and all diblock copolymers showed a clear, monotonic shift in elution time upon chain extension. All diblock copolymers displayed similar M_n 's of ~40 kg/mol with narrow molecular weight distributions as shown in Table 1. Molar feed ratios of DEG and TMA were controlled to examine the impact of TMA incorporation on critical micellization temperatures. Accurately determining the TMA incorporations proved difficult due to the low TMA feed in the copolymerization. All block copolymer compositions reported correspond to the monomer feed ratios of DEG and TMA and were presumed to be equivalent to the average copolymer composition.

ABA triblock copolymers have the proper chain architecture for hydrogel formation since the external A blocks act as physical crosslinks and the internal B block remains hydrophilic and act as network strands. Temperature increase leads to gelation with A blocks associating

into micelle-core-like crosslinks bridged through the hydrophilic B blocks. Long et al. [34] recently described a novel difunctional trithiocarbonate, dCEP, suitable for the RAFT polymerization of alkyl methacrylate monomers. Since dCEP contains similar CTA functionality as CEP, dCEP enabled the synthesis of salt- and temperature-responsive ABA triblock copolymers in two synthetic steps similar to the diblock copolymer synthesis (Scheme 2). Initial polymerization of OEG yielded a precise poly(OEG) macro-CTA ($M_n = 64.9$ kg/mol, PDI = 1.01). Subsequent chain extension with DEG and TMA in different molar feed ratios generated the desired dual responsive triblock copolymers with M_n 's of ~230 kg/mol and PDIs = 1.20 as shown in Table 2. Aqueous SEC confirmed a complete monotonic shift to shorter elution times upon chain extension (Fig. 2).

3.2. Salt- and temperature-responsive micelles

Dynamic light scattering elucidated the salt- and temperature-response of the diblock copolymers. Temperature step studies (2 °C/step) in HPLC-grade water or 0.9 wt% NaCl in water (physiological salt concentration) directly measured the critical micellization temperatures. Fig. 3 summarizes the DLS studies for all diblock copolymers in HPLC-grade water or a salt solution. The critical micellization temperature was defined as the temperature at which the hydrodynamic diameter increased dramatically. After equilibration at higher temperatures, the micelles achieved a steady state size between 25 and 50 nm. Previous literature on PNIPAM diblock copolymers showed a similar trend where a larger micelle occurred at the CMT with the formation of a smaller micelle at higher temperatures, presumably due to dehydration of the PNIPAM core [17]. Poly(OEG-*b*-DEG) displayed a CMT of 30 °C in HPLC-grade water, higher than the LCST of poly(DEG) (26 °C) due to the attachment of the hydrophilic poly(OEG) block. Higher incorporations of TMA resulted in a higher CMT, and poly(OEG-*b*-DEG₉₉TMA₁) displayed a CMT of 32 °C and poly(OEG-*b*-DEG₉₅TMA₅) displayed a CMT greater than 50 °C. Matyjaszewski et al. also synthesized copolymers of DEG and DMAEMA that displayed increasing LCSTs as the DMAEMA content increased due to increased hydrophilicity [23]. The hydrophilicity of TMA primarily promoted an increase in the LCST of the block copolymers.

The addition of a physiological salt concentration (0.9 wt% NaCl in water) dramatically impacted the CMT behavior of the diblock copolymers (Fig. 3b). Table 3 summarizes the CMTs of the diblock copolymers in HPLC water and in aqueous solutions with 0.9 wt% NaCl. Poly(OEG-*b*-DEG) exhibited a 4 °C shift to a lower CMT of 26 °C. Diblock copolymers containing higher TMA concentrations displayed a more dramatic shift in CMT behavior upon the addition of salt. For example, poly(OEG-*b*-DEG₉₅TMA₅) exhibited a shift in CMT behavior from >50 °C to 36 °C upon the addition of salt. From a biological perspective, poly(OEG-*b*-DEG₉₆TMA₄) exhibited an excellent salt- and temperature-response since the CMT of the diblock copolymer in HPLC-grade water was 40 °C while in 0.9 wt% NaCl in water CMT dropped to 34 °C. In the absence of physiological salt poly(OEG-*b*-DEG₉₆TMA₄) dissolves and exists as unimers in solution at and below 36 °C. The biological conditions of 37 °C and 0.9 wt% NaCl will induce micellization.

3.3. Salt - and temperature-responsive hydrogels

ABA triblock copolymers exhibiting salt- and temperature-responsive A blocks with a hydrophilic B block enabled formation of salt- and temperature-responsive hydrogels. The B block consisted of poly(OEG) and the A block consisted of poly(DEG) or poly(DEG_xTMA_y). Solution rheology in HPLC-grade water and 0.9 wt% NaCl in water probed the hydrogel behavior of the triblock copolymers. Fig. 4 highlights oscillatory solution rheology experiments using the temperature ramp to identify the gel point and the overall gel strength of the ABA triblock copolymers in HPLC-grade water. The gel point was estimated as the crossover point of the storage and loss moduli. TMA concentration directly impacted the gel point in HPLC-grade water, increasing from 24 °C to >50 °C as the TMA feed ratio increased from 0 mol% TMA to 3 mol% TMA, respectively. Further rheological experiments will elucidate the frequency independent gel point using frequency step experiments to determine the temperature where $G' \sim G''$ and both moduli exhibit the same power law frequency dependence.

