Novel Aprotic Polar Polymers V. Synthesis of Poly(HMPA) by Ring-Opening Polymerization

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ABSTRACT: The synthesis of a polymer homolog of hexamethylphosphoramide (HMPA) by ring-opening polymerization of the corresponding monomer (*N*-bis(dimethylamino)phosphorylpropylenimine) was conducted. Poly(HMPA) was obtained when polymerization was carried out with cationic initiators at 150°C. Both solution polymerization in 1,1,2,2-tetrachloroethane and bulk polymerization were successful, though anionic polymerization and cationic polymerization at lower temperature afforded no polymer. The obtained poly(HMPA) actually had properties as an aprotic polar polymer such as the amphiphilicity and the miscibility. Poly(HMPA) prepared by ring-opening polymerization showed better miscibility with polystyrene than poly(HMPA) having fewer phosphoryl groups (47%), synthesized by polymer reaction.
  KEY WORDS Poly[*N*-bis(dimethylamino)phosphorylpropylenimine] / Aprotic Polar Polymer / Ring-Opening Polymerization / Poly(HMPA) / Miscibility /

Aprotic polar solvents have interesting properties such as mixing with water freely and dissolving polymers having polar groups. Thus, polymers having repeating structures of aprotic polar solvents are expected to have properties based on their repeating structures such as the amphiphilicity and the miscibility with other polar polymers. Poly(2-methyl-2-oxazoline) (PMeOZO) is an example of such a polymer, a polymer homolog of *N*,*N*-dimethylacetamide, with high hydrophilicity and good miscibility with polar polymers.[1] In previous papers, we prepared polymer homologs of dimethyl sulfoxide[2] and a novel polymer homolog of *N*,*N*-dimethylacetamide having *N*,*N*-dimethylcarbamoyl groups on all main chain carbons.[3] They showed the properties based on their repeating structures.

Among aprotic polar solvents, hexamethylphosphoramide (HMPA) is one of the most useful solvents in organic synthesis due to its high polarity and stability to organic and organometallic reagents.[4] HMPA is utilized not only as a solvent but an additive and a ligand in organometallic chemistry,[5] and as a reagent for changing reaction selectivity.[6] Although HMPA is carcinogenic, it has been widely used because of its usefulness and few alternatives.[7] Therefore, a polymer homolog of HMPA having HMPA repeating structures can be expected to show properties as an aprotic polar polymer and to become good alternative of HMPA.[8] We prepared poly(HMPA) 1 (poly[*N*-bis(dimethylamino)phosphorylethylenimine]) by polymer reaction of linear poly(ethylenimine) synthesized from PMeOZO with bis(dimethylamino)phosphoryl chloride and found that poly(HMPA) 1 had the amphiphilicity and good miscibility with other polymers such as PMeOZO and polystyrene.[9] However, the degree of introduction of phosphoryl units into poly(ethylenimine) was 58% at most and the rest was quaternary ammonium salt. Thus, the ability of poly(HMPA) as an aprotic polar polymer is considered not to be realized sufficiently in this polymer and it could not be utilized as a polymer additive or a

polymer solvent in organic and organometallic reactions.

Poly(HMPA) having 100% phosphoryl units is thought to have better properties as the polymer homolog of HMPA. For this purpose, synthesis of poly(HMPA) not by polymer reaction but by polymerization is appropriate. In fact, poly(HMPA)s 1 and 2 are expected to be prepared by ring-opening polymerization of the corresponding monomers (3 and 4) (Scheme 1). It is reported that 3 and 4 gave the corresponding ring-opening products by the reaction with one equivalent of acidic and basic reagents.[10] This paper describes the synthesis of poly(HMPA) 2 (poly[*N*-bis(dimethylamino)phosphorylpropylenimine]) by ring-opening polymerization of the corresponding monomer 4 and examination of properties of the resulting polymer. Comparison of the miscibility of poly(HMPA) 2 with that of 1 was carried out.

