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A_2BA_2 Block Copolymers of Poly(N-isopropylacrylamide) (A) and Poly(ethylene glycol) (B): Synthesis and Thermal Gelation Properties of Aqueous Solutions

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A_2BA_2 block copolymers of poly(N-isopropylacrylamide) (A, PNIPAM) and poly(ethylene glycol) (B, PEG) were synthesized by SET-LRP for the first time. The ^{1}H-NMR and GPC analyses showed that the block copolymers prepared had in average 3.5–3.8 PNIPAM arms/macromolecule and low polydispersities (M_w/M_n =1.25–1.35). The thermogelation behavior of their 20 wt% aqueous solutions was investigated by DSC, dynamic rheometry and the tube inversion method as a function of the molecular weight of both PEG block and PNIPAM arms. The results showed that both phase transition temperature, as determined by DSC, and gelation temperature, determined by the tube inversion method, increased with the PEG block length and decreased with the MW of the PNIPAM arms, while the forming gels were more stable for longer PEG chains. By comparing the thermoresponsive properties of the H-shaped block copolymers synthesized with those of some linear PNIPAM-PEG-PNIPAM triblock copolymers of similar molecular weights of both PNIPAM side blocks and PEG middle chain, almost identical results were obtained, indicating practically no influence of the shape of the PNIPAM blocks from this point of view.

Keywords: Thermogelation, poly(N-isopropylacrylamide), poly(ethylene glycol), H-shaped, block copolymers, phase separation

1 Introduction

Thermosensitive water-soluble polymers, displaying temperature-triggered hydrophilic-hydrophobic transition in aqueous solutions, have been intensely researched during the last decades due to their large number of applications in various fields, such as drug delivery, tissue engineering, flow modifiers, smart clothing fabrication, etc. (1–7). Amongst them, poly(N-isopropylacrylamide) (PNIPAM), that displays a lower critical solution temperature (LCST) in water of about 32°C, was vastly studied, especially for biomedical applications, because of its LCST close to body temperature, abrupt thermal response and low sensitivity to slight modifications of environmental conditions like pH, concentration or chemical environment (8, 9).

The mechanism of phase separation of PNIPAM aqueous solutions has been thoroughly investigated (8). Below LCST, the polymer is kept in solution by hydrogen bonding with water molecules. As temperature increases, the hydrogen bonds are weakened, while the hydrophobic interactions increase due to hydrocarbon groups dehydration, finally leading to polymer precipitation above LCST (1). Upon PNIPAM precipitation, the solution does not change to an uniform gel even when concentrated, a shrunken gel and an aqueous layer forming in this case instead (10). To obtain full gelation above LCST in the case of concentrated solutions, NIPAM was either statistically copolymerized with hydrophilic monomers (10), or another polymer block with permanent solubility in water in the temperature range investigated was attached to the PNIPAM chain (1, 3).

From this point of view, poly(ethylene glycol) (PEG) has received a great deal of attention as a component of the PNIPAM segmented copolymers because of its special properties, like water solubility, biocompatibility, ability to control the bioactivity of surfaces, lack of toxicity, etc. (11). Both graft (12–19) and block (20–28) copolymers of the PEG–PNIPAM pair have been investigated from the point of view of their thermosensitive properties in aqueous solutions. As far as the block ones are concerned, copolymers

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of various architectures, i.e., diblock copolymers, both linear (20, 21, 23–27) and with an Y-shape (28), linear triblock copolymers (20–22) and star-shaped block copolymers with four- or eight-arm PEG middle block and 4 or 8 PNIPAM side blocks, respectively (21), have been synthesized, and their temperature-responsive properties in aqueous solutions investigated.

Inspired by the previously mentioned works, the present paper deals with the synthesis and thermal gelation properties of aqueous solutions of some novel A_2BA_2 block copolymers of PNIPAM (A) and PEG (B) of various block lengths. To the best of our knowledge, neither the synthesis, nor the thermogelation properties of such PNIPAM-PEG copolymers have been reported in the literature til now, although other block copolymers with similar H-shaped architecture have been described (29–31). For comparison, some linear PNIPAM-PEG-PNIPAM triblock copolymers were also prepared to check the influence of the shape of the PNIPAM side blocks upon the thermogelation properties.

2 Experimental

2.1 Materials

$\alpha, \omega-$Dihydroxy PEGs of 2000 Da ($DHPEG_{2000}$, Fluka), 4000 Da ($DHPEG_{4000}$, Fluka) and 6000 Da ($DHPEG_{6000}$, Scharlau) approximate molecular weight were used as received. Their hydroxyl numbers, determined by the acetylation method, were 54.55, 27.99 and 19.23 mg KOH/g, respectively, corresponding to number average molecular weights ($M_{n,PEG}$) of 2060 Da, 4010 Da and 5850 Da, respectively, calculated assuming the presence of two hydroxyl groups within each PEG macromolecule.

N-Isopropylacrylamide (NIPAM, Aldrich, 97%) was recrystallized from hexane/benzene 3/1 vol/vol mixture, dried under vacuum and stored in the freezer. Copper (I) chloride (CuCl, S.C. Silal Trading SRL) was purified by stirring with glacial acetic acid overnight, filtered, washed with anhydrous ethanol and dried under vacuum. Diethyl ether (Chimopar S.A.) was distilled at atmospheric pressure and stored in a refrigerator. The difunctional macroinitiator α, ω-bis(2-chloropropionate) PEG_{4000} ($BCPEG_{4000}$) was obtained from $DHPEG_{4000}$ and 2-chloropropionyl chloride (CPC, Aldrich, 97%) in toluene, at 105°C, as described in literature (32). Tris(2-dimethylaminoethyl)amine (Me_6TREN) was prepared from tris(2-aminoethyl)amine (TREN, Acros Organics, 96%) by a procedure similar to that of Ciampolini and Nardi (33) and stored under nitrogen. N,N-dimethylformamide (DMF, Fluka, >99%) was used without further purification. Triethylamine (TEA, Merck, 99%) was dried over KOH pellets, while benzene (Fisher Chemicals, 99.9%) was dehydrated over molecular sieves. Distilled water was employed in all experiments involving water.

