Silicon-containing block copolymer membranes

Hotaka Ito, Atsushi Taenaka, Yukio Nagasaki*, Kazunori Kataoka and Masao Kato
Department of Materials Science and Technology, Science University of Tokyo, Noda 278, Japan

and Teiji Tsuruta
Department of Industrial Chemistry, Science University of Tokyo, Shinjuku-ku, Tokyo 162, Japan
(Received 8 March 1995; revised 21 June 1995)

With a high-performance artificial lung as the goal, we synthesized AB-type amphiphilic block copolymers of organosilicon-containing styrene with 2-hydroxyethyl methacrylate (HEMA) via an anionic living polymerization technique. Living poly[4-(bis(trimethylsilyl)methyl)styrene] (poly(BSMS)) was prepared by an anionic polymerization technique using butyllithium as initiator in tetrahydrofuran (THF) at −74°C. When 2-(trimethylsiloxy)ethyl methacrylate (ProHEMA) was added to the living poly(BSMS) solution, block copolymerization started, to form poly(BSMS-*b*-ProHEMA), though prepoly(BSMS) remained to some extent in the mixture. Poly(BSMS-*b*-ProHEMA) yielded a tough membrane by casting from its toluene solution. Deprotection of trimethylsilyl groups was performed by soaking the poly(BSMS-*b*-ProHEMA) membrane in 0.1 N HCl/THF (15/1 (v/v)) solution for 72 h. From solid-state nuclear magnetic resonance analysis, it was confirmed that deprotection of the trimethylsilyl groups from poly(BSMS-*b*-ProHEMA) proceeded completely by this method. Differential scanning calorimetry measurements showed that poly(BSMS-*b*-HEMA) membranes exhibited two endothermic peaks around 70 and 110°C due to the glass transition temperatures, indicating that microphase separation was created in this membrane. The resulting membranes were fairly opaque and brittle. Based on scanning electron microscopy analysis of the block copolymer membrane thus obtained, microporous structures were observed on the surface and in the bulk. As a result, microporous membranes with microphase-separated structures were obtained by deprotection from the membrane. The resulting membranes could have the possibility of applications in the biomedical field.

(Keywords: silicon-containing polymers; anionic polymerization; porous membrane)

INTRODUCTION

Oxygenation of blood by an artificial lung has been widely used as a support for cardiac surgery[1]. Most of the artificial lungs utilized so far have been hollow-fibre-type oxygenators with a porous membrane, which oxygenate blood by direct contact between blood and oxygen gas. They have several problems, however, such as leakage of blood plasma and lowering of the gas exchange ability due to deposition of blood components, including proteins and platelets, on the membrane surface. Consequently, the oxygenator must be replaced every several hours during surgery[2]. In addition, a fairly large amount of heparin must be used due to the low antithrombogenicity of the porous membranes. For successful use of the artificial lung for long periods with a low amount of antithrombogenic agent, new membrane materials possessing both high gas permeability and high blood compatibility must be developed.

We previously found a new synthetic route for organosilicon-containing styrene monomers, the polymers derived from which showed fairly high gas permeability[3]. Especially, a poly[4-(bis(trimethylsilyl)methyl)styrene] (poly(BSMS)) membrane shows a fairly high oxygen permeability among vinyl polymers owing to its high Si content and a fairly large free space between the molecular segments in the membrane. Such styrene derivatives with unique gas permeation characteristics are of great interest because of the facile molecular design through copolymerizations. For example, Okano *et al.*[4] created a highly blood-compatible polymer surface consisting of poly(styrene-*b*-2-hydroxyethyl methacrylate). They reported that the hydrophobic/hydrophilic microphase-separated surface originating from polystyrene and poly(2-hydroxyethyl methacrylate) (poly(HEMA)) segments plays an important role in blood compatibility. If such blood compatibility can be introduced into a polymer with high gas permeability, a new high-performance artificial lung will be substantiated. This paper deals with the synthesis of poly(BSMS-*b*-HEMA) via an anionic polymerization technique and some fundamental characteristics as membranes (*Scheme 1*).