EXPERIMENTAL

General

^{1}H and ^{13}C NMR spectra were obtained with a JEOL JNM-EX270 spectrometer (270 MHz for ^{1}H NMR and 67.9 MHz for ^{13}C NMR) in chloroform-*d*. Gel permeation chromatographic analysis (GPC) using 1,1,1,3,3,3-

3   Poly(HMPA) 1

4   Poly(HMPA) 2
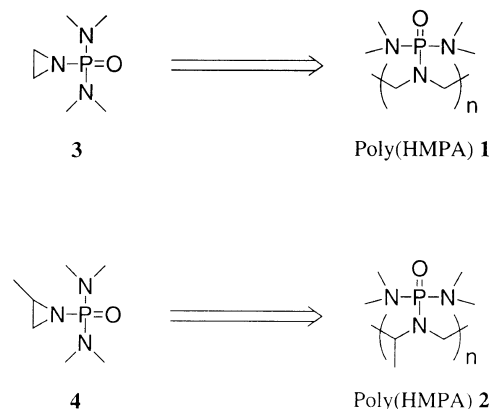
Scheme 1.

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hexafluoroisopropanol + CF$_3$CO$_2$Na (10 mM) as an eluent was carried out on a Tosoh HLC-8020 (TSKgel GMHHR-H column) after calibration with standard poly(methyl methacrylate). Gas-liquid chromatography (GLC) analysis was performed on a Shimadzu GC-4C (glass column packed with 10% SE-30 on Chromosorb W) with Ar as a carrier gas. All DSC analysis was carried out on a Seiko DSC200 instrument using exactly weighed samples (about 10 mg) at heating and cooling rates of 10°C min^{-1}.

Unless otherwise noted, materials were obtained from commercial sources and used after distillation under nitrogen. Chloroform was distilled under nitrogen from P$_2$O$_5$. 1,1,2,2-Tetrachloroethane was distilled from CaCl$_2$. Pyridinium chloride was purchased from Wako Pure Chemical Industries, Ltd. and used as received. Polystyrene (degree of polymerization was *ca.* 100) was obtained from a commercial source and used without further purification.

*Synthesis of N-Bis(dimethylamino)phosphorylpropylenimine 4*

In a two-necked flask containing 4.50 ml (30.4 mmol) of bis(dimethylamino)phosphoryl chloride in diethyl ether (30 ml) was placed triethylamine (4.66 ml, 33.4 mmol). The solution was cooled to 0°C and 2.36 ml (33.4 mmol) of 2-methylaziridine (propylenimine) in 10 ml of diethyl ether was added dropwise over 30 min. The mixture was stirred at room temperature overnight. After filtration, the mixture was concentrated and distilled under reduced pressure to give N-bis(dimethyl-amino)phosphorylpropylenimine 4 in a quantitative yield (bp 65°C/1.7 mmHg). ^{1}H NMR (δ, ppm) 1.23 (-CH$_3$, d, $J = 5.4$ Hz, 3H), 1.68 (-CH$_2$-, *trans*-proton to methyl group, dd, $J = 11.3$, 1.6 Hz, 1H), 2.22 (-CH$_2$-, *cis*-proton to methyl group, dd, $J = 16.7$, 1.4 Hz, 1H), 2.45 (-CH-, m, 1H), 2.69 (-PN(CH$_3$)$_2$, dd, $J = 10.8$, 1.6 Hz, 12H).

Solution Ring-Opening Polymerization of N-Bis(dimethylamino)phosphorylpropylenimine 4. General Procedure. In a two-necked flask containing 0.358 g (1.87 mmol) of N-bis(dimethylamino)phosphorylpropyleni-mine 4 in 1,1,2,2-tetrachloroethane (10 ml) was placed dimethyl sulfate (8.8 × 10^{-3} ml, 0.094 mmol) and the mixture was heated at reflux temperature (147°C) until no peak corresponding to monomer 4 was detected by GLC (20 h). The resulting brown solution was poured into a large amount of *n*-hexane (or diethyl ether) and the precipitate was isolated by suction filtration to afford the corresponding poly(HMPA) 2 as a sticky solid in 84% yield. ^{1}H NMR (δ, ppm) 1.10—1.55 (-CH$_3$, br, 3H), 2.51—2.82 (-PN(CH$_3$)$_2$-, br, 12H), 2.90—3.00 (-CH$_2$-, br, 2H), 3.10—4.22 (-CH-, br, 1H). Similar procedures as described above were conducted for other solution polymerizations.

