Synthesis of Poly(vinyl acetate) and Poly(vinyl alcohol) Containing Block Copolymers by Combination of Cobalt-Mediated Radical Polymerization and ATRP

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ABSTRACT: Poly(vinyl acetate) (PVAc) chains of a low polydispersity ($M_w/M_n \sim 1.1-1.2$) have been prepared by cobalt-mediated radical polymerization of vinyl acetate (VAc). They have been end-capped by an activated bromide by addition of an α-bromoester or an α-bromoketone containing nitroxide and converted into effective macroinitiators for the atom transfer radical polymerization of styrene (Sty), ethyl acrylate, and methyl methacrylate. Because each block is formed by a controlled process, well-defined PVAc containing diblock copolymers are easily prepared. The PVAc-*b*-PS copolymers synthesized from α-bromoketone end-capped PVAc can be converted into well-defined poly(vinyl alcohol)-*b*-polystyrene amphiphiles by methanolysis of the poly(vinyl acetate) block. Self-association of an amphiphilic poly(vinyl alcohol)(3500)-*b*-polystyrene(16 600) in a (4/1) water/tetrahydrofuran mixture results in the formation of vesicles as observed by transmission electron microscopy.

Introduction

Controlled radical polymerization allows for the synthesis of a large variety of well-defined polymers with a complex architecture, such as block and graft copolymers, star-shaped, comb-shaped, and hyperbranched (co)polymers. Many examples of diblock copolymers have been reported which were prepared by sequential controlled radical polymerization of two monomers, by nitroxide-mediated polymerization (NMP),[1] atom transfer radical polymerization (ATRP),[2] and radical addition−fragmentation chain transfer (RAFT).[3]

However, the control of the radical polymerization of vinyl acetate (VAc) is a challenge because the monomer is deprived of any radical stabilizing substituent. At this time, there are only a few reports on this topic: use of *N*,*N*-diethyldithiocarbamate in the iniferter technique,[4] degenerative chain transfer promoted by alkyl iodides,[5] RAFT based on xanthates[6] and dithiocarbamates,[7] and ATRP in the presence of iron catalysts.[8] Consistently, only few examples of poly(vinyl acetate) (PVAc) containing block copolymers synthesized by controlled radical polymerization can be found in the scientific literature. Even though the control is not high, block copolymers have been prepared by RAFT with xanthates[9] and thiophosphorus acid esters,[10] by the iniferter method,[11] with the assistance of 1,1-diphenylethylene,[12] and by ATRP in the presence of $Fe(Cp)(CO)_2I$ and $[Fe(Cp)(CO)_2]_2$.[13] In a less controlled approach, vinyl acetate has been first polymerized by conventional radical polymerization and end-capped by an activated halogen (telomerization with chloroform[14] or initiation by halogenated azo-initiators[15]). These ill-defined PVAc macroinitiators were used to polymerize the second block by ATRP.

Recently, we reported a very efficient method to control the radical polymerization of vinyl acetate based on a cobalt(II) acetylacetonate ($Co(acac)_2$) complex.[16] This paper aims at extending this method to the synthesis of well-defined (defined molar mass (M_n), low polydispersity (M_w/M_n)) block copolymers of vinyl acetate and vinyl comonomers, such as styrene and (meth)acrylates. The PVAc chains prepared by the cobalt-mediated technique were easily end-capped by an activated bromide and used to initiate ATRP of the envisioned comonomers. Provided that the constitutive blocks of the copolymer are connected by a hydrolytically stable link, the PVAc block can be easily derivatized into poly(vinyl alcohol) by methanolysis.

Experimental Section

Materials. Vinyl acetate (VAc) (>99%, Acros), styrene (>99%, Aldrich), ethyl acrylate (99%, Aldrich), and methyl methacrylate (99%, Aldrich) were dried over calcium hydride, degassed by several freeze−thawing cycles before being distilled under reduced pressure, and stored under argon. Toluene and tetrahydrofuran were distilled from sodium benzophenone complex and degassed by bubbling with argon for 30 min. 2,2′-Azo-bis(4-methoxy-2,4-dimethylvaleronitrile) (V-70) (Wakko), 2-bromoisobutyryl bromide (98%, Aldrich), 4-hydroxy-2,2,6,6-tetramethylpiperidine 1-oxyl (>97%, Fluka), 4-oxo-2,2,6,6-tetramethylpiperidine 1-oxyl (Aldrich), copper(I) bromide (98%, Aldrich), copper(I) chloride (>99%, Aldrich), copper(II) chloride (97%, Aldrich), 1,1,4,7,10,10-hexamethyltriethylenetetramine (HMTETA, 97%, Aldrich) cobalt(II) acetylacetonate ($Co(acac)_2$) (>98%, Merck), bromine (>99%, Merck), and triethylamine (99.5%, Aldrich) were used as received.

Characterization. Size exclusion chromatography (SEC) was carried out in THF (flow rate: 1 mL min^{-1}) at 40 °C with a Waters 600 liquid chromatrograph equipped with a 410 refractive index detector and Styragel HR columns (four columns HP PL gel 5 μm: 10^5, 10^4, 10^3, and 10^2 Å). Polystyrene standards were used for calibration. ^1H NMR spectra were recorded with a Bruker AM 400 spectrometer (400 MHz) in $CDCl_3$ or D_2O. ^{13}C NMR spectra were recorded with the same spectrometer (400 MHz) in D_2O/H_2O/2-propanol: 1/3/traces (D_1

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= 2 s, 30 000 scans, 5 wt % polymer). Infrared spectra (IR) were recorded with a Perkin-Elmer FT-IR instrument (KBr). Differential scanning calorimetry (DSC) was performed under a nitrogen flow (50 cm^3/min) at a heating rate of 10 °C/min with a DSC Q100 from TA Instruments. Certified indium wire encapsulated in an aluminum crucible was used for temperature and heat flow calibration. Peak temperature, onset temperature, and enthalpy of melting were determined for all the samples (using the software of the apparatus). Thermogravimetric analysis (TGA) was carried out under a nitrogen flow (60 cm^3/min) using a high-resolution mode (resolution 5, sensitivity 1, initial heating rate of 50 °C/min), from room temperature to 700 °C, with a Hi-Res TGA Q500 from TA Instruments. Transmission electron microscopy (TEM) was carried out with a Philips CM 100 operating at a voltage of 100 kV, equipped with a Gatan 673 CCD camera and a computer loaded with the Kontron KS 100 software. Samples were prepared by depositing a droplet of an aqueous copolymer solution on a Formvar-coated copper TEM grid. Water was let to evaporate under ambient atmosphere for 1 h. Dynamic light scattering (DLS) was performed with a Brookhaven Instruments Corp. DLS apparatus, which consisted of a BI-200 goniometer, a BI-2030 digital correlator, and an Ar ion laser (LEXEL lasers, wavelength = 488 nm, power = 10 mW), scattering angle = 90°. A refractive index matching bath of filtered decalin surrounded the scattering cell, and the temperature was controlled at 25 °C. Elementary analyses (EA) were carried out with a Carlo-Erba elemental analyzer CHNS-O EA1108.