---

* To whom correspondence should be addressed

4-[bis(trimethylsilyl)methyl]styrene
(BSMS)

2-hydroxyethylmethacrylate
(HEMA)

2-trimethylsiloxyethylmethacrylate
(ProHEMA)
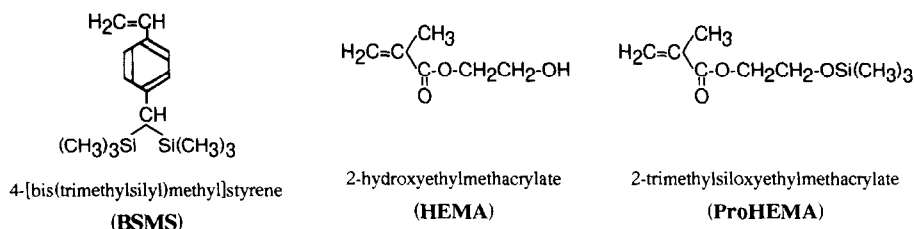
Scheme 1

EXPERIMENTAL

All experiments for monomer syntheses and polymerization reactions were carried out under argon atmosphere in order to eliminate oxygen and moisture.

Materials

Commercial tetrahydrofuran (THF) and 1,1-diphenylethylene (DPE) were purified by conventional methods[5]. Butyllithium (BuLi) was used as a hexane solution, the concentration of which was determined by Gilman's double titration method[6]. BSMS[7] and 2-(trimethylsiloxy)-ethyl methacrylate (ProHEMA)[8] were prepared according to the literature and purified by fractional distillation over calcium hydride *in vacuo*. Lithium chloride (LiCl) was treated with excess BuLi in hexane for 30 min to eliminate hydrated water.

Polymerization procedures

A representative procedure for the anionic polymerizations is described here. The glass wall of a 100 ml round-bottomed flask, which was equipped with a dropping funnel and a three-way stop-cock, was carefully washed with BuLi. THF (15 ml), BSMS (10 mmol) and BuLi (0.26 mmol) were introduced into the flask via a syringe at $-74°C$. After 2 h reaction, a THF solution of LiCl (6 ml; 2.6 mmol; 0.43 mol l^{-1}) was added to the mixture via a syringe and stirred for 20 min. Immediately after the poly(BSMS) living end had been allowed to react with DPE for 30 min to be converted to a relatively stable form, ProHEMA (10 mmol) was introduced into the reaction mixture via a dropping funnel. The reaction was allowed to proceed for a further 10 min, and then the resulting mixture was analysed directly by gas chromatography (g.c.) and gel permeation chromatography (g.p.c.) to determine the conversion of BSMS and Pro-HEMA and the molecular weight (MW) as well as the molecular-weight distribution (MWD) of the polymer formed.

Quantification of living end carbanion

To determine the extent of living polymer formation after the polymerization of BSMS in THF, quantitative analysis of the end carbanion was carried out. To the polymerization system, a precise amount of DPE ($[DPE]_0/[BuLi]_0 = 2$) was added after the monomer was consumed completely. The remaining DPE was determined by g.c. to estimate the extent of the living end.

Benzoylation and n.m.r. measurement of poly(BSMS-b-HEMA) (BSMS/HEMA = 50/50 (mol/mol))

After the block copolymerization of BSMS with ProHEMA (BSMS/ProHEMA = 50/50 (mol/mol)), 1 ml of 0.1 N HCl was added to the mixture and then the mixture was poured into excess water for complete

removal of the trimethylsiloxy groups of the ProHEMA segments. The resulting polymer was dissolved in THF/methanol (80/20 v/v), then recovered by precipitation in diethyl ether/methanol (80/20 v/v), and dried at 40°C *in vacuo*. A pyridine solution of benzoic anhydride (2.5 ml; 36 g dl^{-1}) was added dropwise for 30 min to a pyridine solution (1.2 ml; 8.3 g dl^{-1}) of poly(BSMS-*b*-HEMA) at 0°C, and the reaction mixture was then stirred at room temperature for a further 48 h. The reaction mixture thus obtained was poured into methanol, and the precipitated polymer was collected by filtration. The polymer was redissolved in THF, precipitated in methanol, and subjected to freeze-drying with benzene. A CDCl$_3$ solution (5.0 g dl^{-1}) of the poly(BSMS-*b*-HEMA) was characterized by 400 MHz ^{1}H n.m.r. spectroscopy.

