Polymerization via Zwitterion. 14. Alternating Copolymerizations of Cyclic Imino Ethers with Acrylic Acid and with β-Propiolactone

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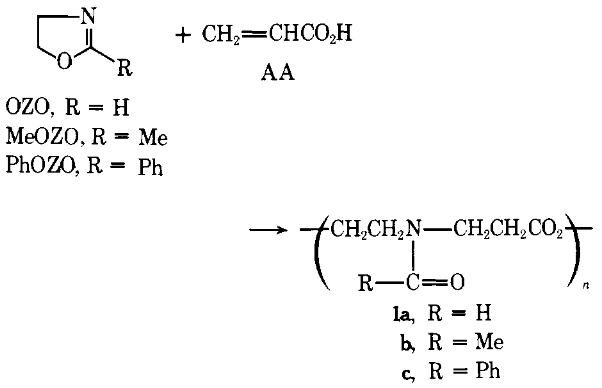
ABSTRACT: This paper describes the copolymerizations of cyclic imino ethers with acrylic acid (AA) and with β-propiolactone (BPL), which occur without added catalyst. Cyclic imino ethers employed are 2-oxazoline (OZO) and its 2-methyl- and 2-phenyl-substituted derivatives (MeOZO and PhOZO) and 5,6-dihydro-4*H*-1,3-oxazine (OZI) and its 2-methyl and 2-phenyl derivatives (MeOZI and PhOZI). In the combinations of AA with cyclic imino ethers, 1:1 alternating copolymers were produced in which the incorporation of AA into the copolymers involved the hydrogen transfer process. In the systems with BPL, on the other hand, 1:1 copolymers were not produced except for the OZO–BPL combination. These observations were consistent with the general scheme of the copolymerization involving a zwitterion intermediate which was generated by the reaction of a cyclic imino ether with AA or with BPL. A zwitterion was actually isolated in the combination of PhOZI with AA.

This paper describes the copolymerizations of various cyclic imino ethers with acrylic acid (AA) and β-propiolactone (BPL). Six cyclic imino ethers were employed in the present study. They are 2-oxazoline (OZO) and its 2-methyl- and 2-phenyl-substituted derivatives (MeOZO and PhOZO, respectively) and 5,6-dihydro-4*H*-1,3-oxazine (OZI) and its 2-methyl and 2-phenyl derivatives (MeOZI and PhOZI, respectively). Copolymerizations of all combinations did occur without any added catalyst. These copolymerizations belong to the so-called "no catalyst copolymerization" in which a nucleophilic monomer (M_N) and an electrophilic monomer (M_E) are reacted with each other to generate a key intermediate of zwitterion.[1] In the present study, cyclic imino ethers function as M_N, and AA and BPL are M_E monomers. It is also of interest to note that the copolymerizations of cyclic imino ethers with AA always gave the 1:1 alternating copolymers. On the other hand, copolymerizations with BPL produced copolymers having higher fractions of BPL unit except for the OZO–BPL system in which a 1:1 alternating copolymer was produced. Among the combinations of copolymerization of the above monomers, the copolymerizations of OZO with BPL[2] and its α-substituted derivatives[3] and with AA[4] have already been reported by us. The present paper gives a comprehensive description and discussion on the no catalyst copolymerizations of cyclic imino ethers with BPL and with AA.

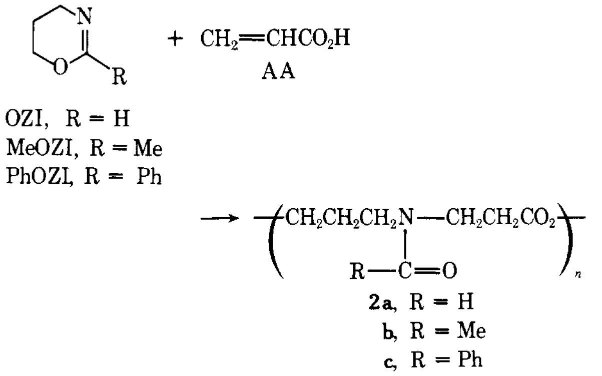
Results and Discussion

Copolymerizations of Cyclic Imino Ethers with AA. As has been reported before,[4] OZO was readily copolymerized with AA to produce an alternating copolymer. No added catalyst was required. This type of copolymerization was extended to the other five analogues of cyclic imino ethers. The results are shown in Table I. In every case, copolymerization took place in acetonitrile and DMF without any added catalyst. The product copolymers were always 1:1 alternating copolymers.