Synthesis of 1-Oxyl-(2,2,6,6-tetramethylpiperidine)-4-yl 2-Bromo-2-methyl-propanoate (2). Dry triethylamine (2.61 g, 25.8 mmol) followed by bromoisobutyryl bromide (4.84 g, 21.0 mmol) was added dropwise to a solution of 4-hydroxy-2,2,6,6-tetramethylpiperidine 1-oxyl (**1**) (3.03 g, 17.6 mmol) in tetrahydrofuran (50 mL), under argon. The red solution was stirred at room temperature for 18 h, and a white precipitate was formed. After dilution with diethyl ether, the solution was filtered, washed two times with aqueous $NaHCO_3$, and dried over Na_2SO_3 before being evaporated under reduced pressure. The residual red-orange powder, corresponding to the product **2** (4.6 g, 14.3 mmol), was stored under an inert atmosphere at −20 °C. Yield = 81%; mp = 83.8 °C. IR (KBr) ν_{max}: 1729.0 (vs, C=O stretch of α-bromoester), 1371.3 (s, N−O•), 684.8 and 652.3 cm^{-1} (m, C−Br stretch). Anal. Calcd for $C_{13}H_{23}O_3NBr$: C, 48.63%; H, 7.22%; N, 4.36%. Found: C, 49.88%; H, 7.89%; N, 4.54%.

Synthesis of 1-Hydroxy-4-oxo-2,2,6,6-tetramethylpiperidine Hydrochloride (4). Concentrated hydrochloric acid (37 wt %, 3.2 mL) was added dropwise, at 5 °C while stirring, to a solution of 4-oxo-2,2,6,6-tetramethylpiperidine 1-oxyl (**3**) (5.00 g, 29.4 mmol) in ethanol (3.6 mL). The solution was stirred at 24 °C for 1 h, before the solvent was evaporated (rotating evaporator) at 50 °C. The yellow residue was crystallized twice in 2-propanol, and the colorless crystals of 1-hydroxy-4-oxo-2,2,6,6-tetramethylpiperidine hydrochloride (3.80 g, 18.4 mmol) were filtered and dried under reduced pressure. Yield = 63%; mp = 164 °C. RMN ^1H (400 MHz, D_2O): 2.71 ppm (4 H, s, $-CH_2-$); 1.31 ppm (12 H, s, $-CH_3$). IR (KBr) ν_{max}: 1725.4 cm^{-1} (s, C=O stretch).

Synthesis of 3-Bromo-4-oxo-2,2,6,6-tetramethylpiperidine 1-Oxyl (5). At room temperature, a bromine solution (2.56 g, 16 mmol) in chloroform (30 mL) was added dropwise to a stirred solution of 1-hydroxy-4-oxo-2,2,6,6-tetramethylpiperidine hydrochloride (**4**) (3.1 g, 15 mmol) in chloroform (analytical purity, 4 mL). After discoloration, the reaction medium was added with an aqueous solution of sodium nitrite (3.0 g in 40 mL) with vigorous stirring and kept at 24 °C for 30 min. The organic phase was separated, washed with water, and dried over anhydrous magnesium sulfate, before the solvent was evaporated (rotating evaporator) at 40 °C. The residue was recrystallized twice from *n*-hexane (at −20 °C), and the collected orange crystals were dried under reduced pressure (0.75 g, 3.0 mmol; yield = 20%). Purity was checked by thin-layer chromatography in chloroform and showed contamination by a small amount of the product **3**; mp = 66 °C. IR (KBr) ν_{max}: 1731.4 (vs, C=O stretch of α-bromoester), 1367.7 cm^{-1} (s, N−O•).

General Recipe for the Synthesis of Poly(vinyl acetate) Macroinitiators End-Capped by Either an α-Bromoester or an α-Bromoketone. V-70 and $Co(acac)_2$ were added into a glass tube capped by a three-way stopcock and purged by three vacuum−argon cycles. After addition of degassed vinyl acetate, the reaction mixture was heated at 30 °C under stirring. After a few hours, the color changed from purple to dark green-brown, and a substantial increase in viscosity was noted. To determine the monomer conversion gravimetrically, a sample was picked out from the reaction medium to which was then added the appropriate nitroxide (**2** or **5**) dissolved in degassed toluene. After reaction for a few hours, the solution was diluted by acetone and eluted through alumina in order to eliminate the cobalt complex. The polymer was precipitated in heptane and dried in vacuo at 40 °C. A colorless poly(vinyl acetate) was collected and stored at −20 °C under an inert atmosphere.

PVAc Macroinitiator I. *Conditions:* V-70 (0.200 g, 6.5 × 10^{-4} mol), $Co(acac)_2$ (52 mg, 2.0 × 10^{-4} mol), VAc (5.0 mL, 4.7 g, 54 × 10^{-3} mol), 40 h at 30 °C, conversion = 38%, α-bromoester containing nitroxide **2** (0.128 g, 4.0 × 10^{-4} mol) in toluene (1.5 mL). *Characteristics*: $M_{n,NMR}$ = 86.09 × (3 × (−C*H*−OCOCH$_3$, PVAc)/(−OC*H*$_3$, V-70)) = 8800 g/mol; $M_{n,theor}$ = 8900 g/mol; M_w/M_n = 1.10; DSC: T_g = 40 °C.

PVAc Macroinitiator II. *Conditions:* V-70 (4.00 g, 13.0 × 10^{-3} mol), $Co(acac)_2$ (1.03 g, 4.0 × 10^{-3} mol), VAc (50.0 mL, 46.7 g, 542 × 10^{-3} mol), 88 h at 30 °C, conversion = 56%, α-bromoester containing nitroxide **2** (1.84 g, 5.7 × 10^{-3} mol) in toluene (5.0 mL). *Characteristics:* $M_{n,NMR}$ = 86.09 × (3 × (−C*H*−OCOCH$_3$, PVAc)/(−OC*H*$_3$, V-70)) = 6700 g/mol; $M_{n,theor}$ = 6500 g/mol; M_w/M_n = 1.20.

PVAc Macroinitiator III. *Conditions:* V-70 (750 mg, 24.4 × 10^{-4} mol), $Co(acac)_2$ (0.19 g, 7.5 × 10^{-4} mol), VAc (16.0 mL, 14.9 g, 173 × 10^{-2} mol), 46 h at 30 °C, conversion = 37%, 3-bromo-4-oxo-2,2,6,6-tetramethylpiperidinyl-1-oxy (**5**) (0.373 g, 15 × 10^{-4} mol) in toluene (3.0 mL). *Characteristics*: $M_{n,NMR}$ = 86.09 × (3 × (−C*H*−OCOCH$_3$, PVAc)/(−OC*H*$_3$, V-70)) = 6900 g/mol; $M_{n,theor}$ = 7400 g/mol; M_w/M_n = 1.15.

General Recipe for the Synthesis of PVAc Containing Block Copolymers by ATRP Initiated by a Poly(vinyl acetate) Macroinitiator. A solution of poly(vinyl acetate) macroinitiator in degassed toluene was added under argon to a glass tube capped by a three-way stopcock. It was heated at 70 °C for 30 min to decompose any residual V-70, followed by toluene evaporation under reduced pressure. The copper complex was then added to the macroinitiator, and the reactor was purged by three vacuum−argon cycles. Degassed toluene, vinyl monomer, and HMTETA solution (0.35 M in toluene) were then added with a syringe. The flask was thermostated at the desired temperature, under stirring. The monomer conversion was determined by weighing the polymer collected upon removing the unreacted monomer from a picked-out sample, in vacuo at 80 °C. The residual monomer was similarly removed from the reaction medium under reduced pressure, and the polymer was diluted by THF, eluted through alumina, and poured in a copolymer nonsolvent. The colorless copolymer was filtered and dried under reduced pressure at 50 °C.