2.2 Synthesis of α, ω-diepoxy PEG_X ($DEPEG_X$)

The $DEPEG_X$ oligomers were synthesized through the reaction between the corresponding oligomer with OH end groups ($DHPEG_X$) and epichlorohydrin, in the presence of NaOH, in benzene, as previously described (34, 35).

2.3 Synthesis of α, ω-Bis(2,3-dihydroxypropyl) PEG_X (Tetrahydroxy PEG_X, $THPEG_X$)

$DEPEG_X$ (5 g) was dissolved in 40 mL distilled water under stirring, and 0.3–1 mL of 0.5 mol/L aqueous H_2SO_4solution was added so that to obtain an epoxy end groups/H_2SO_4 mole ratio equal to 10 (pH = 2–3). The mixture was further stirred at 30–35°C for 24 h to hydrolyze the epoxy groups. The resulting solution was neutralized with aqueous $NaHCO_3$ solution, followed by dilution with distilled water to 60 mL total volume, addition of NaCl (about 5 g) and extraction with CH_2Cl_2 (4×30 mL). The organic layers were dried several hours over anhydrous Na_2SO_4. After filtration, the organic solution was subjected to solvent removal in a rotary evaporator under vacuum. The resulting solid residue was redissolved in 15 mL benzene and the solution was added dropwise to a large excess of cold diethyl ether. The white precipitate formed was collected by filtration on a Buchner funnel and dried under vacuum at room temperature. The yield was around 4.5 g in all cases.

2.4 Synthesis of α, ω-Bis[2,3-di(2-chloropropionyloxy) propyl] PEG_X (Tetrachloro PEG_X, $TCPEG_X$)

$THPEG_X$ (4 g) was dissolved in anhydrous benzene (150 mL), under N_2, and about 100 mL solvent were distilled off to azeotropically remove the water traces. The solution was cooled down in an ice – water bath and triethylamine, followed by 2-chloropropionyl chloride (dropwise), were added via syringes (OH end groups in $THPEG_X$:CPC:TEA = 1:3:3 mole ratio). The reaction was allowed to slowly warm up and stirred at room temperature for 70 h. The heterogeneous reaction mixture was then diluted with 10–20 mL benzene and filtered to remove the salts precipitated. The maroon-colored filtrate was extracted with 3 × 40 mL water and $NaHCO_3$ solution was gradually added to the resulting aqueous phase until a pH of around 7 was obtained. NaCl (about 5 g) was added and the resulting aqueous mixture was further extracted with CH_2Cl_2 (4 × 60 mL). The organic layers were dried several hours over anhydrous Na_2SO_4 and passed through a column filled with neutral alumina. The eluate was filtered and the solvent was removed in a rotary evaporator under vacuum. The resulting solid residue was redissolved in 15 mL benzene and the solution was added dropwise to a large excess of cold diethyl ether. The white precipitate formed was collected by filtration on a Buchner funnel and dried under vacuum at room temperature. The yield was 2.8–3.2 g in all cases.

2.5 Synthesis of the PNIPAM$_2$-PEG$_X$-PNIPAM$_2$ Block Copolymers

A procedure similar to that used by Masci, Giacomelli and Crescenzi to homopolymerize NIPAM (36) was employed by using DMF:water 50:50 (v/v) and CuCl/Me$_6$TREN as the solvent and catalytic system, respectively. The syntheses were carried out in one neck 20-mL round bottom flasks, that were charged with 2.4 g NIPAM, the calculated amount of TCPEG$_X$ macroinitiator, 5 mL DMF and 3 mL distilled water. After all components dissolved, the resulting homogeneous solutions were bubbled with oxygen-free nitrogen through the septum, and the flask was placed in a bath at 20°C. Separately, the catalyst was prepared from the calculated amounts of CuCl and Me$_6$TREN (macroinitiator Cl end groups: CuCl: Me$_6$TREN = 1:2:2 mole ratio) in 2 mL of distilled water under nitrogen. The catalyst solution was transferred via a degassed syringe to the polymerization flask, and the reaction mixture was allowed to polymerize under stirring at 20°C for 6 h. At the end of the polymerization period, the reaction was stopped by exposing the reaction mixture to air, and the solvent was completely removed in a rotary evaporator under vacuum. The solid residue was dissolved in methylene chloride/chloroform mixture and passed through a column filled with neutral alumina to remove the catalyst. The resulting colorless solution was dried over anhydrous Na$_2$SO$_4$ for several hours, filtered, concentrated under vacuum and poured into a large excess of cold diethyl ether. The precipitate was collected and dried under vacuum resulting a white powder. The linear PNIPAM-PEG-PNIPAM triblock copolymers were synthesized in a similar way.

2.6 Characterizations

^{1}H-NMR measurements were carried out on a 300 MHz Varian Gemini 300 BB spectrometer, by employing deuterated chloroform as the solvent.