The presence of physiological salt concentrations dramatically impacted the gel points for all triblock copolymers. As the TMA concentration increased, the gel point decreased more significantly in the presence of 0.9 wt% NaCl. Fig. 5 highlights solution rheology data for poly(DEG₉₇TMA₃-*b*-OEG-*b*-DEG₉₇TMA₃) in HPLC-grade water or 0.9 wt% NaCl in water. The gel point decreased substantially from >50 °C in HPLC water to 28 °C in 0.9 wt% NaCl in water. A systematic increase in the gel point occurred as the TMA concentration increased in the 0.9 wt% NaCl solution as shown in Fig. 6. Table 4 summarizes the gel points for the triblock copolymers in HPLC-grade water and 0.9 wt% NaCl in water. Interestingly, all ABA triblock copolymers formed hydrogels at lower temperatures than compared to the AB diblock copolymer CMTs in both HPLC water or 0.9 wt% NaCl in water. McCormick et al. [35] demonstrated the significant impact of polymer concentration on the gel points of poly(NIPAM-*b*-dimethyl acrylamide-*b*-NIPAM) triblock copolymers. Higher polymer concentrations resulted in lower gel points. Müller et al. [26] observed similar results for their DEG and DMA star block copolymers. All rheological experiments were performed at 25 wt% polymer, suggesting a similar effect where the gel point decreased significantly compared to the CMT of the diblock copolymers at concentrations of 0.1 wt% polymer. Salt screening also reduced the ability of TMA to increase the hydrophilicity of the A block, leading to smaller increases in gel temperatures (Table 4 and Fig. 4).

Overall storage modulus G' for all triblock copolymer hydrogels were between 100 Pa and 2000 Pa at 25 wt% polymer. DEG and DMA star block copolymers from Müller et al. exhibited higher moduli at 20 wt% polymer, presumably due to the multi-arm star that provided an inherently higher crosslink density [26]. Hysteresis experiments probed the reversibility of hydrogel formation, and Fig. 7 shows the heating and cooling temperature ramps for poly(DEG₉₈TMA₂-*b*-OEG-*b*-DEG₉₈TMA₂). Both heating and cooling curves displayed similar storage and loss moduli, and the gel point occurred at ~26 °C, which confirmed minimal hysteresis.

4. Conclusions

RAFT polymerization generated novel salt- and temperature-responsive AB diblock and ABA triblock copolymers in two synthetic steps. Aqueous SEC determined the molecular weights of all block copolymers and confirmed successful chain extension. Dynamic light scattering studies probed the micellization behavior of the AB diblock copolymers. Higher TMA concentrations resulted in higher critical micelle temperatures (CMTs) and the presence of 0.9 wt% NaCl decreased the CMT's of all diblock copolymers. Solution rheology examined the hydrogel behavior of the ABA triblock copolymers. TMA feed ratios from 0 mol% to 3 mol% increased the gel point from 26 °C to >50 °C, respectively. All ABA triblock copolymers exhibited significant salt response, and poly(DEG₉₇TMA₃-*b*-OEG-*b*-DEG₉₇TMA₃) exhibited the largest shift in gel point from >50 °C to 28 °C. Hysteresis experiments using poly(DEG₉₈TMA₂-*b*-OEG-*b*-DEG₉₈TMA₂) confirmed the reversibility of the hydrogel formation with minimal hysteresis. The tailored AB and ABA triblock copolymers displayed tunable salt- and temperature-response with direct applications as drug delivery vehicles, adhesives, and hydrogels.

Acknowledgments

The authors gratefully thank Kimberly-Clark Corporation for financial and material support. This material is based upon work supported in part by the Army Research Office under grant number W911NF-07-1-0452 Ionic Liquids in Electro-Active Devices (ILEAD) MURI. This material is based upon work supported in part by the U.S. Army Research Laboratory and the Army Research Office under the Army Materials Center of Excellence Program, contract W911NF-06-2-0014. This material is based upon work supported by the Army Research Office (ARO) under Award No. W911NF-10-1-0307 (DURIP). Dr. Michael H. Rubinstein would like to acknowledge financial support from the National Science Foundation under grants DMR-1309892, DMR-1121107, and DMR-1122483, the National Institutes of Health under 1-P50-HL107168, 1-P01-HL108808-01A1, and the Cystic Fibrosis Foundation.

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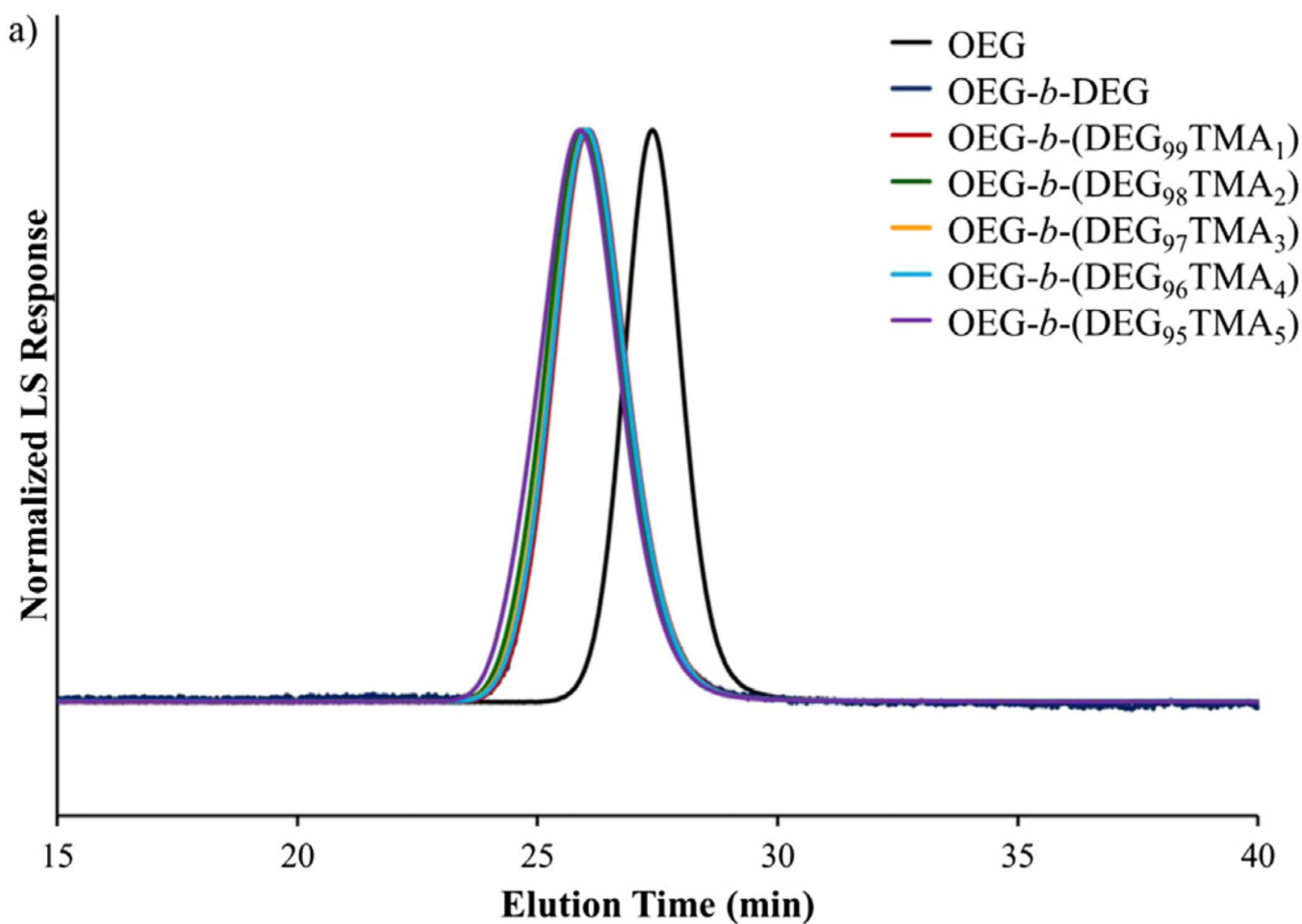


