Syntheses and Physical Properties of Novel Optically Active Poly(ester−carbonate)s by Copolymerization of Substituted Trimethylene Carbonate with ϵ-Caprolactone and Their Biodegradation Behavior

Hajime Yasuda,* Mohad-Serah Aludin, Naoyuki Kitamura, Mari Tanabe, and Hiroyuki Sirahama

Department of Applied Chemistry, Faculty of Engineering, Hiroshima University, Higashi-Hiroshima, 739-8527, Japan

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ABSTRACT: This paper describes the synthesis and the biodegradation of optically active copolymers, poly[(*R*)-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone] and poly[(*S*)-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone] and poly[(*R*,*R*)-1,3-dimethyltrimethylene carbonate-*co*-ϵ-caprolactone] and poly[(*S*,*S*)-1,3-dimethyltrimethylene carbonate-*co*-ϵ-caprolactone]. The copolymers were prepared using a novel organolanthanide or $AlEt_3-H_2O$ as the polymerization initiators, and their biodegradation by various enzymes and acclimated activated sludges was studied as a function of their composition, stereochemistry, crystallinity, T_g (glass transition temperature), T_m (melting point), molecular weight, and polydispersity. The copolymers synthesized exhibited high molecular weights with rather narrow molecular weight distributions and produced thermoplastic films when (*R*)-1-MTC (1-MTC = 1-methyltrimethylene carbonate) or (*R*,*R*)-1,3-DTC (1,3-DTC = 1,3-dimethyltrimethylene carbonate) content is less than 50 mol %. Optically active and *racemic* copolymers prepared using 1-MTC/CL (CL = ϵ-caprolactone) ratios of 17/83 to 19/81 were effectively biodegraded by lipoprotein lipase, cholesterol esterase and activated sludge. For the copolymers prepared using various 1,3-DTC/CL ratios, the poly(*rac*-1,3-DTC-*co*-CL) was biodegraded faster than the poly[(*R*,*R*)-1,3-DTC-*co*-CL] and poly[(*S*,*S*)-1,3-DTC-*co*-CL] copolymers regardless of the 1,3-DTC/CL ratio. Biodegradation of all of these copolymers generated numerous cavities on the outermost surface of polymer films or solid masses without changing their molecular weight and polydispersity.

Introduction

Tailor-made biodegradable polymers may be used for a variety of biomedical applications such as devices for controlled drug release, suture filaments, artificial skin, resorptable prostheses, ligature clamps, and bone fixation plates. Biodegradable polycarbonates and their copolymers with ϵ-caprolactone (CL) form one class of polymer that can potentially be used for these applications. Furthermore, the biodegradation of copolymers containing aliphatic carbonate units has only been reported in a limited number of papers.[1,2] Therefore, we decided to synthesize and study the biodegradation of the copolymers between optically active aliphatic carbonates and ϵ-caprolactone.

The polymerization of five-membered ring aliphatic carbonates produces poly(ether−carbonates) with up to 50% ether linkage by a partial decarboxylation regardless of the initiator and reaction conditions.[3,4] However, the six-membered ring carbonates are known to polymerize to form polycarbonates, and the ring-opening polymerization of six-membered cyclic carbonates (1,3-dioxane-2-ones) such as trimethylene carbonate, 2-phenyltrimethylene carbonate, and neopentylene carbonate has been reported.

Polymerization of six-membered ring carbonates using typical cationic initiators such as triflic acid, methyl triflate, triethyloxonium fluoroborate, and $BF_3(OEt_2)$ always results in low-molecular weight polycarbonates.[5,6] More recently, extensive research has been devoted to the enzyme-catalyzed ring-opening polymerization of trimethylene carbonate.[7,8] However, this method generally leads to rather low molecular weight polymers with high polydispersities. In addition, the copolymerizations of cyclic carbonates with lactide or glycolide,[9−12] various lactones,[13−17] different types of carbonate,[18,19] adipic anhydride,[20] and cyclic imine[21] have also been reported.

To study the biodegradation of polycarbonates, we needed to prepare high molecular weight polymers with narrow molecular weight distributions to minimize their water solubility. Pure and high molecular weight poly(aliphatic carbonate)s have been prepared at moderate temperatures (<100 °C) using initiators such as aluminoxane, $BuSnCl_3$, ZnE_2-H_2O, $AlEt_2OR$, $Sn(Oct)_2$, and NaOMe[22−30] and, therefore, these organometallic initiators were investigated in this effort.

Our main objective was to investigate the relationship between the molecular structure and biodegradability of optically active copolymers. Therefore, we prepared the optically active copolymers, poly[(*R*)-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone] and poly[(*S*)-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone] and poly[(*R*,*R*)-1,3-dimethyltrimethylene carbonate-*co*-ϵ-caprolactone] and poly[(*S*,*S*)-1,3-dimethyltrimethylene carbonate-*co*-ϵ-caprolactone], initiated by novel organolanthanides such as $Sm(C_5Me_5)_2(THF)_2$ and $SmMe(C_5Me_5)_2(THF)$ or the $AlEt_3-H_2O$ catalyst system. This paper describes the synthesis of the copolymers and discusses the effect of their composition, stereochemistry, crystallinity, T_g (glass transition temperature), T_m (melting point), molecular weight, and polydispersity on the biodegradability caused by various enzymes and acclimated activated sludges.

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Table 1. Polymerization of (*R*)-1-Methyltrimethylene Carbonate[a]

catalyst	[I]/[M], mol %	time, h	temp, °C	yield, %	$M_n^c \times 10^3$	M_w/M_n^c	$[\alpha]^{25}$, deg
$AlEt_3-H_2O$(1:0.8)	1.0	48	60	62	65	1.72	−61
	0.5	48	60	45	55	1.50	−60
	0.2	48	60	28	26	1.36	−58
$Sn(Oct)_2$	1.0	48	100	31	14	1.22	−60
	0.5	48	100	24	15	1.25	−63
	1.0[b]	48	100	68	28	1.49	−63
	0.5[b]	48	100	67	42	1.43	−61
$Sm(C_5Me_5)_2$-$(THF)_2$	1.0	1	25	65	23	1.64	−57
	1.0	6	25	66	27	1.86	−57
	0.5	6	25	75	29	1.38	−59
	0.5	6	0	85	22	1.37	−59
$SmMe(C_5Me_5)_2$-(THF)	1.0	6	25	70	27	1.55	−58
	1.0	6	0	75	27	1.40	−58
	0.5	6	25	83	19	1.46	−60
	0.5	6	0	86	14	1.21	−62

[a] Polymerization in toluene, solvent/[M] = 5 vol/vol. [b] Bulk polymerization. [c] Determined by GPC (polystyrene standard).

