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Micellization of Poly(2-(dimethylamino)ethyl methacrylate-*block*-methyl methacrylate) Copolymers in Aqueous Solution

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ABSTRACT: A range of water-soluble hydrophilic−hydrophobic diblock copolymers of 2-(dimethylamino)-ethyl methacrylate and methyl methacrylate were shown to form micelles if first dissolved in a nonselective solvent (THF or methanol) and subsequently diluted with water. Critical micelle concentrations were found to increase with the length of the hydrophobic block if the the hydrophilic block length is fixed. Increasing the overall molar mass of the copolymer also increased the cmc for a given composition. The hydrodynamic diameters and approximate association numbers of these micelles were obtained by dynamic light scattering and analytical ultracentrifugation. Micellar diameters and association numbers were in the range 10−18 nm and 10−33 chains per micelle, respectively, depending on copolymer composition. Increasing the overall molar mass of the copolymer for a given composition produces larger micelles with lower association number. Both micelle size and association number decrease with the length of the hydrophobic block if the hydrophilic block length is fixed. The results suggest that the solubility of the hydrophilic block is at least as important as that of the hydrophobic block, although nonequilibrium effects cannot be excluded. Both the size and the association number of the micelles can be varied in predictable ways by changing the temperature, the pH, or the ionic strength of the solution.

Introduction

When an AB diblock copolymer, or an ABA triblock copolymer, is in a selective solvent, defined as a good solvent for the A block but a nonsolvent for the B block, the copolymer molecules may associate to form micelles.[1,2] Most early studies of copolymer micelles were of styrene−diene or styrene−acrylate copolymers in organic media.[2,3] Reports of the micellization of hydrophilic−hydrophobic block copolymers in water have only appeared in recent years. These latter systems have properties that may prove useful for various technological applications, such as steric stabilization of latex particles[4] and pigment dispersion in printing technologies. Recently, aqueous micelles have been examined for use as drug carriers. For example, Yokoyama et al. synthesized block copolymers of biodegradable poly-(aspartic acid) with poly(ethylene glycol).[5] These were shown to be effective carriers for the anticancer drug doxorubicin.[6] The drug−copolymer conjugate showed reduced toxicity and superior activity against solid tumors *in vivo* compared to the free drug.

Various parameters can be examined in the study of micelles, including micelle size, mass, association number (*i.e* the number of copolymer chains per micelle), and critical micelle concentration (cmc). The effects of overall copolymer chain length, copolymer composition, copolymer architecture, and temperature have been studied for both nonaqueous[7−9] and aqueous micelles.[10−12] Some of the most extensively investigated aqueous systems include copolymers of ethylene oxide/butylene oxide,[13−15] ethylene oxide/propylene oxide,[16−24] ethylene oxide/styrene,[25−27] quaternized 4-vinyl pyridine/styrene,[10,28−32] and methacrylic acid/styrene.[33−41] Booth et al. investigated the micellization and surface properties of both ethylene oxide/butylene oxide[13−15] and ethylene oxide/propylene oxide[17,18] block copolymers. In the former, increasing the copolymer molar mass led to a marked decrease in the critical micelle concentration and increases in both micelle mass and size. Micellization of both the di- and triblocks was studied over the temperature range from 20 to 50 °C. The micelle masses increased with increasing temperature, while their dimensions remained roughly constant. Similar results were obtained, by these and other authors, for ethylene oxide/propylene oxide block copolymers.[16,18] Winnik et al.[25] studied micelles formed by poly(styrene-*block*-ethylene oxide) copolymers in water. Dynamic light scattering indicated secondary association of the micelles to form aggregates of 20−30 micelles. Increasing the overall chain length and the poly(ethylene oxide) content of the copolymers resulted in larger micelles. The relative proportions of micellar aggregates and individual micelles depended on the experimental conditions, such that neither the micelle mass nor the association number could be determined.

The behavior of quaternized poly(styrene-*block*-4-vinyl pyridine)s (PS-*b*-PQVP) in water has been investigated extensively by Selb and Gallot.[10,28−31] Both di- and triblock copolymers containing 70−96 wt % quaternized PQVP were studied, with copolymer molar masses ranging from 12 700 to 318 000 g mol^{-1}. Light-scattering and ultracentrifugation measurements in aqueous electrolyte solutions indicated micellar aggregates, resulting from incomplete dissolution of the copolymers.[28] Micellization of the copolymers was studied in a methanol/water/salt solution.[29] It was found that micellization occurred if the copolymers were first molecularly dissolved in methanol and then aqueous electrolyte added. When the water content of the solvent was increased, the degree of association passed through a maximum. The effects of salt and tempera-

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Table 1. Characteristics of the Block Copolymers Studied

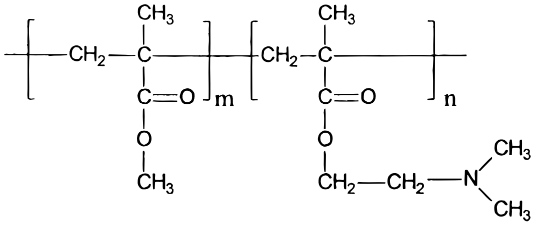
sample	theoretical DMAEMA content, mol %	observed DMAEMA,[a] mol %	theoretical M_n of block copolymer (g mol^{-1})	observed M_n of block copolymer,[b] g mol^{-1}	observed M_w of block copolymer,[b] g mol^{-1}	M_w/M_n[b]
FB068	83.5	84	9 500	12 800	14 300	1.12
FB052	79	79	9 900	11 100	12 500	1.13
FB054	70	68	10 850	15 000	16 500	1.10
FB035	83.5	85	19 000	23 800	26 200	1.10
FB070	79	80	19 900	19 600	22 300	1.14
FB055	70	67	21 700	24 300	26 700	1.10

[a] As determined by ^{1}H NMR spectroscopy. [b] As determined by GPC (reported as PMMA equivalents).