Fig. 1. Aqueous SEC LS curves for the initial poly(OEG) macroCTA and the resulting poly(OEG-*b*-DEG_{*x*}TMA_{*y*}) diblock copolymers.

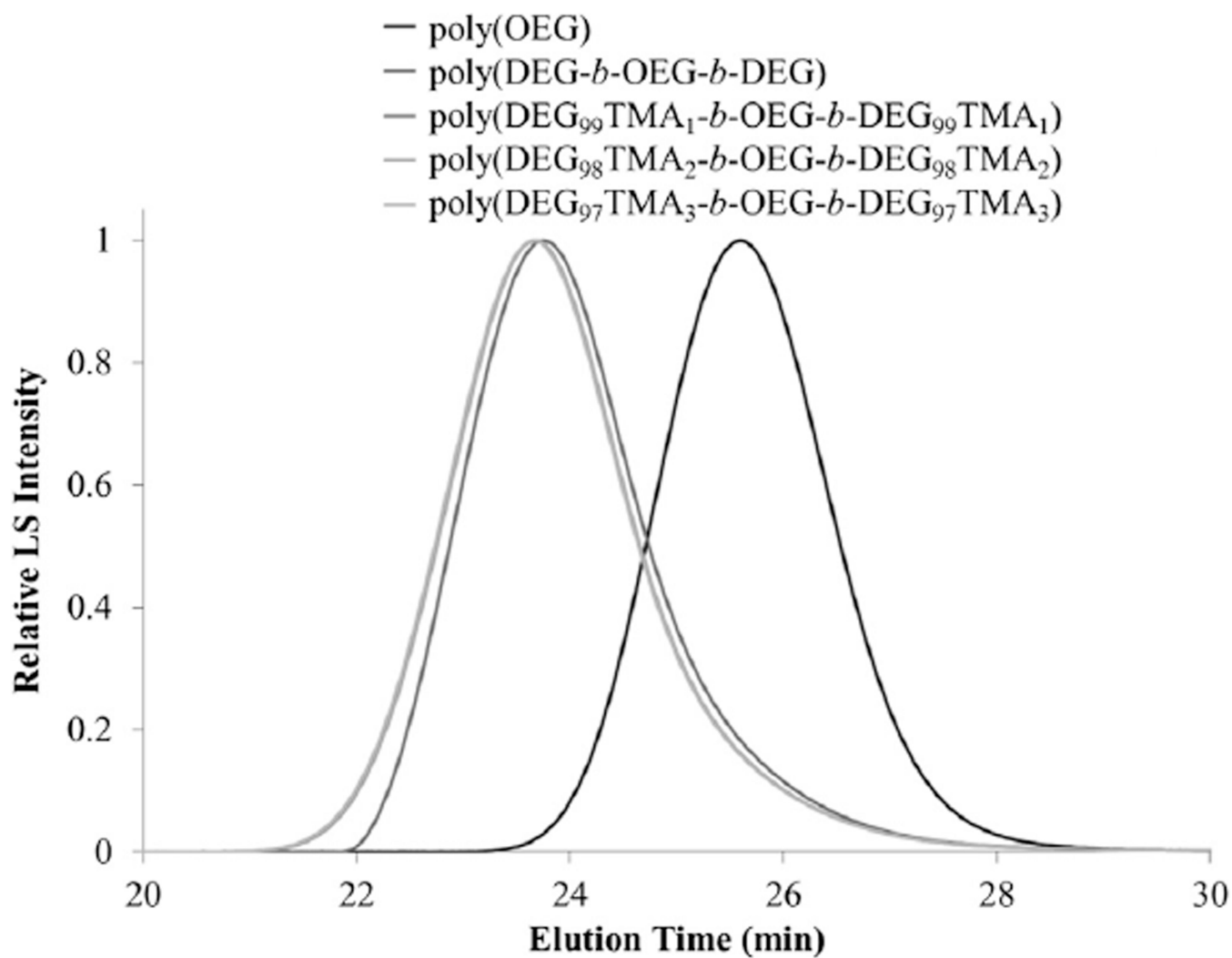


Fig. 2. Aqueous SEC analysis of the difunctional poly(OEG) macroCTA and the resulting triblock copolymers poly(DEG_{*x*}TMA_{*y*}-*b*-OEG-*b*-DEG_{*x*}TMA_{*y*}).