Results and Discussion

1. Synthesis of Poly[(*R*)-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone] or Poly[(*S*)-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone]. The homopolymerization of optically active (*R*)-1-methyltrimethylene carbonate (1-MTC = 1-methyltrimethylene carbonate) was performed in toluene solution using various types of initiators such as $AlEt_3-H_2O$ (1:0.8), $Sn(Oct)_2$ (tin(II) 2-ethylhexanoate), $Sm(C_5Me_5)_2(THF)_2$, and $SmMe(C_5Me_5)_2(THF)$ dissolved in toluene (Table 1). The ring-opening polymerization requires relatively high temperatures (60−100 °C) with the $Sn(Oct)_2$ and $AlEt_3-H_2O$ systems, while $Sm(C_5Me_5)_2(THF)_2$ and $SmMe(C_5Me_5)(THF)$ perform well at room temperature and below. These organolanthanide initiators brought about higher yields and lower polydispersities when the ring-opening polymerization was carried out at 0 °C, while lowering the polymerization temperature to −78 °C resulted in no polymerization. The specific rotation of the polymer obtained by $Sn(Oct)_2$ was marginally higher than that obtained by the organolanthanide systems, and molecular weights obtained using $AlEt_3-H_2O$ were significantly higher than for the copolymers prepared with the other initiators tested. Since we needed high molecular weight copolymers with narrow molecular weight distributions to evaluate their biodegradability, we used the $AlEt_3-H_2O$ system to initiate the copolymerization of 1-MTC with ϵ-caprolactone (CL).

To prepare copolymers with different properties, a series of copolymers composed of various ratios of (*R*)-1-MTC and CL repeating units was synthesized using the $AlEt_3-H_2O$(1:0.8 molar ratio) system as the initiator (Table 2). The number average molecular weights of copolymers were measured by GPC using universal curve calibrated with standard polystyrene. The absolute values were also measured using DAWN DSP laser photometer equipped with GPC. Since these values are nearly identical, M_n was as a rule measured using universal curve. The number-average molecular weight of random copolymers thus obtained exceeds 106 000 at a CL ratio of more than 50 mol % (Scheme 1). CL itself produced a high molecular weight polymer with a rather narrow molecular weight distribution, but the molecular weight of poly[(*R*)-1-MTC] was rather low (41 000). In random copolymerization, the resulting molecular weights and polymer yields gradually decreased with increasing the content of (*R*)-1-MTC, while the molecular weight distribution of the copolymers was slightly affected only by the feeding ratio (1.45 for 10/90 to 1.7 for 30/70 to 70/30). We observed nearly the same results for the copolymerization of *rac*-1-MTC or (*S*)-1-MTC with CL (Tables 3 and 4).

Table 2. Preparation of Poly[(*R*)-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone][a]

(*R*)-1-MTC/CL (molar ratio)						
feed ratio	obsd[b]	yield, %	$M_n^c \times 10^3$	M_w/M_n^c	M_n^d	$[\alpha]^{25}$, deg
0/100	0/100	95.5	100	1.47	97	
10/90	6/94	93.6	180	1.45	178	−2.1
20/80	18/82	94.0	139	1.53		−11.1
30/70	29/71	94.2	112	1.68	110	−21.3
40/60	37/63	89.7	107	1.70		−22.1
50/50	46/54	90.0	106	1.67	105	−22.4
60/40	54/46	87.9	87	1.70		−26.6
70/30	65/35	87.5	68	1.70		−30.3
80/20	79/21	78.5	62	1.49	58	−39.4
90/10	87/13	61.2	57	1.45		−45.9
100/0	100/0	57.3	41	1.46	39	−67.2

[a] Catalyzed by $AlEt_3-H_2O$ (1:0.8). [b] Determined by ^1H NMR. [c] Determined by GPC(polystyrene). [d] Determined by GPC using DAWN DSP (absolute value).

Table 3. Preparation of Poly[*rac*-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone][a]

(*R*,*S*)-1-MTC/CL (molar ratio)				
feed ratio	obsd[b]	yield, %	$M_n^c \times 10^3$	M_w/M_n^c
0/100	0/100	95.5	100	1.47
10/90	8/92	80.8	173	1.95
20/80	17/83	80.5	150	1.54
30/70	28/72	80.3	131	1.62
40/60	35/65	85.2	121	1.60
50/50	46/54	90.0	119	1.57
60/40	58/42	84.9	90	1.62
70/30	66/34	79.5	75	1.65
80/20	75/25	65.5	69	1.46
90/10	88/12	60.3	60	1.48
100/0	100/0	55.8	51	1.35

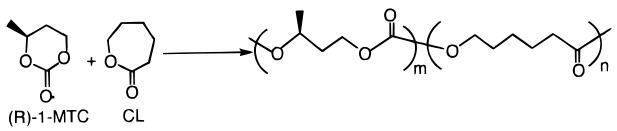
[a] Catalyzed by $AlEt_3-H_2O$(1:0.8), [b] Determined by ^1H NMR, [c] Determine by GPC.

Table 4. Preparation of Poly[(*S*)-1-methyltrimethylene carbonate-*ran*-ϵ-caprolactone][a]

1-MTC/CL (molar ratio)					
feed ratio	obsd[b]	yield, %	$M_n^c \times 10^3$	M_w/M_n^c	$[\alpha]^{25}$, deg
0/100	0/100	95.5	100	1.47	
20/80	18/82	89.2	150	1.71	+12.1
50/50	46/54	85.5	106	1.51	+21.9
100/0	100/0	60.3	51	1.46	+68.0

[a] Catalyzed by $AlEt_3-H_2O$ (1:0.8). [b] Determined by ^1H NMR. [c] Determined by GPC.

Scheme 1



The ^1H NMR spectrum of both homopoly[(*R*)-1-MTC] and poly[(*S*)-1-MTC] exhibited a symmetrical proton resonance expected for the β-methylene moiety (OCH-MeCH_2−) while poly(*rac*-1-MTC) showed an unsymmetrical resonance presumably due to the presence of

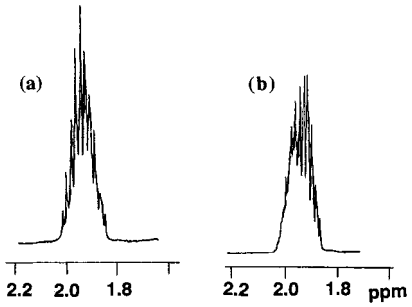
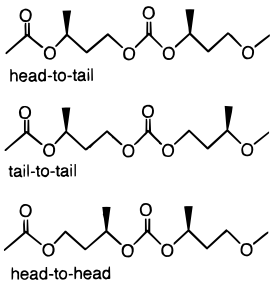


Figure 1. ^{1}H NMR spectrum of β-CH_2 of (a) poly[(*R*)-1-MTC] or poly[(*S*)-1-MTC] and (b) poly(*rac*-1-MTC) (b).

