Synthesis of Water-Soluble Star-Block and Dendrimer-like Copolymers Based on Poly(ethylene oxide) and Poly(acrylic acid)

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ABSTRACT: Star-block copolymers (PEO_3-*b*-PAA_3) and dendrimer-like copolymers (PEO_3-*b*-PAA_6) consisting of three inner poly(ethylene oxide) (PEO) arms and either three or six peripheral poly(acrylic acid) (PAA) blocks were derived by a core-first approach. To this end, the OH end groups of three-arm PEO stars prepared anionically were derivatized into either three or six bromo-ester functions that served to grow the poly(*tert*-butyl acrylate) (P*t*BA) blocks by atom transfer radical polymerization (ATRP) in a controlled fashion. This could be achieved at 80 °C in toluene in the presence of CuBr/pentamethyldiethylenetriamine (CuBr/PMDETA) as the catalyst system. Characterization by size exclusion chromatography and NMR of star-block copolymers (PEO_3-*b*-P*t*BA_3) and dendrimer-like copolymers (PEO_3-*b*-P*t*BA_6) confirmed their well-defined character. Subsequent treatment with trifluoroacetic acid selectively hydrolyzed the P*t*BA blocks, leading to the targeted PEO_3-*b*-PAA_3 and PEO_3-*b*-PAA_6 compounds. Alternatively, an arm-first methodology utilizing a divinylic comonomer as the linking agent was applied to access star-block copolymers incorporating an inner PAA part and a peripheral PEO layer. To this end, preformed PEO-*b*-P*t*BA diblock copolymers were reacted with divinylbenzene in anisole in the presence of CuBr/PMDETA. Some of the factors controlling the formation of $(PtBA\text{-}b\text{-}PEO)_f$ stars were examined. These included the molar ratio of the linking agent to the diblock precursor, the molar mass of the latter species, and the reaction time. Finally, selective hydrolysis led to the expected double hydrophilic star-block copolymers noted $(PAA\text{-}b\text{-}PEO)_f$.

Introduction

Double hydrophilic block copolymers (DHBCs) represent a new class of macromolecular systems that exhibit stimuli-responsive properties in water. DHBCs can associate one polyelectrolyte block with a neutral hydrophilic one, but they can also be comprised of two basic or two acidic blocks.[1] Similar to amphiphilic block copolymers constituted of hydrophobic and hydrophilic moieties, DHBCs can self-assemble and form reversible micelle-like structures in the submicron or the micron size range, for instance, by adjusting the pH or temperature of the solution.[2] This can be achieved in aqueous media by manipulating the hydrophilicity of the responsive block through stimulation, whereas the role of the water-dispersible and noninteracting block is to prevent the aggregates from precipitating. In the recent literature,[3−7] a few authors have synthesized even more complex copolymeric systems such as ABC triblock copolymers that are capable of self-organizing in water in three-layered ("core−shell−coronna") micellar structures. Among possible uses, such water-soluble AB or ABC block copolymers find increasing interest as polymeric surfactants, drug and gene delivery systems, and templates for the controlled growth of inorganic compounds (biomineralization concept).[1]

From a synthetic viewpoint, DHBCs were originally prepared via living ionic (anionic, cationic, or group transfer) polymerizations.[1] However, the range of monomers that can undergo such polymerizations is somewhat limited. In this respect, controlled/living radical polymerization (C/LRP)[8] techniques, owing to their much less demanding experimental conditions and their tolerance to polar functions as compared to ionic procedures, seem very promising for the synthesis of new DHBCs. This was exemplified recently.[9−22] For instance, the Armes team and others employed bromo-ended poly(ethylene oxide) or poly(propylene oxide) macroinitiators for atom transfer radical polymerization (ATRP) of miscellaneous monomers, including sodium methacrylate,[9] ω-methacryloyl poly(ethylene oxide),[10−11] sodium 4-vinylbenzoate,[12] hydroxyethyl methacrylate,[13] 2-(dimethylamino)ethyl methacrylate,[14] and *tert*-butyl acrylate followed by hydrolysis of the ester groups.[15] Neutral-charged DHBCs were prepared in this way. The Armes group also derived zwitterionic as well as acidic block copolymers either directly by sequential nitroxide-mediated polymerization (NMP)[16] or using protecting group chemistry via ATRP.[17] Alternatively, thiocarbonyl thio compounds such as xanthates or dithioesters were used as chain transfer agents in the so-called reversible addition−fragmentation chain transfer (RAFT) to access DHBCs.[18−22]

Even though ionic and radical polymerization procedures proved their value in deriving DHBCs, the structures synthesized so far mainly concern a linear covalent arrangement of blocks (AB type, ABA type, or ABC type).[1−22] To the best of our knowledge, the assembling of two hydrophilic blocks in a starlike architecture was only proposed in one report where star copolymers made of PEO and poly(*N*-isopropylacrylamide) were shown to form gels in a thermoreversible fashion by self-association.[23]

Interest in new types of DHBCs that exhibit a starlike architecture is driven by the expectation that a well-controlled number of branching points can induce dif-