PVAc-*b*-PS$_1$. *Conditions:* PVAc macroinitiator **II** (430 mg, 0.64 × 10^{-4} mol), CuBr (7 mg, 0.5 × 10^{-4} mol), toluene (1.0 mL), styrene (1.5 mL, 1.4 g, 13 × 10^{-3} mol), HMTETA (0.15 mL, 0.35 M, 0.5 × 10^{-4} mol), 5 h 30 at 110 °C, conversion = 24%, precipitation in heptane. *Characteristics*: M_w/M_n = 1.15; $M_{n,NMR\ PVAc}$ = 6700 g/mol; $M_{n,theor\ PS}$ = 5100 g/mol; $M_{n,NMR\ PS}$ = 104 × (3/5) × ((aromatic protons of PS)/(−OC*H*$_3$, V-70)) = 6000 g/mol; $M_{n,theor\ PS}/M_{n,NMR\ PS}$ = 0.85. DSC: $T_{g,PVAc}$ = 36°C, $T_{g,PS}$ = 94 °C. TGA: −38% (292 °C), −41% (399 °C), −10% (426 °C).

PVAc-*b*-PEA. *Conditions:* PVAc macroinitiator **II** (430 mg, 0.64 × 10^{-4} mol), CuBr (7 mg, 0.5 × 10^{-4} mol), toluene (1 mL), ethyl acrylate (1.5 mL, 1.4 g, 14 × 10^{-3} mol), HMTETA (0.15 mL, 0.35 M, 0.52 × 10^{-4} mol), 1 h 30 at 90 °C, conversion = 55%, precipitation in heptane. *Characteristics*: M_w/M_n = 1.50; $M_{n,NMR\ PVAc}$ = 6700 g/mol; $M_{n,\ theor\ PEA}$ = 11 900 g/mol; $M_{n,NMR\ PEA}$ = 101.1 × (3/2) × ((CH$_2$−CH−COOCH_2CH$_3$ of PEA)/

($-OCH_3$, V-70)) = 13 200 g/mol; $M_{n,theor\ PEA}/M_{n,NMR\ PEA} = 0.9$. DSC: $T_g = -13$ °C. TGA: −36% (323 °C), −47% (376 °C), −7% (454 °C).

PVAc-*b*-PMMA. *Conditions:* PVAc macroinitiator **I** (365 mg, 0.41×10^{-4} mol), CuCl (5.5 mg, 0.56×10^{-4} mol), $CuCl_2$ (0.74×10^{-5} mol), toluene (3.2 mL), methyl methacrylate (1.6 mL, 1.5 g, 15×10^{-3} mol), HMTETA (0.15 mL, 0.35 M, 0.52×10^{-4} mol), 6 h at 80 °C, conversion = 48%, precipitation in methanol. *Characteristics*: $M_w/M_n = 1.10$; $M_{n,NMR\ PVAc} = 8800$ g/mol; $M_{n,theor\ PMMA} = 17\,500$ g/mol; $M_{n,NMR\ PMMA} = 100 \times$ (((−OCO−CH_3 of PMMA)/($-OCH_3$, V-70) = 25 000 g/mol; $M_{n,theor\ PMMA}/M_{n,NMR\ PMMA} = 0.7$. DSC: $T_g = 92$ °C. TGA: −27% (232 °C), −26% (312 °C), −38% (382 °C).

PVAc-*b*-PS$_2$. *Conditions:* PVAc macroinitiator **III** (690 mg, 1.0×10^{-4} mol), CuBr (14 mg, 1.0×10^{-4} mol), toluene (2 mL), styrene (2.2 mL, 2.0 g, 19×10^{-3} mol), HMTETA (0.3 mL, 0.35 M, 10^{-4} mol), 4 h 30 at 110 °C, conversion = 36%, precipitation in methanol. *Characteristics*: $M_w/M_n = 1.30$; $M_{n,NMR\ PVAc} =$ 6900 g/mol; $M_{n,theor\ PS} = 7200$ g/mol; $M_{n,NMR\ PS} = 104 \times (3/5) \times$ ((aromatic protons of PS)/($-OCH_3$, V-70)) = 16 600 g/mol; $M_{n,theor\ PS}/M_{n,NMR\ PS} = 0.43$. DSC: $T_{g,PVAc} = 42$ °C, $T_{g,PS} = 101$ °C. TGA: −20% (304 °C), −71% (386 °C).

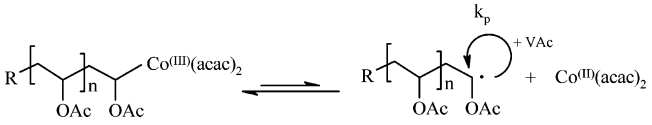
Synthesis of a PVOH-*b*-PS Copolymer by Methanolysis of the Ester Groups of PVAc-*b*-PS$_2$. A solution of potassium hydroxide (0.05 g) in methanol (15 mL, p.a.) was added to the PVAc-*b*-PS_2 copolymer (0.20 g) dissolved in THF (10 mL). After 40 h at room temperature under stirring, the PVOH-*b*-PS copolymer (0.15 mg) was collected by filtration and dried in vacuo at 50 °C. $M_{n,PVOH} = 3500$ g/mol. $M_{n,PS} = 16\,600$ g/mol. DSC: $T_{g,PS} = 106$ °C. TGA: −8% (304 °C), −83% (386 °C).

Preparation of the aqueous copolymer solution for TEM and DLS observations: 10 mL of THF and 150 μL of bidistilled water were added to 2.5 mg of the PVOH-*b*-PS copolymer. The mixture was stirred for 4 days until complete dissolution of the polymer. Then, 4.00 mL of bidistilled water was added dropwise to 1.00 mL of the copolymer solution under stirring.

Synthesis of Poly(vinyl acetate) End-Capped by a Cobalt Complex. $Co(acac)_2$ (0.128 g, 0.50×10^{-3} mol) and V-70 (0.50 g, 1.6×10^{-3} mol) were added into a 100 mL flask and degassed by three vacuum−argon cycles. Degassed vinyl acetate (25.0 mL, 271×10^{-3} mol) was then added with a syringe under argon. The purple mixture was stirred and heated at 30 °C. No polymerization occurred during 21 h. After 26 h, the solution viscosity increased, and the unreacted monomer was distilled off under reduced pressure at room temperature. The actual monomer conversion was 38%. After dissolution in acetone, the polymer was precipitated twice in heptane, filtered, and dried at 70 °C under reduced pressure. 7.5 g of green PVAc was collected ($M_{n,theor} = 17\,700$ g/mol, $M_{n,SEC} = 18\,500$ g/mol, $M_w/M_n = 1.15$).

Synthesis of PVOH by Methanolysis of PVAc End-Capped by a Cobalt Complex. A solution of potassium hydroxide (1.00 g) in methanol (40 mL, p.a.) was added to PVAc (4.00 g, $M_{n,SEC} = 18\,500$ g/mol) dissolved in methanol (200 mL). After 24 h at room temperature under stirring, the PVOH (1.70 g) was collected by filtration, washed several times with ethyl acetate, and dried under vacuum at 70 °C. ^{13}C NMR (400 MHz, D_2O/H_2O/2-propanol: 1/3/traces): 70−64 ppm ($-CH_2-CH(OH)-$); 48−42 ppm ($-CH_2-CH(OH)-$).

