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Synthesis of Well-Defined Amphiphilic Poly(ε-caprolactone)-*b*-poly(*N*-vinylpyrrolidone) Block Copolymers via the Combination of ROP and Xanthate-Mediated RAFT Polymerization

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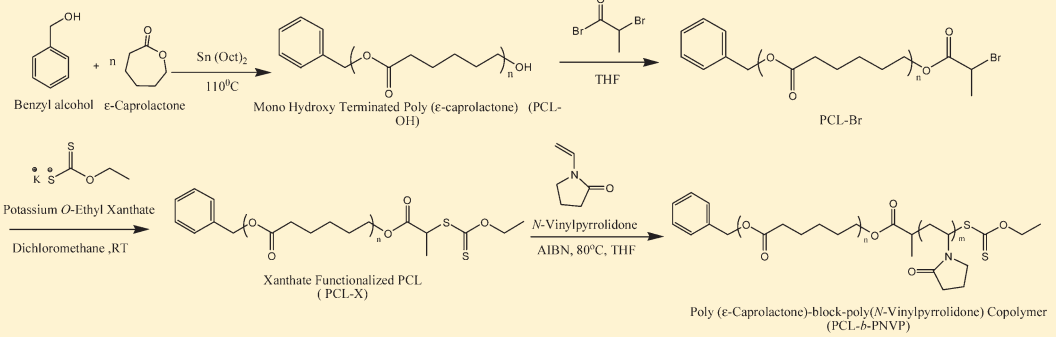
Supporting Information

ABSTRACT:



Well-defined amphiphilic poly(ε-caprolactone)-*b*-poly(*N*-vinylpyrrolidone) (PCL-*b*-PNVP) block copolymers were successfully prepared via the combination of ring-opening polymerization (ROP) and xanthate-mediated reversible addition−fragmentation chain transfer (RAFT) polymerization. Well-defined poly(ε-caprolactone) (PCL−OH) was synthesized by ROP in bulk at 110 °C using benzyl alcohol as initiator and stannous octate [$Sn(Oct)_2$] as catalyst . The −OH end group was then converted into its corresponding xanthate (PCL−X) via the conversion to its corresponding bromide (PCL−Br). These are verified by ^{1}H NMR spectroscopy. PCL-*b*-PNVP block copolymers were synthesized via RAFT polymerization in tetrahydrofuran (THF) at 80 °C using PCL−X as macro-chain transfer agent and characterized by ^{1}H NMR spectroscopy and gel permeation chromatography (GPC). The amphiphilic diblock copolymer PCL_{63}-*b*-$PNVP_{90}$ forms spherical micelles of ∼34 nm diameter in water as shown by transmission electron microscopy (TEM), supported by ^{1}H NMR spectroscopy, and light scattering. The critical micellar concentrations were determined by fluorescence spectroscopy using pyrene as probe. The critical micelle concentration (cmc) value of the block copolymers increases with the increase in the chain length of PNVP block. The overall hydrodynamic radius (R_h) of the micelles remains almost constant over the concentration range above the cmc value and over the angles of scattering measurement.

INTRODUCTION

Recently, the well-defined synthesis of amphiphilic block copolymers using controlled radical polymerization techniques has drawn great attention.[1,2] Because of the presence of both hydrophobic and hydrophilic segments, such block copolymers undergoes self-assembly, which give rise to their interesting aqueous solution and dispersion properties. Potential applications of such copolymer include drug delivery, coating, and colloid stabilization. In these respects, amphiphilic block copolymers containing, a hydrophilic poly(*N*-vinylpyrrolidone) (PNVP) segment will be of interest from the biological point of view owing to its high water solubility, low toxicity, biocompatibility, complexation capability, cryo-protectivity, lypoprotectivity and antibiofouling properties. *N*-Vinylpyrrolidone (NVP) can only be polymerized by radical polymerization due to the nonconjugation of its amide keto group with the vinyl group. Different controlled/living radical polymerization methods[3−15] were explored for the controlled synthesis of its homopolymer and block copolymers. On the other hand, amphiphilic block copolymer containing a hydrophobic poly(ε-caprolactone) (PCL) will also be of a very interesting form the point of its pharmaceutical and biomedical applications owning to its biocompatibility and biodegradability. ε-Caprolactone (CL) can be polymerized by ring-opening polymerization. Therefore, an amphiphilic block copolymer containing a hydrophobic PCL segment and a hydrophilic PNVP segment will be very useful for

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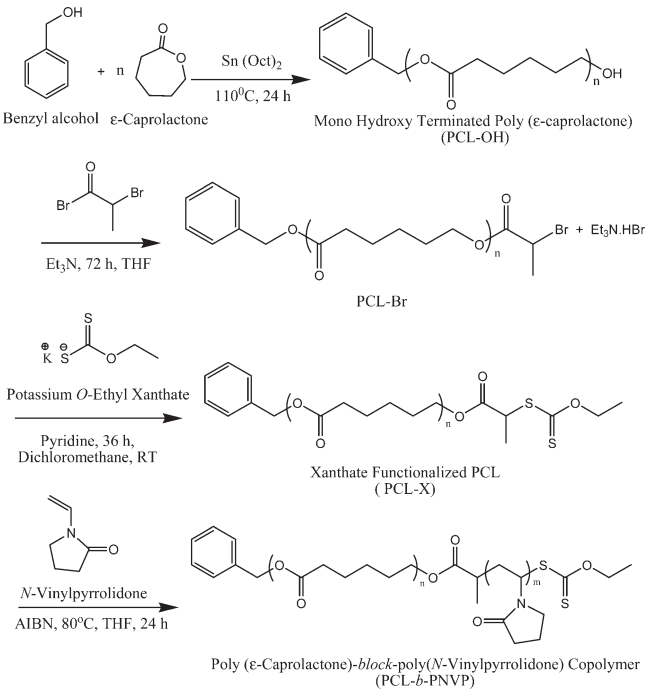
Scheme 1. Synthesis of PCL-*b*-PNVP Block Copolymer by Combined ROP and Xanthate-Mediated RAFT Polymerization Methods



the delivery of hydrophobic drugs. Reports of the synthesis of such block copolymer were very few in the literature.[16−19] Lele and Leroux[16] reported first the synthesis and micellar characterization of PNVP-*b*-PCL-*b*-PNVP block copolymers prepared using conventional radical polymerization of NVP in the presence of novel macromolecular chain transferring agents: α,ω-poly(ε-caprolactone)dithiol (HS-PCL-SH). Later, Cho et al.[17] reported the synthesis and micellar characterization of PCL-*b*-PNVP block copolymer prepared through the combination of conventional radical polymerization of NVP in the presence of 2-mercaptoethanol chain transfer agent, and the controlled ROP of CL using aluminum alkoxide as catalyst. Recently, Chiellini at al.[18] also reported the synthesis and the study of different properties of PCL-*b*-PNVP block copolymers prepared through the combination of conventional radical polymerization in the presence of 2-isopropoxy ethanol chain transfer agent, and the controlled ROP of CL using different catalyst systems like stannous octate ($SnOct_2$), potassium hydride (KH), and diethyl zinc ($ZnEt_2$). Recently, Levia et al.[19] reported the synthesis, characterization, and self-assembly properties of a novel three armed amphiphilic block copolymer with a PCL central block and three PNVP arms, prepared using conventional radical polymerization. Very recently, Jeon et al.[20] reported the synthesis and characterization of well-defined amphiphilic PNVP-*b*-PCL block copolymers prepared through the combination of cobalt-mediated controlled radical polymerization of NVP and controlled ROP of CL. Here, we report for the first time the controlled synthesis of well-defined amphiphilic block copolymers of CL and NVP by combining the controlled ROP of CL and the controlled metal-free xanthate-mediated RAFT polymerization of NVP (Scheme 1). First, PCL with −OH end-group (PCL−OH) was synthesized using ROP. The −OH end-group was then converted to the corresponding −Br end group (PCL−Br) through a reaction with 2-bromopropionyl bromide. Then, this −Br end-group was converted to *O*-ethyl xanthate end group (PCL−X) through an ionic substitution reaction with potassium *O*-ethyl xanthate. Then, the controlled/living radical polymerization of NVP was performed to synthesize well-defined amphiphilic PCL-*b*-PNVP block copolymers using a macro chain transfer agent PCL−X. Further, the self-assembly behavior of the obtained amphiphilic block copolymers was studied using ^{1}H NMR, TEM, fluorescence spectroscopy, and light scattering.