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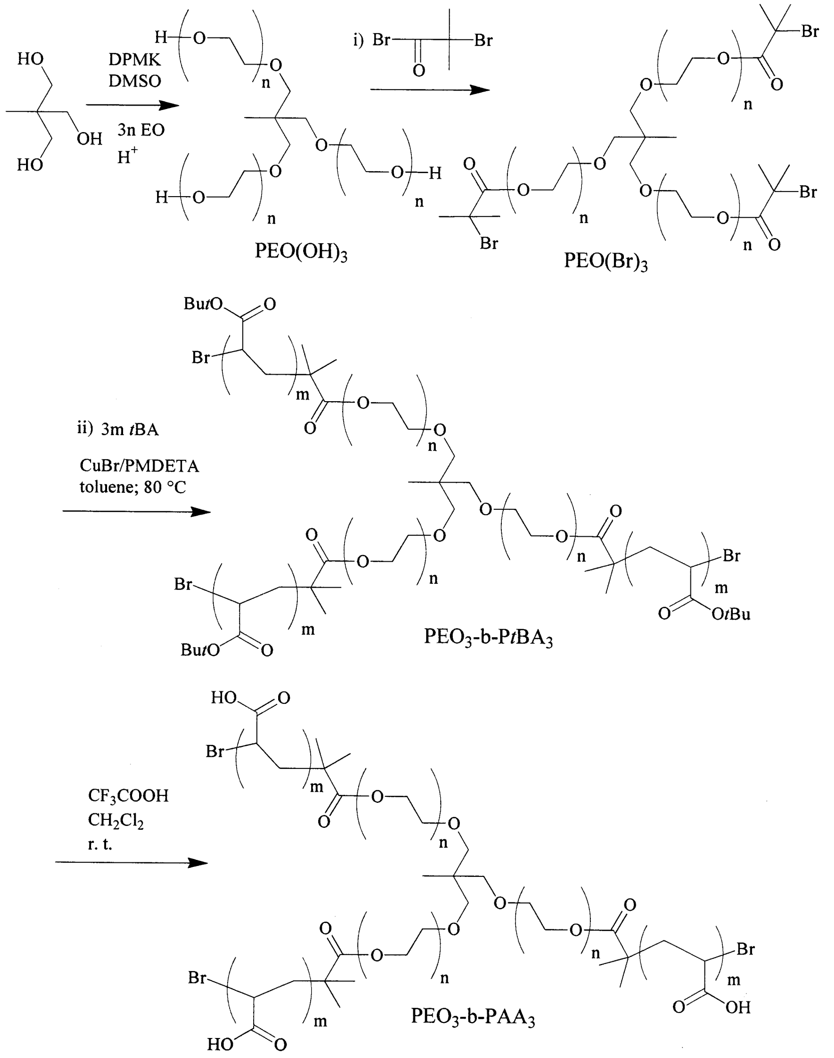
Scheme 1. Synthesis of PEO_3-*b*-PAA_3 Star-Block Copolymers by the Core-First Method



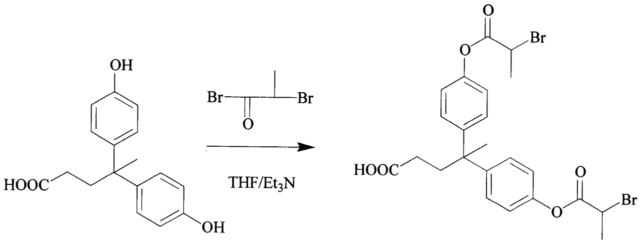
ferent properties as compared to their linear counterparts.[24] Attempts to derive such starlike DHBCs are part of our continuing efforts to tailor well-defined branched amphiphilic systems such as star-block copolymers, miktoarm stars, and dendrimer-like copolymers made of PEO and polystyrene.[25]

In the present work, the core-first approach was employed to derive starlike and dendrimer-like DHBCs including PEO inner blocks and peripheral poly(acrylic acid) (PAA) blocks; the reverse structures with inner PAA blocks and outer PEO blocks were also obtained by the arm-first approach using divinylbenzene as the linking agent. We will therefore describe here the synthesis of novel branched DHBCs. This was achieved by combining the anionic polymerization of ethylene oxide with the ATRP of *tert*-butyl acrylate and subsequent hydrolysis of the *tert*-butyl groups to afford poly(acrylic acid).

Results and Discussion

Star-Block and Dendrimer-like Block Copolymers by the Core-First Route. Well-defined triarm PEO stars of expected molar masses carrying three hydroxy end groups, noted $PEO(OH)_3$, were synthesized by the "core-first methodology" as previously reported[25] (see Scheme 1). Briefly, 1,1,1-tris(hydroxymethyl)ethane was used as the precursor, dimethyl sulfoxide was the polymerization solvent, and diphenylmethylpotassium (DPMK) was used to deprotonate the hydroxyl groups. The amount of DPMK introduced was adjusted so as to deprotonate only 20% of the hydroxyls of the trifunctional precursor. Owing to the rapid exchange of protons between the dormant hydroxyls and the propagating alkoxides relative to the rate of polymerization,[25] all three arms grew at the same rate. Next, the star-type macroinitiators, noted $PEO(Br)_3$ and $PEO(Br)_6$, were prepared by esterification of the $PEO(OH)_3$ sample. For the derivatization of the hydroxyl groups of $PEO(OH)_3$ into twice as many bromo end groups, a branching agent shown in Scheme 2 was designed. The structure of this AB_2 molecule was confirmed by ^1H NMR spectroscopy (see Experimental Section). In this case, the chemical transformation of the OH groups was carried out in dichloromethane using dicyclohexyl

Scheme 2. Synthesis of the Branching Agent



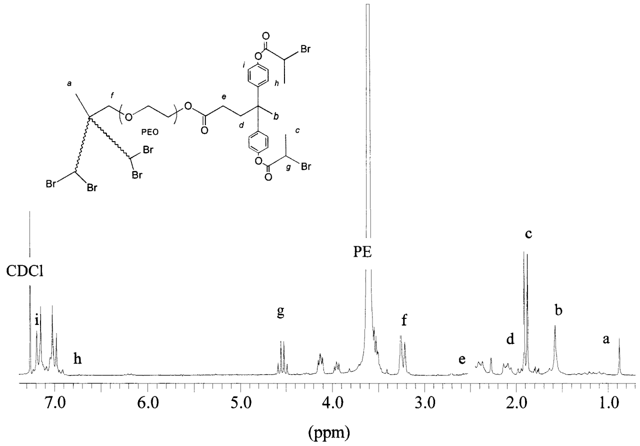


Figure 1. ^{1}H NMR spectrum ($CDCl_3$; 200 MHz) of the macroinitiator $PEO(Br)_6$.

carbodiimide and (*N*,*N*-dimethylamino)pyridine-*p*-toluenesulfonic acid (DCC/DPTS). Complete substitution of the hydroxyl groups was evidenced by NMR spectroscopy; as an illustration, the NMR spectrum of $PEO(Br)_6$ is shown in Figure 1 with assignments of all observed peaks.

Poly(*tert*-butyl acrylate) (P*t*BA) blocks were then grown from these $PEO(Br)_3$ and $PEO(Br)_6$ macroinitiators by copper-mediated ATRP of *tert*-butyl acrylate (*t*BA) producing PEO_3-*b*-P*t*BA_3 star-block copolymers (Scheme 1) and PEO_3-*b*-P*t*BA_6 dendrimer-like copolymers (Scheme 3), respectively.