The molecular weight distributions were measured on an Agilent Technologies 1200 series gel permeation chromatograph with a PLgel Mixed-C column (300 × 7.5 mm) and an Agilent 1200 differential refractometer, in DMF, at 23°C and a flow rate of 1 mL/min. Calibration was made with polystyrene standards.

The rheological measurements were carried out on a Bohlin Gemini 150 (Malvern Instruments) rheometer by employing a 20 mm parallel-plate geometry with a 500 μm gap. The data were collected in the "controlled stress" mode, at a frequency of 1 rad/s and 0.5°C/min heating rate. A solvent trap was employed to avoid solvent evaporation.

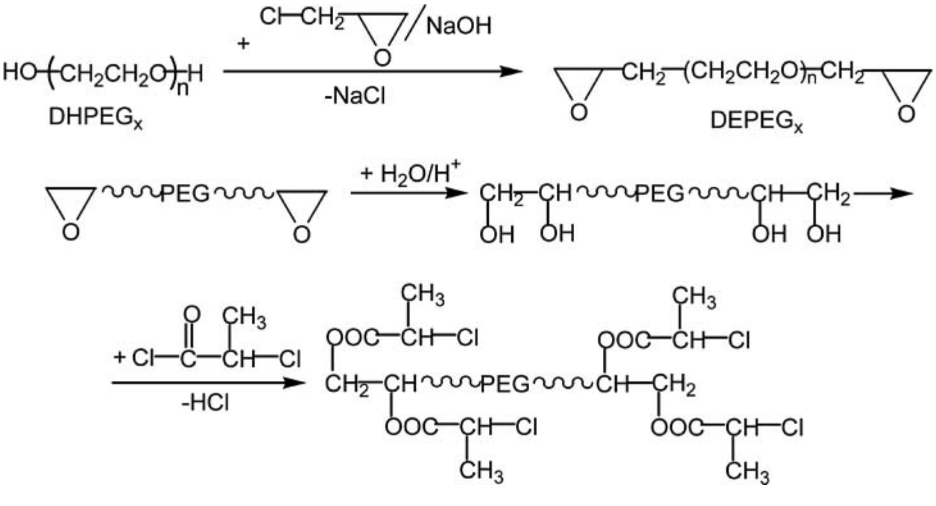
DSC measurements were carried out on a NETZSCH DSC 204 F1 Phoenix instrument operating under nitrogen flow at 1°C/min heating rate. Samples weighing about 20 mg were heated from 20°C to 60°C, and the value corresponding to the maximum of the endotherm peak on the DSC curve was taken as the phase transition temperature (T_{ph}).

The gelation temperature (T_{gel}) was determined by a tube inversion method (10). Aqueous polymer solutions (1 mL) of 20 wt% concentration, placed in 10 mm diameter glass tubes, were kept for 15 minutes at constant temperature (±0.5°C) in a chilling/heating dry plate (Torrey Pines Scientific, Inc, USA) prior to inverting the tube. The experiment was carried out at 1°C intervals, from 25°C to 70°C. T_{gel} was considered the temperature at which the polymer solution did not flow by inverting the tube. The temperature at which syneresis of the already formed gel occurred (T_{syn}) was also visually determined.

3 Results and Discussion

3.1 Synthesis of the TCPEG$_X$ Initiators

The tetrafunctional PEG macroinitiators were synthesized by a three-step procedure starting from commercially available DHPEG$_X$ samples of low polydispersity, as described in Scheme 1.



Sch. 1. Synthesis of TCPEG$_X$ macroinitiators.

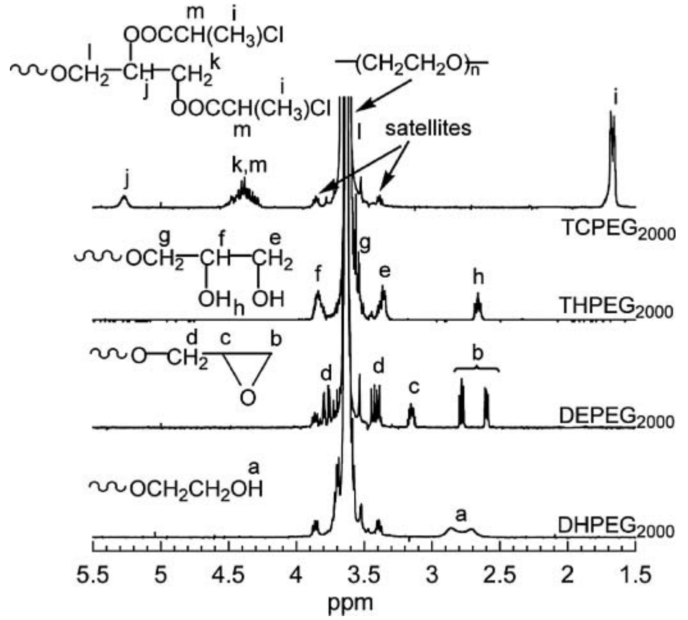


Fig. 1. ^{1}H-NMR spectra of the tetrachloro PEG$_{2000}$ macroinitiator and its precursors.