The structures of these alternating copolymers (**1** and **2**) were established by spectroscopic methods as well as by elemental analyses (Tables II and III). Further support for these structures was obtained by the identification of alkaline hydrolysis products of the copolymers in the typical combinations of OZO–AA and OZI–AA. The hydrolysis of **1a** or **2a** must give **3** or **4** together with an equimolar amount of sodium formate as shown by eq 3. The direct NMR observation of the hydrolysis mixture in D_2O showed the identical spectrum with that of a 1:1 mixture of the authentic samples of **3** or **4** with HCO_2Na in D_2O–NaOH (see Experimental Section).



$$\longrightarrow \left(\mathrm{CH_2CH_2}\underset{\mathrm{R{-}C{=}O}}{\underset{|}{\mathrm{N}}}\mathrm{{-}CH_2CH_2CO_2} \right)_n \qquad (1)$$



$$\longrightarrow \left(\mathrm{CH_2CH_2CH_2}\underset{\mathrm{R{-}C{=}O}}{\underset{|}{\mathrm{N}}}\mathrm{{-}CH_2CH_2CO_2} \right)_n \qquad (2)$$

$$\begin{array}{l} \mathbf{1a} \xrightarrow{\mathrm{NaOH}} \underset{\mathbf{3}}{\mathrm{HOCH_2CH_2NHCH_2CH_2CO_2Na}} + \mathrm{HCO_2Na} \\ \mathbf{2a} \xrightarrow{\mathrm{NaOH}} \underset{\mathbf{4}}{\mathrm{HOCH_2CH_2CH_2NHCH_2CH_2CO_2Na}} + \mathrm{HCO_2Na} \end{array} \qquad (3)$$

Each copolymer consisted of the BPL unit derived from AA as well as of the amide unit formed by the cationic ring-opening polymerization of cyclic imino ethers,[5] i.e., an alternating amide–ester type structure.

In the case of the OZO–AA system, the molecular weight exceeded 10 000, which was much higher than that from the OZO–BPL system where it was 6000 at most.[6]

MeOZO–AA, PhOZO–AA, MeOZI–AA, and PhOZI–AA systems gave copolymers of lower molecular weights. OZI–AA systems, however, produced copolymer of an increased molecular weight of 10 500 (Table I).

Copolymerizations of Cyclic Imino Ethers with BPL. This kind of copolymerization is not limited to AA. Previously,

Table I
Copolymerizations of Cyclic Imino Ethers (M_N) with AA and with BPL (M_E)[a]

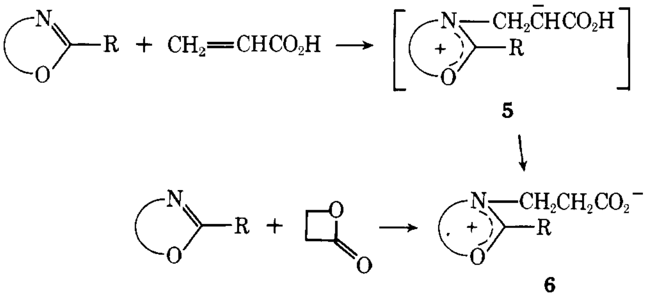
No.	M_N	M_E	Solvent	Temp, °C	Time, h	Copolymer yield, %	Copolymer composition,[b] M_N/M_E	Mol wt[c]
1	OZO	AA	DMF	50	26	40	58/42	1630
2	OZO	AA	Acetonitrile	50–60	28	57	50/50	13200
3	OZO	AA	Acetonitrile	50	17	38	54/46	3710
4	OZO	AA	Acetonitrile	60	15	65	50/50	11000
5	OZO	AA	Acetonitrile	30	24	15	56/44	
6	OZO	AA	Acetonitrile	10–20	72	22	60/40	
7	OZO	BPL	DMF	25	23	86	50/50	2230
8	OZO	BPL	Acetonitrile	10–20	24	61	50/50	3500
9	MeOZO	AA	Acetonitrile	60	15	75	50/50	1600
10	MeOZO	AA	DMF	50	15	68	50/50	1420
11	MeOZO	BPL	Acetonitrile	25	4	29	22/78	
12	PhOZO	AA	Acetonitrile	50	40	6	50/50	1360
13	PhOZO	BPL	Acetonitrile	15	44	8	12/88	
14	OZI	AA	Acetonitrile	50	50	99	50/50	10500
15	OZI	AA	Acetonitrile	50	27	99	50/50	2340
16	OZI	AA	Acetonitrile	RT[d]	72	96	50/50	1000
17	OZI	BPL	Acetonitrile	RT[d]	20	45	25/75	
18	MeOZI	AA	Acetonitrile	50	27	99	50/50	1150
19	MeOZI	BPL	Acetonitrile	RT[d]	20	54	23/77	
20	PhOZI	AA	Acetonitrile	120	130	19	50/50	1350
21	PhOZI	BPL	Acetonitrile	RT[d]	48	34	13/87	