Bulk Ring-Opening Polymerization of N-Bis(dimethyl-amino)phosphorylpropylenimine 4. General Procedure. In a test tube were placed 1.18 g (6.17 mmol) of N- bis-(dimethylamino)phosphorylpropylenimine 4 and 5 mol% of an appropriate initiator. The test tube was evacuated, sealed and heated at 150°C over 60 h. After polymeriza-tion, the contents of the tube were dissolved in a small amount of chloroform and the solution was poured into a large amount of *n*-hexane or diethyl ether to give the
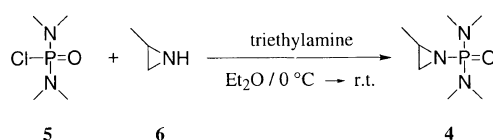
Scheme 2.
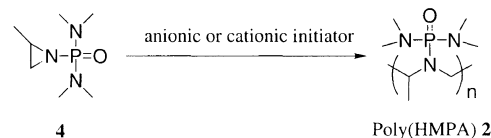
Scheme 3.

corresponding poly(HMPA) 2 as a brown precipitate. ^{1}H NMR spectrum of the polymer prepared by bulk polymerization was essentially the same as that of poly(HMPA) 2 obtained by solution polymerization of the monomer 4 (*vide supra*).

Differential Scanning Calorimetry Analyses

Samples for DSC analysis were prepared as follows: A mixture (0.10 g) of poly(HMPA) 1 or 2 with polystyrene at a desired ratio was dissolved in a small amount of chloroform. The solution was reprecipitated into a large amount of *n*-hexane to give a brown solid. After filtration and freeze-drying of the mixture, the resulting solid was dried *in vacuo* and used for DSC analysis. The midpoint of T_g peak in the thermogram of the second heating scan was adopted as the value of the glass transition temperature.

RESULTS AND DISCUSSION

Monomer 4 [bis(dimethylamino)phosphorylpropyl-enimine] for ring-opening polymerization was prepar-ed by reaction of propylenimine 6 with bis(dimethyl-amino)phosphoryl chloride 5 in a quantitative yield as shown in Scheme 2.[10] Propylenimine was used as the ring portion of the monomer because it is less toxic than ethylenimine, though poly(HMPA) 1 could be synthe-sized with ethylenimine instead of propylenimine. Ring-opening polymerization of 4 was carried out using anio-nic and cationic initiators (Scheme 3). The results of polymerizations are summarized in Table I. No polymer was obtained when anionic initiators were used as shown in entries 1 and 2. The polymerization of 4 by a cationic initiator (pyridinium chloride) at reflux temperature of chloroform (61°C) did not afford any polymeric mater-ials (entry 3). As shown in entries 4—7, poly(HMPA) 2 was obtained when the reactions were carried out with cationic initiators at reflux temperature of 1,1,2,2-tetrachloroethane (147°C) or at 150°C in bulk. Both a protonic acid (pyridinium chloride) and Lewis acids (dimethyl sulfate and methyl tosylate) were found to be effective for polymerization. Poly(HMPA) 2 showed amphiphilicity, being soluble in water, methanol, N,N-dimethylformamide (DMF), acetonitrile, chloroform, and dichloromethane. This indicates that the influence of the methyl groups in the main chain is not so im-portant and that poly(HMPA) 2 actually has the prop-erty as a polymer homolog of HMPA.