EXPERIMENTAL SECTION

Materials. Triethylamine (Loba Chemie, Mumbai, India, 99%), 2-bromopropionyl bromide (Fluka, Israel, >97%), stannous 2-ethylhexanoate [$Sn(Oct)_2$] (Aldrich, St Louis, MO, 99%), diethyl ether (s.d.fine, Mumbai, India), hexane (CDH, Mumbai, India), methanol (Loba Chemie, Mumbai, India, 99%), sodium hydrogen carbonate (Loba Chemie, Mumbai, India), ammonium chloride (s.d.fine, Mumbai, India), anhydrous magnesium sulfate (Loba Chemie, Mumbai, India) were used as received. Benzyl alcohol (s.d.fine, Mumbai, India, 99%) was dried over CaO and then distilled under reduced pressure. ε-Caprolactone (ε-CL) (Aldrich, St Louis, MO, 99%) was dried over calcium hydride (CaH_2) for 48 h at room temperature and then distilled under reduced pressure before use. *N*-Vinylpyrrolidone (Aldrich, St Louis, USA, 99%) was dried over anhydrous magnesium sulfate and distilled under reduced pressure. 2, 2′- Azobis(isobutyronitrile) (AIBN) (Spectrochem, Mumbai, India, 98%) was recrystallized from methanol. Tetrahydrofuran (THF) (Loba Chemie, Mumbai, India) was dried and fractionally distilled from sodium and benzophenone. Ethanol (Saraya Distilliary, India) was stirred over CaO overnight and distilled over fresh CaO. Potassium *O*-ethyl xantate was prepared according to our previous work.[15]

General Methods. ^{1}H NMR spectra were recorded on a JEOL AL300 FTNMR (300 MHz) at room temperature in $CDCl_3$ or D_2O as solvent, and are reported in parts per million (δ) from internal standard tetramethylsilane or residual solvent peak. NVP monomer conversion (%) was determined using ^{1}H NMR spectroscopy in $CDCl_3$ by comparing the integrated peak area of the residual vinylic signals at 4.3−4.4 ppm (2H) and 7.0−7.1 ppm (1H) of the monomer with that of the peak at 3.0−3.4 ppm (2H) of the corresponding polymer. The number-average molecular weight (M_n) and polydispersity index (M_w/M_n) were determined by Youglin ACME 9000 gel permeation chromatography in DMF at 40 °C with flow rate 0.5 mL/min on two polystyrene gel columns [PL gel 5 μm 10E 4 Á columns (300 × 7.5 mm)] connected in series to Younglin ACME 9000 Gradient Pump and a Younglin ACME 9000 RI detector. The columns were calibrated against seven poly(methyl methacrylate) (PMMA) standard samples (Polymer Lab, PMMA Calibration Kit, M-M-10). For PCL homopolymers, molecular weight from ^{1}H NMR spectrum was determined by comparing the ratio of the average peak intensity of backbone methylene peak at ∼4.1, ∼2.4, and ∼1.3 ppm (2H) to that of the benzylic protons of the polymer chain-end at ∼5.1 ppm (2H). For PCL block in PCL-*b*-PNVP block copolymers, molecular weight from ^{1}H NMR spectrum was determined only by comparing the ratio of the peak intensity of backbone methylene peak at ∼4.1 ppm (2H) (relatively less overlapped) to that of the benzylic protons of the polymer chain-end at ∼5.1 ppm (2H) as other backbone methylene protons at ∼2.4, and ∼1.3 ppm (2H) were overlapped with other PNVP protons. The theoretical number-average molecular weight [M_n(theor)] of the resulted PCL-*b*-PNVP block polymer using PCL−X xanthate macro chain-transfer agent was calculated using the following equation:

$$\overline{M}_n(\text{theor}) = \frac{[\text{NVP}]_o}{[\text{PCL}-\text{X}]_o} \cdot x_{\text{NVP}} \cdot M_{\text{NVP}} + M_{\text{PCL}-\text{X}}(\text{NMR})$$

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Here, x_{NVP} is the fraction conversion of monomer, M_{NVP} is the molecular weight of monomer, and M_{PCL-X} (NMR) is molecular weight of the PCL−X xanthate macro chain-transfer agent determined for its ^{1}H NMR (Here, the term for AIBN is not considered because used [PCL−X] ≫ [AIBN]). TEM images were obtained using a Technai 12, FEI, Netherland transmission electron microscope operating at an acceleration voltage of 200 kV. The TEM samples were prepared by dipping the carbon coated copper grid into the aqueous block copolymer solution (1 mg/mL) followed by the removal of extra solution with a filter paper.

Fluorescence Experiments. Fluorescence measurements were carried out on a Varian Cary Eclipse fluorescence spectrometer. A series of aqueous PCL-*b*-PNVP block copolymer solutions with concentrations ranging from 1×10^{-3} to 1 mg/mL were prepared by diluting the stock solution of block copolymer with deionized water. A pyrene stock solution in acetone was transferred to a series of vials, the acetone was evaporated under nitrogen, and the block copolymer solutions were added to the vials to get a final pyrene concentration of 6×10^{-7} M in each vial. After being equilibrated at room temperature overnight, the excitation spectra (300−360 nm) of the solutions were recorded at an emission wavelength of 394 nm using a slit width of 5 nm. The ratio of the peak intensities of the excitation spectra of pyrene at 337.07 nm ($I_{337.07}$) and 333.07 nm ($I_{333.07}$) was analyzed as a function of polymer concentration. The critical micelle concentration (cmc) value was calculated from at interception point of the two tangent straight lines at low concentration (see Figure 6).

Light Scattering Experiments. A Brookhaven laser scattering system[21] equipped with a BI-200SM research goniometer, a TurboCorr digital correlator (BI-9000 AT) with a maximum number of 522 channels, and a He−Ne laser of a wavelength 632.8 nm was used to study the dynamic light scattering behavior of the block copolymers. A 0.45 μm filter was used to remove the dust particles from the polymer solution prior to the experiments. In the dynamic light scattering measurements, the short-term intensity fluctuations (dynamics) of the scattered light arising from the scattering particles undergoing rapid thermal (Brownian) motion was measured at 25 °C to get the intensity autocorrelation function. The obtained intensity autocorrelation functions were analyzed by fitting to a polynomial of second order function using the Cumulant method of the BI-ISDAW software package. The average decay rate "Γ", and scattering vector "q", and apparent hydrodynamic radius of the micelle "R_h" were calculated using the following three equations:

$$\Gamma = q^2 \cdot D$$

where, D = translational diffusion co-efficient.

$$q = 4\pi n_s \sin\left(\frac{\theta}{2}\right)$$

where n_s = refractive index of the solvent, θ = scattering angle.

$$D = \frac{K_B T}{6\pi\eta R_h}$$

where k_B = Boltzmann's constant, T = temperature in kelvin, η = viscosity of the liquid.

For the moderately polydisperse spherical particles in solution,[22,23] the polydispersity $\mu_2/(\bar{\Gamma})^2$, where $\bar{\Gamma}$ and μ_2 are the first and second cumulants of the quadratic fitting of natural logarithm of the normalized first order intensity autocorrelation functions, gives an idea about the size distribution width of the micelle.

Typical Synthesis of Monohydroxy-Terminated Poly(ε-caprolactone) (PCL_{63}−OH) (Run 1, Table 1). Monohydroxy-terminated poly(ε-caprolactone) (PCL−OH) was synthesized via the ROP of CL using benzyl alcohol as initiator and $Sn(Oct)_2$ as the catalyst.