[a] 7.5 mmol of each monomer in 2 ml of solvent. [b] Determined by NMR. [c] Determined by vapor pressure osmometry in DMF at 55 °C. [d] At room temperature.

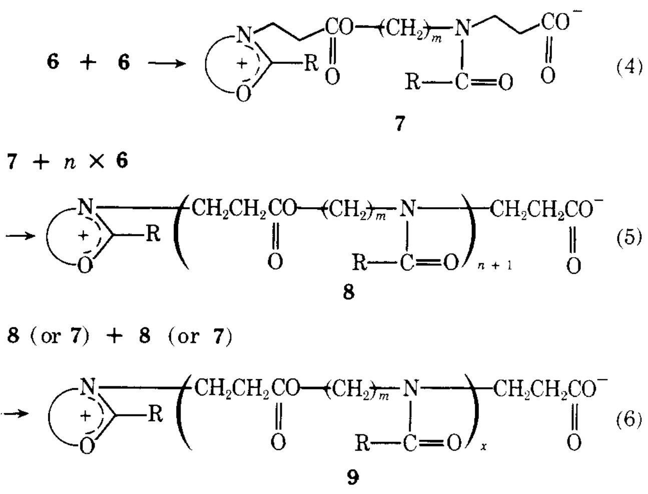
the copolymerizations of BPL with three 2-oxazolines (OZO, MeOZO, and PhOZO) were reported.[2] In the present study, six imino ether monomers were copolymerized with BPL to compare the results with the combinations of cyclic imino ethers and AA. Results are summarized in Table I.

The polymerization reaction took place at lower temperatures (10–25 °C) in all cases without added catalyst. However, the product copolymers were not of 1:1 composition except for the OZO–BPL system.[2] The content of the BPL unit was higher than 50 mol %. On the basis of the general scheme of the no catalyst copolymerization,[1] the production of copolymers of high BPL unit contents is ascribed to the formation of the BPL homosequences. The difference between the copolymerizations with AA and with BPL is explained by the difference of reactivity of homopropagation between AA and BPL monomers. The hydrogen-transfer homopolymerization of AA did not occur below 80 °C,[7] whereas the BPL propagation proceeds even at 0 °C.[8] Thus, AA is preferred to BPL for the preparation of 1:1 alternating copolymers.

Mechanism of Copolymerizations. All findings of the present study are consistent with the following scheme of reactions.



First, the cyclic imino ether adds to the electron deficient double bond of AA to generate a transient zwitterion 5 which has a carbanion site. Then, hydrogen transfer occurs in 5 to produce another zwitterion 6 which is the key intermediate of copolymerization. In the copolymerizations with BPL, 6 is generated directly from M_N and BPL.



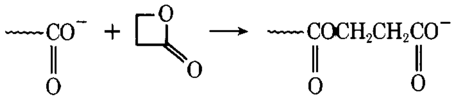
The reaction of 2 mol of 6 produces a dimeric zwitterion 7 which is the smallest species of propagation. By the successive reaction of 7 with 6, 7 grows to a macrozwitterion 8. In addition, the reaction between two propagating species (7 or 8) occurs, especially at a later stage of reaction, to produce a much longer zwitterion 9.[1a] Production of copolymers of higher molecular weights in the OZO–BPL and OZI–BPL combinations may be due to the higher ring-opening reactivities of cyclic onium rings derived from OZO and OZI, which are located at the end of macrozwitterions. In the cases of substituted cyclic imino ethers, the ring-opening reactivities of cyclic oniums are decreased, and hence the intermolecular reaction between two macro zwitterions is slow. Thus the molecular weights of the product copolymers are low.