Membrane preparation and its deprotection

Poly(BSMS-*b*-ProHEMA) membranes were prepared by casting on a Teflon sheet from their toluene solution after low-boiling materials of the reaction mixture were evaporated. Deprotection of trimethylsilyl groups from the poly(BSMS-*b*-ProHEMA) membrane thus prepared was carried out by soaking the membrane in a 0.1 N HCl/THF mixture (15/1 (v/v)) for a few days. The membrane thus obtained was analysed by cross-polarization/magic angle spinning (CP/MAS) ^{29}Si solid-state n.m.r. spectroscopy.

Measurements

A Hewlett-Packard 5890 Series was used (glass capillary column DB-1, 0.25 mm diameter × 30 m) for g.c. measurements. G.p.c. measurements were performed on a Toyo Soda HLC-8020 with an *RI* detector and TSK-Gel G4000HXL + G3000HXL + G2500HXL columns. ^{1}H n.m.r. spectra were measured on a JEOL EX400 spectrometer using CDCl$_3$ as the solvent at room temperature. Chemical shifts relative to CHCl$_3$ (H: $\delta = 7.26$) were employed.

RESULTS AND DISCUSSION

We have found previously that poly(BSMS) with predictable molecular weight (MW) and narrow molecular-weight distribution (MWD) was obtained by anionic polymerization with butyllithium as an initiator in THF even at ambient temperature[9]. Lowered reactivity of the vinyl group of BSMS against the carbanion due to the $\sigma-\pi$ hyperconjugation between polar C–Si σ orbital and phenyl π conjugation system[10] is one for such a facile polymerization technique at ambient temperature. For block copolymerization of BSMS with a methacrylate monomer such as ProHEMA, however, low-temperature conditions must be employed due to the high polymerization rate of the methacrylate monomer. The anionic polymerizations of BSMS were carried out at low
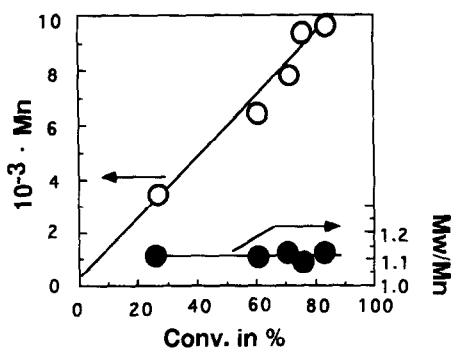
Figure 1 Plots of M_n and MWD *versus* monomer conversion in the anionic polymerization of BSMS in THF at $-74°C$
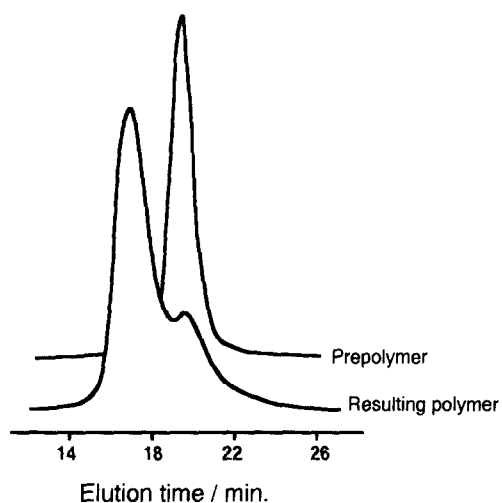