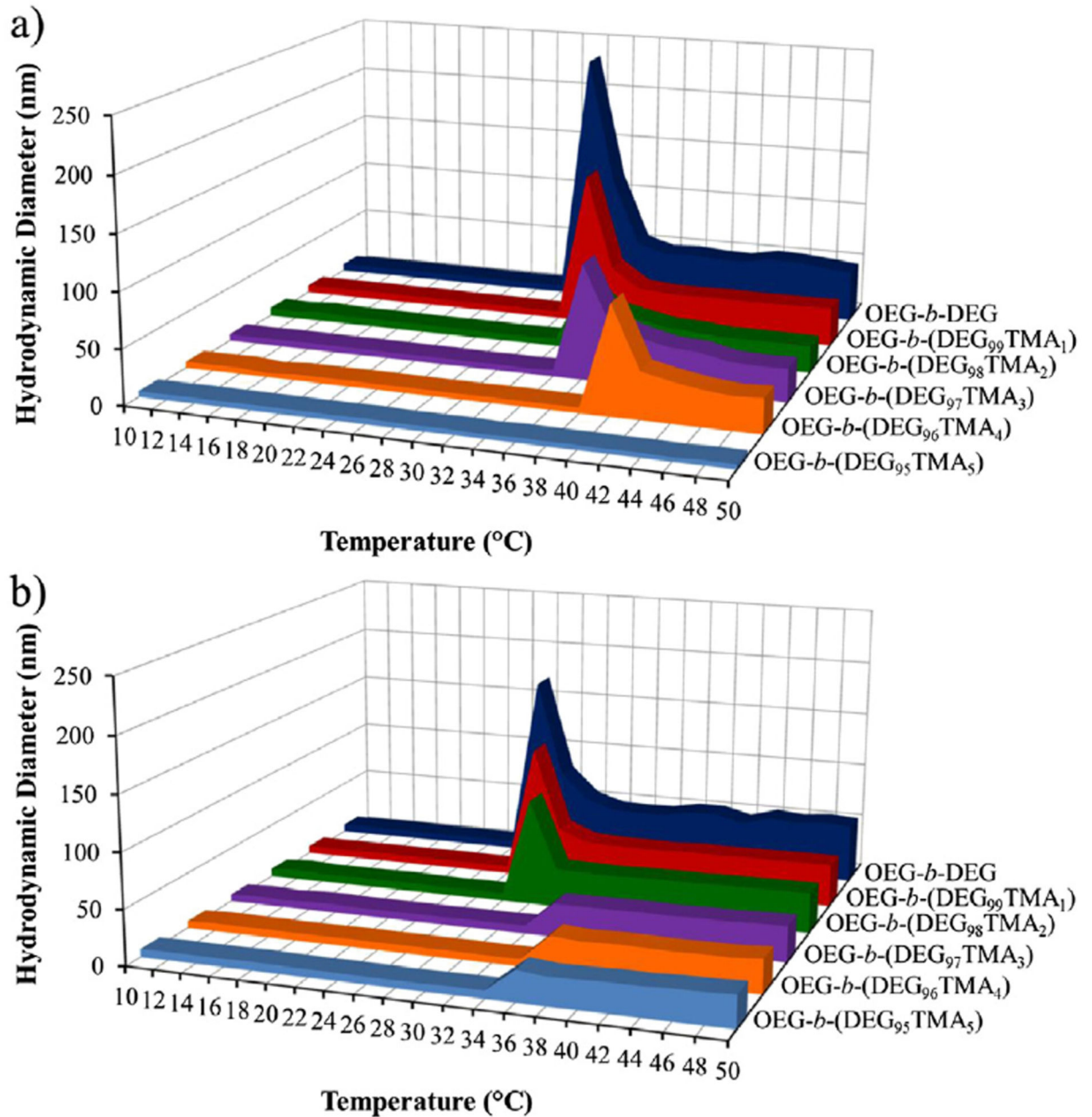


Fig. 3. Temperature-responsive micellization of the poly(OEG-*b*-DEG_{*x*}TMA_{*y*}) diblock copolymer series in a) water and b) 0.9 wt% NaCl in water.