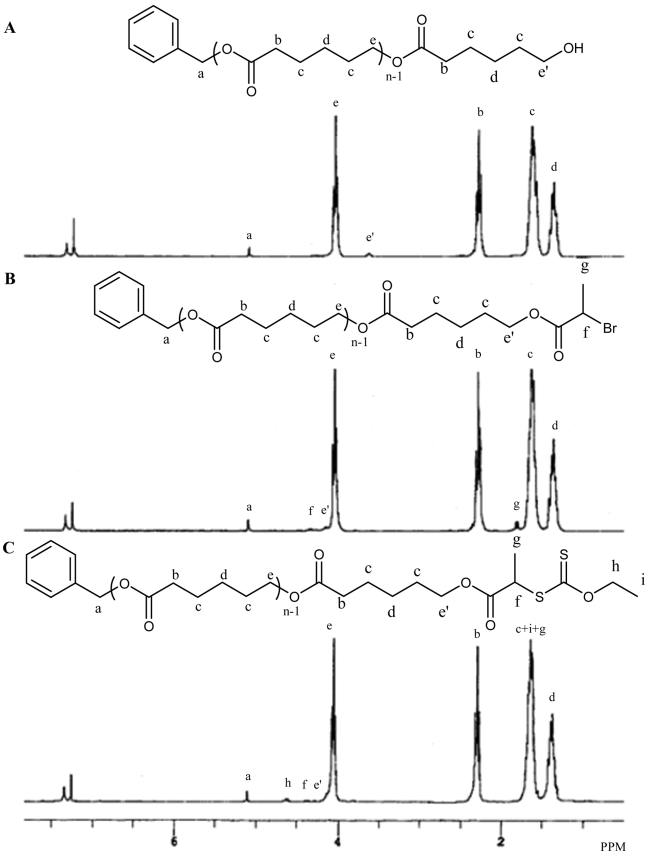

Figure 1. ^{1}H NMR spectra of (A) PCL_{63}−OH, (B) PCL_{63}−Br and (C) PCL_{63}−X in *d*-chloroform at room temperature.

In a typical experiment (run 1, Table 1), 0.7 mL benzyl alcohol (6.7×10^{-3} mol) and 20 mL CL (20.6 g, 0.18 mol) were charged to a 100 mL dry Schlenk tube equipped with a magnetic bar under dry nitrogen atmosphere. After that, 17 μL (21.26 mg, 5.24×10^{-2} mmol) $Sn(Oct)_2$ was added using a dry syringe. The tube was connected to a standard Schlenk line, the reaction mixture was degassed via three freeze−pump−thaw cycles and then immersed in a thermostated oil bath at 110 °C for 24 h. The polymerization was stopped by freezing the reaction mixture with liquid N_2. The crude product was dissolved in 50 mL of THF and precipitated from 600 mL of hexanes. The precipitated polymer was collected by centrifugation. The separated polymer was purified by repeated dissolution in THF, precipitated from hexanes twice, and finally was dried under vacuum at room temperature for 24 h. Yield (gravimetric) = 96%.

^{1}H NMR (300 MHz, $CDCl_3$) [Figure 1a]: δ (ppm) = 1.3−1.4 (m, $2H_d$), 1.5 −1.6 (m, $4H_c$), 2.2−2.3 (m, $2H_b$), 3.6 (t, $2H_e'$), 4.05 (t, $2H_e$), 5.06 (s, $2H_a$), 7.18−7.43 (m, $5H_{Ar}$).

M_n(NMR) = 4493 g mol^{-1}, M_n(GPC) = 7200 g mol^{-1}, M_w/M_n = 1.26.

Typical Synthesis of PCL_{63}-COCH (CH_3) Br (PCL_{63}−Br) (Run 1, Table 2). In a dried and nitrogen purged round-bottom flask, 5 g [1.11×10^{-3} mol, calculated on the basis of molecular weight (4493) obtained from ^{1}H NMR] of PCL_{63}−OH was dissolved in 20 mL of dry THF with 0.43 mL (3.12×10^{-3} mol) of triethylamine with stirring under nitrogen atmosphere. After that, 0.25 mL (2.38×10^{-3} mol) of 2-bromopropionyl bromide was then added dropwise to the above-mentioned reaction mixture that was cooled in an ice bath. The reaction mixture was then stirred for 72 h at room temperature. The precipitated byproduct (i.e., $Et_3N.HBr$), was removed by filtration and the filtrate was

Table 1. Synthesis of PCL−OH by ROP[a]

run	sample	benzyl alcohol (mmol)	yield[b] (%)	M_n(Theor)[c]	M_n(NMR)[d]	M_n(GPC)[e]	PDI[e] (GPC)	comments
1	PCL_{63}−OH	6.7	96	4428	4493	7200	1.26	unimodal
2	PCL_{106}−OH	2.57	97.8	7931	9687	12 100	1.21	unimodal with hump at high mol wt end
3	PCL_{142}−OH	0.85	72.9	18 335	20 885	16 200	1.15	unimodal with hump at high mol wt end
4	PCL_{364}−OH	0.41	98	49 108	46 666	41 600	1.48	bimodal

[a] bulk polymerization using 20.6 g (0.18 mol) of Cl, 21.26 mg (5.24×10^{-2} mmol) of $Sn(Oct)_2$) in the presence of benzyl alcohol at 110 °C for 24 h. [b] Determined gravimetrically from hexane insoluble part after drying at room temperature for 24 h. [c] $M_n(theor) = x_{CL}M_{CL} + M_{BA}$ where x_{CL} = fraction conversion of monomer by gravimetry, M_{CL} = molecular weight of CL monomer and M_{BA} = molecular weight of benzyl alcohol. [d] Determined using ^1H NMR in $CDCl_3$ by comparing the average of the peak area of aliphatic methylene protons of the backbone PCL chain at ∼4.1, ∼2.4, ∼1.3 ppm to that of the benzylic protons of the polymer chain-end at ∼5.1 ppm. [e] Determined by GPC (DMF, 0.5 mL/min, 40 °C) calibrated against PMMA standard.

Table 2. Synthesis of PCL−Br [a]

run	PCL_x−OH (*Mn*/PDI)	THF (mL)	% convn[b] (NMR)	M_n(NMR)[c]	M_n(GPC)[d]	PDI(GPC)[d]
1	PCL_{63}−OH (7200/1.26)	20	84	4216	7200	1.21
2	PCL_{106}−OH (12100/1.21)	30	80	9342	12 600	1.15
3	PCL_{142}−OH (16200/1.15)	35	100	20 885	16 400	1.12
4	PCL_{364}−OH (41600/1.48)	50	-	46 821	41 600	1.48

[a] Using PCL−OH:triethylamine:2-bromopropionyl bromide, 1:2.5:2, in THF at room temperature for 72 h. [b] % conversion of PCL−OH into PCL−Br determined using ^1H NMR by comparing the peak area of the CH_2 of benzylic proton of the polymer chain-end at ∼5. 1 ppm to that of the methyl proton of the 2-bromopropionyl bromide polymer chain-end at ∼1.8 ppm. [c] Determined using ^1H NMR in $CDCl_3$ by comparing the average of the peak area of aliphatic methylene protons of the backbone PCL chain at ∼4. 1,∼2.4, and ∼1.3 ppm to that of the benzylic protons of the polymer chain-end at ∼5.1 ppm. [d] Determined by GPC (DMF, 0.5 mL/min, 40 °C) calibrated against PMMA standard.

Table 3. Synthesis of PCL−X[a]

run	PCL_x−Br (*Mn*/PDI)	DCM (mL)	% convn[b] (NMR)	M_n(NMR)[c]	M_n(GPC)[d]	PDI(GPC)[d]
1	PCL_{63}−Br (7200/1.21)	20	100	4281	7200	1.25
2	PCL_{106}−Br (12600/1.15)	30	100	10 026	12 800	1.16
3	PCL_{142}−Br (16400/1.12)	30	100	21 334	16 500	1.18

[a] Using PCL−Br:potassium *O*-ethyl xanthate:pyridine, 1:3:53, in dichloromethane (DCM) at room temperature for 36 h. [b] % conversion of PCL−Br into PCL−X using ^1H NMR by comparing the peak area of the methine proton of the propionyl group at ∼4.3 with that of the methylene proton of the xanthate group of the polymer chain-end at ∼4.6 ppm. [c] Determined using ^1H NMR in $CDCl_3$ by comparing the average of the peak area of aliphatic methylene protons of the backbone PCL chain at ∼4.1, ∼2.4, and ∼1.3 ppm to that of the benzylic protons of the polymer chain-end at ∼5.1 ppm. [d] Determined by GPC (DMF, 0.5 mL/min, 40 °C) calibrated against PMMA standards.

evaporated to dryness. The residue was dissolved in dichloromethane and washed thoroughly with 5% sodium bicarbonate (4 × 100 mL). The organic layer was further washed with water (4 × 200 mL), dried over anhydrous Na_2SO_4, and filtered. The filtrate was evaporated and dried under vacuum at room temperature. The residue was redissolved in THF, precipitated from hexanes and dried under vacuum at room temperature for 24 h. Conversion (%) (NMR) = 84%.