Scheme 1

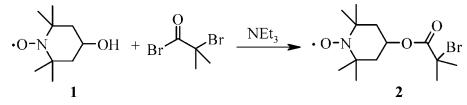


Results and Discussion

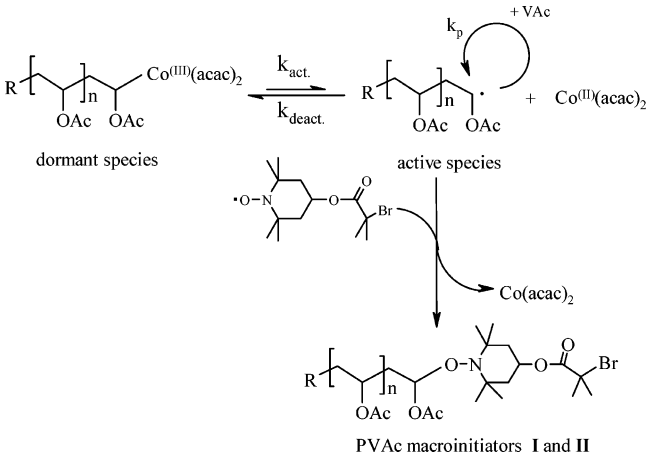
A previous study reported that the cobalt-mediated radical polymerization of vinyl acetate initiated by V-70 at 30 °C is controlled[16] as result of an equilibrium between active and dormant species, as shown in Scheme 1. Accordingly, poly(vinyl acetate) chains end-capped by a cobalt complex can be synthesized with a predictable molar mass and a low polydispersity. Because this methodology cannot impart control to the radical polymerization of other monomers such as styrene, acrylates, and methacrylates, it is not suited to the straightforward synthesis of well-defined poly(vinyl acetate) containing block copolymers. The way to tackle this problem consists of converting PVAc chains prepared by cobalt-mediated polymerization into a macroinitiator for the controlled radical polymerization of the second comonomer.

The cobalt complex at the end of the PVAc chains is easily displaced by nitroxide added to the polymerization medium.[17] The bonding between PVAc and nitroxide is thermally stable, consistent with the failure of the NMP process to control the radical polymerization of vinyl acetate. Indeed, the exceedingly high thermal stability of the dormant species does not allow growing chains to be released in the medium.[18] On the basis of this observation, well-defined, cobalt-free, functional poly(vinyl acetate) chains have been prepared by addition of the desired function containing nitroxyl radical to the controlled polymerization medium.[17] This strategy has been extended in this work to the end-capping of PVAc by a function able to initiate the controlled radical polymerization of vinyl monomers by ATRP.

Scheme 2



Scheme 3



A. Synthesis of Poly(vinyl acetate) Containing Block Copolymers. Synthesis of PVAc Macroinitiators End-Capped by an α-Bromoester. The α-bromoester containing radical **2** has been synthesized by acylation of the 4-hydroxy-2,2,6,6-tetramethylpiperidine 1-oxyl radical (**1**) (TEMPO-OH) by 2-bromoisobutyryl bromide in the presence of triethylamine (Scheme 2).[19] The nitroxyl radical **2** has been added to the cobalt-mediated polymerization medium of vinyl acetate, at low monomer conversion. Two well-defined poly(vinyl acetate) samples with an α-bromoester end group have been collected, which are potential macroinitiators for ATRP processes (Scheme 3). The cobalt complex has been eliminated by elution of the polymer solution through alumina, and colorless PVAc has been accordingly recovered by precipitation in heptane. Characteristics of these poly(vinyl acetate) macroinitiators are listed in Table 1.

Table 1. Characteristics of the Poly(vinyl acetate) (PVAc) Macroinitiators End-Functionalized by an α-Bromoester[a]

	$M_{n,NMR}$[b]	$M_{n,theor}$[c]	$M_{n,theor}/M_{n,NMR}$	M_w/M_n
PVAc **I**[d]	8800	8900	1.01	1.10
PVAc **II**[e]	6700	6500	0.97	1.20

[a] Molar masses (M_n) (g/mol). [b] ^{1}H NMR in $CDCl_3$. [c] $M_{n,theor}$ = ([monomer]$_0$/[Co]$_0$) × MW_{VAc} × conv. [d] [V-70]/[Co(acac)$_2$]/[VAc]: 3.25/1/270, 40 h at 30 °C, conv = 38%, [α-bromoester containing nitroxide **2**]/[Co(acac)$_2$] = 2. [e] [V-70]/[Co(acac)$_2$]/[VAc]: 3.25/1/135, 88 h at 30 °C, conv = 56%, [α-bromoester containing nitroxide **2**]/[Co(acac)$_2$] = 1.4.

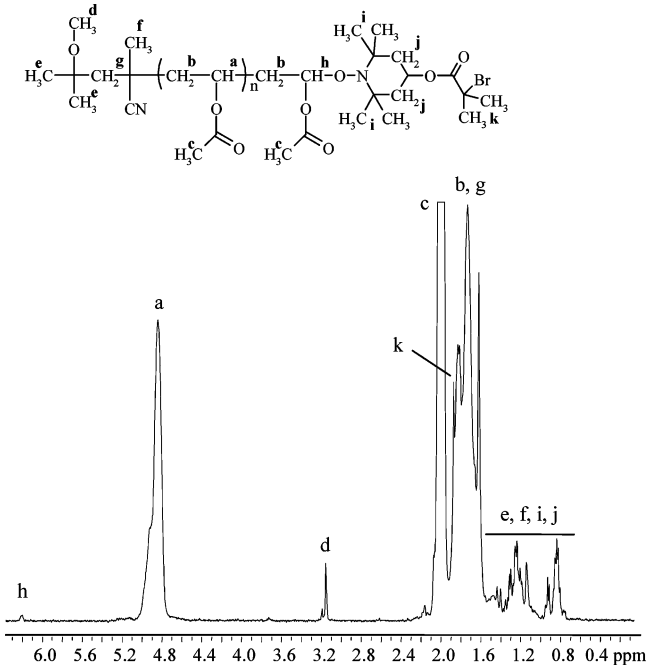


Figure 1. ^{1}H NMR spectrum for the poly(vinyl acetate) macroinitiator **I** ($M_{n,NMR}$ = 8800 g/mol) end-capped by an α-bromoester (Table 1).

The PVAc end-functionalization is illustrated by the ^{1}H NMR spectrum for the macroinitiator **I** (Figure 1). In addition to the major peaks characteristic of the PVAc chain (**a**, **b**, **c**) and peaks for the V-70 initiator fragment (**d**, **e**, **f**), resonances typical of the piperidyl group (**i**, **j**), the CO−C(C*H*$_3$)$_2$Br protons (**k**), and the hydrogen (**h**) at the junction between the PVAc chain and the nitroxyl group (AcO−C*H*−ON−) can be observed.

Synthesis of PVAc Containing Block Copolymers by ATRP. The two poly(vinyl acetate) samples end-capped by an activated bromide have been used as macroinitiators for the atom transfer radical polymerization of styrene (Sty), ethyl acrylate (EA), and methyl methacrylate (MMA) to synthesize the parent poly(vinyl acetate) containing block copolymers according to Scheme 4. Copolymerization data are listed in Table 2, and SEC chromatograms are shown in Figure 2. Obviously, polymerization of styrene is resumed by the poly(vinyl acetate) macroinitiator **II**, in the presence of copper(I) bromide and hexamethyltriethylenetetramine (HMTETA), as assessed by an initiation efficiency of 85% and illustrated by the comparison of the SEC chromatograms for the PVAc macroinitiator and the final copolymer (Figure 2a). The elution peak for the macroinitiator is clearly shifted toward higher molar mass, leaving very few PVAc chains unreacted in agreement with a low polydispersity for the PVAc-*b*-PS$_1$ copolymer (M_w/M_n = 1.15). This copolymer has been analyzed by ^{1}H NMR (Figure 3). The expected resonances are observed for the PVAc block (**a**, **b**, **c**) and the PS one (**h**, **i**, **j**) together with small peaks for the methoxy protons of the initiator fragment (**d**) and protons of the nitroxide end group (**g**). The molar mass of each block is easily determined from the relative intensity of the signals **a** and **d** for the PVAc block (6700 g/mol) and the signals **j** and **d** for the PS block (6000 g/mol). Comparison of $M_{n,theor}$ and $M_{n,NMR}$ for the PS block leads to the previously mentioned PVAc macroinitiator efficiency of 85% (Table 2).