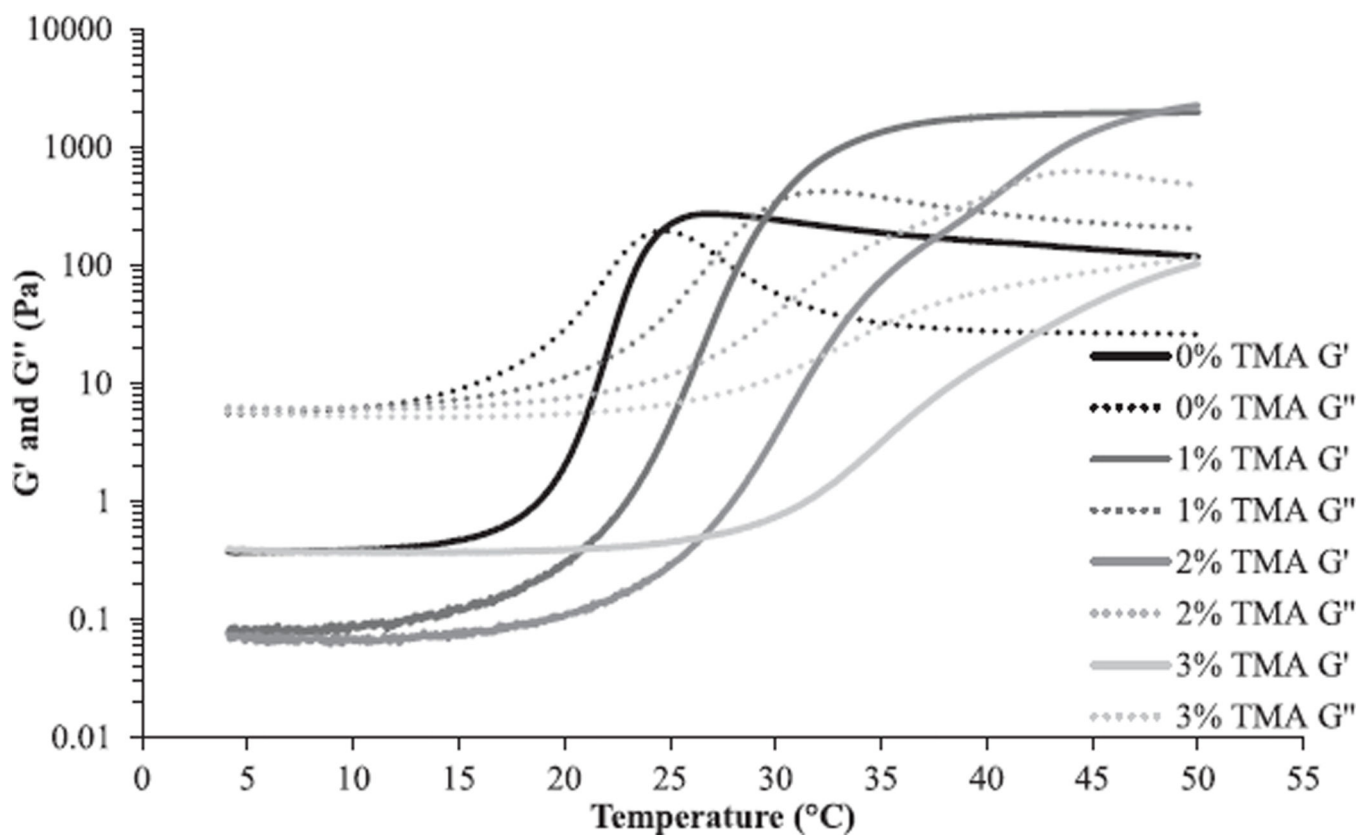


Fig. 4. Storage G' and loss G'' moduli at $\omega = 1$ Hz during a temperature sweep allows estimation of the sol-gel transition for 25 wt% poly(DEG_xTMA_y-*b*-OEG-*b*-DEG_xTMA_y) in HPLC-grade water.

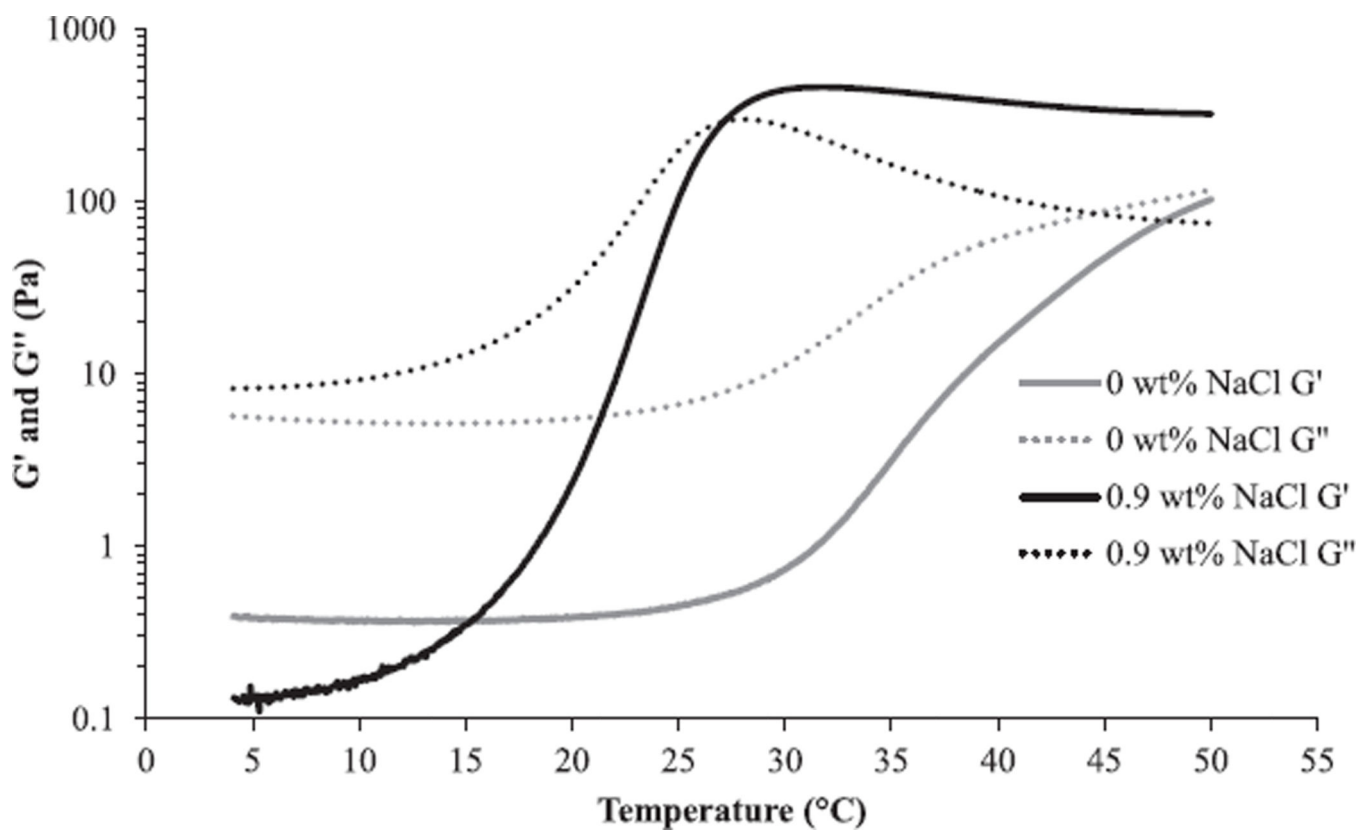


Fig. 5. Temperature- and salt-responsive nature of poly($\text{DEG}_{97}\text{TMA}_3$ - b -OEG- b - $\text{DEG}_{97}\text{TMA}_3$) probed using solution rheology with 25 wt% polymer in HPLC-grade water or 0.9 wt% NaCl in water.