ture were also studied.[30] In the case of copolymers with a low molar mass polystyrene block (M_w = 2700 g mol^{-1}), the unimer/micelle equilibrium was easily shifted toward unimers by increasing the temperature or decreasing the ionic strength. If the polystyrene block was longer (M_w = 6000−13 000 g mol^{-1}) the micelle mass was little influenced by either factor. The influence of the molecular characteristics of the PS-*b*-PQVP block copolymers on their dilute solution properties was investigated[31] in water/methanol/LiBr, a selective solvent for the polyelectrolyte component. It was found that the degree of association depended much more upon the length of the insoluble hydrophobic part than on the length of the soluble hydrophilic part. More recently, Eisenberg et al. have investigated PS-*b*-PQVP copolymers which contain long polystyrene blocks and short poly(4-vinylpyridinium methyl iodide) blocks.[32] These copolymers form so-called "crew-cut" micelles in water, with the short soluble PQVP blocks forming the corona. Their preparation was difficult, since such copolymers are not easily dissolved in nonsolvents for the longer block.

Munk et al. have investigated poly(methacrylic acid-*block*-styrene) copolymers, which form micelles with polystyrene cores in water.[12,33−41] These copolymers do not directly dissolve in water but form micelles when dissolved in dioxane-rich water/dioxane mixtures. These micelles can be transferred into water-rich mixtures, water, or aqueous buffers by stepwise dialysis. Experiments to determine the micelle size, association number, and critical micelle concentration, in a mixed solvent containing 80/20 v/v dioxane/water, were carried out using static and dynamic light scattering, viscometry, and sedimentation.[41] Good agreement was obtained between micelle masses measured by static light scattering, the Svedberg method based on analytical centrifugation, and a combination of diffusion coefficient and limiting viscosity number. Association numbers were generally higher for diblocks compared to triblock copolymers for a given molar mass and copolymer composition. Larger association numbers were obtained for both types of copolymer as the hydrophobic content was increased. Tuzar et al.[37] examined the effect of solvent composition on the hydrodynamic size of poly(methacrylic acid-*block*-styrene) micelles. It was found that the hydrodynamic size increased with increasing dioxane content, apparently due to swelling of the polystyrene cores. In the absence of dioxane, the hydrodynamic size depends on the corona swelling only, since the polystyrene core is in its glass state. As the pH was increased from 5 to 7.8, the diameters of micelles formed by one copolymer increased from 54 to 72 nm as the poly(methacrylic acid) corona became more ionized and therefore better solvated.

In a program of studies of near-monodisperse, water-soluble block copolymers, we have recently prepared a range of hydrophilic−hydrophobic block copolymers (**I**) with poly(2-(dimethylamino)ethyl methacrylate) (PDMAEMA) as the major, hydrophilic component and poly(methyl methacrylate) (PMMA) as the minor, hydrophobic component.[42] Preliminary studies indicated that these block copolymers form micelles in water, with a PMMA core and a solvated PDMAEMA corona. In this paper we report more detailed studies of the micellization of these copolymers.



I

Experimental Section

Copolymer Synthesis. A series of diblock copolymers of 2-(dimethylamino)ethyl methacrylate and methyl methacrylate (PDMAEMA-*b*-PMMA) was prepared by sequential monomer addition (DMAEMA first) *via* group transfer polymerization (GTP) as described previously.[42] Control over the copolymer molar mass was achieved by varying the monomer/initiator ratio. The molar masses and polydispersities were determined by gel permeation chromatography (GPC) using PMMA standards in THF. The copolymer compositions were determined using ^{1}H NMR spectroscopy and agreed well with those expected from the comonomer feed. The characteristics of the two series of copolymers chosen for the present work are shown in Table 1. In the first series, the length of the DMAEMA chain was held nominally constant at 70 units while the PMMA chain was varied from 14 to 40 units. In the second, both sets of numbers were increased, so that the DMAEMA chain was nominally held at 130 units while the PMMA chain was varied from 24 to 60 units.

Static Light Scattering. Static light scattering (SLS) studies on one of the copolymers, FB054, in methanol were carried out at IMC (Prague, Czech Republic) using a Sofica instrument equipped with a He−Ne laser. The refractive index increment, d*n*/d*c*, was determined using a Brice-Phoenix differential refractometer. Five dilute solutions were used (highest concentration was 0.4 w/v %) and extraneous dust was removed by centrifugation. The M_w of this copolymer was computed using Zimm analysis. No disymmetry was observed and there was no evidence for either micelles or larger aggregates.

SLS studies on the copolymer micelles were carried out at Sussex using a Malvern PCS 4700 spectrometer, equipped with a 40 mW He−Ne laser operating at λ_0 = 633 nm. All experiments were carried out at 24 °C, using the angle range 50°−130°. Zimm analysis was used to fit the data. The d*n*/d*c* value of one of the block copolymer samples (FB054) was calculated using the Gladstone−Dale rule:[43]

$$\frac{dn}{dc_2} = \nu_2(n_2 - n_1)$$

where ν_2 is the specific volume of the polymer solution and n_1

and n_2 are the refractive indices of the pure solvent and the copolymer, respectively. The refractive index n_2 of this copolymer (cast as a film from diethyl ether) was measured by interferometry, using a He–Ne laser operating at 633 nm.[44] The calculated dn/dc value for FB054 was 0.137 mL g^{-1}. The dn/dc of the same block copolymer was also measured directly at the same wavelength using a Brice-Phoenix differential refractometer, giving a value of 0.146 mL g^{-1} in a 5/95 w/w mixture of methanol and water. All solutions were filtered through either 0.45 or 0.20 μm filters prior to light-scattering measurements.