The terminology “dendrimer-like” copolymers refers to a new class of macromolecular systems that exhibit similar features to those of regular dendrimers (precise number of branching points and outer functions, presence of a central core) but in this case, the successive generations consist of true polymeric chains.[25−27] Generally speaking, dendrimer-like polymers have distinct properties compared to their purely star homologues.[25−27]

Optimal conditions for polymerizing *tert*-butyl acrylate were at 80 °C using toluene as a solvent in the presence of CuBr/pentamethyldiethylenetriamine (PMDETA) as the catalytic system. The characteristics of the copolymers obtained are given in Table 1. All the materials obtained were completely soluble with no insoluble cross-linked material detected. SEC characterization of the samples unambiguously showed the formation of the P*t*BA blocks from the $PEO(Br)_3$ star (see Figure 2a). After ATRP of *tert*-butyl acrylate, the SEC trace shifted to the higher molar mass region along with complete disappearance of the peak of the precursor peak. Similar results were observed when using the $PEO(Br)_6$ precursor for the growth of the dendrimer-like structures.

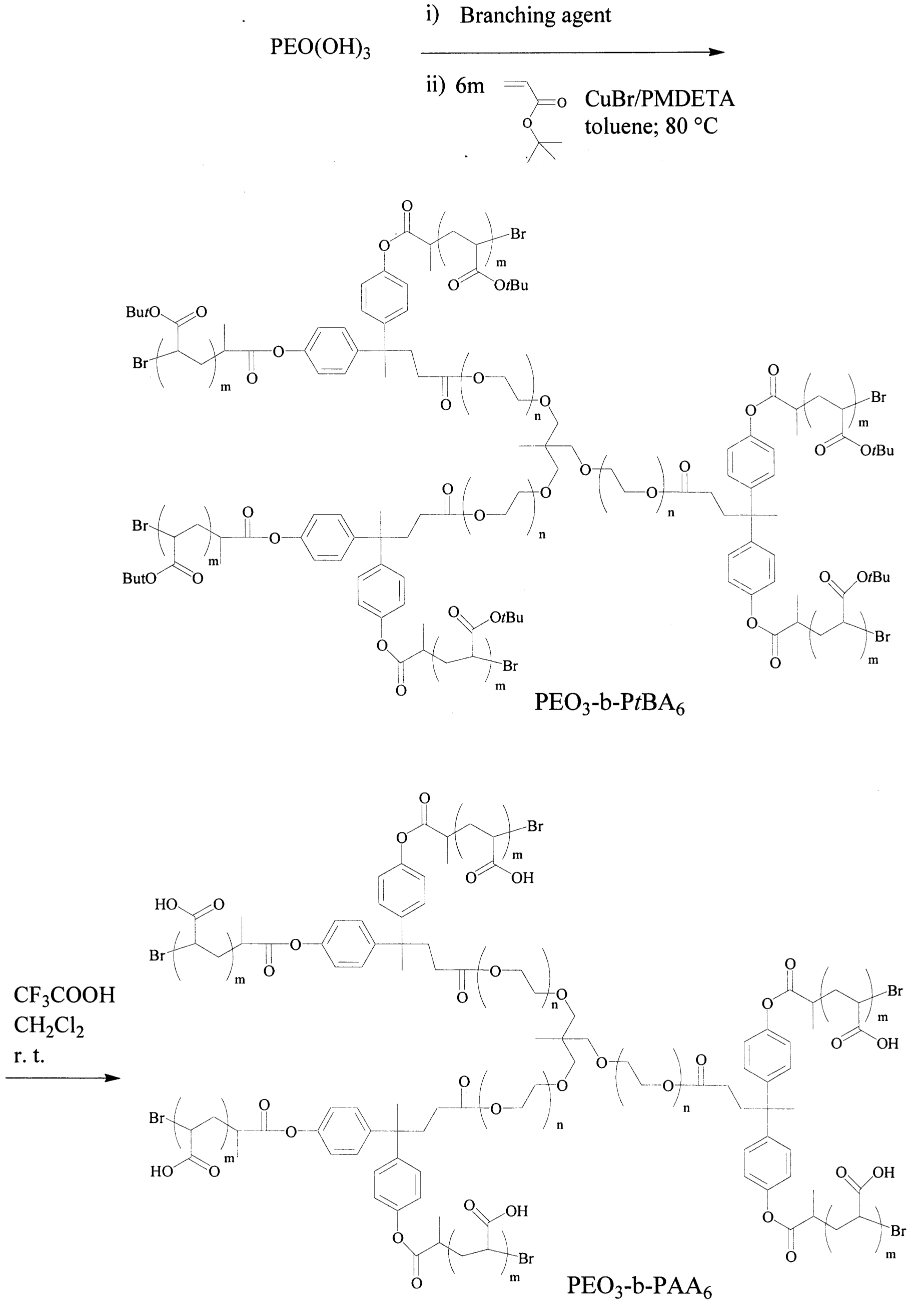
Figure 3A shows the ^{1}H NMR spectrum of a typical PEO_3-*b*-P*t*BA_3 star-block copolymer in $CDCl_3$; all the expected peaks were clearly detected. Using a good solvent for both blocks prevented the formation of micelles, and the relative content of PEO and P*t*BA could be estimated by NMR from the integration of the signals at 1−2.5 and 3.5 ppm due to the protons of the P*t*BA and the PEO blocks, respectively. As indicated in Table 1, experimental values agreed well with those expected for both PEO_3-*b*-P*t*BA_3 and PEO_3-*b*-P*t*BA_6 compounds.

To access the targeted branched DHBCs, hydrolysis of the P*t*BA blocks was ultimately accomplished. The chemical transformation of the *t*BA units into acrylic acid ones was performed by adding an excess of trifluoroacetic acid in dichloromethane and stirring the medium at room temperature for 24 h. The materials progressively precipitated out during the course of the reaction but could eventually be redissolved in aqueous media after they were dried under vacuum. The cleavage reaction was monitored by ^{1}H NMR. The ^{1}H NMR spectra (Figure 3B) showed a dramatic decrease of the signal at 1.5 ppm due to the removal of the *tert*-butyl protons of the P*t*BA blocks. The relative integration in the 2−1.5 ppm region is consistent with quantitative hydrolysis. Importantly, the *tert*-butyl groups removal was selective and did not affect the ester linkages between the two types of blocks. This was further supported by aqueous SEC characterization that did not reveal the presence of any free PEO fraction after hydrolysis (Figure 2b).