Figure 2 G.p.c. traces of the polymers formed by the anionic polymerization before and after the addition of ProHEMA (the same sample as run 5 in *Table 1*)

temperatures to investigate the living character of the system. *Figure 1* shows the change in MW and MWD of poly(BSMS) in the anionic polymerization at $-74°C$ as a function of monomer conversion. The MW of the polymer formed increased directly with increasing monomer conversion, keeping the constant MWD maintained at a low value (≈ 1.1) regardless of conversion, indicating that no significant termination reaction occurred during the polymerization reaction. The living polymerization of character of BSMS was further investigated by a chemical reaction technique using DPE. According to the procedure described in the Experimental section, 90.5% of the chain end was living at $-74°C$. On the basis of these results, it was concluded that the living poly(BSMS) with predictable MW and narrow MWD can be obtained at $-74°C$ within 2 h. As we reported previously[11], the stability of the living end of poly(Pro-HEMA) in anionic polymerization was strongly affected by the monomer concentration in the reaction system even at low temperature, meaning that some unknown side reactions take place to kill the living end immediately after no more monomer molecules are present in the vicinity of the growing species. When a stop-cock technique was employed for introducing the monomer (in other words, the monomer molecules were added fast enough into the reaction system), polymer with controlled MW was then obtained in quantitative yield.

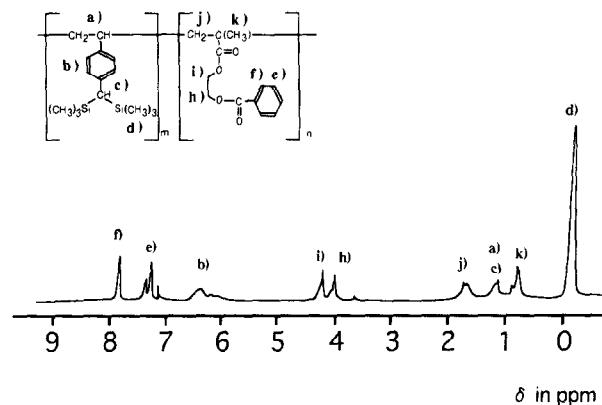*Figure 2* shows g.p.c. traces of the BSMS prepolymer

Figure 3 The ^1H n.m.r. spectrum of poly[BSMS-*b*-2-(benzoyloxy)-ethyl methacrylate] in chloroform-d

and the copolymer formed after ProHEMA addition. After the addition of ProHEMA, the peak of the polymer was shifted to the higher MW side, indicating that effective block copolymerization occurred, though a small amount of prepolymer remained. The MWD of the block copolymer was 1.30, which was higher than that of the prepolymer (1.10). To verify that block copolymerization actually took place, the polymer of the higher MW side was isolated from the reaction mixture by the precipitation technique described in the Experimental section. After the benzoylation of the polymer thus obtained by benzoic anhydride (see Experimental section), the g.p.c. showed no poly(BSMS) prepolymer in the low-MW region, indicating complete exclusion of the deactivated prepolymer. Based on ^1H n.m.r. measurement of the polymer thus obtained (*Figure 3*), it was found that both components appeared in the spectrum, indicating a true block copolymer. From the proton intensity ratio of benzoate and HEMA, it was confirmed that the OH groups of the HEMA units in the copolymer were completely converted to benzoate groups. The mole fraction of BSMS in the copolymer was 0.44 as determined from ^1H n.m.r. (the ratio of peak area (b) vs. (i) + (h) was employed), which agreed well with that calculated by the following equation:

$$X_{BSMS}(\text{calc}) = \frac{[BSMS]_0 \times (\text{block efficiency})}{[BSMS]_0 \times (\text{block efficiency}) + [HEMA]_0}$$