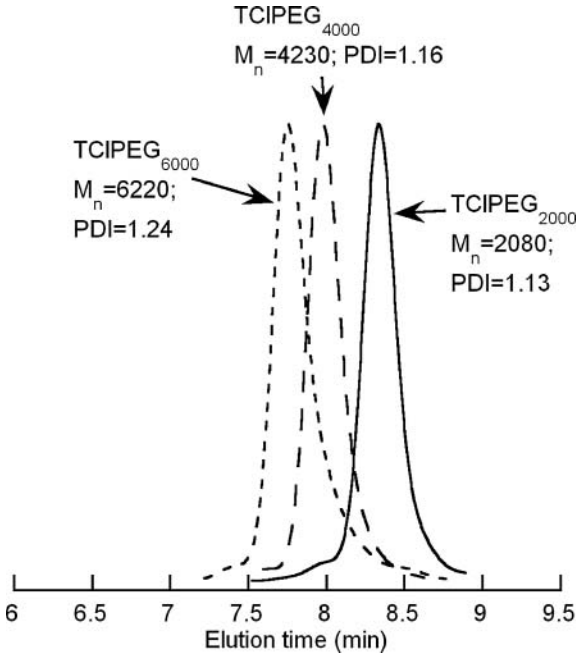


Fig. 2. GPC traces of the tetrachloro macroinitiators prepared.

In the first step, DHPEG$_X$ was reacted with ECH, in the presence of NaOH, in benzene, under solid-liquid phase transfer catalysis conditions, with the PEG chains acting as the phase transfer catalyst (34, 35), to give the corresponding diepoxy-terminated oligomer. The ^{1}H-NMR spectra of DEPEG$_X$ displayed in all cases the characteristic peaks for both the oxyethylene chain and epoxy end groups (Fig. 1), while the functionality f_{DEPEG} of the diepoxy - terminated oligomers prepared was close to 2 in all cases (Table 1), as determined both titrimetrically by the HCl addition method and by ^{1}H-NMR measurements, by comparing the areas of the peaks corresponding to the epoxy ring methine proton ($\delta = 3.15$ ppm, Fig. 1) and oxyethylene unit protons ($\delta = 3.6$ ppm).

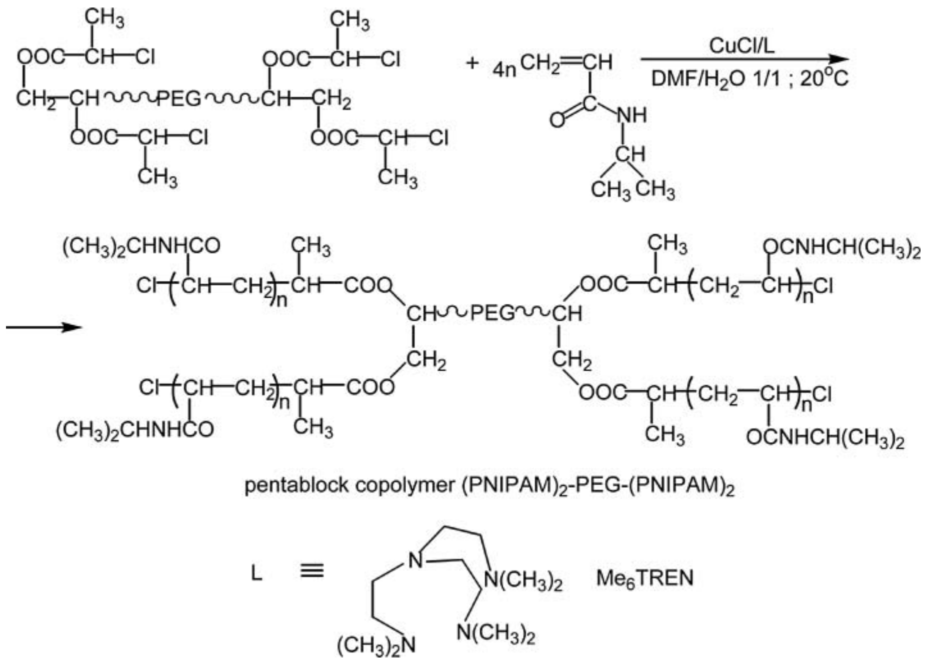
Next, the epoxy end groups were hydrolyzed at 30–35°C under acidic catalysis to yield the tetrahydroxy-ended oligomers (THPEG$_X$). The working procedure was adapted from that described by Jayamaran and coworkers for the preparation of polyolefin macromonomers with dihydroxy end groups (37). The ^{1}H NMR measurements (Fig. 1) proved full hydrolysis of the epoxy rings, as their characteristic peaks completely disappeared from the THPEG$_X$ spectra, and new peaks corresponding to the hydroxy (-**O**H, $\delta = 2.67$ ppm), methylene (C**H**$_2$-OH, $\delta = 3.35$ ppm) and methine (C**H**-OH, $\delta = 3.84$ ppm) protons in the newly formed 2,3-dihydroxy propyl end groups.

Table 1. Functionality of the synthesized TCPEG$_X$ macroinitiators and their DEPEG$_X$ precursors

Initial oligomer	f^a_{DEPEG}	f^b_{DEPEG}	f^b_{TCPEG}
DHPEG$_{2000}$	1.99	1.97	3.8
DHPEG$_{4000}$	1.91	1.89	3.7
DHPEG$_{6000}$	1.83	1.80	3.5

[a] determined titrimetrically by HCl addition to the epoxy ring in dioxane at room temperature (34); [b] determined by ^{1}H-NMR.