Scheme 2



a (*R*)−(*R*) or (*S*)−(*S*) diad sequence in combination with a (*R*)−(*S*) or (*S*)−(*R*) sequence (ca. 1:1 ratio) (Figure 1). The ^{13}C NMR spectrum of the homopolymers exhibited three peaks at 154.6, 154.8, and l55.0 ppm in a 1:98:1 ratio (Scheme 2) for the carbonyl carbon resonances. Therefore, only the 2% of the homopolymer involved bonding through head-to-head or tail-to-tail structures.

The ^{1}H NMR and ^{13}C NMR spectra of random copolymer of *rac*-1-MTC with CL (46/54) are shown in Figures 2 and 3, respectively. The CL carbonyl carbon resonance at around 173.5 ppm separated into two signals; one is from the poly(CL) units and the other is from poly(1-MTC/CL) units in a 1-MTC/CL ratio of 65/35. The 1-MTC carbonyl carbon also separated into two peaks in the same ratio, while the homopoly(*rac*-1-MTC) showed only a singlet peak at 154.8 ppm. Therefore, the resulting copolymer is concluded to partially consist of block sequences of poly(1-MTC) and poly(CL). In the present copolymerization, any elimination of CO_2 from 1-MTC was not observed as evidenced by the absence of a triplet peak due to the CH_2CH_2O group (ca. 3 0.4 ppm) in the ^{1}H NMR spectrum.

The specific rotation of the copolymers of (*R*)-1-MTC/CL was measured, and the values are listed in Table 2. The specific rotation varied from −2.1 to −67.2° indicating the presence of poly(1-MTC) and poly(CL) units in the expected ratio. The exact values of the specific rotation tell us that any helical structure is absent for this type of copolymer.

Thermal properties of the homo- and copolymers are shown in Table 5. An increase in the copolymers' 1-MTC content resulted in a drastic change of crystallinity ($-\Delta H_f$) in the case of 1-MTC/CL = 18/82. Further addition of 1-MTC units (28/72) improved the copolymer's crystallinity, melting point (T_m), and T_g values due to the formation of semicrystalline polymers. When the 1-MTC content increased more than 45−46%, T_m and $-\Delta H_f$ disappeared indicating that the resulting copolymer becomes completely amorphous.

2. Preparation of Poly[(*R*,*R*)-1,3-dimethyltrimethylene carbonate-*co*-ϵ-caprolactone]. Homopolymerization of (*R*,*R*)-1,3-dimethyltrimethylene carbonate (1,3-DTC) was explored using various initiators such as $Sn(Oct)_2$, $AlEt_3-H_2O$, $Sm(C_5Me_5)_2(THF)_2$, and $SmMe(C_5Me_5)_2(THF)$ (Table 6). The initiators $Sn(Oct)_2$ and $Zr(OBu)_4$ produced copolymers only in low yield, even at

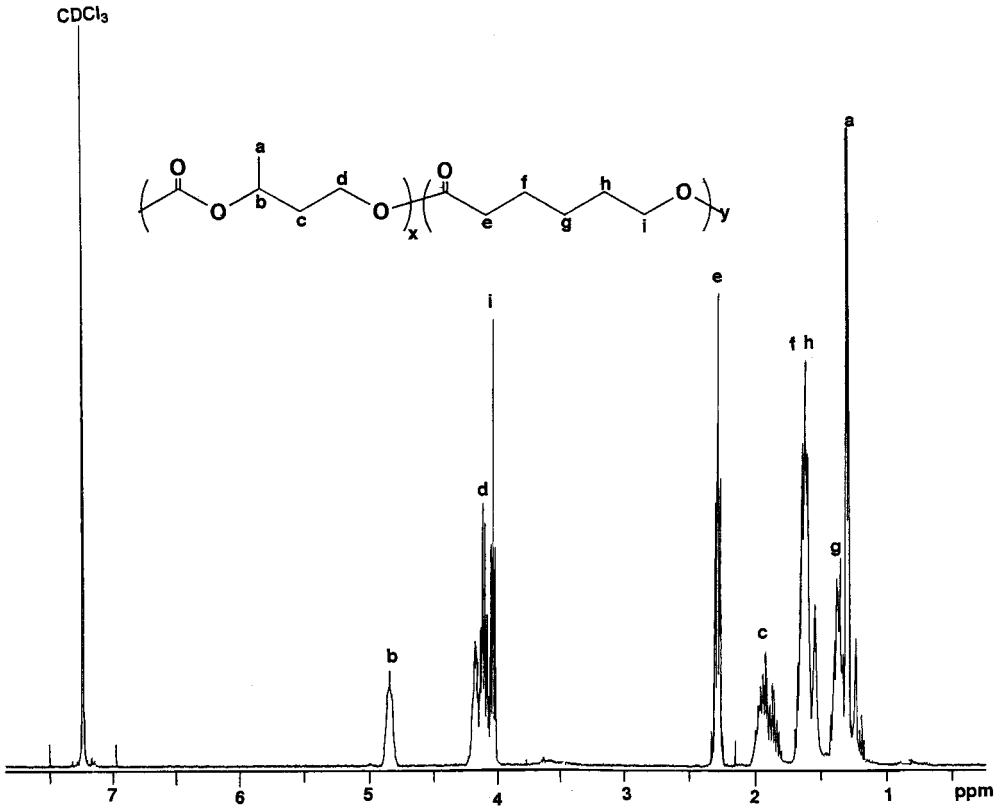


Figure 2. ^{1}H NMR spectrum of poly(*rac*-1-MTC-*co*-CL)(46/54) random copolymer in $CDCl_3$.