Similarly, the poly(vinyl acetate) **II** is an effective macroinitiator for the ethyl acrylate polymerization, in the presence of CuBr and HMTETA, so making the PVAc-*b*-PEA block copolymer available (Table 2). Although the molar mass of the polyacrylate block is very close to the theoretical value, the polydispersity of the recovered block copolymer is quite high (M_w/M_n = 1.50), which indicates that the initiation of the second block is slow compared to propagation. SEC chromatograms for the macroinitiator and the block copolymer are shown in Figure 2b. The PVAc-*b*-PEA copolymer has been analyzed by ^{1}H NMR (Figure 4). Typical signals for the PVAc block (**a**, **b**, **c**) and the PEA block (**h**, **i**, **j**, **k**) are clearly observed. Protons for the α end group (**d**, **e**, **f**, initiator fragment) and the nitroxide group at the junction of the two blocks (**g**) are also detected. The

Scheme 4

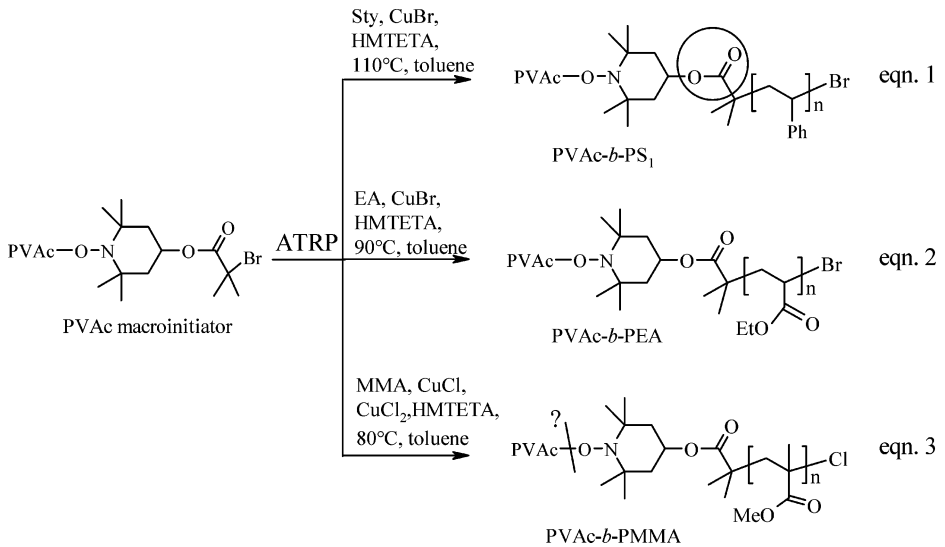


Table 2. Synthesis of Various Block Copolymers by Atom Transfer Radical Polymerization of Styrene (Sty), Ethyl Acrylate (EA), and Methyl Methacrylate (MMA) Initiated by PVAc Macroinitiators[a]

	PVAc	second block					copolymer	
	$M_{n,NMR}$	T (°C)	conv (%)	$M_{n,theor}$	$M_{n,NMR}$[d]	$M_{n,theor}/M_{n,NMR}$	$M_{n,SEC}$[e]	M_w/M_n
PVAc-*b*-PS_1	6700[b]	110	24	5 100	6 000	0.85	18 500	1.15
PVAc-*b*-PEA	6700[b]	90	55	11 900	13 200	0.90	23 500	1.50
PVAc-*b*-PMMA	8800[c]	80	48	17 500	25 000	0.70	33 500	1.10

[a] Molar masses (M_n) (g/mol). [b] PVAc **II**. [c] PVAc **I**. [d] ^{1}H NMR in $CDCl_3$. [e] Size exclusion chromatography (SEC) in tetrahydrofuran with PS standards. Detailed conditions are reported in the Experimental Section.

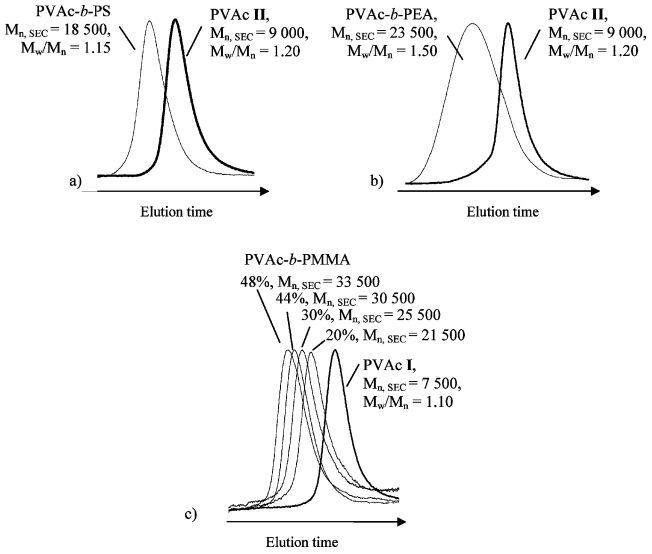


Figure 2. Size exclusion chromatography for the polymerization of (a) styrene, (b) ethyl acrylate, and (c) methyl methacrylate, initiated from a poly(vinyl acetate) macroinitiator (Table 2).

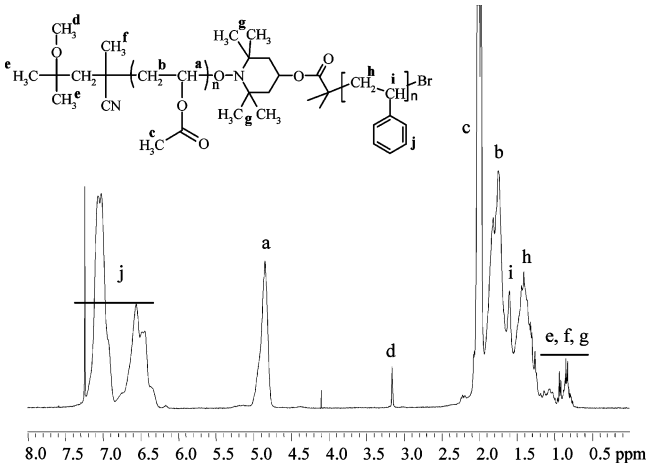


Figure 3. ^{1}H NMR spectrum for the poly(vinyl acetate)(6700)-*b*-polystyrene(PS_1,6000) block copolymer in $CDCl_3$ (Table 2).

molar masses of the constitutive blocks have been determined from the intensity of the signals **a** and **d** for the PVAc block (6700 g/mol) and that one of the signals **j** and **d** for the PEA block (13 200 g/mol). The macroinitiator efficiency of the PVAc **II** is quite high (90%) as calculated from $M_{n,theor}$ and $M_{n,NMR}$ for the second block, which proves the efficiency of the block copolymerization strategy proposed in this work (Table 2).

Finally, the ATRP of methyl methacrylate has been initiated by the poly(vinyl acetate) macroinitiator **I** with the purpose to prepare a PVAc-*b*-PMMA copolymer (Table 2). The MMA polymerization is actually resumed by PVAc as assessed by an increase in the molar mass

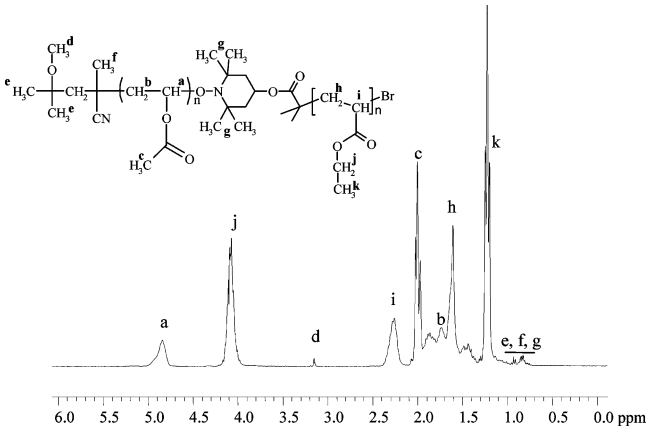


Figure 4. ^{1}H NMR spectrum for the poly(vinyl acetate)(6700)-*b*-poly(ethyl acrylate)(13 200) block copolymer in $CDCl_3$ (Table 2).