The conversion of the hydroxy groups in THPEG$_X$ to the 2-chloropropionate initiating moieties was carried out through reaction with 2-chloropropionyl chloride, in the presence of TEA, at room temperature. The presence of the characteristic peaks of the 2-chloropropionate groups in the ^{1}H-NMR spectra, i.e. methyl (CH-C**H**$_3$) at $\delta = 1.67$ ppm, chloromethine (Cl-C**H**-CH$_3$) and ester methylene (C**H**$_2$-OOC) at $\delta = 4.25$ - 4.52 ppm, and ester methine (C**H**-OOC) at $\delta = 5.27$ ppm (Fig. 1), proved the formation of the chlorine-ended macroinitiator. The functionality f_{TCPEG} of the macroinitiators, calculated from the ^{1}H NMR spectra, by comparing the areas of the peaks corresponding to the methyl protons ($\delta = 1.67$ ppm) and oxyethylene unit protons ($\delta = 3.6$ ppm) assuming the initial degree of polymerization for the PEG chains, was between 3.5 and 3.8, close to the target value of 4. The functionalities of the TCPEG$_X$ prepared were a little lower than expected based on the functionality of the corresponding DEPEG$_X$, very likely due to a small amount of coupling occurring during the hydrolysis step, as indicated by the small peak at higher molecular weight in the GPC traces of the TCPEG$_X$ (Fig. 2). The GPC measurements showed that the macroinitiators prepared were practically monomodal, except a very small shoulder at higher molecular weights, and with a low polydispersity.



Sch. 2. Synthesis of the (PNIPAM)$_2$-PEG-(PNIPAM)$_2$ block copolymers.

3.2 Synthesis and Characterization of the H-shaped Block Copolymers

The (PNIPAM)$_2$-PEG-(PNIPAM)$_2$ block copolymers were synthesized by NIPAM polymerization initiated by the tetrachloro PEG macroinitiators prepared and catalyzed by CuCl/Me$_6$TREN in DMF/water 1/1 (v/v) (Sch. 2). The reaction occurs through a single-electron-transfer living radical polymerization (SET-LRP) mechanism (38), instead of a classical atom transfer radical polymerization (ATRP) (36), as recently proven. After 6 h reaction time, under the experimental conditions employed, the monomer conversion was almost complete (above 90%) in all cases, in agreement with the results of Masci and coworkers (36).

The ^{1}H-NMR spectra of the H-shaped block copolymers synthesized displayed the characteristic peaks of both PEG and PNIPAM blocks (Fig. 3). By comparing the areas of the methine peak of the isopropyl group in the NIPAM units (-CONHC**H**(CH$_3$)$_2$) at $\delta = 4.0$ ppm and ethylene oxide units peak (-OC**H**$_2$C**H**$_2$-), the number average molecular weight of the PNIPAM arms ($M_{n,\text{PNIPAMarm}}$) was calculated, assuming that all PNIPAM arms have the same molecular weight and the number of arms equals the initiator functionality.

The molecular weights of the PNIPAM arms thus determined were in good agreement with the target ones (Table 2, H series). The first number in the sample codes in Table 2 indicates the approximate MW of the PEG block (i.e. 2 for 2000 Da, 4 for 4000 Da, etc.), while the second one is indicative for the target MW of the PNIPAM arm (i.e. 5 stands for 5 kDa, 10 stands for 10 kDa, etc.). For example, H2-10 is the code of the block copolymer with PEG$_{2000}$ as the middle block and PNIPAM side arms of around 10 kDa molecular weight. Table 2 shows also the characteristics of two linear PNIPAM-PEG$_{4000}$-PNIPAM triblock copolymers (L series, sample codes similar to H series) synthesized in order to compare their properties to those of similar H-shaped block copolymers (see below).

All H-shaped and linear block copolymers synthesized displayed monomodal distributions (Fig. 4) and low polydispersities (Table 2).

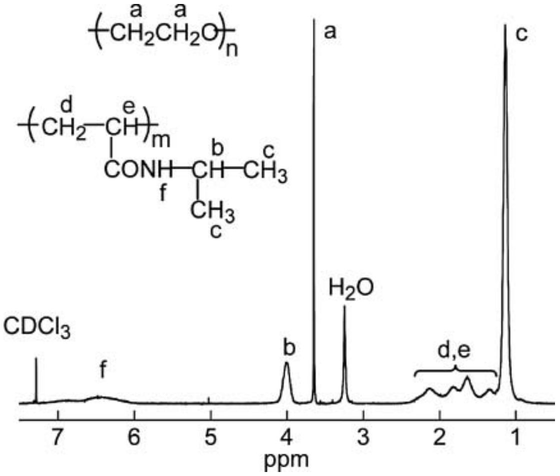


Fig. 3. ^{1}H-NMR spectrum of the (PNIPAM)$_2$-PEG$_{4000}$-(PNIPAM)$_2$ block copolymer – H4-15 sample.

Table 2. Molecular characteristics of both $(PNIPAM)_2$-PEG_X-$(PNIPAM)_2$ (H samples) and PNIPAM-PEG_{4000}-PNIPAM (L samples) block copolymers synthesized and some thermal gelation properties of their 20 wt% aqueous solutions

Sample	$M_{n,DHPEG}$ *Da*	$M_{n,targetPNIPAMarm}$ *Da*	$M^{a}_{n,PNIPAMarm}$ *Da*	PDI^{b}	T_{ph}°*C*	T_{gel}°*C*	T_{syn}°*C*
H2-10	2060	10000	9460	1.35	34.7	35	36
H4-5	4010	5000	5290	1.29	37.5	41	-$^{c)}$
H4-10	4010	10000	10080	1.30	35.3	36	64
H4-15	4010	15000	15800	1.28	34.4	35	60
H6-10	5850	10000	10400	1.25	36.5	37	61
L4-10	4010	10000	10800	1.22	38.3	41	-$^{c)}$
L4-20	4010	20000	20500	1.35	35.5	36	69

^{a}determined by ^{1}H-NMR; ^{b}determined by GPC; ^{c}Demixing did not occur up to 70°C.