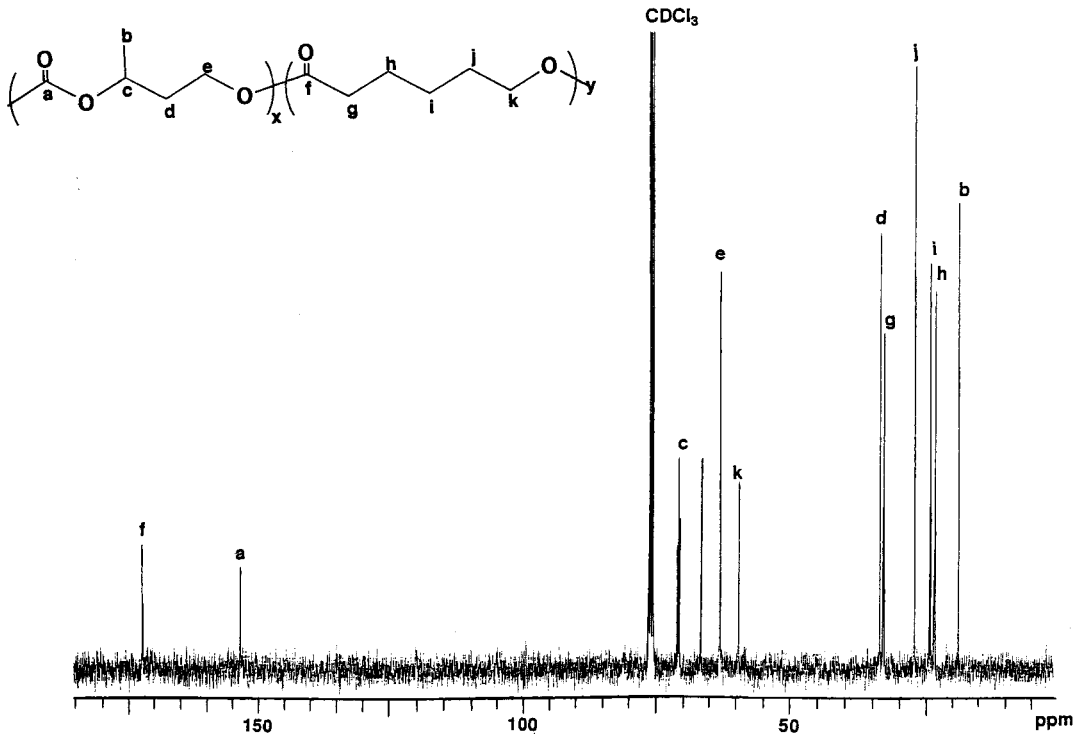


Figure 3. ^{13}C NMR spectrum of poly(*rac*-1-MTC-*co*-CL)(46/54) random copolymer in $CDCl_3$.

Table 5. Thermal Properties of Homopoly(1-MTC) and Copolymers Poly(1-MTC/CL)

composition	$M_n \times 10^3$	T_g,[a] °C	T_m,[a] °C	$-\Delta H_f$,[a] J/g
poly[(*R*)-1-TMC]	41	−10.0		
poly[*rac*-1-TMC]	51	−10.5		
poly[(*S*)-1-TMC]	51	−9.8		
poly[CL]	100	−60.0	60.5	118.2
poly[(*R*)-1-TMC-*co*-CL]				
6/94	180	−59.2	58.2	70.7
18/82	139	−54.1	37.2	24.3
29/71	112	−51.3	49.4	50.1
46/54	106	−49.4		
65/35	68	−45.7		
poly[*rac*-1-TMC-*co*-CL]				
8/92	173	−57.5	58.2	70.7
17/83	150	−53.9	37.1	26.9
28/72	131	−50.3	49.4	48.0
46/54	119	−49.3		
65/35	75	−45.7		
poly[(*S*)-1-TMC-*co*-CL]				
18/82	150	−58.9	37.5	22.6
46/54	106	−49.3		

[a] Determined by DSC.

Table 6. Homopolymerization of (*R*,*R*)-1,3-Dimethyltrimethylene Carbonate

catalyst	[I]/[M], mol %	time, h	temp, °C	yield, %	$M_n \times 10^3$	M_w/M_n	$[\alpha]^{25}$, deg
$AlEt_3-H_2O$[a]	2.0	48	60	35	13	1.08	−65
(1:0.8)	1.0	48	60	22	11	1.53	−65
	0.5	48	60	10	11	1.55	−65
$Sn(Oct)_2$[b]	2.0	48	100	17	12	1.15	−66
	1.0	48	100	8	11	1.10	−62
	0.5	48	100	2	10	1.11	−63
$Zr(OPr)_4$[b]	2.0	48	100	2	8	1.08	−65
	1.0	48	100	22	8	1.10	−65
	0.5	48	100	40	11	1.14	−64
$SmMe(C_5Me_5)_2$-	1.0	24	25	96	24	1.53	−68
(THF)[a]	1.0	6	0	*c*	30	1.16	−68
	1.0	24	0	95	21	1.17	−68
$Sm(C_5Me_5)_2$-	1.0	24	25	75	21	1.26	−68
$(THF)_2$[a]	1.0	24	0	27	25	1.25	−68

[a] Polymerization in toluene, solvent/[M] = 3.0 vol/vol. [b] Bulk polymerization. [c] Trace.

Table 7. Copolymerization of (*R*,*R*)-1,3-Dimethyltrimethylene Carbonate with CL[a]

1,3-(*R*,*R*)-DTC/CL (mol %)								
feed ratio	obsd[b]	yield, %	$M_n \times 10^3$	M_w/M_n	$[\alpha]^{25}$, deg	T_m, °C	T_g, °C	$-\Delta H_f$, J/g
10/90	3/97	91	50	1.20	-2	64.2	-58	111
20/80	14/86	88	49	1.17	-13	54.2	-51	85
30/70	22/78	87	47	1.18	-19	45.2	-48	65
40/60	34/66	79	41	1.16	-26	36.4	-45	33
50/50	42/58	80	39	1.14	-33	30.7	-33	25
60/40	56/44	72	31	1.14	-42	45.7	-20	16
80/20	71/29	65	25	1.10	-63	86.8	2	32

[a] Monomer/initiator (mol/mol) = 200; $SmMe(C_5Me_5)_2(THF)$ 5.0 × 10^{-3} M, Polymerization was conducted in toluene at 0 °C; solvent/monomer (vol/vol) = 3.0. [b] Determined by ^1H NMR.

high polymerization temperatures and in the absence of solvent. The absolute value of the specific rotation was also lower than those obtained using $SmMe(C_5Me_5)_2(THF)$. The $AlEt_3-H_2O$ system catalyzed the polymerization at 60 °C to produce moderate yields. The organometallic compound, $SmMe(C_5Me_5)_2(THF)$, gave the best results with respect to the polymer yield, molecular weights and specific rotations, when the polymerization was carried out at 25 °C. Therefore, we chose the $SmMe(C_5Me_5)_2(THF)$ complex to initiate the copolymerization of 1,3-DTC and CL.

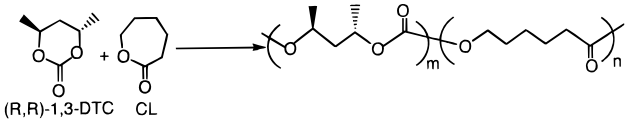
The results of copolymerization of (*R*,*R*)-1,3-DTC with CL and (*S*,*S*)-1,3-DTC or *rac*-1,3-DTC with CL are shown in Tables 7 and 8, respectively (Scheme 3). All the polymers exhibited high molecular weights, sufficiently low polydispersities, and high polymer yields. ϵ-Caprolactone reacts readily with (*R*,*R*)-1,3-DTC or (*S*,*S*)-1,3-DTC in toluene, and the composition of the copolymers agreed well with the monomer feeding ratio. However, the reactivity of *rac*-1,3-DTC with CL is significantly lower (less than half of that of *R*,*R*-1,3-

Table 8. Copolymerization of (*S,S*)-1,3- or *rac*-1,3-Dimethyltrimethylene Carbonate with CL[a]

1,3-DTC/CL (mol %)								
feed ratio	obsd[b]	yield, %	M_n[c] × 10^3	M_w/M_n	$[\alpha]^{25}$, deg	T_m, °C	T_g, °C	$-\Delta H_f$, J/g
S,S								
5/95	2/98	91	50	1.29	+1	64.6	−61	112
20/80	11/89	99	48	1.13	+11	59.7	−51	93
40/60	32/88	89	42	1.12	+29	42.5	−44	37
60/40	55/45	87	39	1.10	+45	48.3	−20	9
rac								
20/80	6/94	77	47	1.11		59.2	−55	102
40/60	16/86	60	44	1.08		51.3	−43	79
60/40	30/70	42	41	1.06		45.4	−47	46

[a] $SmMe(C_5Me_5)_2(THF)$, toluene, 0 °C. [b] Determined by ^1H NMR. [c] Determined by GPC.