Starlike (PAA-*b*-PEO)$_f$ Block Copolymers by the Arm-First Route. To derive starlike DHBCs, noted (PAA-*b*-PEO)$_f$, composed of one ionizable PAA part as the inner layer and an outer neutral PEO-based layer, we resorted to an arm-first approach based on the use of a divinylic comonomer as a linking agent (“nodulus” method). Such a synthetic route to star polymers was developed with anionic polymerizations in the early 1960s[28−31] but was recently applied to C/LRP methodologies, including ATRP[32−37] or NMP.[38−43] The number of chains attached to the core depends on a number of experimental variables, including the molar ratio (*r*) of the divinylic compound to the preformed (co)polymer, the nature of the linking agent, the size of the precuror, the chemical nature of the solvent, and the concentration of the reaction mixture.[28−43] In contrast to stars synthesized by the core-first methodology, however, one cannot expect to obtain stars carrying a precise number of arms by this “nodulus” approach but at best to minimize the fluctuation of their functionality. On the other hand, there is only one example of synthesis of star-block copolymers utilizing the “nodulus” method by a C/LRP route: stars with hydrophobic methacrylic copolymeric branches were derived by ATRP in this way.[35] Here we describe the use of the “nodulus” method for the preparation of stars containing hydrophilic copolymeric arms. This was achieved according to the synthetic route shown in Scheme 4. Thus, linear amphiphilic PEO-*b*-P*t*BA block copolymers of various molar masses were first prepared by copper-mediated ATRP of *tert*-butyl acrylate, using ω-brominated PEO macroinitiators. The best results were obtained when carrying out the polymerization at 70 or 80 °C, using toluene as the solvent and CuBr/PMDETA as the catalytic system. Figure 4 shows the shift toward the higher molar mass area and a low polydispersity index in the SEC traces of different PEO-*b*-P*t*BA diblock copolymers, after ATRP of *t*BA from the ω-bromo PEO precursor. The characteristics of other PEO-*b*-P*t*BA diblock samples obtained from PEO precursors with various molar masses and following similar conditions are also presented in Table 2.

These linear diblock precursors were then reacted with divinylbenzene (DVB) as the linking agent, using anisole as the solvent and CuBr/PMDETA as the catalyst at 110 °C for various time periods following a reported procedure.[32] In the first series of experiments, the feed ratios (*r*) of DVB to the diblock copolymer were varied. Figure 5 shows that increasing this ratio led to

Scheme 3. Synthesis of PEO_3-*b*-PAA_6 Dendrimer-like Copolymers



a progressive disappearance of the SEC trace of the linear diblock precursor and a shift to the higher molar mass region. The major population had an apparent peak molar mass (M_p) of 49 000 by SEC, which is much higher than that of the linear diblock precursor (M_p = 8300 by SEC). This supported the formation of a star polymer consisting of diblock arms and a microgel core, as illustrated in Scheme 4. As shown in earlier reports,[28−43] small size stars were presumably produced in an initial stage which eventually underwent intermolecular couplings to generate stars of higher molar masses.

By comparing the area under the two SEC peaks, the yield of the star formation was estimated between 40 and 80% depending on the amount of DVB added. Explanations for residual linear precursor include incomplete addition of the divinylic comonomer onto the linear precursor, loss of ω-termini of the dormant species (halogens in the present work), or steric hindrance around the core.[32−43] In our case, monitoring the coupling reactions with time by SEC for a [DVB]/[PEO-*b*-P*t*BA] ratio of 10 (Figure 6) indicated no further evolution after 15 h of reaction.

As expected, it was observed that the higher the DVB concentration, the higher the apparent molar mass of the star which is consistent with the proposed mechanism shown in Scheme 4. Also, the molar mass of the PEO-*b*-P*t*BA precursor had a significant effect on the yield of the star formation, for a constant *r* value equal to 10. This is illustrated in Table 2; the higher the molar mass of the linear precursor, the lower the yield in the star formation.

Since the SEC technique usually underestimates molar masses of star polymers due to their compactness, absolute molar masses and thereby the number of branches could be estimated by using a multiangle laser light scattering (MALLS) detector coupled to the SEC line (MALLS/SEC), but not all the samples were char-

Table 1. Molecular Characteristics of PEO_3-*b*-P*t*BA_3 Star-Block and PEO_3-*b*-P*t*BA_6 Dendrimer-like Copolymers[a] and of PEO_3-*b*-PAA_3 and PEO_3-*b*-PAA_6 Samples Obtained after Selective Hydrolysis

	PEO/P*t*BA-based copolymers					PEO/PAA-based copolymers			
PEO precursor[b]	conv (%)	$M_{n,theo}$[c] (g mol^{-1})	$M_{n,SEC}$[d] (g mol^{-1})	PDI[d]	$M_{n,NMR}$[e] (g mol^{-1})	$M_{n,theo}$[f] (g mol^{-1})	$M_{n,SEC}$[g] (g mol^{-1})	PDI[g]	$M_{n,NMR}$[h] (g mol^{-1})
$PEO(Br)_3$	16	13 100	12 200	1.23	12 000	9 500	15 300	1.15	8 100
	31	30 000	22 200	1.29	27 500	18 000	25 600	1.13	21 500
$PEO(Br)_6$	17	13 100	12 100	1.15	12 500	10 200	7 700	1.26	10 400
	37	19 000	12 800	1.28	17 500	13 000	8 200	1.26	9 000

[a] ATRP of *t*BA was performed at 80 °C in toluene (concentration = 20 vol %) in the presence of CuBr/PMDETA as the catalyst, using either $PEO(Br)_3$ or $PEO(Br)_6$ as the macroinitiator: [Br]/CuBr/PMDETA = 1/1/2. [b] The molar mass of the three-arm $PEO(OH)_3$ precursor was M_n = 8600 g mol^{-1} by SEC with THF as the eluent (Figure 2A) and M_n = 5800 g mol^{-1} by SEC in the aqueous eluent (Figure 2B). [c] Theoretical molar mass: $M_{n,theo}$ = ([*t*BA]/[$PEO(Br)_{3\text{ or }6}$] × conv (%) × 128) + 5800), where 128 and 5800 are the molar mass of one *t*BA unit and that of the $PEO(OH)_3$ precursor, respectively. [d] Determined by SEC in THF (calibration with polystyrene standards). [e] Determined by ^{1}H NMR in $CDCl_3$ knowing the M_n of the PEO precursor (see text). [f] Estimation based on the removal of the *tert*-butyl groups in the PEO/P*t*BA-based samples. [g] Determined by SEC in the aqueous eluent (calibration with PEO standards). [h] Determined by ^{1}H NMR in D_2O knowing the M_n of the PEO precursor (see text).