3.3 The Thermogelation Process

The temperature-sensitive character of the H-shaped block copolymers synthesized was proved by DSC, dynamic rheometry and tube inversion method measurements carried out on polymer aqueous solutions of 20 wt% concentration.

The DSC measurements record the endothermic effect due to the break of the hydrogen bonds between the water molecules and the polymer chain. Therefore, the DSC peak maximum represents the temperature where the highest amount of hydrogen bonds dissociates, and in many paper its value was taken as the phase transition temperature (T_{ph}) (20, 21, 28). The measurements revealed that T_{ph} depended on the molecular weight of both PNIPAM arms and PEG middle block (Table 2, Fig. 5), similarly to other PNIPAM-PEG di- and triblock copolymers (22,23,28). At constant PEG chain length (compare H4-5, H4-10, H4-15, Table 2, Fig. 5a), T_{ph} decreased as the MW of the PNIPAM side arms increased, in agreement with the previously reported dependence of the T_{ph} of the PNIPAM aqueous solutions on PNIPAM molecular weight (39), which was explained through the decrease of the polymer–solvent interactions as the MW increases (39, 40). Conversely, for similar molecular weights of the PNIPAM side arms

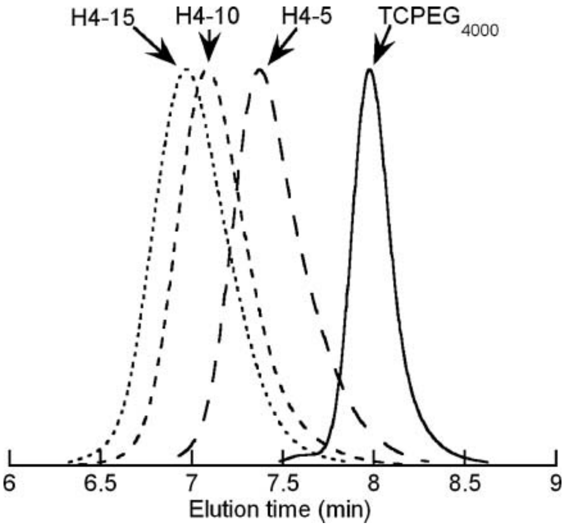


Fig. 4. GPC traces of the H-shaped copolymers with PEG_{4000} middle block and PNIPAM side arms of various lengths (Table 2).

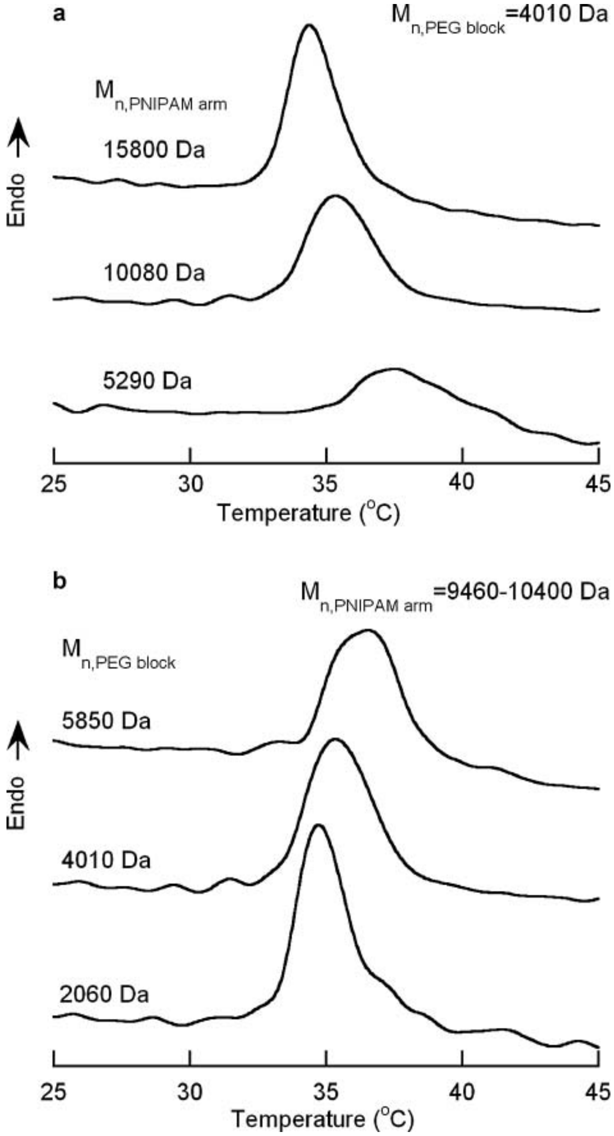


Fig. 5. DSC traces showing T_{ph} dependence on the molecular weights of both PNIPAM arms (a) and PEG block (b).

(H2-10, H4-10, H6-10, Table 2, Fig. 5b), T_{ph} increased with the PEG chain length, which can be ascribed to the partial mixing of PNIPAM and PEG chains during the association/aggregation process, rather than to the modification of the overall hydrofilicity of the block copolymers (13, 14, 22). At lower MW, the PEG chains were more compatible with the PNIPAM chains, and their mixing was more pronounced leading to an increase of T_{ph} of the PNIPAM block in comparison to that of the PNIPAM chains alone. As the MW of the PEG blocks increased, their compatibility with the PNIPAM chains decreased, as well as their mixing degree, and therefore, the PNIPAM blocks aggregated at lower temperatures, closer to that of pure PNIPAM of the same MW (22).