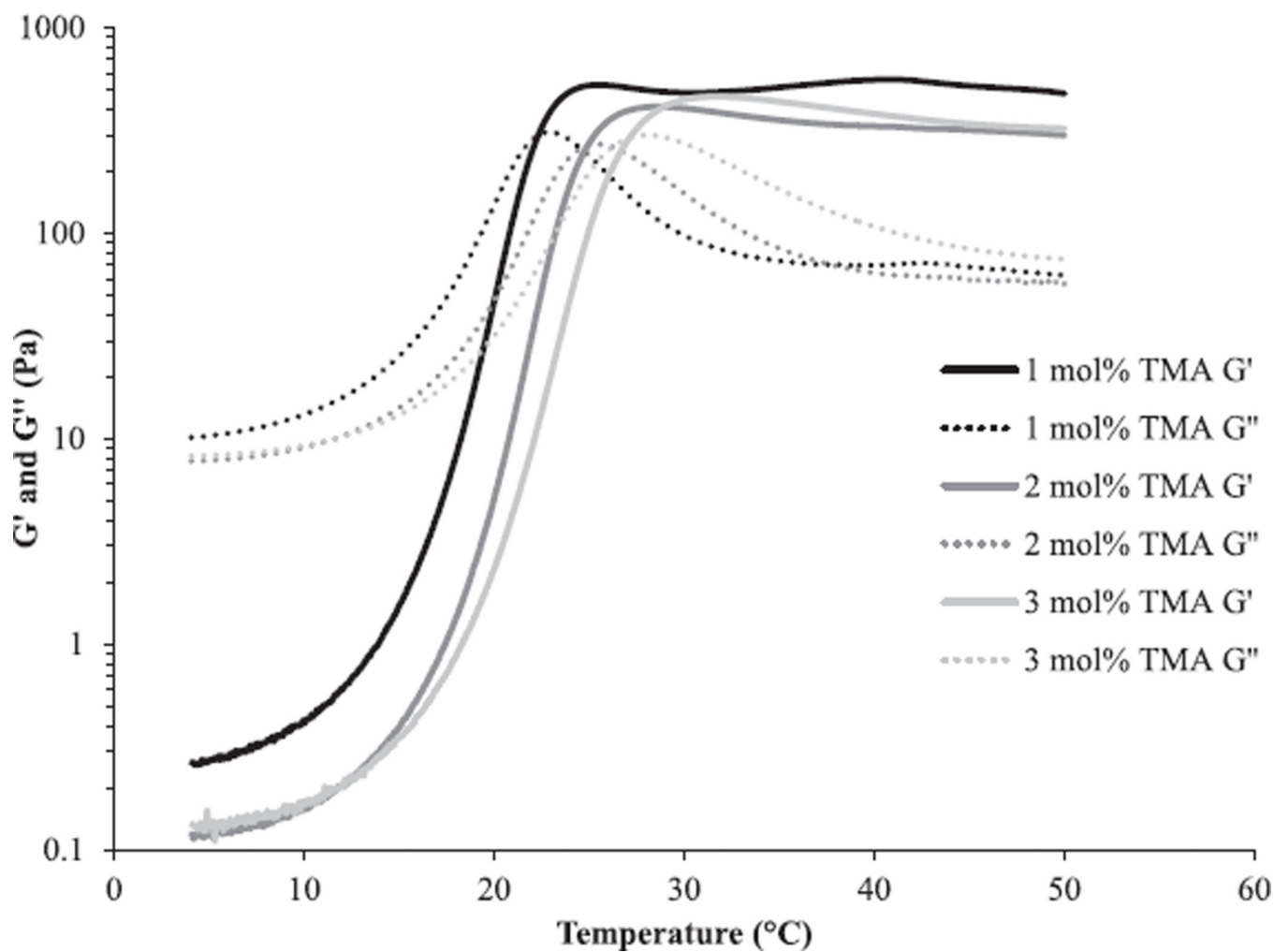


Fig. 6. Impact of TMA concentration on sol-gel transitions for 25 wt% poly($\text{DEG}_x\text{TMA}_y\text{-}b\text{-OEG-}b\text{-DEG}_x\text{TMA}_y$) in 0.9 wt% NaCl water solution.