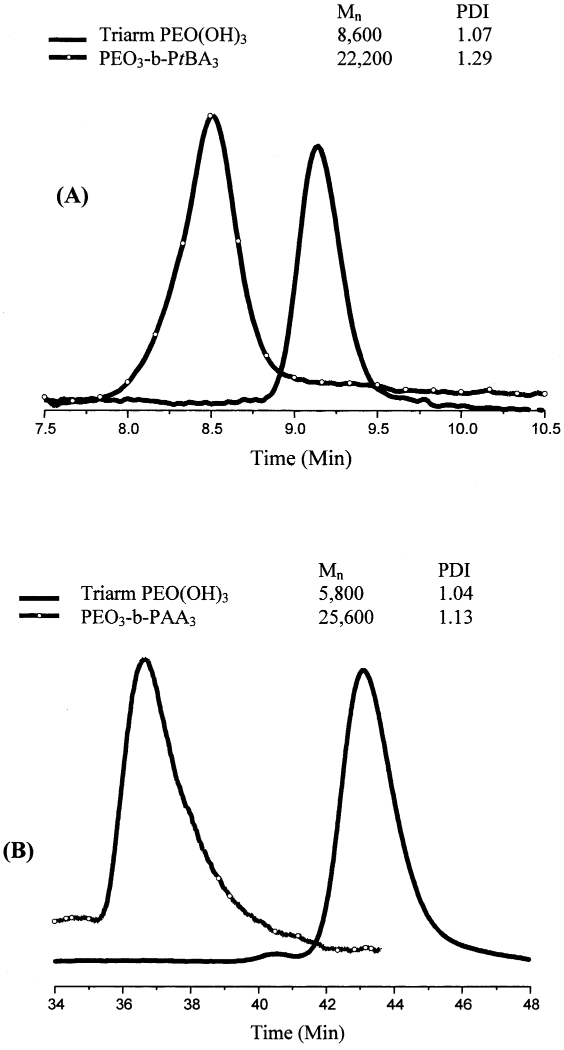


Figure 2. SEC traces (RI detector) of (A) a $PEO(OH)_3$ three-arm star precursor (right) and PEO_3-*b*-P*t*BA_3 star-block copolymer (left) in THF as eluent and (B) a three-arm $PEO(OH)_3$ star precursor (right) and PEO_3-*b*-PAA_3 star-block copolymer (left) in the aqueous eluent.

acterized by the latter technique. For this calculation, only the main peak of the SEC traces corresponding to the star was taken into account. We assumed in this case that the increment of refractive index (d*n*/d*c*) was a linear function of the star composition, which was deduced by NMR measurements (see Table 2). Table 2 shows that the M_w of the stars determined in this way were 3−9 times higher than the apparent M_W delivered by SEC, indicating that the hydrodynamic volume of our stars were dramatically smaller compared to the linear polystyrene standards of same molar mass that were used to calibrate the SEC device.

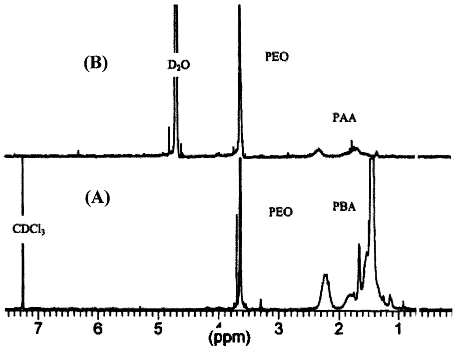


Figure 3. ^{1}H NMR spectrum (200 MHz) of (A) PEO_3-*b*-P*t*BA_3 star-block copolymer in $CDCl_3$ and (B) the resulting PEO_3-*b*-PAA_3 star-block copolymers in D_2O.

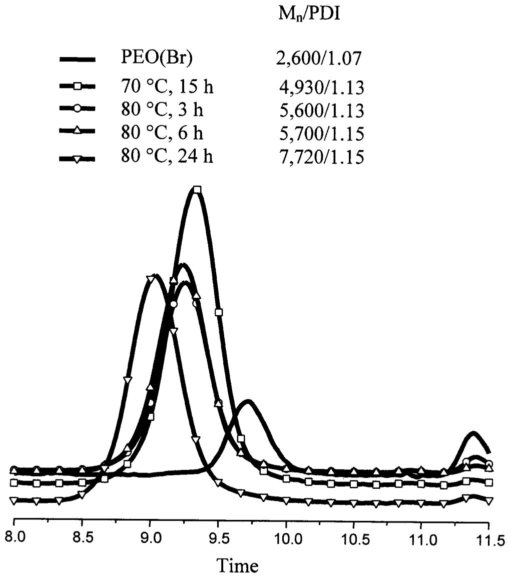
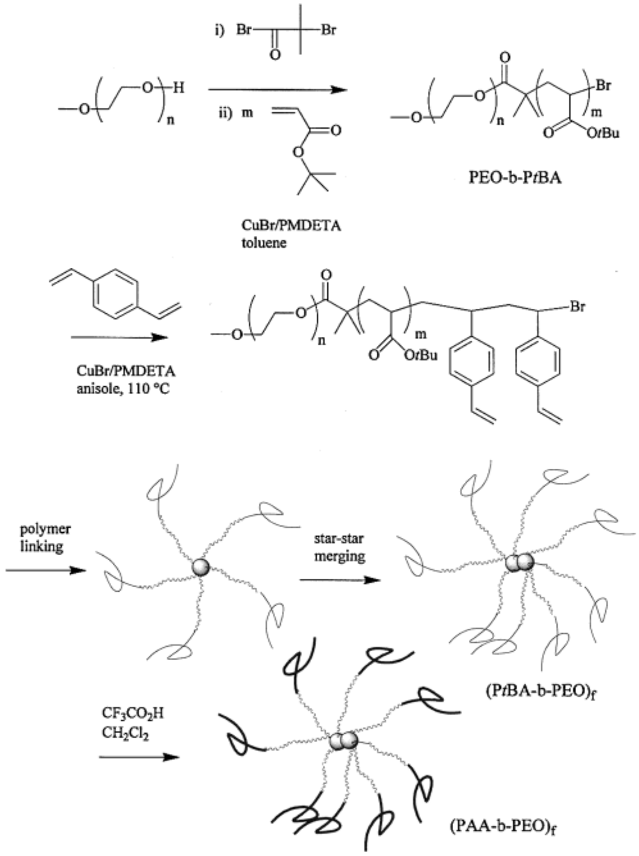