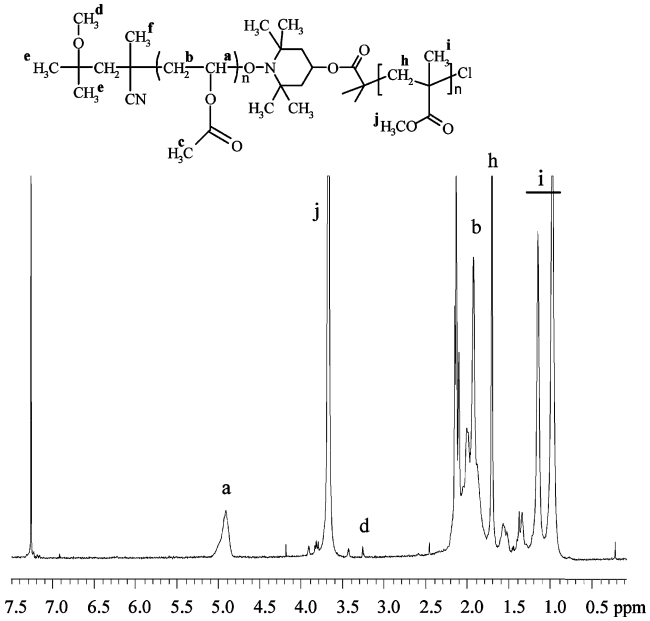


Figure 5. ^{1}H NMR spectrum for the poly(vinyl acetate)(8800)-*b*-poly(methyl methacrylate)(25 000) block copolymer in $CDCl_3$ (Table 2).

with the monomer conversion and by the low polydispersity of the block copolymer formed ($M_w/M_n \sim 1.1-1.2$). An additional evidence for the efficient initiation can be found in Figure 2c which compares the SEC traces for the PVAc macroinitiator and the copolymers formed at increasing conversions. The ^{1}H NMR analysis of the PVAc-*b*-PMMA block copolymer confirms the coexistence of PVAc (**a**, **b**, **c**) and PMMA (**h**, **i**, **j**). Moreover, a small peak is observed for the methoxy protons of the V-70 fragment (**d**) (Figure 5). From M_n of the PVAc block (8800 g/mol) and the relative intensity of the signals **a** and **d** and the signals **j** and **d**, M_n of the PMMA block (25 000 g/mol) could be determined.

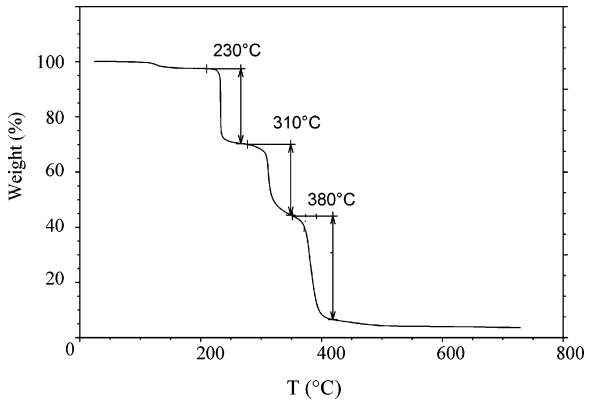


Figure 6. Thermogravimetric analysis of the poly(vinyl acetate)(8800)-*b*-poly(methyl methacrylate)(25 000) block copolymer.

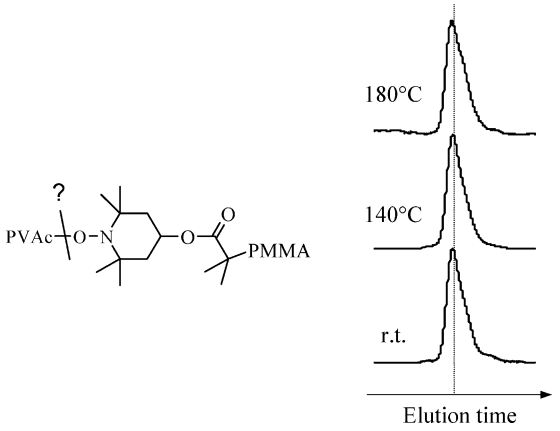


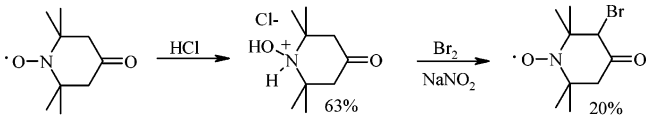
Figure 7. Size exclusion chromatograms for the poly(vinyl acetate)(8800)-*b*-poly(methyl methacrylate)(25 000) block copolymer before and after heating at 140 and 180 °C, respectively.

The difference between the experimental molar mass of the PMMA block (^{1}H NMR) and the theoretical value (17 500 g/mol) might be at least partly explained by the poor accuracy of the integration of the small signal (**d**) (Table 2).

The strategy that combines cobalt-mediated polymerization and ATRP proves to be highly efficient for the synthesis of well-defined, cobalt-free, PVAc containing diblocks, such as PVAc-*b*-PS, PVAc-*b*-PEA, and PVAc-*b*-PMMA copolymers. The question of the stability of these copolymers that contain a carbon−nitroxide bond between the two blocks has been addressed. As a rule, the constitutive blocks are stable until 220 °C. However, TGA does not provide any direct information on the stability of the junction between blocks because no weight loss is expected to occur. Therefore, a PVAc-*b*-PMMA copolymer has been heated for 2 h at constant temperatures (140 and 180 °C, respectively), lower than the temperature at which the first weight loss is noted (230 °C) (Figure 6). The copolymer has been analyzed by size exclusion chromatography. Figure 7 shows that the SEC chromatogram for the PVAc-*b*-PMMA copolymer remains unchanged before and after thermal treatment, and no elution peak for released blocks can be detected, which confirms the thermal resistance of the block junction at least until 180 °C.

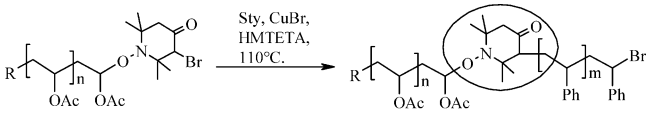
Poly(vinyl acetate) is very well-known as a precursor of poly(vinyl alcohol), the hydrolysis of the acetate groups being an easy derivatization reaction.[20] Hydrolysis of the poly(vinyl acetate) block of the diblocks

Scheme 5



3 **4** **5**

Scheme 6



synthesized in this work is thus a straightforward route to a variety of poly(vinyl alcohol) containing block copolymers. However, the simultaneous hydrolysis of the ester at the junction of the two blocks (see eq 1, Scheme 3) makes this strategy unacceptable, except whether a hydrolytically stable junction between the two blocks can be found out.