Dynamic Light Scattering. DLS measurements were made on 1.0 w/v % copolymer solutions at a fixed scattering angle of 90°, using the Malvern PCS 4700 spectrometer described above. Experiments were carried out at 24 °C unless otherwise stated. Monomodal cumulants analysis was used to fit the data. The effects of solvent composition and temperature on micelle size were studied at the IMC using a homodyne spectrometer. The temperature of the copolymer solutions was controlled with an accuracy of ±0.05 °C. The incident light was the 514.5 nm line of a Carl Zeiss, Jena, argon laser ILA 120-1. Light scattered at 90° was detected using a photomultiplier (RCA C31034) and a Spex PC-1 photon counter. The signal was analyzed using a 96-channel digital correlator, and REPES analysis was used to fit the data.[45] Viscosity data for methanol/water mixtures at various temperatures were obtained from the literature.[46-48]

Analytical Ultracentrifugation. Sedimentation coefficients were determined using a Beckman Model E ultracentrifuge operating at 52 000 rpm with Schlieren optics. Photographic images were taken at 8 min intervals; typically fifteen images were taken for each run. All experiments were carried out at 24 °C and at a copolymer concentration of 1.0 w/v %. In order to calculate the molar mass of a solute from sedimentation velocity analysis, the diffusion coefficient and the specific volume of the solute and the density of the solvent are required. In these experiments the diffusion coefficients of the micelles were determined by dynamic light scattering using the Malvern 4700 instrument (see above). The specific volume of the micelles and the density of the solvent were determined using an Anton Paar DMA60 densitometer, calibrated using both air and water. Data were obtained at a single concentration and so an apparent micelle mass was calculated. To obtain more accurate values both the sedimentation coefficient and diffusion coefficient should be determined at several concentrations and the data then extrapolated to infinite dilution. However, by dividing the apparent micelle mass (determined using the Svedberg equation) by the weight-average molar mass of the copolymer (obtained by GPC), it is possible to estimate the micelle association number.

Surface Tension. The surface tension (γ) measurements were carried out using a White Electrical Instrument Co. torsion balance and platinum ring. All measurements were carried out at 20.5 ± 0.5 °C. Measurement accuracy was verified by frequent determination of the surface tension of doubly distilled deionized water (72–73 mN m^{-1}).

Results

Dynamic Light Scattering. DLS measurements were used to estimate the hydrodynamic diameters of the micelles in aqueous solution. The samples were prepared by two methods. In the first, the copolymer was dispersed directly in water. In the second, the copolymer was first dissolved in a nonselective cosolvent (THF or methanol) and the solution diluted with water. The micelle diameters were independent of the method of preparation only for the lowest molar mass copolymers containing less than 30 mol % PMMA. For all other copolymers, direct dissolution in water invariably gave larger hydrodynamic diameters than if the copolymer was first dissolved in a cosolvent and subsequently diluted with water. For example, the hydrodynamic diameters measured for copolymer FB054 in various media are shown in Table 2. When the copolymer was dissolved into water its hydrodynamic diameter was 20 nm; when it was first dissolved in methanol and subsequently diluted with water, its diameter was only 10.5 nm. The method of preparation of the copolymer in 4/96 w/w methanol/water mixtures was also important. If the solvents were mixed before addition of the copolymer, a larger hydrodynamic diameter of 18.5 nm, similar to that in pure water, was observed. This result confirms the importance of molecularly dissolving the copolymer prior to the addition of the selective solvent (water). These observations have been verified independently in dynamic light scattering studies carried out at IMC. For all subsequent measurements the micelles were prepared by first molecularly dissolving the copolymer in a cosolvent (methanol or THF) and then diluting with water.

Table 2. Effect of Solvent on Hydrodynamic Diameter of Micelles Formed from Sample FB054

solvent	hydrodynamic diameter[a] (nm)	association number
water	20	45
methanol[b]	4.4	1
4/96 v/v methanol/water[c]	18.5	
4/96 v/v methanol/water[d]	10.5	13

[a] As determined by dynamic light scattering. [b] Measured at the Institute of Macromolecular Chemistry, Prague, Czech Republic. [c] Solvents mixed prior to addition of copolymer. [d] Copolymer dissolved in methanol and subsequently diluted with water.

Table 3. Hydrodynamic Diameters of Micelles As Measured by Dynamic Light Scattering

sample	observed DMAEMA,[a] mol %	M_w of block copolymer,[b] g mol^{-1}	hydrodynamic diameter, nm	
			4/96 MeOH/ water,[c]	4/96 THF/ water[c]
FB068	84	14 300	15.5	14.8
FB052	79	12 500	13.5	13.3
FB054	68	16 500	10.5	10.0
FB035	85	26 200	17.2	16.5
FB070	80	22 300	14.6	14.5
FB055	67	26 700	12.0	11.5

[a] As determined by ^{1}H NMR spectroscopy. [b] As determined by GPC (reported as PMMA equivalents). [c] As determined by dynamic light scattering in 4 vol % cosolvent (MeOH or THF)/96 vol. % water.

The DLS results for all of the copolymers are shown in Table 3. The micelle diameters measured in methanol/water and THF/water mixtures were in good agreement. The micelle diameter decreases as the length of the hydrophobic PMMA block increases at constant PDMAEMA chain length. This trend is seen for both series of copolymers. The micelle diameters are much less affected by the overall chain length of the copolymer at constant composition. For the two copolymers containing approximately 84 mol % DMAEMA, doubling the overall molar mass results in only a small increase in the hydrodynamic diameter from around 15 to 17 nm, whereas doubling the hydrophobic block content from 15 to 30 mol % resulted in a 30% decrease in diameter. SLS could not be used to verify these measurements since no disymmetry was observed in the angular dependence of the scattered light.

Surface Tension. Figure 1 shows a typical surface tension versus concentration plot, for sample FB052. The data show a clear break point at around 0.05 wt %. Although this break point is less clearly defined than that for a small molecule surfactant, it can be estimated with reasonable precision and associated with the critical micelle concentration for the copolymer. Table 4 shows the cmc's estimated from surface tension data.