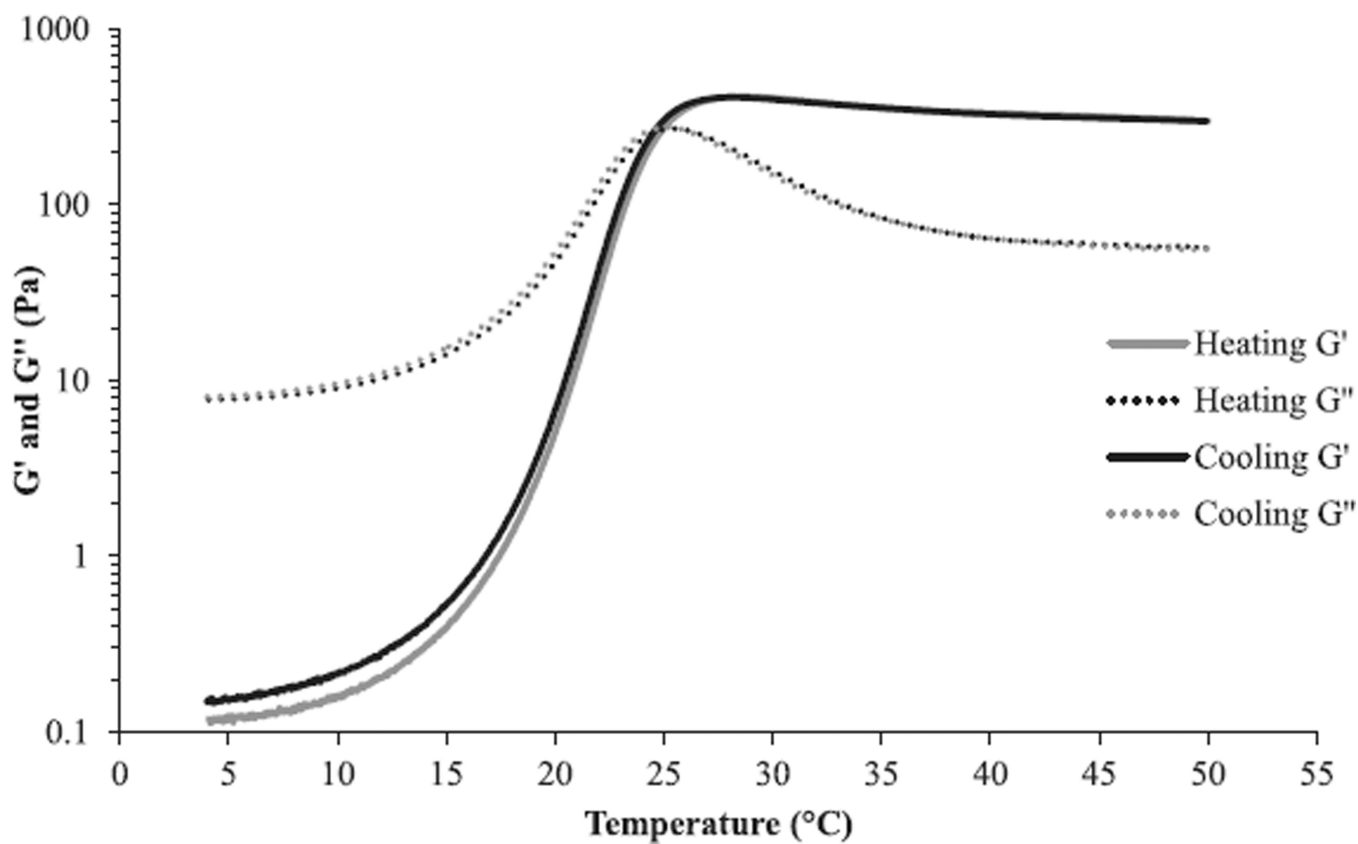
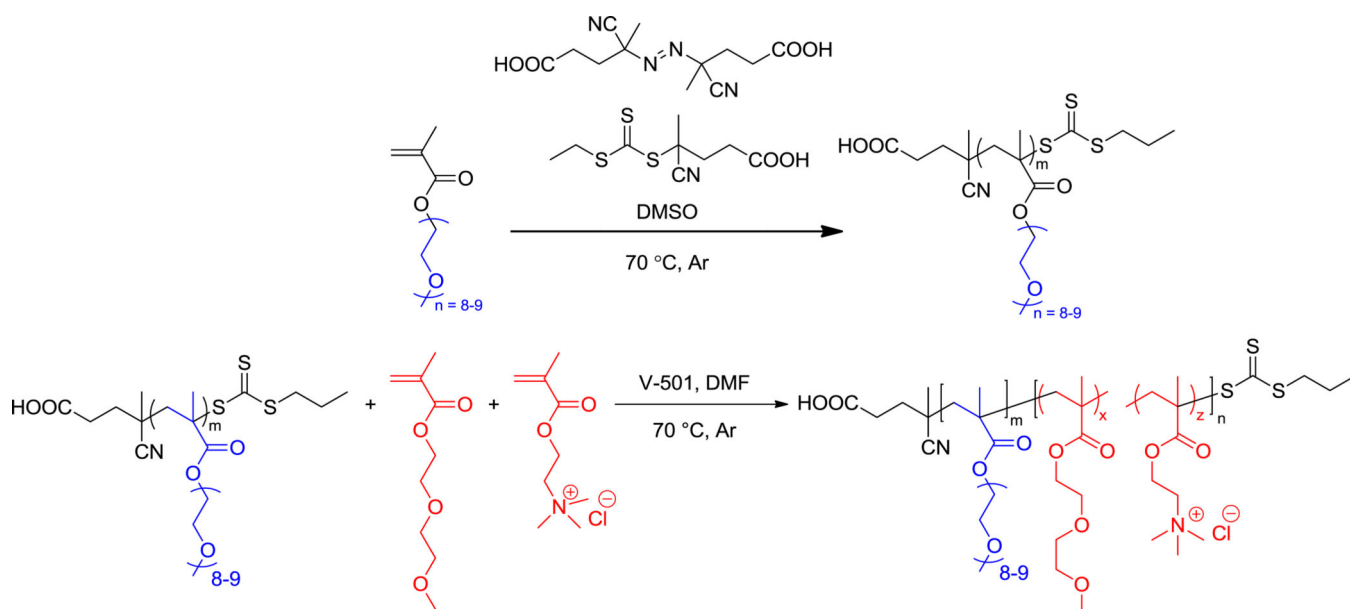
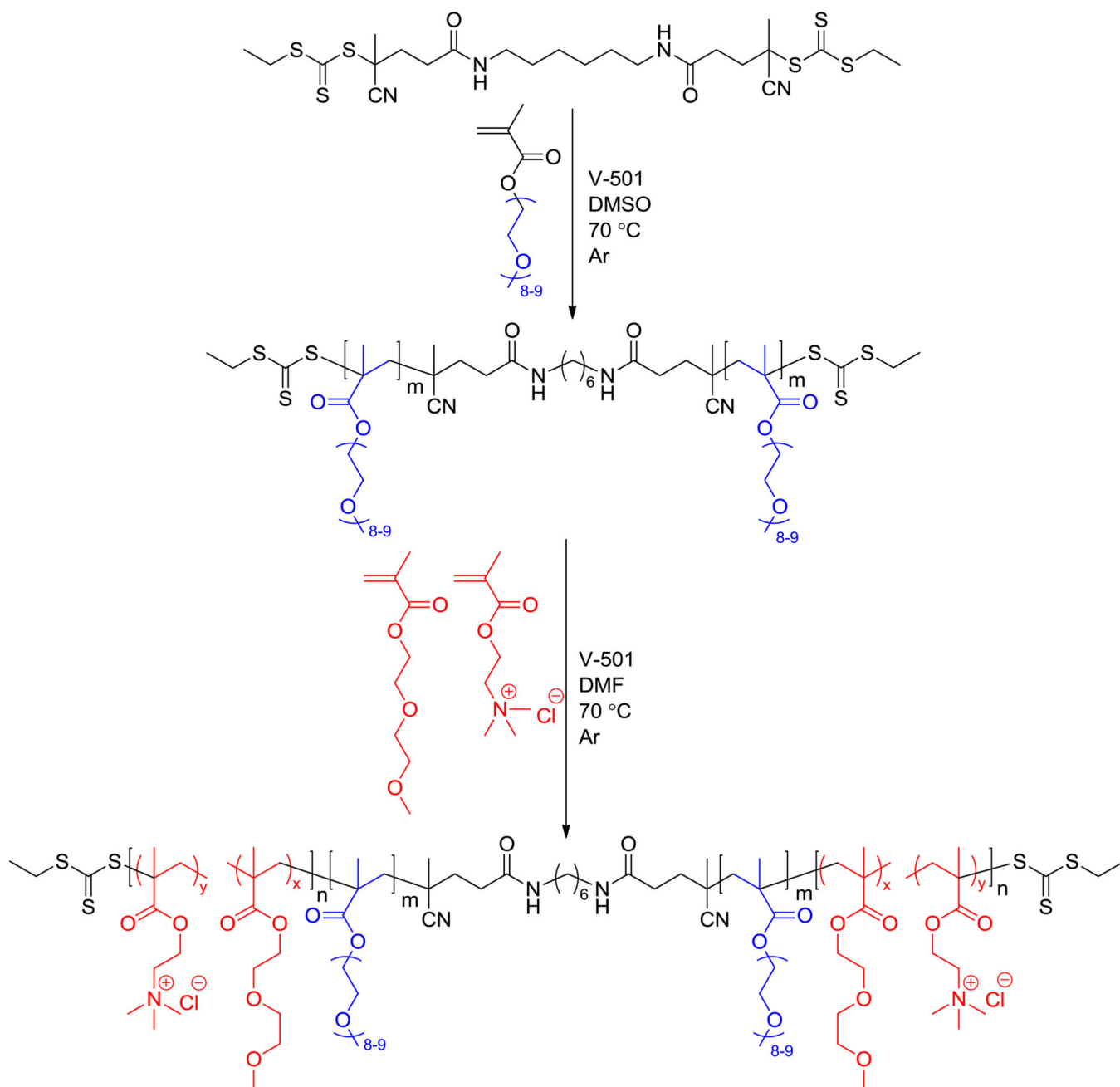