Scheme 3



DTC) due to the presence of *meso* type compounds (*R,S*- or *S,R*-1,3-DTC). T_m values and the crystallinity of the 1,3-DTC/CL copolymers increased with increasing CL content of the copolymers.

3. Biodegradation of poly[(*R*)-1-methyltrimethylene carbonate-co-ϵ-caprolactone] or poly[(*S*)-1-methyltrimethylene carbonate-*co*-ϵ-caprolactone]. In the previous paper, we described the excellent biodegradation of poly[(*R*)-MOHEL-*co*-CL] (MOHEL = 3-methyl-4-oxa-6-hexanolid) in a 9/91−14/86 ratio by the enzymes, seawater, and activated sludge.[31]

The poly[(*R*)-1-MTC-*co*-CL] containing more than 80 mol % CL units exhibited good film-formability, but those containing less than 70 mol % CL units do not give thermoplastic films. Therefore, solid masses (thickness 1.0 mm) were used for evaluating the relative biodegradability of the 1-MTC/CL copolymers with various enzymes. To establish a reference point, we first tested the resistance of the copolymers to hydrolysis in TES and Tricine buffer solutions. All but one sample tested was resistant to chain cleavage up to 200 days by hydrolysis with TES and Tricine buffer solutions even when the buffer solution was shaking. No change in molecular weight and polydispersity was observed for these copolymers. The exception was that significant chain scission occurred for poly(trimethylene carbonate-*co*-CL) (TC/CL ratio =12/88 mol %) with $M_n = 120 \times 10^3$ leading to $M_n = 50 \times 10^3$ after hydrolysis over a period of 400 days with phosphate buffer solution.[1]

The homopolymers, poly(CL) and poly[(*R*)-1-MTC], degraded unexpectedly slowly in lipoprotein lipase, and the extent of degradation was unaffected by molecular weight, storage temperature and shaking motions. The weights of homopolymers remaining after 200 h immersion were 74% and 92%, respectively. Poly(trimethylene carbonate), exhibiting no alkyl substituent, is known to show high biodegradability as evidenced by the decomposition at peritoneal cavity of rats.[32] Poly(ethylene carbonate) also exhibits good bioabsorption in vivo, while branched poly carbonate, poly(1-methylethylene carbonate), shows no biodegradability.[33] Thus the methyl substituent on the carbonate unit is expected to suppress the attack by lipoprotein lipase as was observed. Degradation of the copolymers varied largely

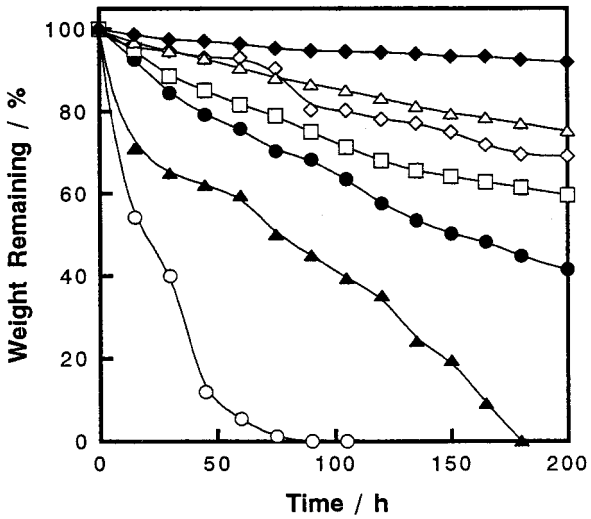


Figure 4. Enzymatic degradation of poly[(*R*)-1-MTC-*co*-CL] by lipoprotein lipase (solid masses, 37 °C, pH 8.0). 1-MTC/CL: 100/0 (−◆−); 65/35 (−△−); 46/54 (−□−); 30/70 (−●−); 18/82 (−○−); 6/94 (−▲−); 0/100 (−◇−).

depending on the polymer composition and the enzymes used. Figure 4 shows the effect of lipoprotein lipase on the degradation of poly[(*R*)-1-MTC-*co*-CL] with various 1-MTC/CL ratios. The copolymers, poly[(*R*)-1-MTC-*co*-CL], with 1-MTC/CL ratios of 18/82 and 6/94 were rapidly biodegraded. The copolymer composed of 18/82 ratio showed ∼95% (not complete at 50 h in Figure 4) degradation after immersing the sample in enzyme solution for 50 h. This fast degradation probably originated from the reduction of crystallinity as indicated by the heat of fusion (e.g. $-\Delta H_f$ of poly(CL) is 118 J/g; that of poly[(*R*)-1-MTC-*co*-CL](18/82) is 24.3 J/g). However, the biodegradation tests using lipoprotein lipase indicate that the copolymers containing more than 30 mol % (*R*)-1-MTC units showed extremely low degradability. Thus, the degradability of copolymers containing greater than 30 mol % (*R*)-1-MTC units decreased markedly.

To elucidate the effect of stereochemistry of the monomers on biodegradation, we also investigated the degradability of poly[*rac*-1-MTC-*co*-CL] or poly[(*S*)-1-MTC-*co*-CL] with lipoprotein lipase. As shown in Figures 5 and 6, the degradation behavior of both poly[(*S*)-1-MTC-*co*-CL] and poly(*rac*-1-MTC-*co*-CL) were nearly the same as for poly[(*R*)-1-MTC-*co*-CL], especially for copolymers with 1-MTC/CL ratios between 17/83 and 18/82. Thus, the degradability of 1-MTC/CL copolymers could be effectively improved by adding a small amount of *rac*-carbonate and does not require the use of expensive optically active carbonates.