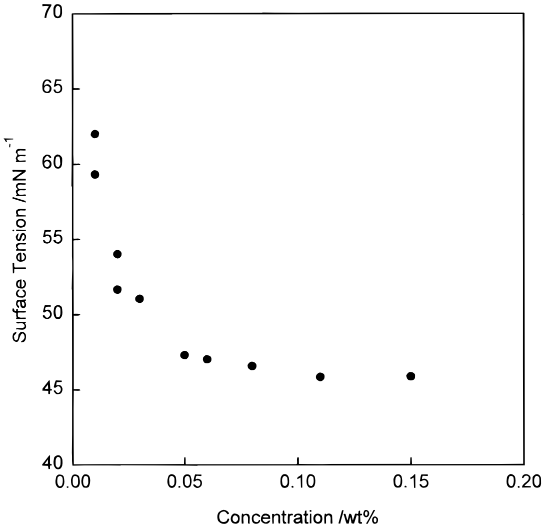


Figure 1. Typical surface tension dependence on concentration for FB052 in 4/96 w/w water/methanol.

Table 4. Critical Micelle Concentrations of All Copolymers Studied

sample	observed DMAEMA,[a] mol %	M_w of block copolymer,[b] g mol^{-1}	cmc,[c] w/v %
FB068	84	14 300	0.029
FB052	79	12 500	0.049
FB054	68	16 500	0.112
FB035	85	26 200	0.111
FB070	80	22 300	0.148
FB055	67	26 700	0.218

[a] As determined by ^{1}H NMR spectroscopy. [b] As determined by GPC (reported as PMMA equivalents). [c] As determined by surface tension measurements.

They clearly increase as either the overall chain length or the length of the hydrophobic group is increased. A fuller discussion of the surface adsorption properties of these copolymers as studied by neutron and X-ray reflection is presented elsewhere.[49]

Analytical Ultracentrifugation. The effect of different solvents on the micellization of one copolymer was investigated using analytical ultracentrifugation. Figure 2 shows the results for copolymer FB054 in different solvents: methanol, water, and 4/96 w/w methanol/water. In methanol one slow-moving boundary ($s = 2.5$ s) can be observed, which indicates molecularly dissolved block copolymer. In water a fast-moving species ($s = 9.9$ s) is observed, which corresponds to micellar aggregates. In contrast, only a slower moving boundary ($s = 5.8$ s) corresponding to micelles was detected in the methanol/water mixture; no unimer boundary was observed. The molar masses of the aggregates in water and of the micelles in methanol/water were estimated to be 754 000 and 216 000 g mol^{-1}, respectively, using the Svedberg equation. As can be seen from Table 5, the block copolymers formed micelles consisting of 9–23 chains per micelle. In these sedimentation experiments a slow-moving boundary, presumably corresponding to unimers, was also observed for all copolymers except FB054 and FB055, which contain the highest proportion of hydrophobic PMMA. There is a clear trend of decreasing association number with increasing hydrophobic PMMA content within both copolymer series.

The effect of ionization of the DMAEMA block was studied. One copolymer (FB054) was dissolved at pH 2 in 4/96 w/w methanol/dilute HCl and its sedimentation rate measured at various KCl concentrations. At this pH the water-soluble DMAEMA component should be completely ionized. In 0.01 M KCl one slow-moving boundary was observed, which probably corresponds to molecularly dissolved unimers ($s = 1.5$ s) (see Figure 3a). However, in 1.0 M KCl a faster moving boundary (see Figure 3b) corresponding to micelles was observed ($s = 5.0$ s).

Static Light Scattering. The molar mass of one of the PDMAEMA-*b*-PMMA block copolymers (FB054) dissolved in methanol was assessed by SLS. The d*n*/d*c* of this copolymer in methanol was 0.161 cm^3 g^{-1} and its weight-average molar mass was found to be 16 300 g mol^{-1}. This value is in good agreement with that obtained by GPC ($M_w = 16\ 500$ g mol^{-1}) using PMMA standards. Thus, this copolymer is molecularly dissolved in methanol, which acts as a good solvent for both blocks. Methanol was preferred to THF as the cosolvent for the micelle measurements since it is almost isorefractive with water. The refractive index increment of copolymer FB054 was measured directly, giving a value of 0.146 mL g^{-1} in 5/95 w/w methanol/water. This value is expected to be very close to that for copolymer FB055, which has approximately the same DMAEMA content. The third copolymer investigated was FB052, which contains a slightly higher proportion of DMAEMA. This relatively small compositional difference was assumed to have a negligible effect on the value of d*n*/d*c*. In addition, the refractive index increment for copolymer FB054 was calculated using the Gladstone–Dale rule, giving a value of 0.137 mL g^{-1}. This value was also used for the other two copolymers, FB055 and FB052. Micelle masses calculated using these two d*n*/d*c* values are presented in Table 6. Reasonably good agreement was found between the association numbers determined from ultracentrifugation and static light scattering.

Discussion

Micellization Equilibrium. One question which arises in any discussion of the nature of copolymer micelles is whether they are equilibrium structures or their structure is determined by the method of preparation. This is a particular concern when the hydrophobic block is a glassy polymer, as with PS or PMMA.

Both DLS and ultracentrifugation experiments (see Table 2 and Figure 3) show that our copolymers form much larger aggregates when they are dissolved directly into water than if they are first molecularly dissolved in methanol and subsequently diluted with water. Thus the method of preparation affects micelle formation; these copolymers apparently form nonequilibrium structures when dissolved directly into water.

Similar behavior has been observed by other workers for PS-*b*-PQVP copolymers in aqueous solution.[28,32] Stejskal et al.[8] attributed it to microphase separation of their copolymers in the solid state. When selective solvents are used for the dissolution of such copolymers, their solid-state morphology may be partly preserved in solution because the solvent (in our case water) is unable to dissolve the phase-separated glassy polymer (in our case PMMA). Dissolution will give a range of nonequilibrium structures, the size and shape of which depend on the original solid-state morphology. A similar influence of solid-state morphology probably accounts for the differences in micelle diameter observed for the water and methanol/water mixtures in our case.