Figure 4. SEC traces (RI detector) of different PEO-*b*-P*t*BA diblock copolymers ($M_{n,theo}$ = 11 000 g mol^{-1} for 100% conversion of *t*BA) obtained by ATRP of *t*BA in toluene solution (concentration = 20 vol %) from a PEO(Br) precursor ($M_{n,SEC}$ = 2150 g mol^{-1}), using CuBr/PMDETA as the catalyst, evolution as a function of the temperature used and the reaction time. Conditions: *t*BA/PEO(Br)/PMDETA/CuBr: 68/1/2/1).

Scheme 4. Synthesis of (PEO-*b*-PAA)$_f$ Star-Block Copolymers by the Arm-First Method



In this series, the effect of the size of the diblock precursor on the number of branches (*f*) was also examined with the ratio *r* being constant at a value of 10. The longer the chain length of the precursor, the lower the *f* number. These results are consistent with those observed for stars obtained by ionic procedures[28−31] or by NMP.[41] This could be explained by a lesser steric hindrance of shorter arms whose access and reaction with the central core are certainly easier than for large precursors. Very recently, however, Sawamoto et al. observed the opposite trend (*f* decreased when the molar mass of the precursor decreased) in their ruthenium-catalyzed living radical polymerization.[37] This unexpected result was ascribed to a difference in the rates of coupling as a function of the size of the prepolymer; the longer the chain, the shorter the time to react with the linking agent and hence the greater the number of arms.

Finally, attempts to obtain (PEO-*b*-P*t*BA)$_f$ star-block copolymers using another divinylic linking agent, namely (butanediol)bis(acrylate) (BDA), was successfully conducted. In this case, the reaction was carried out at 85 °C in toluene in the presence of CuBr/PMDETA as the catalyst. The progress of the reaction is illustrated in Figure 7.

The final step in the synthesis of our (PEO-*b*-PAA)$_f$ was the selective hydrolysis of the P*t*BA blocks under the same experimental conditions as described above. Here again, the preservation of the star-block architecture of the resulting hydrophilic materials was confirmed by NMR and SEC analyses in water. In some cases, samples were purified by dialysis in order to eliminate residual linear PEO-*b*-PAA diblocks.

Conclusion

Novel water-soluble block copolymers based on PEO and PAA were covalently assembled in starlike and dendrimer-like architectures. Their synthesis was accomplished through the combination of anionic polymerization of ethylene oxide, derivatization of the PEO chain ends, copper-mediated ATRP of *tert*-butyl acrylate, and hydrolysis of the *tert*-butyl ester groups. Both core-first and arm-first approaches were applied to derive block copolymers exhibiting a branched architecture and carrying ionizable blocks either at the periphery or inside the structure. The aqueous solution properties of these systems (effect of pH and temperature on the micellar size) are currently under investigation and will be the scope of future disclosures.

Experimental Section

Materials. Ethylene oxide (Fluka, 98%) was transferred from its steel tank into a three-neck flask in which it was dried over sodium at −40 °C for 3 h before being distilled into a graduated buret. *tert*-Butyl acrylate (*t*BA) (Aldrich, 99%) was stored over CaH$_2$ and then vacuum-distilled before polymerization. Diphenylmethylpotassium (DPMK) and (*N*,*N*-dimethylamino)pyridine-*p*-toluenesulfonic acid (DPTS) were prepared according to refs 44 and 45, respectively. 1,1,1-Tris(hydroxymethyl)ethane (Aldrich, 99%) and α-methoxy-ω-hydroxy(poly(ethylene oxide)) (Aldrich, 99%) were purified by freeze-drying from a dioxane solution. Dimethyl sulfoxide (Aldrich, 98%) was purified by distillation over calcium hydride into a Schlenk apparatus just before use. Divinylbenzene (DVB, Aldrich, 80%) and (1,4-butanediol)bis(acrylate) (BDA) were distilled just before use. *N*,*N*,*N*,*N*,*N*-Pentamethyldiethylenetriamine (PMDETA), copper(I) bromide (CuBr), 2-bromoisobutyryl bromide, 2-bromopropionyl bromide, *N*,*N*-dicyclohexylcarbodiimide (DCC), 4,4′-bis(4-hydroxyphenyl)valeric acid, trifluoroacitic acid (TFA), triethylamine (TEA), toluene, tetrahydrofuran (THF), dichloromethane, dioxane, and anisole were used as received.