$$= 0.41$$

Teyssié *et al.* reported that LiCl stabilized the growing carbanion in the anionic (meth)acrylate ester polymerizations with organolithium compounds as initiator to form polymers with predictable MW and narrow MWD[12,13]. In the case of the block copolymerization in the presence of LiCl, the copolymer obtained had a narrower MWD (1.18) than that obtained in the absence of LiCl as shown in *Figure 4*, even though a small amount of the prepolymer still remained. Thus, it was concluded that poly(BSMS-*b*-HEMA) with controlled MW and narrow MWD was obtained under the conditions described above. Further results of the synthesis of the block copolymer with several compositions are summarized in *Table 1*.
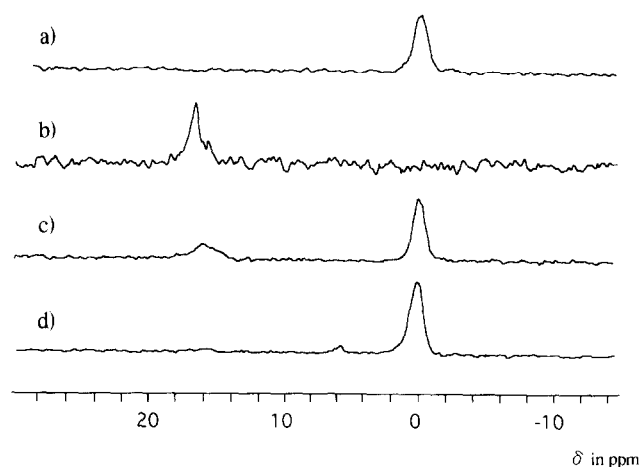
Preparation and properties of poly(BSMS-b-HEMA) membrane

It is well known that the solubility of block copolymers
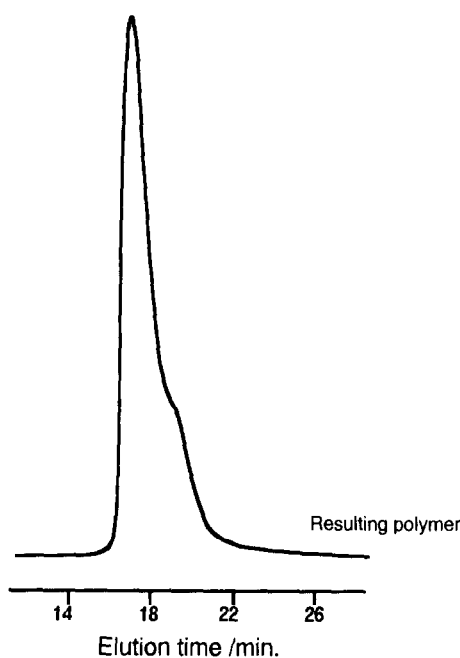
Figure 4 G.p.c. trace of poly(BSMS-*b*-ProHEMA) prepared by anionic polymerization in the presence of LiCl (the same sample as run 2 in *Table 1*)

Figure 5 CP/MAS ^{29}Si n.m.r. spectra of (a) poly(BSMS), (b) poly-(ProHEMA), (c) poly(BSMS-*b*-ProHEMA) (58/42) and (d) poly(BSMS-*b*-HEMA) (the same sample as (c) after deprotection; see text)

composed of hydrophilic and hydrophobic segments is not consistent with their compositions and MW^{14}. Poly(BSMS-*b*-HEMA) with ca. 50 mol % of each segment hardly dissolves in common organic solvents such as THF, benzene, hexane and chloroform (these are good solvents for poly(BSMS)), and methanol and ethanol (these are good solvents for poly(HEMA)). Because both the segments of poly(BSMS-*b*-ProHEMA) are hydrophobic, in contrast to poly(BSMS-*b*-HEMA), the poly-(BSMS-*b*-ProHEMA)s of any composition were soluble in aprotic solvents such as THF, toluene, dioxane, chloroform and hexane. Using 10 wt % toluene solution of poly(BSMS-*b*-ProHEMA), a membrane was prepared by the casting method. Our idea was to obtain a poly(BSMS-*b*-HEMA) membrane, by deprotection of the trimethylsilyl groups from the poly(ProHEMA) segments after the formation of a poly(BSMS-*b*-ProHEMA) membrane, which was transparent and possessed good toughness. The deprotection from the membrane was carried out by soaking the membrane in a mixture of 0.1 N HCl aqueous solution with THF (15/1 (vol/vol)) for 72 h. It was noticeable that the membrane became