^1H NMR (300 MHz, $CDCl_3$) [Figure 1b]: δ (ppm) = 1.3−1.4 (m, $2H_d$), 1.5−1.6 (m, $4H_c$), 1.82 (d, $3H_g$), 2.2−2.3 (m, $2H_b$), 4.05 (t, $2H_e$), 4.1 (t, $2H_e'$), 4.3 (q, $1H_f$), 5.06 (s, $2H_a$), 7.18−7.43 (m, $5H_{Ar}$).

M_n(NMR) = 4,216 g mol^{-1}, M_n(GPC) = 7,200 g mol^{-1}, M_w/M_n = 1.21.

Typical Synthesis of PCL_{63}−C(O)CH(CH_3)SC(S)OC_2H_5 (PCL_{63}−X) (Run 1, Table 3). In a dried and nitrogen purged round-bottom flask, 4.0 g (9.49×10^{-4} mol) of PCL−Br and 0.48 g of potassium *O*-ethyl xanthate (3.0×10^{-3} mol) were dried and degassed by three freeze−pump−thaw cycles. In another dried and nitrogen purged round-bottom flask, 4.2 mL (5.3×10^{-2} mol) pyridine was dissolved in 20 mL CH_2Cl_2 while stirring under nitrogen. This solution was added to the previous reaction mixture during stirring under nitrogen. The reaction mixture was stirred at room temperature for 36 h and diluted with 100 mL CH_2Cl_2. The solution was washed consecutively with saturated NH_4Cl solution (4 × 50 mL), saturated $NaHCO_3$, solution (4 × 50 mL), and water (4 × 100 mL). The organic layer was dried over anhydrous $MgSO_4$, filtered and the filtrate was dried under vacuum at room temperature for 12 h. The residue was redissolved in THF, precipitated from hexanes and dried under vacuum at room temperature for 24 h. Conversion (%) (NMR) = 100%.

^1H NMR (300 MHz, $CDCl_3$) [Figure 1c]: δ (ppm) = 1.3−1.4 (m, $2H_d$), 1.5−1.6 (m, $4H_c$+$3H_g$ +$3H_i$), 2.2−2.3 (m, $2H_b$), 4.05 (t, $2H_e$), 4.1 (t, $2H_e'$), 4.3 (q, $1H_f$), 4.6 (q, $2H_h$), 5.06 (s, $2H_a$), 7.18−7.43 (m, $5H_{Ar}$).

M_n(NMR) = 4281 g mol^{-1}, M_n(GPC) = 7200 g mol^{-1}, M_w/M_n = 1.25.

Synthesis of the Block Copolymer PCL_{63}-*b*-NVP_{44} (Run 1, Table 4). In a dried and nitrogen purged Schlenk tube, 0.6 g [1.4×10^{-4} mol, calculated on the basis of molecular weight (4281) obtained from ^1H NMR] of PCL−X was dissolved in 3 mL of THF. To it were added 1.6 mL (1.66 g, 1.42×10^{-2} mol) of NVP, and 6.1 mg (3.57×10^{-5} mol) of AIBN. A homogeneous solution was obtained after stirring and degassed under nitrogen for 45 min. The Schlenk tube was then immersed in an oil bath preheated at 80 °C for 24 h. The reaction was stopped by freezing the reaction mixture with liquid nitrogen. A small portion of the polymerization mixture was used to determine the monomer conversion by ^1H NMR. The rest of the polymerization mixture was

Table 4. Characteristic Data of PCL-*b*-PNVP Block Copolymer[a]

run	block copolymer	PCL_x−X (*Mn*/PDI)	NVP[b] (equiv)	convn[c] (%)	M_n (Theor)[d]	M_n (NMR)[e]	M_n (GPC)[f]	PDI[f]	X_{PNVP} (NMR)[g]	X_{PNVP} (GPC)[g]	cmc (mg/mL) (fluorescence)
1	PCL_{63}-*b*-$PNVP_{44}$	PCL_{63}−X (7200/1.25)	100	60.7	11 027	8291	12 100	1.24	0.48	0.40	0.0035
2	PCL_{63}-*b*-$PNVP_{90}$	PCL_{63}−X (7200/1.25)	200	72.8	20 463	19 918	17 200	1.39	0.78	0.58	0.0058
3	PCL_{106}-*b*-$PNVP_{23}$	PCL_{106}−X (12800/1.16)	200	74	26 474	11 269	15 400	1.16	0.13	0.17	-
4	PCL_{142}-*b*-$PNVP_{27}$	PCL_{142}−X (16500/1.19)	200	53	33 115	26 876	19 200	1.17	0.10	0.14	-

[a] Using 0.2 equiv AIBN with respect to PCL−X macroinitiator in THF at 80 °C for 24 h. [b] With respect to PCL−X macroinitiator. [c] Conversion was determined by comparing the peak area of the residual vinylic sigments of the NVP monomer at ∼4.3−4.4 ppm (2H) and 07.0−7.1 ppm (1H) with that of the methylene proton of the PNVP block of the polymer use of ^{1}H NMR. [d] M_n(theor) = ^{1}H NMR mol wt of PCL−X + ($[NVP]_o/[PCL-X]_o$ × fraction conversion of NVP × mol wt of NVP). [e] Determined from ^{1} H NMR by compairing the peak area of the benzylic protons of the polymer chain-end with that of the methylene protons of PCL block at ∼4.1 ppm and the methylene proton of PNVP block at ∼3.0−3.4 ppm. [f] Determined by GPC (DMF, 0.5 mL/min, 40 °C) calibrated against PMMA standard. [g] X_{PNVP} = mol fraction of PNVP.

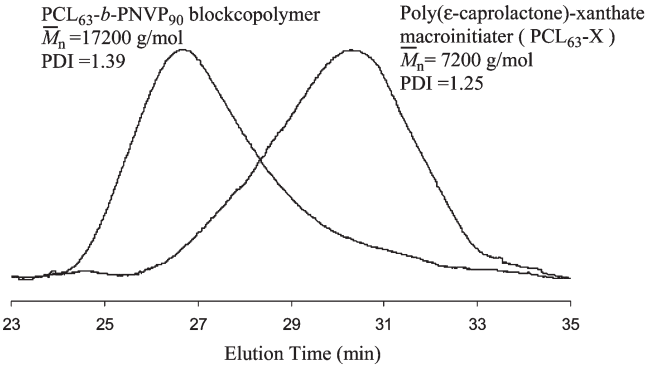

Figure 2. Gel permeation chromatograms of PCL macro-chain transfer agent and the resulted PCL_{63}-*b*-$PNVP_{90}$ (run 2, Table 4).

dissolved in 20 mL of THF, precipitated from 350 mL of hexanes and dried under vacuum at room temperature for 24 h. This block copolymer may contain PCL and PNVP homopolymers as impurities. In order to get rid of PCL homopolymers, this block copolymer was dispersed in (200 mL × 3) ethyl acetate, which is a good solvent for PCL, but bad solvent for the block copolymer, and collected, by centrifugation thrice. This polymer was dried under vacuum at room temperature for 24 h. In order to get rid of PNVP homopolymer impurities, this polymer was dispersed in (200 mL × 3) water, which is a good solvent for PNVP, but a poor solvent for the block copolymer, and collected by centrifugation thrice. Finally, this polymer was dried under vacuum at room temperature for 24 h. The polymer was redissolved in 20 mL of THF, precipitated from 350 mL hexanes and dried under vacuum at room temperature for 24 h. Observed monomer conversion by ^{1}H NMR = 60.7%.

^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 1.3−2.5 (m, $2H_b + 4H_c + 2H_d + 3H_g + 3H_i + 2H_l + 2H_o + 2H_p$), 2.9−4.5 (m, $2H_e + 2H_j + 1H_k$), 5.06 (s, $2H_a$), 7.18−7.43 (m, $5H_{Ar}$).

M_n(GPC) = 12 100 g mol^{-1}, M_w/M_n = 1.24.