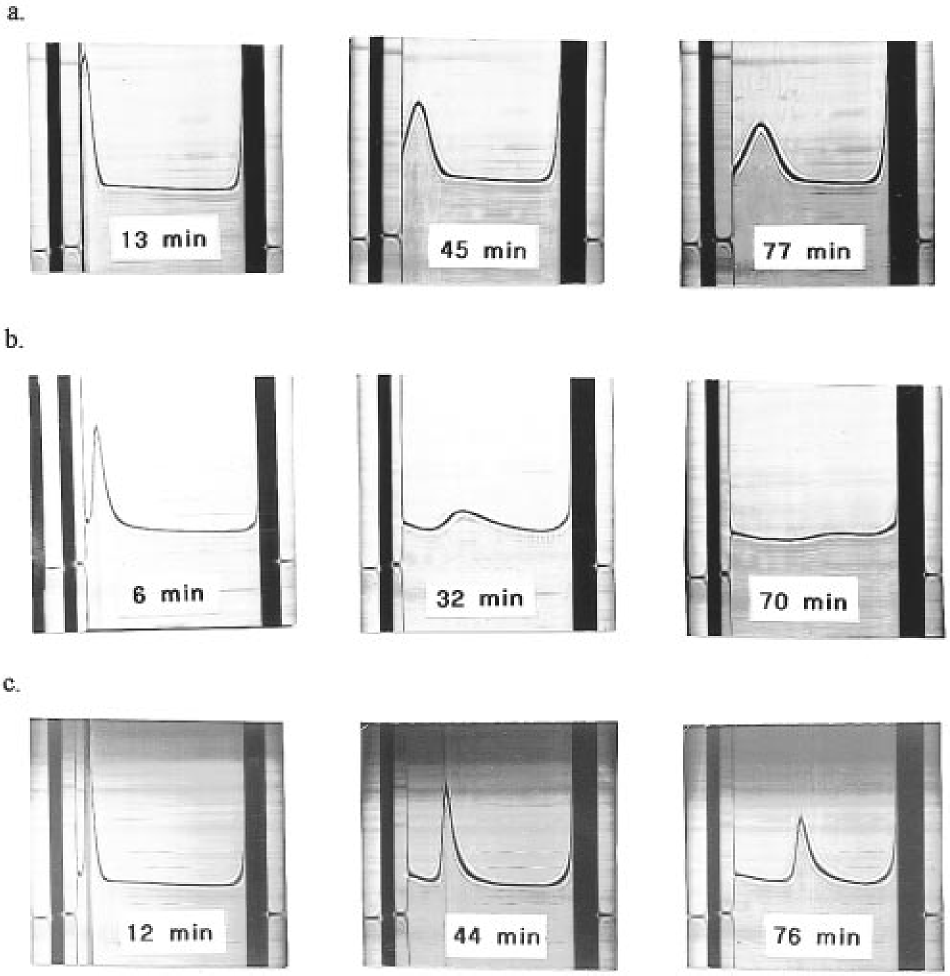


Figure 2. Ultracentrifuge measurements of a poly(DMAEMA-*block*-MMA) copolymer in various solvents: (a) FB054 in methanol ($s = 2.5$ s), (b) FB054 in water ($s = 9.9$ s), and (c) FB054 in water/methanol ($s = 5.8$ s).

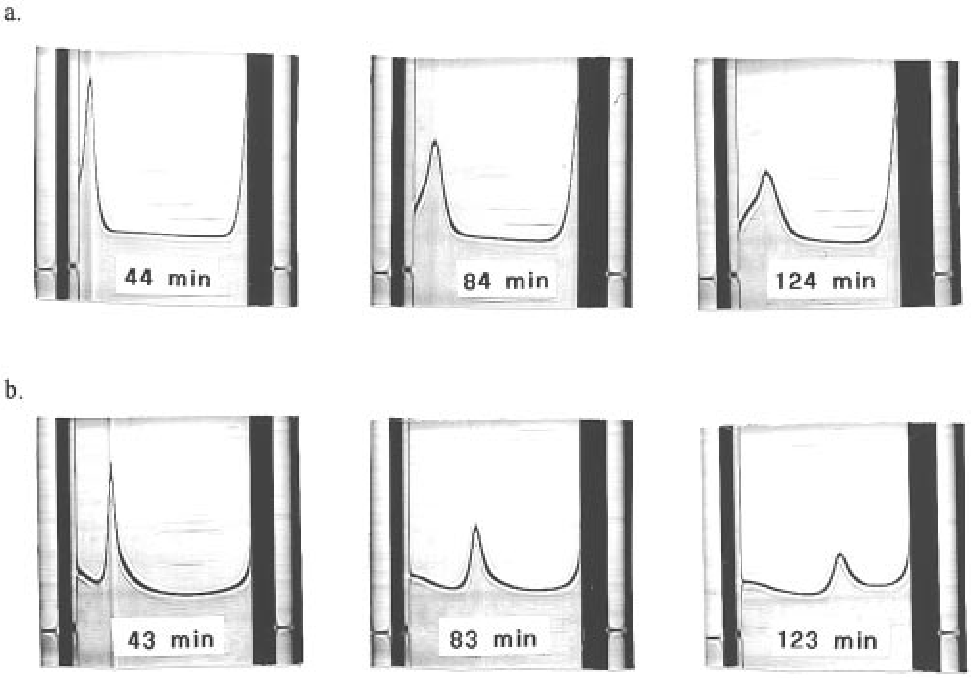


Figure 3. Effect of added salt on the ultracentrifuge measurements of an ionized PDMAEMA-*b*-PMMA copolymer (FB054): (a) pH 2 MeOH/H_2O 0.01 M KCl ($s = 1.5$ s) and (b) pH 2 MeOH/H_2O 1.0 M KCl ($s = 5.0$ s).

Water cannot easily penetrate the glassy PMMA domains (T_g around 100 °C) and the copolymer will dissolve to give aggregates for which the structure reflects the morphology of the solid copolymer.