Number-average molecular weights of the polymers

Table I. Ring-opening polymerization of monomer **4**

Entry	Initiator (5 mol%)	Solvent	Condition	Yield[a]/%	$M_n(M_w/M_n)$[b]
1	n-BuLi	THF	r.t./68 h	0	—
2	NaOMe	CH₃CN	82°C/23 h	0	—
3	Pyridinium chloride	CHCl₃	64°C/27 h	0	—
4	Pyridinium chloride	Cl₂CHCHCl₂	147°C/53 h	98	4400 (1.74)
5	Pyridinium chloride	—	150°C/64 h	42	7200 (1.10) 2800 (1.10)
6	Dimethyl sulfate	Cl₂CHCHCl₂	147°C/20 h	84	2800 (1.12)
7	MeOTs	Cl₂CHCHCl₂	147°C/25 h	45	3400 (1.12) 1800 (1.02)
8	—	Cl₂CHCHCl₂	147°C/34 h	73	3600 (1.40)
9	—	—	150°C/68 h	0	—

[a] Yield of reprecipitate from n-hexane. [b] Measured by GPC using 1,1,1,3,3,3-hexafluoroisopropanol + CF₃CO₂Na as an eluent (PMMA standard).
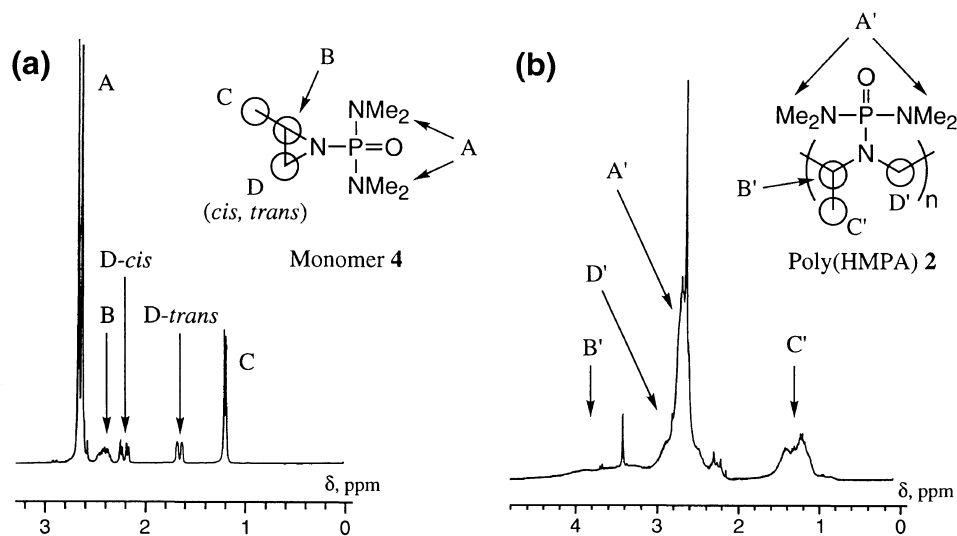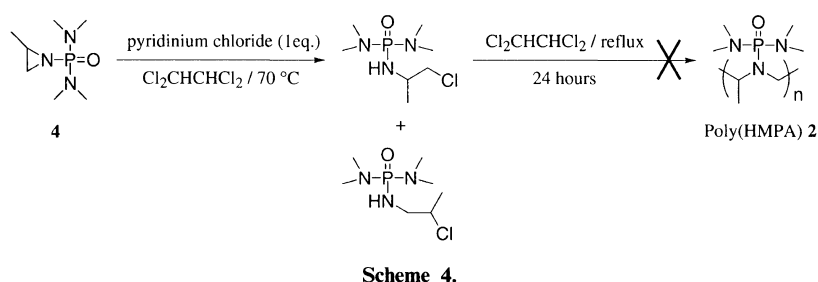
Scheme 4.

Figure 1. ¹H NMR spectra (270 MHz) of the monomer **4** (a) and the corresponding poly(HMPA) **2** (b).

were in the thousands, and bimodal GPC curves were observed in some cases. It may be the reason for bimodal curve that both thermal polymerization and cationic polymerization occurred in the reaction system. To examine this notion, polymerizations of **4** without initiator were investigated. No polymer was obtained when polymerization was conducted in bulk as shown in entry 9, though poly(HMPA) **2** was obtained by thermal polymerization in 1,1,2,2-tetrachloroethane (entry 8). These results are thought to rule out the possibility of simple thermal polymerization of the monomer **4**. The polymerization in 1,1,2,2-tetra-chloroethane might be initiated by contaminated HCl in the solvent.[11] We also examined the possibility of cationic ring-opening and thermal polymerization as