Synthesis of the Block Copolymer PCL_{63}-*b*-NVP_{90} (run 2, Table 4). This block copolymer was prepared as mentioned in the previous paragraph using 0.6 g (1.4×10^{-4} mol, calculated on the basis of molecular weight (4281) obtained from ^{1}H NMR) of PCL−X, 3.2 mL (3.33 g, 3.0×10^{-2} mol) of NVP, 6.1 mg (3.57×10^{-5} mol) of AIBN, and 5 mL of THF. This block copolymer may contain PCL and PNVP homopolymers as impurities. In order to get rid of PCL homopolymers, this block copolymer was dispersed in (200 mL × 3) ethyl acetate, which is a good solvent for PCL, but bad solvent for the block copolymer, and collected, by centrifugation thrice. This block

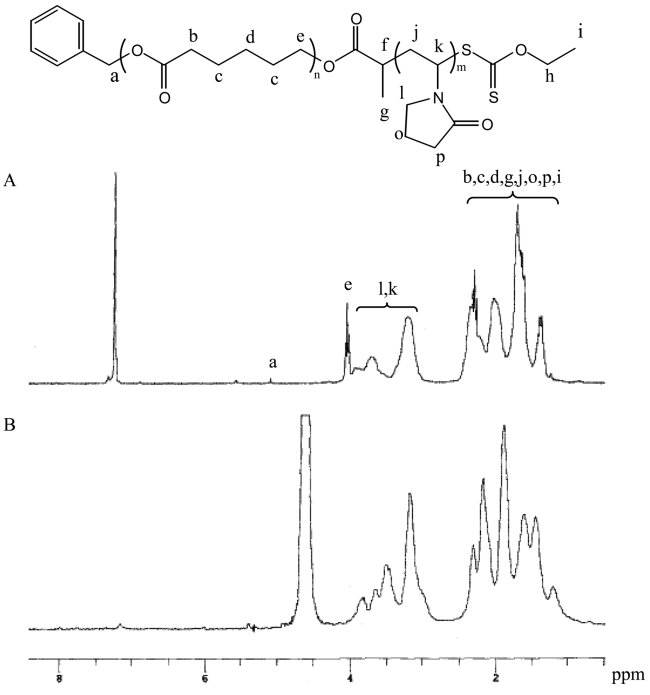

Figure 3. ^{1}H NMR spectra of PCL_{63}-*b*-$PNVP_{90}$ diblock copolymer in (A) *d*-chloroform, and (B) D_2O at room temperature.

polymer was dried under vacuum at room temperature for 24 h. Observed monomer conversion by ^{1}H NMR = 72.8%.

^{1}H NMR (300 MHz, $CDCl_3$ [Figure 3a]: δ (ppm) = 1.3−2.5 (m, $2H_b + 4H_c + 2H_d + 3H_g + 3H_i + 2H_l + 2H_o + 2H_p$), 2.9−4.5 (m, $2H_e + 2H_j + 1H_k$), 5.06 (s, $2H_a$), 7.18−7.43 (m, $5H_{Ar}$).

M_n(GPC) = 17 200 g mol^{-1}, M_w/M_n = 1.39.

RESULTS AND DISCUSSION

Synthesis of PCL-*b*-PNVP Diblock Copolymers. A new method for the synthesis of PCL-*b*-PNVP is shown in Scheme 1. It was synthesized via the combination of ROP and xanthate mediated RAFT polymerization. In the first step, PCL−OH was synthesized via ROP of CL in bulk at 110 °C using benzyl alcohol as initiator and $Sn(Oct)_2$ as the catalyst. Table 1 shows the results of the synthesis and characterization of PCL−OH prepared using different CL/benzyl alcohol feed ratios. Polymer yields are

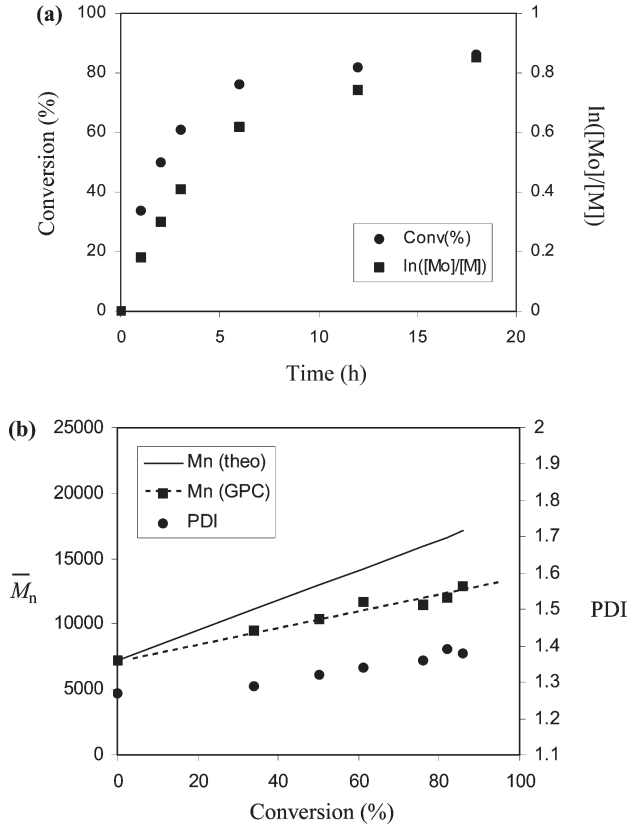

Figure 4. (a) Plots of time vs monomer conversion and $\ln[M_o]/[M]$ (where $[M_o]$ = concentration of the monomer at time t = 0 min and [M] = concentration of the monomer at the corresponding time) and (b) Plots of number-average molecular weight M_n and polydispersity (PDI) vs monomer conversion in the polymerization of *N*-vinylpyrrolidone in THF using [NVP]:[PCL_{63}−X macroinitiator]:[AIBN] = 100:1:0.2 at 80 °C.

high. The observed molecular weights increased with the increase in the feed ratio of CL/benzyl alcohol, as expected. The theoretical molecular weights [M_n(theor)] calculated on the basis of polymer yields are close to the molecular weights estimated using ^{1}H NMR [M_n(NMR)]. Unimodal GPC chromatogram was observed for run 1 (Table 1) with M_n(GPC) = 7200 and PDI = 1.26. GPC chromatograms of runs 2 and 3 (Table 1) were unimodal with the presence of a hump at higher molecular weight end. Bimodal GPC chromatogram was obtained with run 4 (Table 1). The observed difference in molecular weights determined by ^{1}H NMR [M_n(NMR)] and GPC [M_n(GPC)] is due to the use of PMMA standards for calibration in the analysis of the GPC method. Figure 1A shows the typical ^{1}H NMR spectra of the PCL−OH polymer obtained in run 1 (Table 1).

These PCL−OH polymers were reacted with 2-bromopropionyl bromide in the presence of triethylamine to prepare 2-bromopropionyl-terminated PCL (PCL−Br) (Scheme 1). Table 2 shows the results of the synthesis and characterization of PCL−Br polymers from the corresponding PCL−OH polymers. Figure 1(B) shows the typical ^{1}H NMR spectra of the resultant PCL−Br polymer obtained in run 1 (Table 2). The incorporation of the 2-bromopropionyl group was confirmed from the appearance of methine (f) and methyl (g) protons of 2-bromopropionyl end-group of the PCL−Br at around 4.3 and

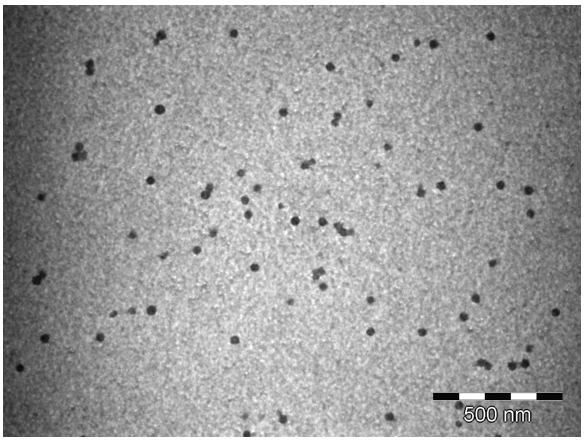

Figure 5. TEM image of the micelles obtained from aqueous solution of PCL_{63}-*b*-$PNVP_{90}$ (run 2, Table 4)(1 mg/mL).