Fig. 7. Hysteresis analysis of poly(DEG₉₈TMA₂-*b*-OEG-*b*-DEG₉₈TMA₂) under heating and cooling cycles with 25 wt% polymer in 0.9 wt% NaCl water solution.

**Scheme 1.**

RAFT polymerization of OEG and subsequent chain extension with DEG and TMA to synthesize dual-responsive diblock copolymers.

**Scheme 2.**

RAFT polymerization to synthesize temperature- and salt-responsive triblock copolymers.

Table 1Molecular weight analysis of the poly(OEG-*b*-DEG_xTMA_y) diblock copolymers.

Polymer	M_n (kg/mol)	PDI	DP of A block	DP of B block
Poly(OEG)	13.6	1.04	0	28
Poly(OEG- <i>b</i> -DEG)	41.6	1.03	149	28
Poly(OEG- <i>b</i> -DEG ₉₉ TMA ₁)	39.4	1.03	137	28
Poly(OEG- <i>b</i> -DEG ₉₈ TMA ₂)	44.0	1.03	161	28
Poly(OEG- <i>b</i> -DEG ₉₇ TMA ₃)	41.2	1.02	147	28
Poly(OEG- <i>b</i> -DEG ₉₆ TMA ₄)	40.3	1.02	141	28
Poly(OEG- <i>b</i> -DEG ₉₅ TMA ₅)	41.7	1.03	149	28

Table 2

Molecular weight analysis of the poly(OEG) macroCTA and the resulting triblock copolymers poly(DEG_xTMA_y-*b*-OEG-*b*-DEG_xTMA_y).

Polymer	M_n (kg/mol)	Total M_n (kg/mol)	PDI
Poly(OEG)	64.9	64.9	1.01
Poly(DEG- <i>b</i> -OEG- <i>b</i> -DEG)	84.6- <i>b</i> -64.9- <i>b</i> -84.6	234	1.14
Poly(DEG ₉₉ TMA ₁ - <i>b</i> -OEG- <i>b</i> -DEG ₉₉ TMA ₁)	87.1- <i>b</i> -64.9- <i>b</i> -87.1	239	1.17
Poly(DEG ₉₈ TMA ₂ - <i>b</i> -OEG- <i>b</i> -DEG ₉₈ TMA ₂)	82.1- <i>b</i> -64.9- <i>b</i> -82.1	229	1.20
Poly(DEG ₉₇ TMA ₃ - <i>b</i> -OEG- <i>b</i> -DEG ₉₇ TMA ₃)	82.6- <i>b</i> -64.9- <i>b</i> -82.6	230	1.19

Table 3

Critical micellization temperatures for diblock copolymers in HPLC water or 0.9 wt% NaCl in water.

Polymer	CMT	
	No salt (°C)	0.9 wt% salt (°C)
Poly(OEG- <i>b</i> -DEG)	30	26
Poly(OEG- <i>b</i> -DEG ₉₉ TMA ₁)	32	28
Poly(OEG- <i>b</i> -DEG ₉₈ TMA ₂)	34	30
Poly(OEG- <i>b</i> -DEG ₉₇ TMA ₃)	36	34
Poly(OEG- <i>b</i> -DEG ₉₆ TMA ₄)	40	36
Poly(OEG- <i>b</i> -DEG ₉₅ TMA ₅)	>50	36

Table 4

Sol–gel transitions for triblock copolymers with 25 wt% polymer in pure water or 0.9 wt% NaCl solutions.

Polymer	Gel point	
	No salt (°C)	>0.9 wt% salt (°C)
Poly(DEG- <i>b</i> -OEG- <i>b</i> -DEG)	26	22
Poly(DEG ₉₉ TMA ₁ - <i>b</i> -OEG- <i>b</i> -DEG ₉₉ TMA ₁)	30	23
Poly(DEG ₉₈ TMA ₂ - <i>b</i> -OEG- <i>b</i> -DEG ₉₈ TMA ₂)	40	26
Poly(DEG ₉₇ TMA ₃ - <i>b</i> -OEG- <i>b</i> -DEG ₉₇ TMA ₃)	>50	28

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