B. Synthesis of Poly(vinyl alcohol) Containing Block Copolymers. Synthesis of PVAc Macroinitiators End-Capped by an α-Bromoketone. The basic problem to be faced is the synthesis of a nitroxide that contains an ATRP initiator and is free from any hydrolyzable group. These requirements are actually met in the case of 3-bromo-4-oxo-2,2,6,6-tetramethylpiperidine 1-oxyl (**5**) as result of the coexistence of a nitroxide and stability against hydrolysis. A two-step

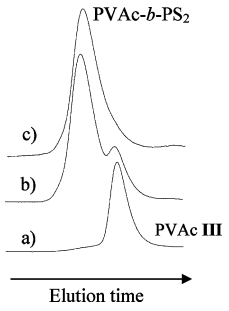


Figure 8. Size exclusion chromatograms for (a) the poly(vinyl acetate) macroinitiator **III** and the poly(vinyl acetate)(6900)-*b*-polystyrene(PS_2,16 600) diblock (b) before and (c) after precipitation in methanol (Table 3).

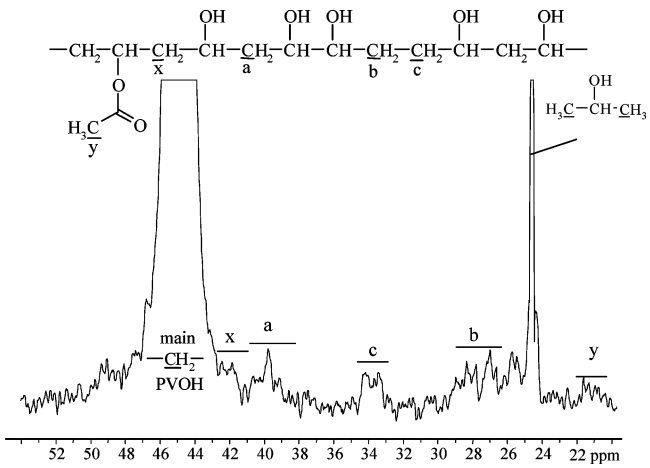


Figure 9. ^{13}C NMR spectrum for the poly(vinyl alcohol) prepared by methanolysis of the poly(vinyl acetate) chains end-capped by the cobalt complex (in D_2O/H_2O/2-propanol: 1/3/traces).

Table 3. Synthesis of a Poly(vinyl acetate)-*b*-polystyrene Block Copolymer by Atom Transfer Radical Polymerization Initiated by a PVAc Macroinitiator[a]

macro PVAc **III**	PS block					PVAc-*b*-PS_2[d]	
$M_{n,NMR}$	T (°C)	conv (%)	$M_{n,theor}$	$M_{n,NMR}$[c]	$M_{n,theor}/M_{n,NMR}$	$M_{n,SEC}$[e]	M_w/M_n
6900[b]	110	36	7200	16 600	0.43	32 000	1.30

[a] Molar masses (M_n) (g/mol). [b] PVAc **III**. [c] ^{1}H NMR in $CDCl_3$. [d] Precipitated in methanol. [e] SEC in tetrahydrofuran with PS standards.

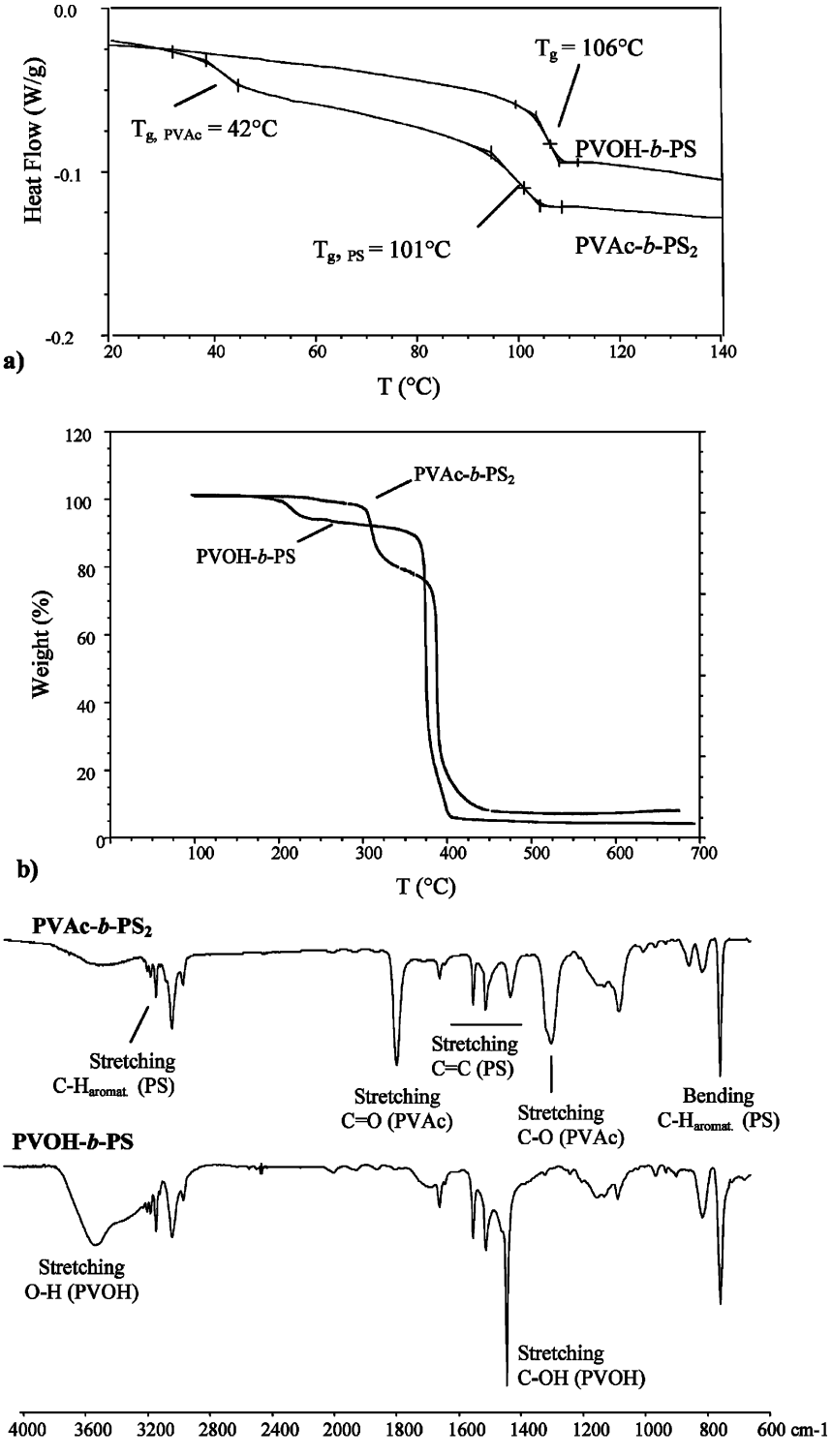


Figure 10. (a) Differential scanning calorimetry thermograms, (b) thermogravimetric analysis traces, and (c) infrared spectra for the original poly(vinyl acetate)(6900)-*b*-polystyrene(PS_2,16 600) and the final poly(vinyl alcohol)(3500)-*b*-polystyrene(16 600) block copolymers.

synthetic pathway reported by Sosnovsky et al.[21] has been extended to the 4-oxo-2,2,6,6-tetramethylpiperidine 1-oxyl radical (**3**) (Scheme 5). Although crystallized in hexane, the radical **5** is contaminated by a small amount of the nitroxide **3**, more likely because of the uncomplete bromination of 1-hydroxy-4-oxo-2,2,6,6-

Scheme 7

tetramethylpiperidine hydrochloride (**4**). Nevertheless, the nitroxide **5** has been used successfully as a trapping agent for the cobalt-mediated radical polymerization of vinyl acetate with formation of a well-defined PVAc **III** ($M_{n,NMR}$ = 6900 g/mol; $M_{n,SEC}$ = 9700 g/mol; M_w/M_n = 1.15).