The weight loss of the 1-MTC/CL copolymers exceeded that of poly(2,2-dimethyltrimethylene carbonate-*co*-CL) (13/87), which is observed to be 80%.[34] However, the low biodegradation of poly(*rac*-l-MTC-*co*-CL)(46/54), containing a relatively high 1-MTC content, implies that the biodegradability of poly[(*R*)-MTC-*co*-CL] and poly-[(*S*)-1-MTC-*co*-CL] is superior to poly(*rac*-1-MTC-*co*-CL) copolymers, presumably due to the complete lack of crystallinity (or turning to totally amorphous state) of poly(*rac*-1-MTC-*co*-CL). On the basis of this observation, we conclude that some crystalline or semicrystalline sequence is needed as scaffolding to endow the sample with good biodegradability.[35]

Enzymatic degradation of poly(1-MTC-*co*-CL) by cholesterol esterase from *Pseudomonas* sp was also exam-

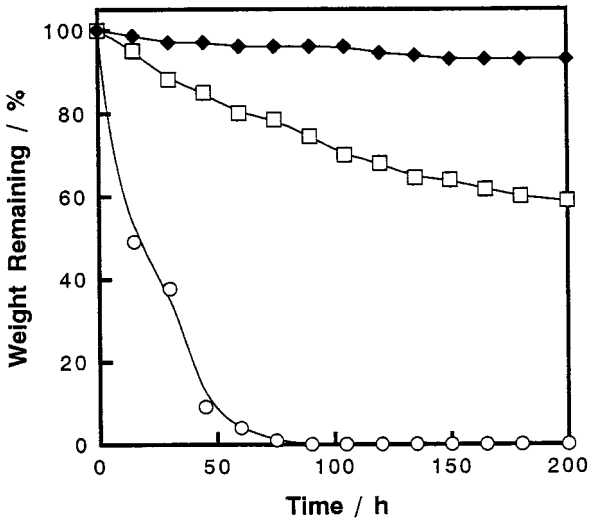


Figure 5. Enzymatic degradation of poly[(*S*)-1-MTC-*co*-CL] by lipoprotein lipase. 1-MTC/CL: 100/0 (−◆−); 46/54 (−□−); 18/82 (−○−).

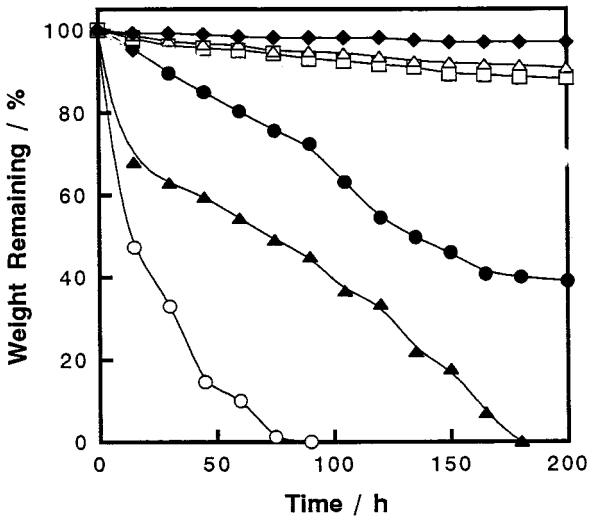


Figure 6. Enzymatic degradation of poly(*rac*-1-MTC-*co*-CL) by lipoprotein lipase. 1-MTC/CL: 100/0 (−◆−); 65/35 (−△−); 46/54 (−□−); 30/70 (−●−); 17/83 (−○−); 6/94 (−▲−).

ined using (*R*)-, (*S*)- and *rac*-1-MTC in various ratios (Figure 7). Poly[(*R*)-1-MTC-*co*-CL] (18/82 molar ratio) shows the best degradability, and the higher content of (*R*)-1-MTC resulted in less biodegradability. The use of (*S*)-1-MTC and *racemic* isomers in a 18/82 ratio again resulted in the best degradation regardless of the stereochemistry of 1-MTC (Figure 8).

To investigate the biodegradability of these copolymers in natural environments, degradation with acclimated activated sludge was measured using three types of copolymers, i.e., poly[(*R*)-1-MTC-*co*-CL], poly-[(*S*)-1-MTC-*co*-CL], and poly(*rac*-MTC-*co*-CL). Figure 9 depicts the observed weight loss for poly(1-MTC-*co*-CL) after immersion in acclimated activated sludge for 75 days. Both poly[(*R*)-1-MTC-*co*-CL] and poly[(*S*)-1-MTC-*co*-CL] showed a slightly higher weight loss compared with poly(*rac*-1-MTC-*co*-CL). This result is consistent with the degradation by cholesterol esterase.

4. **Biodegradation of Poly[(*R*,*R*)-1,3-dimethyltrimethylene carbonate-*co*-ϵ-caprolactone] or Poly-[(*S*,*S*)-1,3-dimethyltrimethylene carbonate-*co*-ϵ-caprolactone].** These copolymers, containing less than 50 mol % 1,3-dimethyltrimethylene carbonate (1,3-DTC)

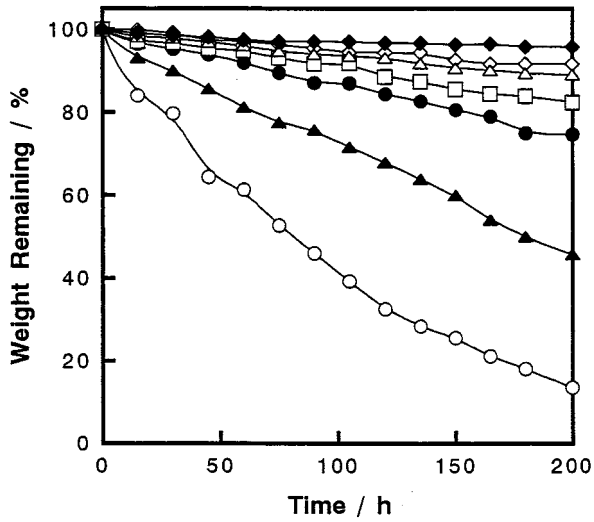


Figure 7. Enzymatic degradation of poly(*rac*-1-MTC-*co*-CL) by cholesterol esterase. 1-MTC/CL: 100/0 (−◆−); 65/35 (−△−); 46/54 (−□−); 30/70 (−●−); 18/82 (−○−); 6/94 (−▲−); 0/100 (−◇−)

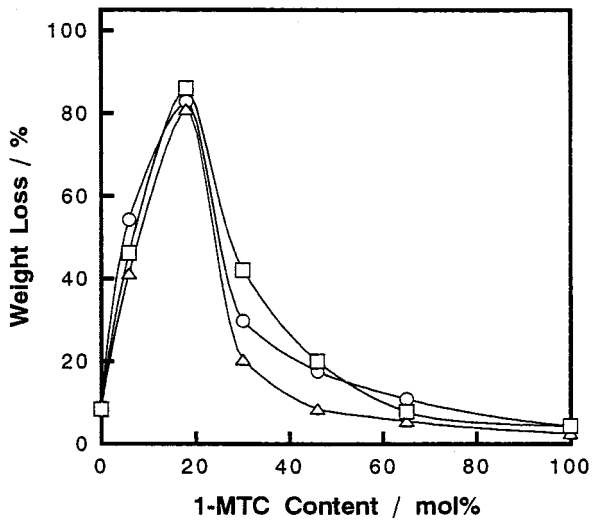


Figure 8. Weight loss of poly(1-MTC-*co*-CL) as a function of 1-MTC content after 200 h exposure to cholesterol esterase solution: poly[(*R*)-1-MTC-*co*-CL] (−○−); poly[(*S*)-1-MTC-*co*-CL] (−□−); poly(*rac*-1-MTC-*co*-CL) (−△−).

units, were capable of forming an elastic film. Therefore, the biodegradation test was carried out using translucent films. All of the polymers, poly[(*R*,*R*)-1,3-DTC-*co*-CL], poly[(*S*,*S*)-1,3-DTC-*co*-CL], or poly[*rac*-1,3-DTC-*co*-CL], showed no hydrolytic degradation in TES or Tricine buffer after subjecting the sample over a period of 250 h regardless of the composition (2/98−55/45). In sharp contrast to this behavior, significant enzymatic degradation of the polymer films of poly[(*R*,*R*)-1,3-DTC-*co*-CL]((3/97−14/86), containing a relatively small amount of 1,3-DTC units, was observed using cholesterol esterase in TES buffer (Figure 10).