1.8 ppm, respectively. The calculated conversion (%) of −OH end-group into its corresponding 2-bromopropionyl end-group was obtained by comparing the peak area of methyl (g) protons of 2-bromopropionyl end-group with that of the benzylic (a) protons of polymer chain-end at ∼5.1 ppm is ∼84%. The observed M_n (NMR) of this polymer calculated by dividing average peak area of methylene protons "e", "b", and, "d" of the PCL backbone chain by the peak area of "a" is 4278. The corresponding observed M_n(GPC) and PDI are 7200 and 1.21, respectively. Similarly, in runs 2 and 3 (Table 2), with increase of molecular weight of PCL−OH from 12,100 to 16,200, respectively, almost quantitative (∼80−100%) conversion of −OH functional group into its corresponding 2-bromopropionyl group were observed. But, on further increase of molecular weight of PCL−OH to 41600 (run 4, Table 2), no conversion of −OH functional group into its corresponding bromide group was observed as it is evidenced by the absence of the peak corresponds to the methine (f) protons of 2-bromopropionyl end-group in the ^{1}H NMR spectrum of the corresponding resulted polymer. Therefore, the efficiency of the conversion of −OH end-group (of the PCL−OH polymer) into its corresponding 2-bromopropionyl end-group is drastically decreased with the increase of the molecular weight of the PCL−OH (*vide* run 3 and 4, Table 2).

PCL−Br polymers were further reacted with potassium *O*-ethyl xanthate to convert the bromo end-group into their corresponding xanthate (PCL−X) by ionic substitution reaction (Scheme 1). Table 3 shows the results of the synthesis and characterization of PCL−X polymers from the corresponding PCL−Br polymers. Figure 1C shows the typical ^{1}H NMR spectra of the resultant PCL−X polymer obtained in run 1 (Table 3). The conversion of bromo end-group into the corresponding xanthate end-group was confirmed by the appearance of the new characteristic peak attributed to the methylene proton "h" of the xanthate end group at 4.6 ppm. The corresponding peaks of the methyl protons "i" of xanthate end-group and "g" of the propionyl group were overlapped within the peak of the methylene protons "c" of the PCL backbone chain. We also did not able to find a separate peak of methylene protons "c" using DMSO-d_6 solvent. The calculated conversion (%) (from its ^{1}H NMR [Figure 1C]) of −Br end-group into its corresponding xanthate end-group obtained by comparing peak area of methine protons "f" of the propionyl group with that of the methylene

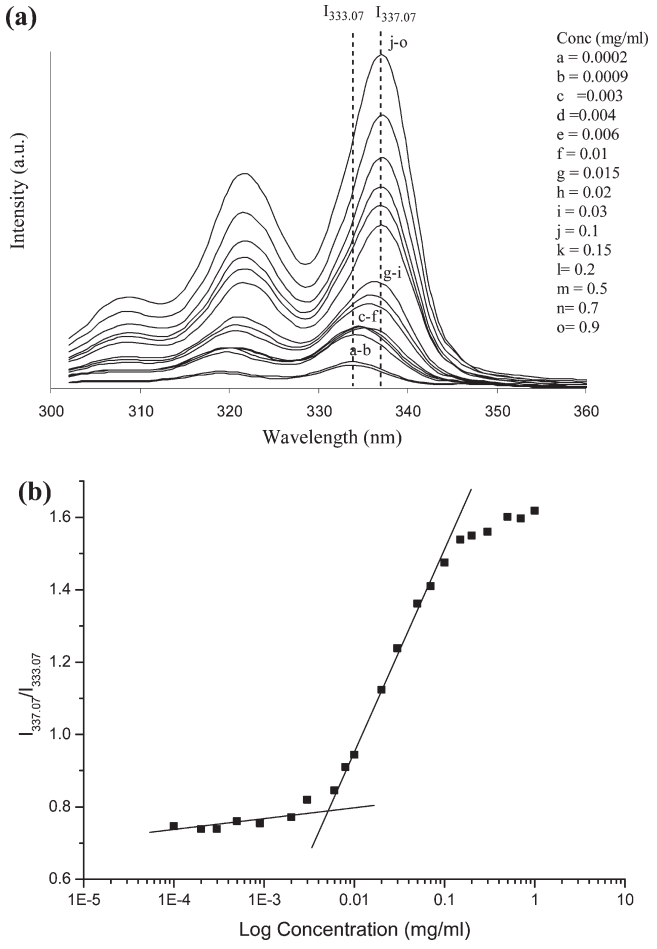

Figure 6. (a) Fluorescence excitation spectra (monitored at λ_{em} = 394 nm) of pyrene (6×10^{-7} M) in the presence of increasing concentration (C) (mg/mL) of block copolymer PCL_{63}-*b*-$PNVP_{90}$ (run 2, Table 4) solution in water: (curves a, 0.0002 mg/mL, b, 0.0009 mg/mL, c, 0.003 mg/mL, d, 0.004 mg/mL, e, 0.006 mg/mL, f, 0.01 mg/mL, g, 0.015 mg/mL, h, 0.02 mg/mL, i, 0.03 mg/mL, j, 0.1 mg/mL, k, 0.15 mg/mL, l, 0.2 mg/mL, m, 0.5 mg/mL, n, 0.7 mg/mL, and o, 0.9 mg/mL) and (b) semilogarithmic plot of the fluorescence excitation intensity ratio ($I_{337.07}/I_{333.07}$) of pyrene (6×10^{-7} M) (monitored at λ_{em} = 394 nm) vs the concentration of PCL_{63}-*b*-$PNVP_{90}$ (run 2, Table 4) block copolymer in water.

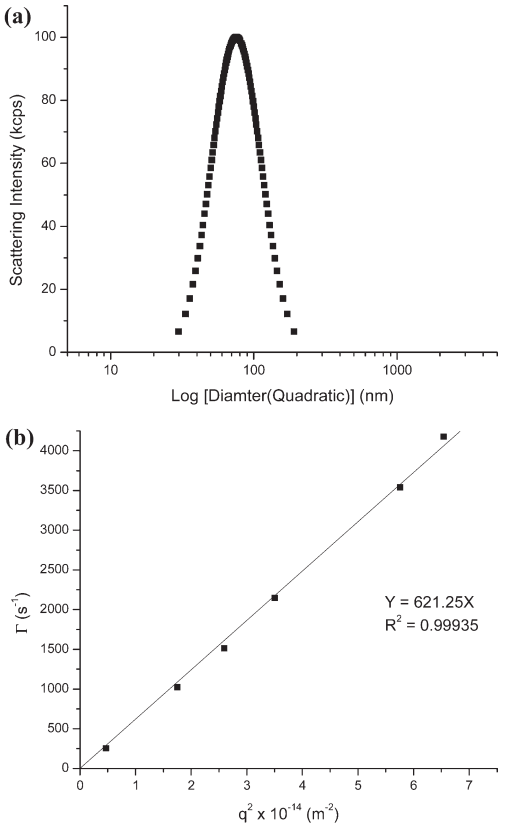

Figure 7. (a) Hydrodynamic diameter (quadratic) distributions/plot of scattering intensity vs effective hydrodynamic diameter (quadratic) of PCL_{63}-*b*-$PNVP_{90}$ at 0.3 mg/mL concentration in water at 90° scattering angle and (b) plot of average decay rates (Γ) vs the square of the scattering vector (q^2) of PCL_{63}-*b*-$PNVP_{90}$ at 0.3 mg/mL concentration in water.

protons "h" of the xanthate end-group is ~100%. This result confirms the quantitative conversion of −Br end-group into the corresponding xanthate end-group. In addition, the characteristic UV absorption peak of the −S−(C═S)− functional group of the xanthate chain end-group of the resulted polymer PCL−X was observed in its THF solution at $\lambda \sim 280$ nm. The observed M_n (NMR) of this polymer calculated from its ^{1}H NMR [Figure 1C] by dividing the peak area of "e", "b", and "d" by the peak area of "a" is 4,281. The corresponding observed M_n(GPC) and PDI are 7200 and 1.25, respectively. Therefore, the molecular weights and PDI values of the converted PCL−X polymers are almost close to the value observed for the corresponding PCL−Br polymers. Similarly, for runs 2 and 3 (Table 3), with increase of molecular weight of PCL−Br from 12 600 to 16 400, respectively, the calculated conversion (%) of −Br end-groups into their corresponding xanthate end-groups are also ~100%. Therefore, the efficiency of the conversion of −Br end-group into its corresponding xanthate end-group is quantitative irrespective of the molecular weights of the PCL studied here.