When the above scheme of reactions occur exclusively, 1:1 alternating copolymer would be produced. In fact, the 1:1 alternating copolymerizations with AA are explained by the above scheme. In the cases of BPL, however, the carboxylate

Table II
Spectroscopic Analyses of 1:1 Alternating Copolymers from Cyclic Imino Ethers and Acrylic Acid

1a	NMR (D_2O): δ 2.80 (m, CH_2CO_2, 2 H), 3.77 (m, $-CH_2NCH_2-$, 4 H), 4.33 (m, $-CO_2CH_2-$, 2 H), 8.07 (d, NCHO, 1 H) IR (KBr): 2960, 1735 (ester), 1670 (amide), 1400, 1170, 1050, etc., cm^{-1}
1b	NMR ($CDCl_3$): δ 2.10 (s, $CH_3C{=}O$, 3 H), 2.61 (m, CH_2CO_2, 2 H), 3.57 (m, $-CH_2NCH_2-$, 4 H), 4.19 (m, $-CO_2CH_2-$, 2 H) IR (film): 2960, 1735 (ester), 1640 (amide), 1430, 1200, 1040, etc., cm^{-1}
1c	NMR ($CDCl_3$): δ 2.61 (m, CH_2CO_2, 2 H), 3.65 (m, $-CH_2NCH_2-$, 4 H), 4.19 (m, CH_2O, 2 H), 7.33 (m, $C_6H_5C{=}O$, 5 H) IR (film): 2960, 1725 (ester), 1620 (amide), 1420, 1260, 1170, 1015, 780, 700, etc., cm^{-1}
2a	NMR (D_2O): δ 1.97 (m, CCH_2C, 2 H), 2.88 (m, CH_2CO_2, 2 H), 3.54 (m, $-CH_2NCH_2-$, 4 H), 4.18 (m, $-CO_2CH_2-$, 2 H), 8.19 (d, NCHO, 1 H) IR (KBR): 2950, 1730 (ester), 1660 (amide), 1400, 1175, 1053, etc., cm^{-1}
2b	NMR ($CDCl_3$): δ 1.94 (m, CCH_2C, 2 H), 2.10 (d, $CH_3C{=}O$, 3 H), 2.60 (m, CH_2CO_2, 2 H), 3.44 (m, $-CH_2NCH_2-$, 4 H), 4.09 (m, $-CO_2CH_2-$, 2 H) IR (film): 2930, 1720 (ester), 1630 (amide), 1420, 1185, 1040, etc., cm^{-1}
2c	NMR ($CDCl_3$): δ 1.92 (m, CCH_2C, 2 H), 2.60 (m, CH_2CO_2, 2 H), 3.42 (m, $-CH_2NCH_2-$, 4 H), 4.10 (m, $-CO_2CH_2-$, 2 H), 7.33 (m, $C_6H_5C{=}O$, 5 H IR (film): 2950, 1720 (ester), 1620 (amide), 1430, 1250, 1175, 1050, 788, 700, etc., cm^{-1}

anion at an end of zwitterions may also attack free BPL monomer to produce the BPL homosequence (eq 7).



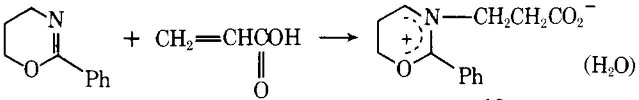
(7)

6-9

The propagation of eq 7 corresponds to the propagation in the anionic homopolymerization of BPL,[8] which is deemed quite possible under the conditions of the present study. Thus, the copolymerizations with BPL consist of the two competitive processes, i.e., the alternating propagation of eq 4–6 and the homopropagation of BPL of eq 7. The composition of the product copolymer is determined by the competition between the two processes. On the basis of kinetic studies,[5] the cationic homopropagation of cyclic imino ether from the cationic site of the zwitterion is assumed to be extremely slow under the reaction conditions in Table I.

In addition to the series of reactions of copolymerization, the possibility of the intramolecular reaction of the zwitterion to produce the so-called macrocyclic compounds should be considered. A preliminary experiment,[9] however, indicated that the contribution of the cyclization reaction is very small, e.g., the yield of cyclic oligomer was below 0.1% in the OZO–BPL copolymerization.

Isolation of the Zwitterion Intermediate. In the PhOZI–AA combination, the genetic zwitterion **10** was actually isolated in a reaction at lower temperature. This result is taken to be direct support not only for the mechanism of this specific combination of copolymerization but also for the general scheme of the no catalyst copolymerization via zwitterion intermediate. An equimolar mixture of PhOZI and AA in acetonitrile was kept at 5 °C for 10 days. From the reaction mixture, a zwitterion of **10** was isolated as a crystalline material containing 1 mol of water of crystallization. It is very hygroscopic and water may have been incorporated during the work-up procedure.