The weight loss decreases noticeably with an increase of (*R*,*R*)-1,3-DTC content in the copolymer. Homopoly-(CL) itself can be bulk degraded when the sample used was in a film state, but the 3/97 copolymer degrades more quickly during the 150 h period. The degradation behavior of poly[(*S*,*S*)-1,3-DTC-*co*-CL] resembles that of poly[(*R*,*R*)-1,3-DTC-*co*-CL] (Figure 11). Note that the (*R*,*R*)-1,3-DTC/CL or (*S*,*S*)-1,3-DTC/CL copolymers with DTC/CL ratios of 55/45 exhibited no biodegradability.

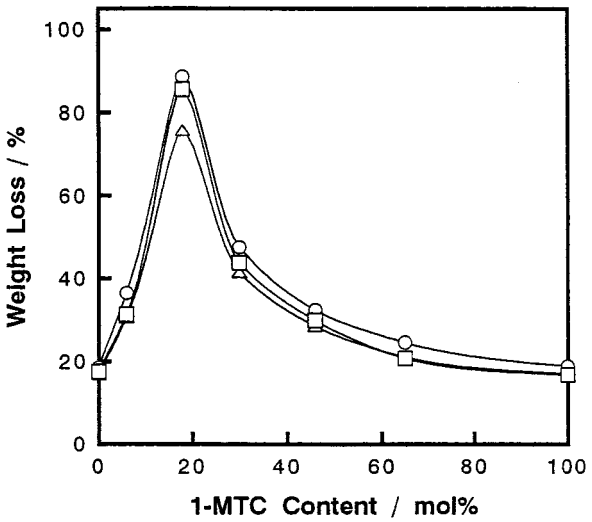


Figure 9. Weight loss of poly(1-MTC-*co*-CL) as a function of 1-MTC content after 75 days degradation in activated sludge: poly[(*R*)-1-MTC-*co*-CL] (−○−); poly[(*S*)-1-MTC-*co*-CL] (−□−); poly(*rac*-1-MTC/CL) (−△−).

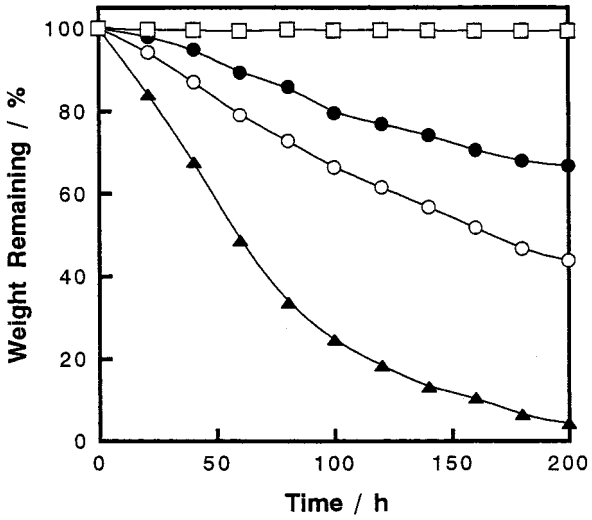


Figure 10. Degradation of poly[(*R*,*R*)-1,3-DTC-*co*-CL] by cholesterol esterase in TES buffer (37 °C, pH 7.4): 56/44 (−□−); 34/66 (−●−); 14/86 (−○−); 3/97 (−▲−).

In contrast, poly(*rac*-1,3-DTC-*co*-CL) showed a much higher degradability for every feeding ratio (Figure 12). The 6/94 copolymer degraded completely when the mixture was stirred for 100 h. More pronounced weight loss was observed in the case of poly(*rac*-1,3-DTC-*co*-CL) (16/84 ratio) in the initial stage (<50 h).

The ^{1}H NMR spectrum indicates that the *rac*-1,3-DTC monomer is composed of (*R*,*R*)- or (*S*,*S*)-1,3-DTC and *meso*-1,3-DTC in a ca. 1:1 ratio (Figure 13b). Therefore, the resulting 1,3-DTC copolymer contains the *meso*-1,3-DTC unit in ca. 50 mol %. The *meso*-1,3-DTC unit showed higher enzymatic degradability than (*R*,*R*)- or (*S*,*S*)-1,3-DTC units due to the lack of crystallinity and the steric repulsion between neighboring methyl groups. The ease of enzymatic degradation is estimated to be *RR*/*SR* sequence > *RR*/*RS* and *RR*/*SS* > *RR*/*RR* or *SS*/*SS* (Scheme 4).

The enzymatic degradation of poly[(*R*,*R*)-1,3-DTC-*co*-CL] (3/97) and poly[(*S*,*S*)-1,3-DTC-*co*-CL] (2/98) was obviously faster with lipoprotein lipase than cholesterol esterase. A 95% weight loss was realized in only 10 h with lipoprotein lipase. Also, poly(*rac*-1,3-DTC-*co*-CL) (5/95) showed complete weight loss in 7 h, while poly(*rac*-1,3-DTC-*co*-CL) (16/84) showed complete weight loss in 45 h (Figure 14). Thus, the caprolactone copolymers containing small amounts of 1,3-DTC units show high enzymatic degradation.

The biodegradation also proceeds very rapidly when poly(*rac*-1,3-DTC-*co*- CL) (5/95) was immersed in activated sludge, while poly[(*R*,*R*)-1,3-DTC-*co*-CL] (34/66) and poly[(*S*,*S*)-1,3-DTC-*co*-CL] (32/68) did not degrade so rapidly (Figure 15) and poly[(*R*,*R*)-1,3-DTC-*co*-CL]

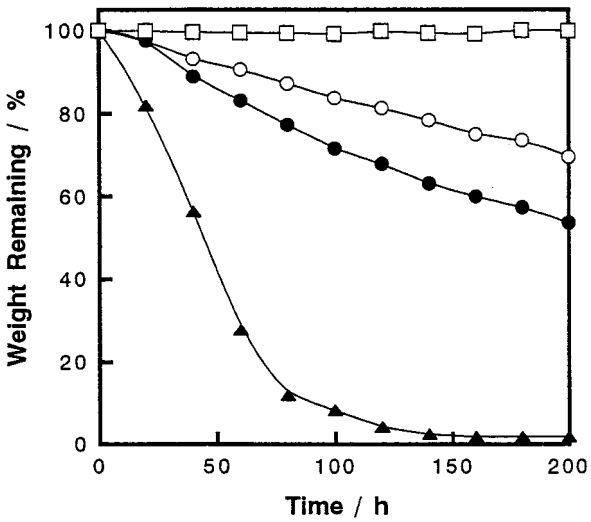


Figure 11. Enzymatic degradation of poly[(*S*,*S*)-1,3-DTC-*co*-CL] by cholesterol esterase: 55/45 (−□−); 32/68 (−●−); 11/89 (−○−); 2/98 (−▲−).