The PCL−X was then used as macro-chain transfer agent (macroinitiator) for the xanthate mediated RAFT polymerization of NVP in THF using [PCL−X]:[AIBN] = 1:0.2 at 80 °C for 24 h (Table 4). Table 4 shows the results of the synthesis and characterization of PCL-*b*-PNVP block copolymers from the corresponding PCL−X polymers. Runs 1 and 2 (Table 4) correspond to 100 and 200 equiv of NVP monomer loading with respect to PCL_{63}−X xanthate macro-chain transfer agent, respectively. Molecular weight of the corresponding block copolymers increases with increase in monomer loading as expected. The observed mole fraction of poly(NVP) block in these block copolymers calculated on the basis of ^{1}H NMR and GPC molecular weights are within the range 0.40−0.78. Typical GPC chromatograms of run 2 (Figure 2) show the shift of the polymer peak toward higher molecular weight. Moreover, the ^{1}H NMR spectrum of this block copolymer in $CDCl_3$ (Figure 3A) shows, in addition to the characteristic peaks of the PCL block, the presence of the characteristic peaks of the PNVP backbone methine proton "k" at ~3.5−4.0 ppm, the methylene protons "l" of the pyrrolidone ring at ~3.3 ppm apart from methylene protons in the PNVP backbone and other pyrrolidone ring methylene protons of the PNVP block overlapped between of ~1.0−2.5 ppm. In runs 3 and 4 (Table 4), two high molecular weight PCL−X macro-chain transfer agents used with 200 equiv

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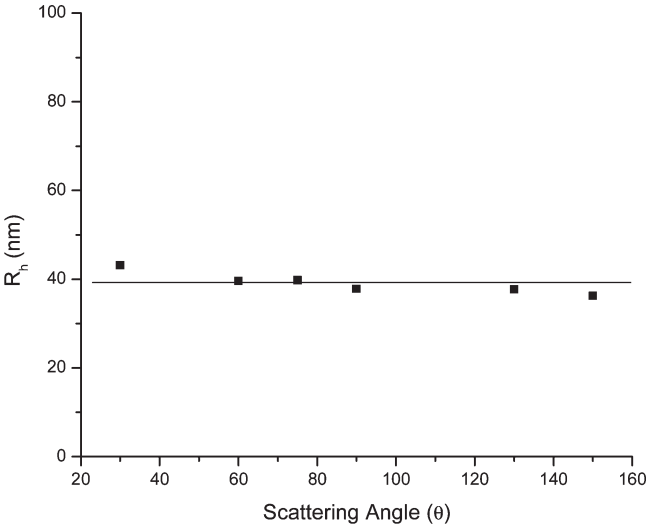

Figure 8. Plot of DLS measurement/scattering angles vs the hydrodynamic radius (R_h) of the micelles of the block copolymer PCL_{63}-*b*-$PNVP_{90}$ at 0.3 mg/mL in water.

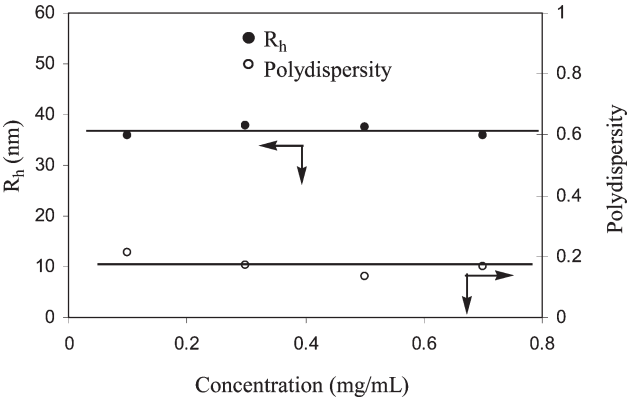

Figure 9. Plots of R_h and Polydispersity of the micelles in water vs the concentration of the block copolymer PCL_{63}-*b*-$PNVP_{90}$ in water.

NVP monomer. The resulted block copolymers are sparingly soluble in water. The observed mole fraction of poly(NVP) block in these block copolymers calculated on the basis of ^{1}H NMR and GPC molecular weights are within the range 0.10 - 0.17. The observed differences in different molecular weights may be either (i) due to the change in the hydrodynamic volume owing to the incorporation of PNVP black in the related block copolymer, or (ii) due to the use of standard PMMA polymers for calibration in GPC, or (iii) due to the formation of poly(NVP) homopolymers, or (iv) due to all of the above. All these results indicate that the efficiency of the functional groups conversion from −OH to the corresponding −X through the corresponding −Br decreases with the increase in the molecular weight of the PCL−OH. Thus, the most successful occurrence of the chain extensions occurs with PCL_{63}−X having M_n(GPC) = 7200 and PDI = 1.25.

In order to check the livingness of this polymerization system, the kinetic study of the polymerization of NVP was carried out in THF at 80 °C using PCL_{63}−X macro chain-transfer agent with molar ratio [NVP]:[PCL_{63}−X]:[AIBN] = 100:1:0.2, monitored by using ^{1}H NMR spectroscopy and GPC. Figure 4a shows the plot of the monomer conversion (%) and ln([M_o]/[M]) vs time. Monomer conversion (%) increases almost linearly up to around 76% conversion. The corresponding plot of ln([M_o]/[M]) vs time is also linear up to around 76% conversion. So the pseudofirst order monomer conversion kinetics was followed up to around 76% conversion. Figure 4(b) shows the plot of M_n and PDI vs monomer conversion (%). Experimental molecular weight [M_n(GPC)] increases linearly with monomer conversion (%). The observed deviation of M_n(GPC) from M_n(theor) is due to the change of the hydrodynamic volume of the block copolymer with the increase of its PNVP block length. The corresponding PDI increases slightly with increase in conversion. It may be either due to the loss of xanthate moieties from the chain-end or, due to the considerable chain transfer reaction to monomer. Such increase of PDI of the resulted polymer with the increase in the monomer conversion in the polymerization of NVP using xanthate mediated RAFT agents was already reported in the literature.[5,15] All these results confirm the livingness of this polymerization system up to 76% monomer conversion under the experimental conditions.

Self-Assembly of Amphiphilic PCL-*b*-PNVP Block Copolymers in Aqueous Solution. It is well-known that amphiphilic copolymers can form nanostructured aggregates via self-assembly. Figure 3B is a ^{1}H NMR spectrum of PCL_{63}-*b*-$PNVP_{90}$ block copolymer in deuterium oxide. In comparison with the ^{1}H NMR spectrum obtained in *d*-chloroform as shown in Figure 3A, the peaks attributed to PCL block totally disappear in Figure 3B. This observation indicates that the micelles aggregates were formed in aqueous solution with PCL block as the cores and PNVP blocks as the shells. In order to study the critical micellar concentration of two block copolymers, PCL_{63}-*b*- $PNVP_{44}$ and PCL_{63}-*b*-$PNVP_{90}$, in water, fluorescence spectroscopy was used with pyrene as the probe. Figure 6a shows the fluorescence excitation spectra (300−360 nm) of pyrene (6×10^{-7} M) at different PCL_{63}-*b*-$PNVP_{90}$ concentrations recorded at an emission wavelength of 394 nm. Figure 6b shows the corresponding plot of the ratio of the peak intensities of the excitation spectra of pyrene at 337.07 nm ($I_{337.07}$) and 333.07 nm ($I_{333.07}$) vs the log of the block copolymer concentration (mg/mL) in water. The critical micelle concentration (cmc) value was taken from the interception point of two straight lines at lower concentration. The observed cmc of the block copolymer PCL_{63}-*b*-$PNVP_{90}$ was ∼0.0058 mg/mL. The observed cmc of the block copolymer PCL_{63}-*b*-$PNVP_{44}$ was ∼0.0035 mg/mL. The lower cmc value of PCL_{63}-*b*-$PNVP_{44}$ with respect to that of PCL_{63}-*b*-$PNVP_{90}$ is due to the smaller hydrophilic PNVP block segment in the block copolymer. Similar types of results were reported in the literature.[24]