The triarm PEO stars PEO(OH)$_3$ and PEO(Br)$_3$ were prepared according to the procedure reported in a previous paper.[25]

Synthesis of the Branching Agent. In a 250 mL three-neck flask equipped with a magnetic stirrer, 4,4-bis(4-hydroxyphenyl)valeric acid (7.15 g, 25 mmol) was dissolved in freshly distilled THF (120 mL). TEA (8.4 mL, 60.2 mmol) and 2-bromoisobutyryl bromide (5.8 mL, 55.3 mmol) were added dropwise at room temperature through a cannula. After 48 h, the reaction mixture was filtered and the obtained solution was concentrated. Purification by column chromatography on silica gel using dichloromethane as eluent afforded a white solid compound (yield = 82%). ^{1}H NMR (δ_{ppm}, CDCl$_3$): 7.2 (aromatic, 4H, d), 7.05 (aromatic, 4H, d), 4.55 (CHBr, 2H, q), 2.4 (CH$_2$, 2H, m), 2.15 (CH$_2$, 2H, m), 1.9 (CH$_3$, 6H, d), 1.6 (CH$_3$, 3H, s)

Synthesis of the Three-Arm Star Macroinitiator PEO-(Br)$_6$. The three-arm PEO(OH)$_3$ (3.00 g, 0.53 mmol, M_n = 5600 g mol^{-1}), the branching agent (1.11 g, 2.13 mmol), and DPTS (91 mg, 0.31 mmol) were dissolved in dry dichloromethane (20 mL) at room temperature. Then DCC (660 mg, 3.2 mmol) was added dropwise under a constant flow of nitrogen upon stirring. After 72 h of reaction, the white solid was filtered out and the final product was recovered by precipitation in diethyl ether (yield = 68%). ^{1}H NMR (δ_{ppm}, CDCl$_3$): 7.15 (aromatic, 12H, d), 7.00 (aromatic,12H,d), 4.55 (CHBr, 6H, q), 3.7−3.4 (PEO, broad peak), 2.4 (CH$_2$, 6H, m), 2.1 (CH$_2$, 6H, m), 1.88 (CH$_3$, 18H, d), 1.55 (CH$_3$, 9H, s), 0.87 (CH3, 3H, s).

Synthesis of α-Methoxy-ω-bromoisobutyrate(poly(ethylene oxide)). In a three-neck flask equipped with a magnetic stirrer, the α-methoxy-ω-hydroxy-PEO (6.05 g, 8.07 mmol, M_n = 750 g mol^{-1}) was first dissolved in freshly distilled THF (115 mL) before TEA (2.4 mL, 17.2 mmol) and 2-bromoisobutryl

Table 2. Molecular Characteristics of (P*t*BA-*b*-PEO)$_f$ Starlike DHBCs Obtained from the Reaction between DVB and Linear PEO-*b*-P*t*BA Copolymers for $r = 10$[a]

PEO-*b*-P*t*BA diblock copolymers[b]				(PEO-*b*-P*t*BA)$_f$ star-block copolymers			
M_{PEO}[c]	$M_{\mathrm{n,SEC}}$[d] ($M_{\mathrm{n,theo}}$; conv)[e]	PDI[d]	$M_{\mathrm{n,NMR}}$[f]	$M_{\mathrm{w,SEC}}$[g]	PDI[g]	$M_{\mathrm{w,LS}}$[h]	f[i]
350	1850 (3700; 80%)	1.27	3460	40 200	1.55	388 400	82
750	4350 (5100; 83%)	1.15	4960	57 100	1.32	494 500	80
2000	6400 (7900; 78%)	1.13	8070	52 300	1.26	161 000	16
5000	16700 (23500; 47%)	1.26	22900	67 500	1.93	140 500	5

[a] The coupling reaction was carried out at 110 °C in anisole in the presence of CuBr (1 equiv relative to the concentration of the bromo end groups) and PMDETA (2 equiv). [b] These were synthesized using different α-methoxy-ω-hydroxy PEO precursors that were first brominated and subsequently used as macroinitiators for ATRP of *t*BA ($t = 24$ h) following a similar procedure to that described in Figure 4. [c] Molar mass of the α-methoxy-ω-hydroxy PEO precursor (commercial reagent). [d] Number-average molar mass of PEO-*b*-P*t*BA determined by SEC in THF with PS standards. [e] Theoretical molar mass: $M_{\mathrm{n,theo}} = ([t\mathrm{BA}]/[\mathrm{PEO(Br)}] \times \mathrm{conv}\ (\%) \times 128) + M_{\mathrm{PEO}})$, where 128 is the molar mass of one *t*BA unit and conv (%) is the conversion of *t*BA. [f] Number-average molar mass and polydispersity index of PEO-*b*-P*t*BA diblock copolymers determined by NMR in $CDCl_3$ (knowing the molar mass of the PEO precursor). [g] Mass average molar mass determined by SEC in THF (calibration with PS standards). [h] Mass average molar mass of (P*t*BA-*b*-PEO)$_f$ determined by MALLS/SEC (see text). [i] Number of copolymer arms in (P*t*BA-*b*-PEO)$_f$; $f = M_{\mathrm{w,LS}}{}^{\mathrm{e}}/M_{\mathrm{w,SEC}}{}^{\mathrm{b}}$.

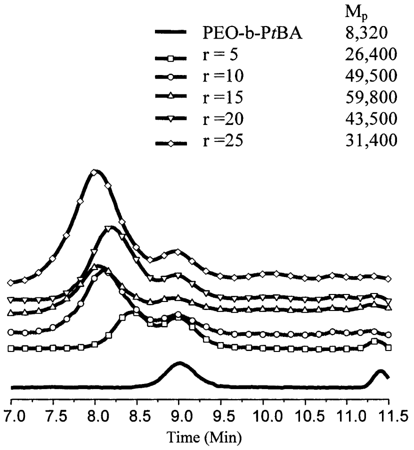


Figure 5. SEC traces (RI detector) of (P*t*BA-*b*-PEO)$_f$ star-block copolymers obtained by the "arm-first" approach at different r = [DVB]/[PEO-*b*-P*t*BA] values; $T = 110$ °C and reaction time = 15 h.

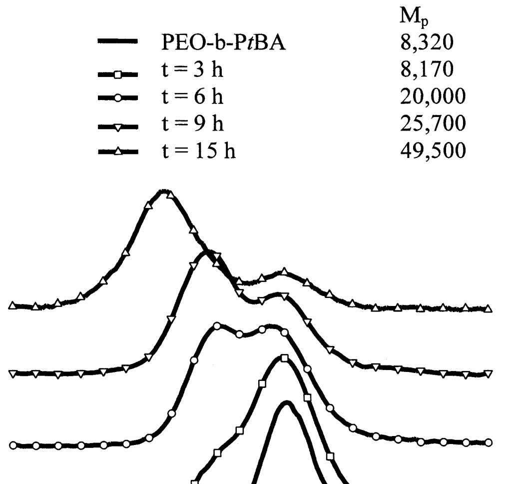


Figure 6. SEC traces (RI detector) of (P*t*BA-*b*-PEO)$_f$ star-block copolymers obtained by the coupling reaction between a PEO-*b*-P*t*BA diblock copolymer and DVB as the linking agent ($r = 10$), at different reaction times at $T = 110$ °C.