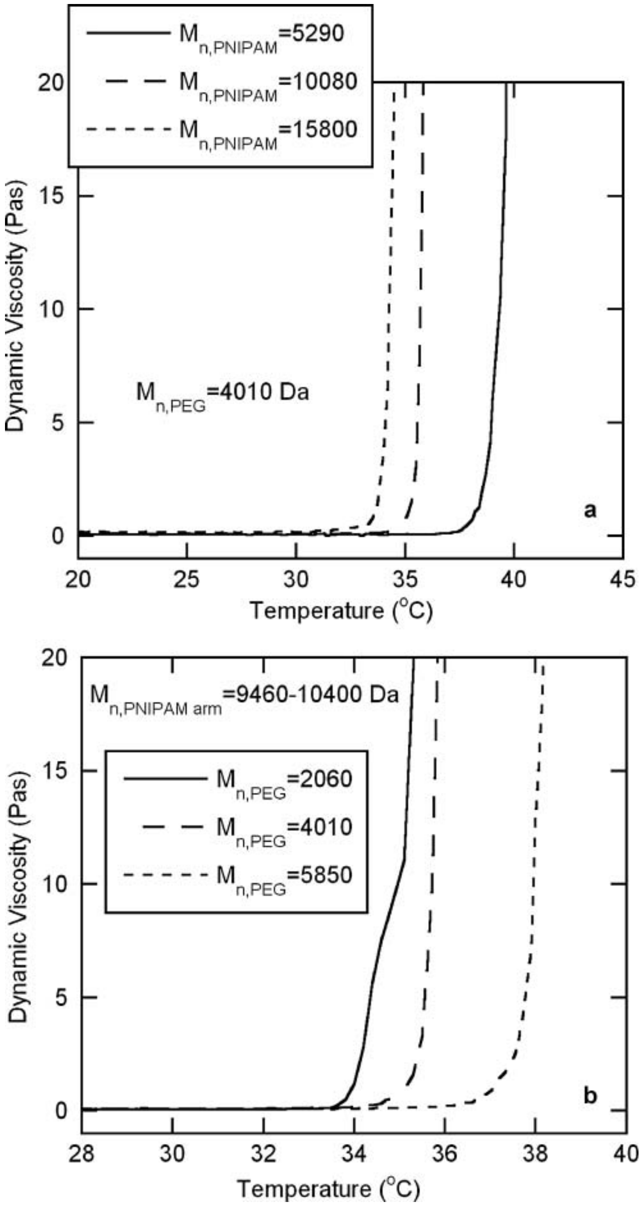


Fig. 6. Increase of the dynamic viscosity with temperature as a function of the molecular weights of both PNIPAM arms (a) and PEG block (b).

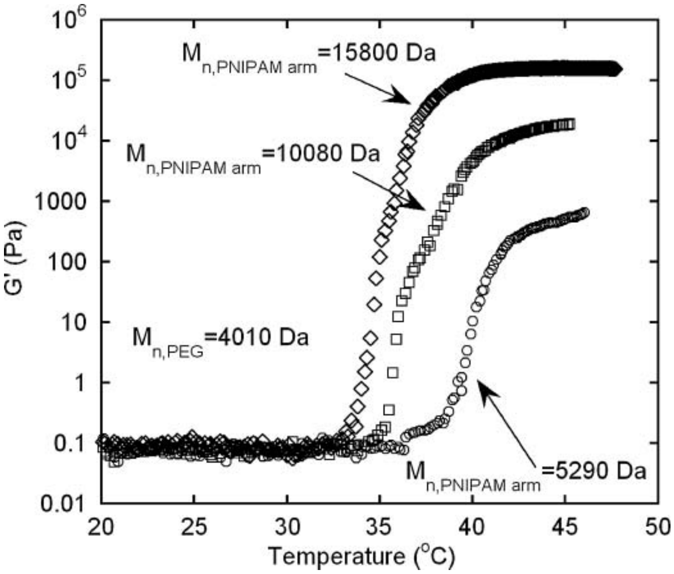


Fig. 7. Dependence of the storage modulus G' on temperature and the MW of PNIPAM arms.

Similarly to other block copolymer solutions, the gelation of the higher concentration $(PNIPAM)_2$-PEG_X-$(PNIPAM)_2$ block copolymer aqueous solutions is expected to take place at or above the T_{ph} of the temperature-sensitive PNIPAM blocks, and it should be associated with an increase of both dynamic viscosity and storage modulus (G') of the polymer solution, because of the formation of a physically crosslinked network, whose crosslinking points are represented by the precipitated PNIPAM blocks, while the solvated PEG middle blocks form the connecting chains (21, 22). Indeed, the dynamic rheometry measurements on the copolymer aqueous solutions showed that both dynamic viscosity (Fig. 6) and G' increased at different temperatures, depending on both molecular weight of PNIPAM side arms and chain length of the PEG middle block, thus supporting the DSC results.

The rheological measurements showed also that the plateau value of G' strongly depended on the MW of the PNIPAM side arms, being higher for longer PNIPAM chains (Fig. 7), similarly to the case of linear PNIPAM-PEG-PNIPAM triblock copolymers (22).

The gelation temperature (T_{gel}), i.e., the temperature at which the solution does not flow anymore, of the H-shaped block copolymer solutions, as determined by the tube inversion method, agreed well with T_{ph} for all H samples, except H4-5, where the higher proportion of hydrophilic EO units in the block copolymer, combined with the shorter PNIPAM chains led to a T_{gel} value higher by 3.5°C than the corresponding T_{ph}. This indicated that a larger number of PNIPAM chains should precipitate in order to obtain the non-flowing state of the solution (22).