soluble in the 0.1 N HCl/THF medium containing more than 10 vol % of THF. After drying this membrane under reduced pressure for 24 h, a solid-state n.m.r. measurement of the membrane was carried out to confirm the deprotection. *Figure 5* shows CP/MAS ^{29}Si n.m.r. spectra of poly(BSMS-*b*-ProHEMA) before and after deprotection by the HCl/THF solution, together with those of poly(BSMS) and poly(ProHEMA). As can be seen in *Figure 5c*, ^{29}Si signals originating from the poly(ProHEMA) and poly(BSMS) segments appeared around 16 and 0 ppm, respectively, while the signal around 16 ppm disappeared completely in the sample treated with HCl/THF solution shown in *Figure 5d*. This fact indicates the formation of poly(BSMS-*b*-HEMA) with complete removal of the trimethylsilyl groups in the poly(HEMA) segment even by the heterogeneous reaction.

To obtain information on the characteristics of the block copolymer membranes thus obtained, differential scanning calorimetric (d.s.c.) analysis was carried out. The d.s.c. measurement of the block copolymer before deprotection (poly(BSMS-*b*-ProHEMA) (10/90)) showed two different glass transition temperatures ($T_{g1} = 15.4°C$, $T_{g2} = 112°C$), indicating microphase separation of the membrane, though the solubilities of both segments are similar. *Table 2* shows the results of the d.s.c. measurements. Regardless of the composition, the block copolymers after deprotection also showed two different T_g values, appearing around 60–75°C (T_{g1}) and 110–120°C (T_{g2}). Contrary to the consistent T_{g2}, T_{g1} increased

Table 1 Anionic block copolymerizations of BSMS with ProHEMA in THF at −74°C

Run no.	Sample[a]	[BSMS][b] (mmol)	[BuLi] (mmol)	[LiCl][c] (mmol)	[ProHEMA][d] (mmol)	$10^{-4}M_n$ Calcd.	$10^{-4}M_n$ G.p.c.	M_w/M_n	Fraction of deactivated prepolymer (%)
1	BH(30)	15	0.70	7.0	35	1.6	1.7	1.06	26.5
2	BH(50)	10	0.15	1.5	10	1.8	2.3	1.18	n.d.[e]
3	BH(58)	22	0.47	4.7	16	1.9	1.4	1.17	n.d.
4	BH(80)	30	0.70	7.0	7.5	1.3	1.4	1.17	n.d.
5	BH(50)	10	0.15	0	10	1.8	2.0	1.30	30.0

[a] The value in parentheses indicates the mole percentage of BSMS in the block copolymers
[b] Solvent (THF) = 14 ml
[c] THF solution of LiCl (0.7 mol l^{-1}) was added to the prepolymer solution
[d] ProHEMA was added by dropping funnel after addition of LiCl solution
[e] Not determined

Table 2 Results of d.s.c. measurements of poly(BSMS-*b*-HEMA)

Sample[a]	T_{g1} (°C)	T_{g2} (°C)
BH(37)	76.2	111.0
BH(50)[b]	70.8	115.4
BH(58)[c]	73.5	117.9

[a] The values in parentheses indicate the mole percentage of BSMS in the block copolymers
[b] The same sample as run 5 in *Table 1*
[c] The same sample as run 3 in *Table 1*

10KV ×5000 6 μm

Top view

10KV ×5000 6 μm

Cross section

Figure 6 SEM micrographs of top view and cross-section of BH(80) membrane (the same sample as run 4 in *Table 1*)

significantly after the acid treatment, which also supports complete deprotection. On the basis of these results, it was concluded that a microphase-separated structure of the poly(BSMS-*b*-HEMA) membranes had been formed during the membrane preparation process of poly-(BSMS-*b*-ProHEMA) but was not brought about by the deprotection process. It is known that the micro-

tacticity in poly(HEMA) influences its glass transition temperature. For example, syndiotactic poly(HEMA) has a T_g of 110°C[15], while the isotactic polymer shows a T_g of 35°C[15,16]. From the T_{g1} values (60–70°C), it seems that the poly(HEMA) segment in the block copolymer has one of the tactic structures. A lower T_{g2} than that of poly(BSMS) (ca. 150°C[17]) may be due to the low MW of the segment. Actually, poly(BSMS) with low MW (=10 000) showed almost the same value (T_g = 110°C) as the T_{g2} of the block copolymers.