PhOZI

10

Furthermore, heating **10** at 120 °C in vacuo produced the copolymer **2c** in a quantitative yield with a molecular weight of about 800. Thus, the occurrence of the homopolymerization of **10** has been shown, which is an interesting example of the so-called "death-charge polymerization" proposed by Hatch et al.[10]

In the above copolymerization, the isolation of the zwitterion **10** is not necessary, i.e., an equimolar mixture of PhOZI and AA was first kept at 5 °C for 10 days and then the mixture was heated at 100 °C for 5 h to produce the copolymer **2c** in a yield of 25%.

Experimental Section

Materials. Solvents (acetonitrile and dimethylformamide) were purified as previously reported.[2] AA and BPL were commercial reagents and were purified by two careful distillations. Monomers, OZO,[2,11] OZI,[5d] MeOZI,[5e] and PhOZI,[5f] were prepared and purified as previously reported. MeOZO monomer was a commercial sample (Aldrich Chemical Co.) and was purified by fractional distillation (bp 110 °C). PhOZO was prepared by the isomerization reaction of *N*-benzoylethylenimine according to Kagiya's method;[12] bp 53 °C (0.5 mm) (lit.[12] 75.7–78.2 °C (2 mm)). All distillations were carried out under nitrogen. The authentic compounds of *N*-(2-hdyroxyethyl)-β-alanine[2,4] and *N*-(3-hydroxypropyl)-β-alanine[13] were prepared by the equimolar reactions of BPL with 2-aminoethanol and with 3-aminopropanol, respectively.

Polymerization Procedure. A typical example is as follows. In a sealed tube an equimolar mixture of OZO and AA (7.5 mmol each)

Table III
Elemental Analyses of 1:1 Alternating Copolymers of Cyclic Imino Ethers with AA

				Anal.					
				Calcd[a]			Found		
Copolymer	Appearance	Formula[a]	Sample No.	C	H	N	C	H	N
1a	Pale yellow gum	$(C_6H_9NO_3)_n$	2	50.34	6.34	9.79	50.32	6.33	9.69
1b	Colorless gum	$(C_7H_{11}NO_3)_n$	9	53.49	7.05	8.91	53.31	7.31	9.24
1c	Pale yellow grease	$(C_{12}H_{13}NO_3)_n$	12	65.74	5.98	6.39	65.51	6.05	6.39
2a	Pale yellow gum	$(C_7H_{11}NO_3)_n$	14	53.49	7.05	8.91	53.29	7.17	9.23
2b	Yellow gum	$(C_8H_{13}NO_3)_n$	18	56.12	7.65	8.18	55.93	7.80	8.22
2c	Colorless gum	$(C_{13}H_{15}NO_3)_n$	20	66.93	6.48	6.01	66.78	6.33	5.94

[a] For the 1:1 compositions of copolymers.

was dissolved in acetonitrile (2 ml) containing 0.04 mmol of *p*-methoxyphenol as a radical inhibitor under nitrogen. After the tube was maintained at 60 °C for 15 h, the reaction mixture was poured into a large amount of diethyl ether to precipitate the copolymer. After purification, the copolymer was dried in vacuo and weighed. The structure was determined by IR, NMR, and elemental analyses. The analytical data of the 1:1 copolymers are shown in Tables II and III.

In the cases of the copolymerization with BPL, the procedure was similar but the radical inhibitor was not added. The copolymer composition was determined by NMR. All the results are shown in Table I.

Molecular Weight Determination. The molecular weights of the cpolymers were measured by a vapor pressure osmometer (Hitachi Perkin-Elmer Model 115) in DMF at 55 °C.

Alkaline Hydrolysis of Copolymer. To 0.05 g of copolymer was added 1.0 ml of a 10% solution of NaOH in D_2O, and the reaction mixture was refluxed for 3 h. Then, the reaction mixture was subjected to NMR measurement. The NMR spectrum was compared with that of authentic compounds in alkaline D_2O solution. The results were as follows; the hydrolysis mixture of **1a**, i.e., **3** + HCO_2Na: NMR (D_2O) δ 8.40 (s, HCO_2Na, 1 H), 3.60 (t, OCH_2, 2 H), 2.64 (t, $-CH_2NCH_2-$, 4 H), 2.33 (t, CH_2CO_2, 2 H); the hydrolysis mixture of **2a**, i.e., **4** + HCO_2Na: NMR (D_2O) δ 8.40 (s, HCO_2Na, 1 H), 3.58 (t, OCH_2, 2 H), 2.16–2.95 (m, $CH_2NCH_2CH_2CO_2$, 6 H), 1.66 (m, CCH_2C, 2 H).