Methanol is usually considered to be a nonsolvent for PMMA. However, dynamic light scattering measure-

Table 5. Association of Copolymers As Measured by Ultracentrifugation

sample	observed DMAEMA,[a] mol %	sedimentation coefficient,[b] $s \times 10^{13}$ s	diffusion coefficient,[c] $D \times 10^{8}$ cm^2/s	micelle mass, g mol^{-1} d	M_w of block copolymer,[d] g mol^{-1}	association number
FB068	84	5.76	30.9	328 000	14 300	23
FB052	79	5.40	36.1	259 000	12 500	21
FB054	68	5.77	46.0	216 000	16 500	13
FB035	85	4.50	29.8	260 000	26 200	10
FB070	79	4.55	32.9	235 000	22 300	11
FB055	67	6.89	43.7	241 000	26 700	9

[a] As determined by ^{1}H NMR spectroscopy. [b] As determined by analytical ultracentrifugation. [c] As determined by dynamic light scattering. [d] As determined by GPC (reported as PMMA equivalents).

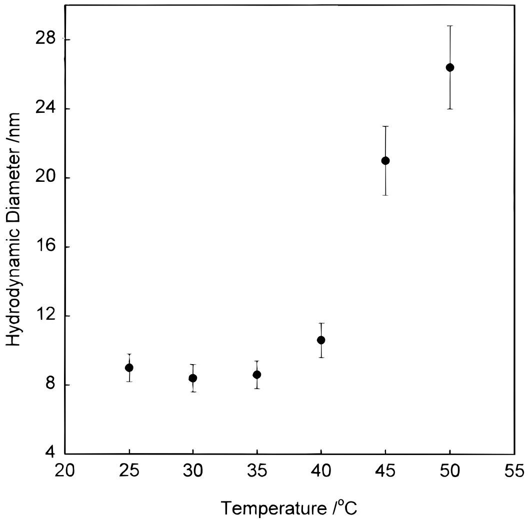


Figure 4. Effect of temperature on micelle size determined by DLS for copolymer FB054 in 5/95 w/w methanol/water mixture.

ments on one PDMAEMA-*b*-PMMA copolymer (FB054) in methanol gave a relatively small hydrodynamic diameter of 4.4 nm. Furthermore, the ^{1}H NMR spectrum of this copolymer in methanol-d_4 shows that both the DMAEMA and MMA components are fully solvated[50] and SLS measurements on this copolymer in methanol gave a very similar molar mass to that obtained from GPC in THF. Thus, we believe that methanol acts as a nonselective solvent for the PDMAEMA-*b*-PMMA copolymers. This is not particularly surprising since the PMMA is only a minor component and the PMMA block lengths are relatively short (<5000 g mol^{-1}). Fox et al.[51] reported that low molar mass PMMA ($\leq$20 000 g mol^{-1}) is soluble in methanol. Furthermore, Riess and Hutrez[52] observed that block copolymers of PMMA and poly(acrylic acid) were molecularly dissolved in methanol when the molar mass of the PMMA block was *ca*. 12 000 g mol^{-1}. However, copolymers with higher molar mass PMMA sequences (22 000−28 500 g mol^{-1}) formed micelles in methanol, indicating that the PMMA was insoluble. Thus when our copolymers are initially dissolved as unimers in THF or methanol any residual "memory" effect should be destroyed. Other workers have described the use of cosolvents to aid micelle formation in both aqueous[25,32] and nonaqueous[53] media.

Astafieva et al.[54] found that styrene-*block*-(sodium acrylate) copolymers show decreasing solution viscosity with prolonged heating (up to 200 h at 100 °C). However, the cmc's were essentially independent of thermal history. They concluded that the effect on viscosity did not depend on the micelle−unimer equilibrium but reflects the slow break up of supermolecular aggregates. Our copolymer solutions could not be heated to disrupt the PMMA core since precipitation occurs at temperatures above 35−40 °C (*i.e.* well below the T_g of PMMA) due to the inverse temperature−solubility behavior of the PDMAEMA; for this reason a cosolvent (THF or MeOH) was always used to prepare micelles. The surface adsorption properties of the copolymers are consistent with reversible micellization if the copolymers are prepared from molecular solutions.[49] It therefore seems reasonable to attempt to discuss structure−property relations in terms of equilibrium arguments, although Astafieva et al.[54,55] have pointed out that the complexity of block polyelectrolyte systems in water is such that only a qualitative picture is possible.

Effect of Copolymer Composition and Molar Mass. For convenient discussion, Table 7 summarizes the relevant properties of all of our polymers.

The cmc of a block copolymer is determined by the relative free energy of chains adsorbed at the surface, unimers in solution, and micelles; thus the free energy of micellization is directly related to the cmc. Given the number of possible variables it is perhaps not surprising that literature reports of the effect of copolymer composition on cmc are confusing. Many authors have suggested that the cmc increases with increasing hydrophilicity.[15,54,56] The argument is that adding hydrophilic units to a hydrophobic polymer will increase the solubility of single isolated chains in the solution and increase the cmc. Astafieva et al.[55] have referred to this as the "short ionic block region" (SIBR).

In contrast, Ruth et al.[57] reported data for styrene-*block*-(vinyl alcohol) copolymers in 80/20 v/v dioxane/water and found that increasing the proportion of the hydrophobic block increases the cmc. Similarly, Nicholas et al.[15] studied micellization of ethylene oxide/butylene oxide/ethylene oxide triblock copolymers in aqueous solution and found that cmc's decreased markedly as the overall copolymer chain length was increased. More recently, Astafieva et al.[55] showed that the cmc of styrene-*block*-(sodium acrylate) copolymers can pass through a maximum as the hydrophilic block length changes. They argue that there is a "long ionic block region" (LIBR), in which the behavior of the micelles is controlled by the very high crowding of the long polyelectrolyte chains around the insoluble core; effectively the high local concentration of ions reduces the solvent quality of the water in the micelle. There also must be a point in the LIBR where the repulsive interactions of the long ionic blocks in the surface of the water will become more significant in reducing their stability there than are the attractive forces between hydrophobic blocks in increasing it.