It is of interest to note the effect of elimination of the trimethylsilyl groups from the poly(ProHEMA) segments on the surface and bulk morphology of the membrane. SEM analysis of BH(80) shows a porous structure with ca. 0.5 μm pores not only on the surface but also in the bulk, as shown in *Figure 6*. Change in solubility after the elimination of the bulky trimethylsilyl groups may trigger off such micropore formation in this process. THF in the reaction medium was incorporated into the poly(BSMS-*b*-ProHEMA) membrane to swell the polymer membrane. Such swelling of the membrane facilitated proton attack on the ProHEMA segments. After deprotection, however, the poly(HEMA) segments shrank due to the non-solubility of poly(HEMA) in THF. Such a unique poly(BSMS-*b*-HEMA) porous membrane with a microphase-separated structure is expected to be useful for a high-performance artificial lung. A detailed study of the characteristics of poly(BSMS-*co*-HEMA) will be published elsewhere.

ACKNOWLEDGEMENT

REFERENCES

1   Terasaki, H. and Morioka, T. *Artif. Organs Today* 1991, **1**, 115
2   Akasu, H. and Anazawa, T. *Jpn J. Artif. Organs* 1990, 141
3   Nagasaki, Y., Kurosawa, K., Suda, M., Takahasi, S., Tsuruta, T., Ishihara, K. and Nagase, Y. *Makromol. Chem.* 1990, **191**, 2103
4   Okano, T., Nishiyama, S., Shinohara, I., Akaike, T., Sakurai, Y., Kataoka, K. and Tsuruta, T. *J. Biomed. Mater. Res.* 1981, **15**, 393
5   Perrin, D. D., Armarego, W. I. F. and Moor, F. W. 'Purification of Laboratory Chemicals', Pergamon Press, Oxford, 1980
6   Gilman, H., Langham, W. and Moor, F. W. *J. Am. Chem. Soc.* 1941, **62**, 2327
7   Nagasaki, Y. and Tsuruta, T. *Makromol. Chem.* 1986, **187**, 1583
8   Hirao, A., Kato, H., Yamaguchi, K. and Nakahama, S. *Macromolecules* 1986, **19**, 1294
9   Kato, N., Nagasaki, Y. and Kato, M. *Polym. Adv. Technol.* 1990, **1**, 341
10 Nagasaki, Y., Tsuruta, T. and Hirano, T. *Makromol. Chem.* 1989, **190**, 1855
11 Nagasaki, Y., Ito, H., Kato, M., Kataoka, K. and Tsuruta, T. *Polym. Bull.* 1995, **35**, 137
12 Fayt, R., Forte, R., Jacobs, C., Jerome, R., Ouhadl, T., Teyssié, Ph. and Varshney, S. K. *Macromolecules* 1991, **24**, 1442
13 Varshney, S. K., Jacobs, C., Hautekeer, J. P., Bayard, P., Jerome, R., Fayt, R. and Teyssié, Ph. *Macromolecules* 1991, **24**, 4997
14 Aggarwal, S. L. 'Block Copolymers', Plenum Press, New York, 1970
15 Russell, G. A., Hiltner, D. A., Gregonis, D. E., De Visser, A. C. and Andrade, J. D. *J. Polym. Sci., Polym. Phys. Edn.* 1980, **18**, 1271
16 Sung, Y. K., Gregonis, D. E., Russell, G. A. and Andrade, J. D. *Polymer* 1978, **19**, 1362
17 Nagasaki, Y., Suda, M., Tsuruta, T., Ishihara, K. and Nagase, Y. *Makromol. Chem., Rapid Commun.* 1989, **10**, 255