A typical hydrodynamic diameter (quadratic) distribution function, obtained from DLS measurement at 90° scattering angle for 0.3 mg/mL aqueous solution (above its cmc value) of PCL_{63}-*b*-$PNVP_{90}$ is shown in Figure 7a. The observed unimodal distribution functions indicate the formation of relatively similar size micellar aggregates (*vide* Figure S1 in the Supporting Information). Figure 7b shows the plot of the corresponding angle dependent average decay rates Γ vs the square of the scattering vector (q^2). The observed linearity of this plot confirms that the block copolymer micelles are really formed from translational diffusion. Similar results were also observed for the block copolymer PCL_{63}-*b*-$PNVP_{44}$ at its 0.09 mg/mL (above its cmc value) keeping other experimental conditions the same as above (*vide* Figure S2 and S3 in the Supporting Information). The corresponding translational diffusion coefficients (D) (vide Figure 7a and Figure S2(b) in the Supporting Information) are ∼621 and 324 m^2s^{-1} for the micelles formed from PCL_{63}-*b*-

$PNVP_{90}$ and PCL_{63}-*b*-$PNVP_{44}$ block copolymers, respectively. The observed hydrodynamic radius (R_h) and the corresponding polydispersity (μ_2/Γ^2) of the micelles formed from PCL_{63}-*b*-$PNVP_{90}$ block copolymer at 90° scattering angle are ~37.8 nm and ~0.172, respectively. The same from PCL_{63}-*b*-$PNVP_{44}$ block copolymer are ~72.2 nm and ~0.240, respectively. The observed smaller translational diffusion coefficient (D) and larger hydrodynamic radius (R_h) of the micelles formed from PCL_{63}-*b*-$PNVP_{44}$ is as expected from its smaller PNVP segments. Similar results were reported in the literature.[17] Figure 8 shows the typical plot of R_h vs DLS scattering angle (θ) for the block copolymer PCL_{63}-*b*-$PNVP_{90}$ at 0.3 mg/mL concentration in water. The almost consant hydrodynamic sizes of the micelles at different angles for both copolymer systems (*vide* Figure S4 in the Supporting Information for PCL_{63}-*b*-$PNVP_{44}$) indicate the formation of spherical micellar aggregates. This observation was supported by the TEM result (Figure 5) of PCL_{63}-*b*-$PNVP_{90}$ block copolymer system. It is to be noted here that the average particle radius ~17 nm of the micelles observed from TEM measurement is smaller than that (~37.8 nm) observed from DLS measurement. This is expected owing to the collapse of the micellar structure on TEM grids due to the dehydration. Figure 9 shows the plots of R_h and polydispersity of the micelles vs block copolymer concentration for PCL_{63}-*b*-$PNVP_{90}$ block copolymer system. These plots show that R_h and polydispersity of the micelles are almost independent of copolymer concentration. Similar results were also obtained for PCL_{63}-*b*-$PNVP_{44}$ block copolymer (*vide* Figure S5 in the Supporting Information). These may be due to the micellization through close association mechanism.[23]

All these results confirmed the amphiphilic character of these two block copolymers.

CONCLUSION

In conclusion, well-defined amphiphilic diblock copolymers of CL and NVP were successfully synthesized by combining ROP and xanthate-mediated RAFT polymerization. The resulted block copolymer forms spherical micelles in water as revealed by TEM, and supported by ^{1}H NMR spectroscopy, and light scattering. The critical micellar concentration of the block copolymers was determined by fluorescence spectroscopy using pyrene as a probe. The cmc value of the block copolymer increases with the increase in the chain length of the PNVP segment. The effective hydrodynamic ratio (R_h) remains almost constant over the concentration range above the corresponding cmc value and over the angles of scattering measurements. Synthesis of such well-defined amphiphilic block copolymer will find extensive applications in drug delivery and metal nanoparticle synthesis.

ASSOCIATED CONTENT

Supporting Information. GPC chromatograms, particle size distributions, hydrodynamic diameter (quadratic) distributions, light scattering data of polymers, and plots of R_h and polydispersity of the micelles. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

(1) Ouchi, M.; Terashima, T.; Sawamoto, M. *Chem. Rev.* **2009**, *109* (11), 4963–5050.
(2) Yamago, S. *Chem. Rev.* **2009**, *109* (11), 5051–5068.
(3) Chiefari, J.; Mayadunne, R. T. A.; Moad, G.; Rizzardo, E.; Thang, S. H. *PCT Int Appl* W099/31144.
(4) Coessens, V.; Pintaver, T.; Matyzaszewski, K. *Prog. Polym. Sci.* **2001**, *26*, 337–377.
(5) Wan, D.; Satoh, K.; Kamigaito, M.; Okamoto, Y. *Macromolecules* **2005**, *38*, 10397–10405.
(6) Devasia, R.; Bindu, R. L.; Mougia, N.; Gnanou, Y. *Macromol. Symp.* **2005**, *229*, 8–17.
(7) Bilalis, P.; Pitsikalis, M.; Hadjichristidis, N. *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 659–665.
(8) Yamago, S.; Ray, B.; Iida, K.; Yoshida, J. I.; Tada, T.; Yoshizawa, K.; Kwak, Y.; Goto, A.; Fukuda, T. *J. Am. Chem. Soc.* **2004**, *126*, 13908–13909.
(9) Ray, B.; Kotani, M.; Yamago, S. *Macromolecules* **2006**, *39*, 5259–5265.
(10) Yusa, S. I.; Yamago, S.; Sugahara, M.; Morikawa, S.; Yamamoto, T.; Morishima, Y. *Macromolecules* **2007**, *40*, 5907–5915.
(11) Yamago, S.; Kayahara, E.; Kotani, M.; Ray, B.; Kwak, Y.; Goto, A.; Fukuda, T. *Angew. Chem., Int. Ed.* **2007**, *46*, 1304–1306.
(12) Lu, X.; Gong, S.; Meng, L.; Li, C.; Yang, S.; Zhang, L. *Polymer* **2007**, *48*, 2835–2842.
(13) Pound, G.; Eksteen, Z.; Pfukwa, R.; McKenzie, J. M.; Lange, R. F. M.; Klumperman, B. *J. Polym. Sci., Part A: Polym. Chem.* **2008**, *46*, 6575–6593.
(14) Pound, G.; Aguesse, F.; McLeary, J. B.; Lange, R. F. M.; Klumperman, B. *Macromolecules* **2007**, *40*, 8861–8871.
(15) Patel, V. K.; Mishra, A. K.; Viswakarma, N. K.; Biswas, C. S.; Ray, B. *Polym. Bull.* **2010**, *65*, 97–110.
(16) Lele, B. S.; Leroux, J. C. *Macromolecules* **2002**, *35*, 6714–6723.
(17) Chung, T. W.; Cho, K. Y.; Lee, H.-C.; Nah, J. W.; Yeo, J. H.; Akaike, T.; Cho, C. S. *Polymer* **2004**, *45*, 1591–1597.
(18) Bartolozzi, I.; Solaro, R.; Schacht, E.; Chiellini, E. *Eur. Polym. J.* **2007**, *43*, 4628–4638.
(19) Levia, A.; Quina, F. H.; Araneda, E.; Gargallo, L.; Radić, D. *J. Colloid Interface Sci.* **2007**, *310*, 136–143.
(20) Jeon, H. J.; You, Y. C.; Youk, J. H. *J. Polym. Sci., Part A: Polym. Chem.* **2009**, *47*, 3078–3085.
(21) Paria, T. K.; Banerjee, S.; Raula, M.; Kotal, A.; Si, S.; Mandal, T. K. *Macromolecules* **2010**, *43*, 4050–4061.
(22) Štěpánek, P. In *Dynamic Light Scattering—The Method and Some Applications*; Brown, W., Ed.; Clarendon: Boston, MA, 1993; pp177—241.
(23) Chu, B., *Laser Light Scattering: Basic Principles and Practices*; 2nd ed.; Academic Press: New York, 1991; pp 1361.
(24) Hussain, H.; Tan, B. H.; Gudipati, C. S.; Liu, Y.; He, C. B.; Davis, T. P. *J. Polym. Sci., Part A: Polym. Chem.* **2008**, *46*, 5604–5615.