Isolation of Zwitterion 10 from PhOZI and AA. At 0 °C under nitrogen, 1.21 g (7.5 mmol) of PhOZI and 0.54 g (7.5 mmol) of AA were dissolved in 2 ml of acetonitrile in a tube. The tube was then sealed and maintained at 5 °C for 10 days. The solution was poured into an excess of diethyl ether to yield an oily product, which was dissolved in 3 ml of methylene chloride and reprecipitated in diethyl ether to give a white crystalline material. By filtration and drying 0.184 g of product **10** was isolated (11%), mp 145–146 °C. The structure was determined by the usual methods; NMR ($CDCl_3$) δ 2.28 (m, CCH_2C, 2 H), 2.50 (t, J_H = 7 Hz, CH_2CO_2, 2 H), 2.97 (t, J_H = 7 Hz, $-CH_2NCH_2-$, 4 H), 4.62 (t, J_H = 7 Hz, OCH_2, 2 H), 7.60 (m, C_6H_5C, 5 H); IR (KBr) 3430, 2960, 1725 (CO_2H), 1630 ($\nu_{C=N}$), 1400, 1280, 1110, 860, 710, etc., cm^{-1}. Anal. Calcd for $C_{13}H_{15}NO_3(H_2O)$: C, 62.18; H, 6.82; N, 5.57. Found: C, 61.63; H, 6.76; N, 5.51. The water in the hydrate would have been incorporated during work-up.

The polymerization of **10** was carried out as follows, i.e., 0.3 g of **10** was heated to 150 °C to melt it and then maintained at 120 °C for 5 h under vacuum. The product was dissolved in 1 ml of chloroform and reprecipitated into an excess of diethyl ether. The yield of polymer **2c** was quantitative.

References and Notes

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Polymerization via Zwitterion. 15. Alternating Copolymerizations of Cyclic Imino Ethers with Hydroxyalkyl Acrylates Involving Hydrogen Transfer of the Acrylates

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ABSTRACT: This paper describes an extension of studies on the no catalyst copolymerization, in which a nucleophilic monomer (M_N) and an electrophilic monomer (M_E) are mixed to produce the key intermediate of a zwitterion. In the present study, M_N monomer is a cyclic imino ether, i.e., 5,6-dihydro-4*H*-1,3-oxazine (OZI) or 2-methyl-2-oxazoline (MeOZO), and M_E monomer is 2-hydroxyethyl (HEA) or 3-hydroxypropyl acrylate (HPA). Reactions of the 1:1 monomer feed ratio gave 1:1 alternating copolymers of **3a**, **3b**, **3c**, and **3d**, respectively, from the combinations of OZI–HEA, OZI–HPA, MeOZO–HEA, and MeOZO–HPA without any added catalyst. A mechanism via zwitterion intermediate **8** was proposed, which involves the proton-transfer step from the hydroxy group (OH) to generate a zwitterion **8**. The produced copolymer **3** is composed of three functional groups of amide, ester, and ether.

The present paper describes an extension of studies on the no catalyst copolymerization,[1] in which a nucleophilic monomer (M_N) and an electrophilic monomer (M_E) are mixed to produce the key intermediate of a zwitterion. Alternating copolymerization of 2-oxazoline (M_N) with acrylic acid (M_E) to produce a copolymer of amide–ester type structure **1** has recently been described.[2] The interconversion of acrylic acid (AA) to the ester unit in **1** involves a proton-transfer step of the acid (Scheme I).

In a similar way, cyclic imino ethers were copolymerized with acrylamide (AM) to produce 1:1 alternating copolymers having amide–imidate structure, e.g., **2**, which were also supposed to be copolymers produced via zwitterions.[3] These findings prompted us to examine the copolymerizations of hydroxyalkyl acrylate as M_E which is also capable of proton transfer. In the present study, a hydroxyalkyl acrylate, 2-hydroxyethyl acrylate (HEA) or 3-hydroxypropyl acrylate, was paired with M_N of cyclic imino ethers of 5,6-dihydro-4*H*-1,3-oxazine (OZI) and 2-methyl-2-oxazoline (MeOZO). In all of the four combinations of M_N and M_E, the alternating