shown in Scheme 4. Cationic ring-opening was carried out with one equivalent pyridinium chloride in 1,1,2,2-tetrachloroethane at 70°C,[10] and after confirming the disappearance of the monomer **4** by GLC, the reaction mixture was refluxed for 24 h. No polymer insoluble in Et₂O was obtained. Thus, "ring-opening and thermal" polymerization mechanism would be inappropriate, though cationic species may add to ring-nitrogen of the monomer without ring-opening, and the resulting "monomer" would be thermally polymerized in addition to the cationic ring-opening polymerization of the monomer **4**.

Figure 1 shows ¹H NMR spectra of the monomer **4** (a) and poly(HMPA) **2** (b). In Figure 1a, two peaks corresponding to cis and trans ring protons (D-cis

Table II. Miscibility of poly(HMPA)s with polystyrene (DP = 100)

Poly(HMPA) : Polystyrene	T_gs (°C) of the mixture of polystyrene with:	
	Poly(HMPA) 1	Poly(HMPA) 2
100 : 0	30	32
80 : 20	**51**	**47**
50 : 50	39, 62	**58**
30 : 80	45, 78	**72**
0 : 100	100	100
M_n of poly(HMPA)[a]	20000	7200

Structure of poly(HMPA)

$m : n = 47 : 53$
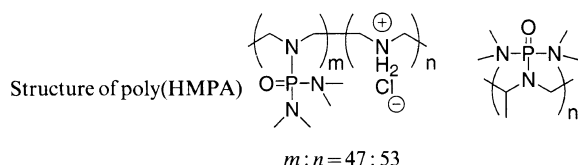
[a] Measured by GPC using 1,1,1,3,3,3-hexafluoroisopropanol + CF_3-CO_2Na as an eluent (PMMA standard).

and D-*trans*) are observed. After polymerization, the peaks assigned to the monomer **4** disappeared and new peaks were observed as shown in Figure 1b. From these spectra, it became clear that the monomer **4** was polymerized to give poly(HMPA) **2**.

Aprotic polar polymers have the miscibility with other polymers because of the repeating structure of an aprotic polar solvent.[1-3,9] Poly(HMPA) **1** containing 47% phosphoryl units, prepared by polymer reaction, had the miscibility with other HMPA-soluble polymers.[9] Especially, mixtures of **1** with polystyrene showed large shifts of glass transition temperatures and the mixture in the ratio of 80 : 20 had only one glass transition temperature between those of the original polymers. Therefore, poly(HMPA) **2** having 100% phosphoryl units is expected to show better miscibility than poly(HMPA) **1**. We examined the miscibility of poly(HMPA) **2** with polystyrene by differential scanning calorimetry (DSC) and compared the results with the miscibility of poly(HMPA) **1** with polystyrene. Samples for DSC analysis were prepared as described in the EXPERIMENTAL. The samples were subjected to DSC analysis at a heating rate of 10°C min^{-1}. The miscibility was estimated by comparing the glass transition temperatures of the mixture of two polymers with those of the original polymers. The results are summarized in Table II. As shown in the table, poly(HMPA) **2** showed one glass transition temperature at all ratios and had higher miscibility than poly(HMPA) **1**. These results reflect that poly(HMPA) **2** had 100% phosphoryl units while poly(HMPA) **1** did not, and that the effect of the methyl

groups in the main chain of poly(HMPA) **2** should be quite small.

In summary, poly(HMPA) **2** having 100% phosphoryl groups in the main chain was prepared by cationic ring-opening polymerization of the monomer **4**. The polymerization occurred around 150°C and the resulting polymer had a number-average molecular weight in the thousands. Poly(HMPA) **2** was amphiphilic and showed higher miscibility with polystyrene than poly(HMPA) **1** prepared by polymer reaction. These results indicate that poly(HMPA) **2** actually has the properties as a polymer homolog of HMPA and the degree of introduction of phosphoryl groups is important for the properties of the polymers. Examination of properties as a polymer solvent and a polymer additive using poly(HMPA) **2** possessing 100% phosphoryl units is in progress.

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