The data in Table 7 show that the cmc's of our PDMAEMA-*b*-PMMA copolymers increase almost linearly with the length of their hydrophobic blocks at constant hydrophilic chain length (implying that the

Table 6. Comparison of Micelle Properties As Measured by Different Techniques

				static light scattering			
		analytical ultracentrifuge		dn/dc = 0.146 mL g^{-1}		dn/dc = 0.137 mL g^{-1}	
sample	solvent conditions	M_{mic}, g mol^{-1}	association number	M_{mic}, g mol^{-1}	association number	M_{mic}, g mol^{-1}	association number
FB052	MeOH/water	259 000	21	245 000	20	283 000	23
FB054	MeOH/water	216 000	13	190 500	12	218 000	13
FB055	MeOH/water	241 000	9	205 000	8	242 000	9
FB054	MeOH/water + 0.01 M KCl	546 000	33	460 500	28	523 000	32

Table 7. Summary of Solution Properties of the Copolymers Studied

sample	copolymer M_{n},[a] g mol^{-1}	mol % DMAEMA[b]	MMA units	DMAEMA units	cmc, w/v %	hydrodynamic diameter,[c] nm	association number[d]
FB068	10 600	84	14	60	0.029	15.5	23
FB052	10 300	79	17	57	0.049	13.5	21
FB054	13 200	68	36	67	0.112	10.5	13
FB035	19 100	85	24	125	0.111	17.2	10
FB070	17 400	79	27	107	0.148	14.6	11
FB055	22 200	67	60	120	0.218	12.0	9

[a] As determined by GPC with PMMA standards. [b] As determined by ^{1}H NMR spectroscopy. [c] As determined by dynamic light scattering in 4/96 methanol/water. [d] As determined by analytical ultracentrifugation.

micelles are energetically less stable and micellization becomes more difficult). This increase is more rapid as the molar mass of the hydrophilic fraction is increased. We suggest that these copolymers are in the LIBR.

Similar behavior is suggested by studies of the surface adsorption properties of these copolymers, which will be reported elsewhere.[49] We find that they adsorb at the air–water interface as unimers below the cmc and as aggregates above it. Copolymers with short hydrophobic blocks are more weakly adsorbed than the more hydrophobic ones and are also more readily soluble in water. The cmc is controlled both by the solubility of the unimers and by packing of the copolymer chains at the air–water interface. This packing is partly controlled by the repulsive interactions of the large polyDMAEMA chains, and the PMMA components are contributing somewhat less, particularly at low molar mass. Thus, as the PMMA chain length is increased at constant hydrophilic chain length, the copolymer becomes less soluble, but more chains will locate at the interface. As the overall chain length is increased at constant composition, the effect of the increasing length of the ionic block in increasing solubility is greater than the effect of the hydrophobic block in reducing it.

The association numbers and micelle dimensions are also determined by the free energy of micellization and depend on the competition between the hydrophobic attraction of the PMMA chains, the repulsive interaction between the cationic PDMAEMA chains, the complex effect of ionic concentrations, and the loss of water structure in the vicinity of the micelle. In our case, we see systematic trends in both micelle size and number of chains in both series of copolymers, and at first sight, the trends are counterintuitive. Thus, from the data in Table 7, we can see that increasing the hydrophobic block length at constant hydrophilic chain length causes both the association number and the micelle size to fall. The effect is less marked as the molar mass of the hydrophilic fraction is increased.

This behavior is unusual, but the same trend has been reported by Yamaoka et al.[58] They studied block copolymers comprising hydrolyzed 2-(vinyloxy)ethyl acetate (hydrophilic component) and phenyl 2-(vinyloxy)ethyl ether (hydrophobic component) in aqueous solution using small-angle X-ray scattering (SAXS). The number of hydrophilic segments was fixed at 50 and the number of hydrophobic units was varied from 7 to 30. Radius of gyration measurements indicated that the micelle size decreased as the proportion of hydrophobic units was increased. In addition, the SAXS data were consistent with a sphere-to-ellipsoid transition in micelle shape as the hydrophobic block length was increased. On the other hand, most groups have reported increasing micelle size with hydrophobic block length,[10,59] as has also been predicted by theory.[60,61]

The origin of the effects we see is not entirely clear. The most significant effect is that roughly doubling the hydrophilic block length reduces the association number substantially irrespective of the hydrophobic block, which suggests that the repulsion between polyelectrolyte chains combined with the ion concentration effects is dominant. However, it is not clear why more, smaller micelles should be formed as the hydrophobic chain length increases for constant hydrophilic block length. One possibility may be that there is an increasing tendency to form nonequilibrium “locked” micelles as the polymer becomes more hydrophobic; formation of micelles from the molecularly dissolved polymer on addition to water would occur earlier for longer hydrophobic chains, giving greater nucleation density and smaller micelles.

Effect of Charge and Added Electrolyte. Ultracentrifugation measurements reveal only one, slow-moving peak for copolymer FB054 dissolved at pH 2 (see Figure 3). There is some possibility of electroviscous drag effects under these conditions, which could restrict the mobility of any copolymer micelles that might be present. However, given that typical micelle association numbers are in the range 9–33, it is unlikely that such effects would be large enough to cause the micelles to move as slowly as unimers. Thus, on the basis of the ultracentrifuge data, we believe that FB054 is dissolved as unimers at pH 2. As KCl electrolyte is added under these conditions, micellization occurs, since the increased salt concentration screens the repulsion between the cationic charges on the PDMAEMA chains and so allows aggregation.