Synthesis of PVAc-*b*-PS Block Copolymers by ATRP. The ATRP of styrene has been initiated by the colorless, cobalt-free, PVAc macroinitiator **III**, end-capped by an α-bromoketone function, in the presence of copper bromide and HMTETA (Scheme 6). Figure 8 shows a substantial shift of the original chromatograms of PVAc **III** toward higher molar mass in agreement with the formation of a PVAc-*b*-PS_2 block copolymer. Inactive PVAc chains have been removed by selective precipitation of the copolymer in methanol. Table 3 reports experimental details on this copolymerization and the PVAc-*b*-PS_2 copolymer collected after purification. Expectedly, the molar mass of the polystyrene block is higher than predicted and the initiation efficiency ($M_{n,theor\ PS}/M_{n,exp\ PS}$ = 0.43) is consistent with the PVAc dead chains observed by SEC.

Methanolysis of the PVAc Block of a PVAc-*b*-PS Diblock. Before methanolysis of the PVAc-*b*-PS_2 diblock, this reaction has been tested with a poly(vinyl acetate) sample ($M_{n,SEC}$ = 18 500 g/mol; M_w/M_n = 1.15) prepared by cobalt-mediated radical polymerization. This polymer has been dissolved in methanol in the presence of KOH, and poly(vinyl alcohol) has been recovered by filtration after 24 h. Formation of PVOH has been confirmed by ^{13}C NMR, i.e., intense signals of the secondary (−CH_2−CHOH−) carbons of the PVOH chains at 42−48 ppm (Figure 9). Furthermore, the efficacy of the derivatization process is proved by the very low intensity of the signals **x** and **y**, assigned to non-methanolyzed acetate functions.[22] Other small signals (**a**, **b**, **c**) are characteristic of the head-to-head addition of the vinyl acetate.

Then PVAc-*b*-PS_2 diblock copolymer of a reasonably low polydispersity (1.3) has been hydrolyzed by KOH in a methanol/THF mixture, according to the same procedure, without any risk of rupture between the constitutive blocks (Scheme 7). After this treatment, the recovered polymer has been analyzed by DSC, TGA, and IR (Figure 10). Because no common solvent for PVOH and PS has been identified, SEC analysis has not been carried out. An interesting piece of information is that no homopolymer can be separated from the diblock whatever the selective solvent used. T_g of the PVAc block is no longer observed after hydrolysis (Figure 10a), whereas the TGA profile is deeply modified (Figure 10b). The success of the PVAc conversion into PVOH is also confirmed by comparison of the infrared spectra for the original PVAc-*b*-PS_2 and the final PVOH-*b*-PS (Figure 10c). Indeed, methanolysis results in the disappearance of the typical bands of PVAc (C=O and C−O stretching, at 1739 and 1242 cm^{-1}, respectively), the observation of the characteristic bands of PVOH (O−H and C−OH stretching, at 3414 and 1384 cm^{-1}, respectively), and the persistence of PS bands (C−H_{arom} stretching and C−H_{arom} bending, at 3060 and 756−698 cm^{-1}, respectively).

Finally, the self-association of this amphiphilic block copolymer in a water/THF mixture (v/v: 4/1) has been investigated by dynamic light scattering (DLS) and by transmission electron microscopy (TEM) (Figures 11 and 12, respectively). Large vesicles (average diameter = 996 ± 77 nm), identified by a "hollow" core, are observed consistent with the composition structure of the copolymer, consisting of a small hydrophilic PVOH block (M_n = 3500 g/mol) and a large hydrophobic PS block

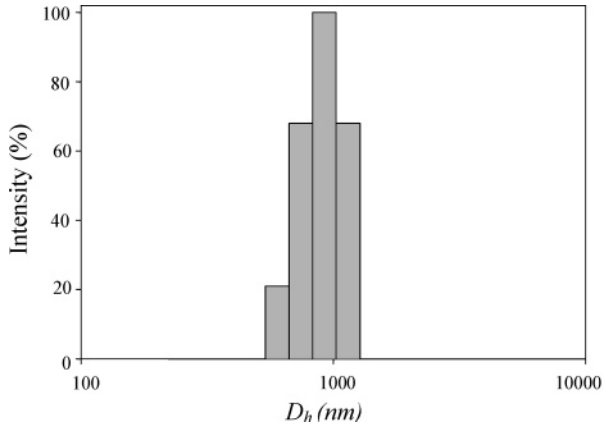


Figure 11. Size distribution of the vesicles formed by poly(vinyl alcohol)(3500)-*b*-polystyrene(16 600) in a water/tetrahydrofuran (4/1) mixture.

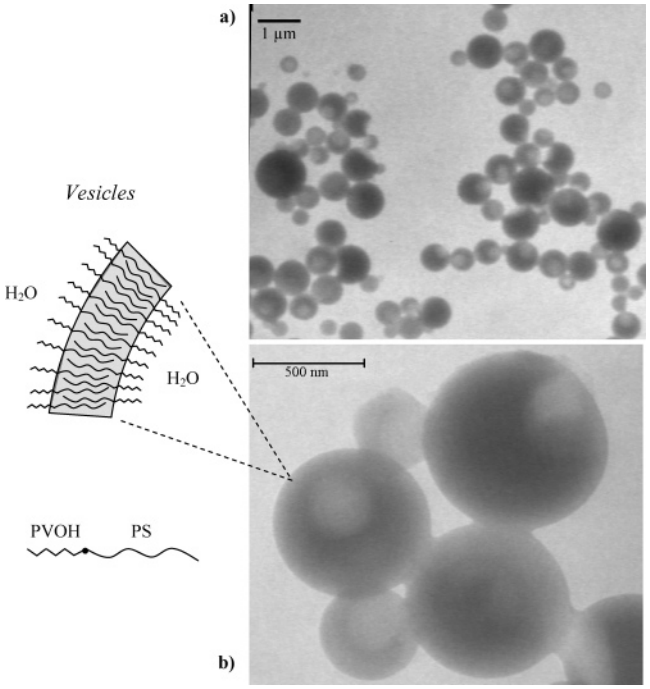


Figure 12. Transmission electron microscopy (TEM) pictures for the vesicles formed by the diblock poly(vinyl alcohol)(3500)-*b*-polystyrene(16 600). TEM pictures have been recorded at low (A) and high (B) magnifications.

(M_n = 16 600 g/mol). Formation of vesicles confirms the integrity of most of the −C(OH)−O−N− functions at the junction of the two blocks.

Even though this strategy is not straightforward, it is efficient to prepare poly(vinyl alcohol)-*b*-polystyrene block copolymers.

Conclusions

This paper has reported a new method for the synthesis of well-defined poly(vinyl acetate) containing block copolymers, which relies on the combination of the cobalt-mediated polymerization of vinyl acetate and ATRP of styrene and (meth)acrylates. Vinyl acetate is first polymerized in a controlled manner, and the chains are terminated by an α-bromoester containing nitroxide, i.e., a macroinitiator for the ATRP of vinyl monomers. According to this methodology, well-defined PVAc-*b*-PS, PVAc-*b*-PEA, and PVAc-*b*-PMMA block copolymers have been synthesized. The carbon−nitroxyl bond at the junction of the two blocks is proved to be thermally stable until at least 180 °C. Provided that the nitroxide terminating agent is hydrolytically stable, the subsequent methanolysis of the PVAc block of PVAc-*b*-PS diblocks leads to the formation of the parent PVOH-*b*-PS copolymers of well-defined structure and composition. These amphiphilic block copolymers self-associate in aqueous medium and form micelles with a shape that depends on the volume fraction of the constitutive blocks.

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