T_{syn} (Table 2) illustrates the ability of the synthesized A_2BA_2 block copolymers to form stable gels in aqueous solutions. The results showed that the lowest stability ($T_{syn} = 36°C$) was recorded in the case of the copolymer with the shortest PEG middle block, i.e., H2-10, whereas in the case of all the other hydrogels syneresis occurred above 60°C. The results shown here, together with those presented before in the case of PNIPAM-PEG-PNIPAM trilock copolymers (22), seem to suggest that the syneresis phenomenon is affected mainly by the length of the PEG chains. If one look the gel formed as a hydrophilic network (similar to crosslinked hydrogels), where the PEG chains represent the bridges between the crosslinking points (the precipitated PNIPAM domains), the longer these bridges are, the larger the water absorption is (35). Therefore, the gels containing longer PEG chains can retain larger amounts of water, while the opposite is true for shorter PEG chain gels. On the other hand, the PNIPAM domains still retain water even after the aggregation of the PNIPAM blocks, their water content decreasing as they shrink with temperature increase. Thus, by increasing the temperature of the gel, the PNIPAM-rich domains contracts by expelling the water associated, which can be retained within the gel, in the case of longer PEG chains, or drove out of the gel, leading to syneresis, in the case of shorter PEG chains. T_{syn} seems also to be affected, but to a much lesser extent, by the length of the PNIPAM chain. For high enough MW of the PEG block, shorter PNIPAM side arms seem to lead to a little bit higher T_{syn}, which may be explained by the increased water-PNIPAM interactions due to the lower MW of the PNIPAM block, leading to water elimination from the hydrophobic domains at higher temperature.

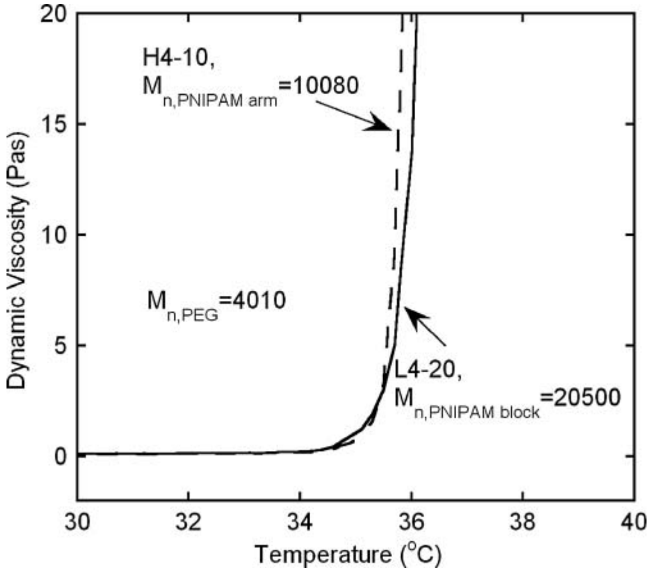


Fig. 8. Comparison of the dynamic viscosity increase with temperature in the case of H-shaped (H4-10) and linear triblock (L4-20) copolymers with similar MW of the PNIPAM side blocks.

To assess the influence of the block copolymer shape on the thermal gelation of their aqueous solutions, linear PNIPAM-PEG-PNIPAM triblock copolymers of similar PEG and PNIPAM block lengths with some of the $(PNIPAM)_2$-PEG-$(PNIPAM)_2$ block copolymers were synthesized (22), i.e., H4-5 vs. L4-10 and H4-10 vs. L4-20. The results showed that, for the same MW of the PEG middle block, the architecture of the PNIPAM block, either linear or H-shaped, had no influence upon the thermal properties of the 20 wt% copolymer aqueous solutions (Table 2). For similar molecular weights of the PNIPAM side blocks, i.e. about 10 kDa for H4-5 and L4-10, and about 20 kDa for H4-10 and L4-20, practically no differences were recorded between the corresponding T_{ph} and T_{gel}. Also, the dependence of dynamic viscosity on temperature was very similar for both H-shaped and linear triblock copolymers (Fig. 8).

4 Conclusions

H-shaped PNIPAM-PEG block copolymers with PEG middle block and PNIPAM side arms of various lengths were synthesized by SET-LRP for the first time. PEG macroinititiators with molecular weights in the range 2000–6000 Da and functionalities ranging between 3.5 and 3.8 were synthesized through a three-step procedure first. NIPAM living/controlled polymerization was carried out then in 1/1 vol/vol DMF/water mixture at 20°C with the catalytic system $Me_6TREN/CuCl$, to produce low polydispersity block copolymers with molecular weights very close to the expected ones. These block copolymers were then employed to investigate the thermogelation behavior of their 20 wt% aqueous solutions as a function of the molecular weight of both PEG block and PNIPAM arms. The phase transition temperature, determined by DSC measurements, as well as the gelation temperature T_{gel}, determined by the tube inversion method, decreased with the MW of the PNIPAM arms and increased with the length of the PEG chain. These results were also supported by dynamic rheometry measurements showing that both dynamic viscosity and storage modulus increased at different temperatures, depending on the molecular weight of both PNIPAM and PEG segments.

To assess the influence of the shape of the PNIPAM side blocks upon the termosensitive properties of the copolymers, some linear PNIPAM-PEG-PNIPAM triblock copolymers were synthesized and the thermal gelation properties of their 20 wt% aqueous solutions were also determined and compared with those of the equivalent H-shaped block copolymers. Almost identical values for T_{ph} and T_{gel}, as well as similar dependence of the dynamic viscosity on temperature were recorded, which seems to indicate practically no influence from this point of view of the shape of the PNIPAM side blocks.

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