Similar behavior has been reported by Selb and Gallot,[30] for quaternized poly(4-vinyl pyridine-*block*-styrene) in methanol/water mixtures with increasing concentrations of LiBr, and also by Astafieva et al.,[59] for poly(styrene-*block*-sodium acrylate). We have already reported that the addition of KCl affects the size of PDMAEMA-*b*-PMMA micelles at pH 9.5.[42] The

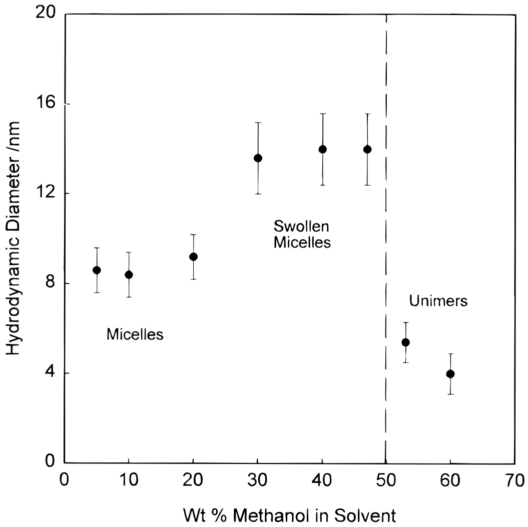


Figure 5. Effect of methanol/water ratio on micelle size determined by DLS for copolymer FB054 in water/methanol mixtures at 30 °C.

micelle size increased from around 10 nm up to 24 nm diameter as the KCl concentration was increased from 0 to 0.01 M. In the present study, SLS and ultracentrifugation measurements both indicate that the micelle association number also increases under these conditions. In the absence of salt, there were 13 copolymer chains per micelle, whereas at 0.01 M KCl there were 38 chains per micelle. The fact that the association number can change with added salt is further evidence that the micelles (at least for this short-chain copolymer) are able to exchange chains and reequilibrate on the time scale of our measurements. It is well-known that the cloud points of water-soluble polymers which exhibit inverse-temperature solubility are usually lowered by the addition of electrolyte.[62] Thus it is understandable that reducing the solubility of the PDMAEMA corona results in an increase in both micelle size and association number.

Effect of Solvent Composition and Temperature. The effect of temperature and solvent composition on the micellization of copolymer FB054 was studied. In 60/40 w/w methanol/water this copolymer was molecularly dissolved throughout the temperature range studied (25−50 °C). In contrast, in 5/95 w/w methanol/water, the copolymer formed micelles with a hydrodynamic diameter of approximately 9 to 11 nm between 25 and 40 °C. Above 40 °C the micelle size increased dramatically; at 50 °C the micelle diameter was approximately 26 nm (see Figure 4). A similar increase in micelle size from 10 to 26 nm was observed when KCl electrolyte was added. Thus, as the solvent power for the PDMAEMA corona is worsened, the association number of micelles increases and hence also their size.

Interestingly, no macroscopic precipitation of the copolymer was observed even at 50 °C, even though the cloud point for the PDMAEMA corona is only *ca.* 40 °C in aqueous solution. This is probably due to the improved solvent power provided by the methanol cosolvent. It is also noteworthy that no increase in micelle size occurred when the solvent mixture contained a higher proportion of methanol. For example, micelles formed in 40/60 w/w methanol/water had an effectively unchanged hydrodynamic diameter of 13−14 nm between 25 and 50 °C.

The effect of solvent composition on micelle diameter at one temperature, 30 °C, can be seen in Figure 5. As the methanol content of the solvent is increased from 5 to 47 wt %, the micelle size increased from around 9 to 14 nm. Eventually, in solutions containing more than 50 wt % methanol, copolymer FB054 is molecularly dissolved. The increase in micelle diameter with increasing methanol content is most likely due to swelling of both the PMMA cores and the corona. Tuzar and coworkers have observed similar results for poly(styrene-*block*-methacrylic acid) copolymer micelles in dioxane/water.[37] As the dioxane content of the solvent was increased from 40 to 80 vol %, the micelle diameter increased from 37 to 49 nm due to swelling of the polystyrene core only.

Conclusions

There is evidence from several techniques for the formation of aggregates when solutions are prepared by direct dissolution of these copolymers in water. Both DLS and ultracentrifugation show different species when solutions are prepared by direct dissolution of the copolymer in water or mixed aqueous solutions. In particular, direct dissolution of the copolymers in water leads to aggregated structures which are not present if the final solution is prepared from molecularly dissolved unimers. Both static and dynamic light scattering and analytical ultracentrifugation measurements indicate that the block copolymers are molecularly dissolved in methanol. Most of the behavior of solutions prepared by molecularly dissolving a copolymer in methanol and diluting with water to the desired concentration appears to be consistent with the idea that the micelles can be described as close to equilibrium; in particular, the association numbers can be varied by changing salt concentrations.

The influence of block copolymer composition on micellization has been evaluated for two different hydrophilic chain lengths (*ca.* 12 000 and 24 000 g mol^{-1}). DLS and ultracentrifugation show that the size and association numbers of the micelles both decrease as the hydrophobic content is increased. This behavior is unusual; most other workers have observed the opposite trend, which is more consistent with theory. The trend in the cmc's of the block copolymers is also somewhat unusual in that they increase with the hydrophobic content. Thus, a decrease in the hydrophobic component apparently promotes micelle formation at lower concentrations. Increasing the overall chain length of the block copolymers resulted in lower association numbers and higher cmc's. Thus a decrease in the overall chain length of the block copolymers also promotes micelle formation. Most of these data are consistent with the idea that repulsive interactions between the large hydrophilic cationic PDMAEMA chains play a large part in determining size and association number.

The effect of charge on micellization has been studied by protonating the DMAEMA component with HCl. When it is completely ionized PDMAEMA behaves as a cationic polyelectrolyte. Ultracentrifugation measurements have shown that when the DMAEMA is charged micellization will only occur in the presence of salt (at least 0.01 M KCl), which helps to screen the repulsion between like charges on the PDMAEMA chains in the micelle corona.

As a micellar solution in 5/95 w/w methanol/water was heated, an abrupt increase in micelle size was observed at 40 °C, approximately the cloud point of

PDMAEMA homopolymer. As the methanol content was increased from 5 to 47 wt % at 30 °C, the micelle size increased from 4.6 to 8.4 nm as the micelle cores became swollen with methanol. Above 50% methanol the micelles dissolve completely to form unimers. Thus both the size and the association number of the micelles can be varied by changing the temperature, pH, composition, and ionic strength of the solution.

Although much of the behavior of these polyelectrolyte micelles is as expected, some of it is anomalous and needs further study. Small-angle neutron scattering experiments using partially deuterated block copolymers are planned in collaboration with Dr. R. K. Thomas' group at Oxford University. Such studies should show whether or not the micelles have a distinct core−shell morphology.

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