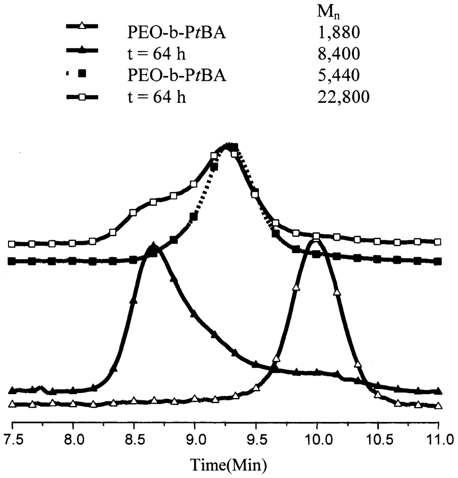


Figure 7. SEC traces (RI detector) of (P*t*BA-*b*-PEO)$_f$ star-block copolymers obtained by the coupling reaction between two different PEO-*b*-P*t*BA diblock copolymers and BDA as the linking agent, at different reaction times. In both cases the following experimental conditions were used: [BDA]/[PEO-*b*-P*t*BA]/PMDETA/CuBr: 10/1/2.0 /1.0; $T = 85$ °C and reaction time = 64 h.

bromide (2.0 mL, 16.2 mmol) were added dropwise at room temperature. After 48 h of reaction, the obtained suspension was filtered and the filtrate was concentrated. The final product was recovered by precipitation in a large excess of diethyl ether and dried under vacuum. ^{1}H NMR (δ_{ppm}, $CDCl_3$): 4.3 (CH_2O, 2H, m), 3.7−3.6 (PEO, broad peak), 3.37 (CH_3O, 3H, s), 1.93 ($(CH_3)_2CBr$, 6H, s).

Synthesis of PEO-*b*-P*t*BA Diblock Copolymer by ATRP. In a typical polymerization, a Schlenk flask was charged with α-methoxy-ω-bromoisobutyrate-PEO (500 mg, 2.33×10^{-4} mol, $M = 2150$ g mol^{-1}), *tert*-butyl acrylate (2.3 mL, 1.57×10^{-2} mol), PMDETA (97 μL, 4.65×10^{-4} mol), and distilled toluene (8 mL). After degassing, CuBr (33 mg, 2.32×10^{-4} mol) was added under nitrogen. The reaction mixture was evacuated with three freeze−thaw cycles and heated at 80 °C for 6 h. The polymerization was quenched by simply exposing the reaction mixture to the air after a given reaction time and then filtered through neutral alumina to remove the catalyst using either THF or dichloromethane as the eluent. The final copolymer was dried under vacuum at 30 °C, and the conversion was determined by gravity (conversion = 67%). Characterization by SEC gave $M_n = 6400$ g mol^{-1}, and characterization by ^{1}H NMR allowed to determine the overall composition ($M_n = 8070$ g mol^{-1}). The data pertaining to these compounds are given in Figure 4 and Table 2.

Synthesis of the PEO$_3$-*b*-P*t*BA$_3$ Star-Block Copolymers by ATRP. In a typical polymerization, a Schlenk flask was charged with the three-arm star macroinitiator, PEO(Br)$_3$ (0.2 g, 3.44×10^{-5} mol, $M_n = 5800$ g mol^{-1}), *tert*-butyl acrylate (2.4 mL, 1.64×10^{-2} mol), PMDETA (44 μL, 2.06×10^{-4} mol), and distilled toluene (8 mL) and CuBr (15 mg, 1.03×10^{-4} mol) under nitrogen. After workup (conversion = 16%), this afforded a sample with $M_n = 12\,200$ g mol^{-1} by SEC and $M_n = 12\,500$

g mol^{-1} by ^{1}H NMR (see also Table 1). The **PEO$_3$-*b*-P*t*BA$_6$ dendrimer-like copolymers** were synthesized following a similar procedure, except that the three-arm star macroinitiator, PEO(Br)$_6$, was used in this case.

Synthesis of the Arm-First Star-Block Copolymers (PEO-*b*-P*t*BA)$_f$. In a Schlenk flask, PEO-*b*-P*t*BA diblock copolymer (112 mg, 0.06 mmol Br), divinylbenzene (85 μL, 0.6 mmol), and PMDETA (15 μL, 0.072 mmol) were dissolved in anisole (2 mL). The solution was degassed three times before adding CuBr (5 mg, 0.035 mmol) under nitrogen. The flask was immersed in an oil bath preheated at 110 °C for a given reaction time. The final compounds were recovered using the same protocol described above for ATRP experiments. A similar procedure was implemented when BDA was used as the linking agent (see Figure 7).

Hydrolysis of PEO-*b*-P*t*BA Copolymers. Into a dichloromethane solution of the diblock compound (300 mg), trifluoroacetic acid (0.9 mL, 11.7 mmol) was slowly added at 0 °C with vigorous stirring. The reaction was kept at 0 °C for 3 h and then overnight at room temperature. The reaction mixture was carefully evacuated and then redissolved in dioxane for purification by freeze-drying. The NMR characterization before and after hydrolysis is illustrated in Figure 3.

Characterization. ^{1}H NMR spectra were obtained using a Bruker AC 200 NMR spectrometer. CDCl$_3$ was used as the solvent. In the case of poly(ethylene oxide)/poly(acrylic acid) copolymers, DMSO-d_6 was used. The polymer molar masses were determined using size exclusion chromatography (SEC) with tetrahydrofuran as eluent (1 mL/min) at 25 C. This apparatus was equipped with a refractive index detector (Varian RI-4) and a PSS column (8 × 300 mm, 5 μm) provided by PSS. Molar masses were determined from a calibration curve based on linear polystyrene standards. The actual molar masses of the star-block copolymers were calculated from the response of a multiangle laser light scattering detector (Wyatt Technology) that was connected to a SEC (MALLS/SEC) line with a laser source (633 nm). The d*n*/d*c* values of the star-block samples were assumed to vary linearly with the composition which was deduced by NMR measurements in THF at 25 °C.

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