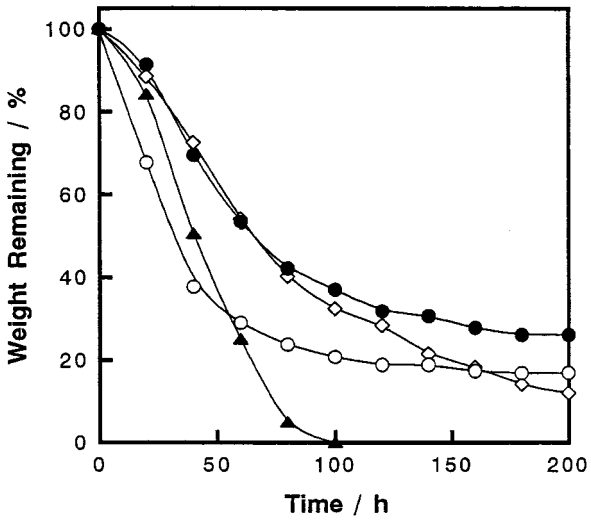


Figure 12. Degradation of poly(rac-1,3-DTC-*co*-CL) by cholesterol esterase in TES buffer (37 °C, pH 7.4): 36/62 (−●−); 16/84 (−○−); 6/94 (−▲−); 0/100 (−◇−).

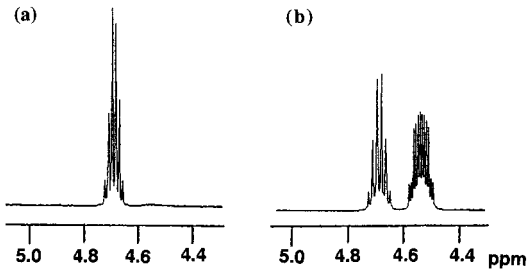


Figure 13. ^{1}H NMR spectra of (*R*,*R*)-1,3-DTC or (*S*,*S*)-1,3-DTC (a) and *rac*-1,3-DTC including (*R*,*R*)- and (*S*,*S*)-isomers and (*R*,*S*)- or (*S*,*R*)-*meso* isomers (b).

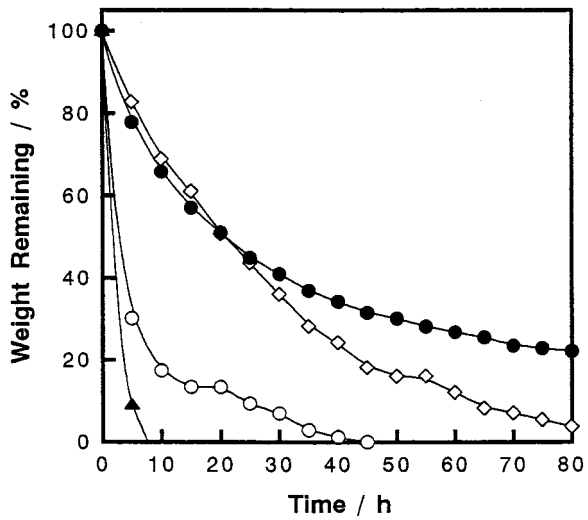


Figure 14. Degradation of poly(*rac*-1,3-DTC-*co*-CL) by lipoprotein lipase in Tricine buffer (37 °C, pH 8.0): 30/70 (−●−); 16/84 (−○−); 5/95 (−▲−); 0/100 (−◇−).

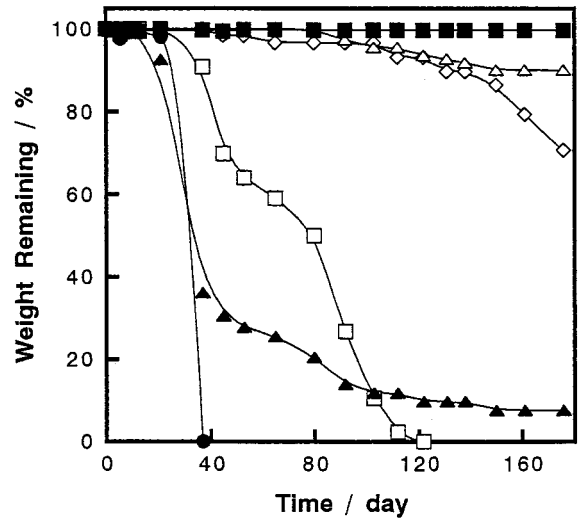
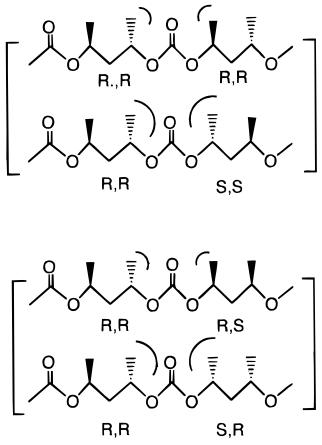


Figure 15. Biodegradation of poly(*rac*-1,3-DTC-*co*-CL) by activated sludge: 5/95 (−●−); 30/70 (−▲−); (*R*,*R*)-1,3-DTC-*co*-CL 14/86 (−□−); 34/66 (−◇−); (*S*,*S*)-1,3-DTC-*co*-CL 32/68 (−△−), 55/45 (−■−).

Scheme 4



(56/44) and poly[(*S*,*S*)-1,3-DTC-*co*-CL] (55/45) showed no biodegradability.

5. Biodegradability of Blended Polymers. Blended polymer films of polycarbonate/poly(CL) in a 5/95 molar ratio were prepared by a casting method after mixing poly[(*R*)-1-MTC], poly[(*S*)-1-MTC], poly(*rac*-1-MTC), poly-[(*R*,*R*)-1,3-DTC], poly[(*S*,*S*)-1,3-DTC], or poly(*rac*-1,3-DTC) with poly(CL) in THF. The biodegradation tests for these films were carried out with two enzymes and activated sludge. Microscopically homogeneous poly[(*R*)-1-MTC]/poly(CL) or poly[(*S*)-1-MTC]/poly(CL) blends revealed relatively low biodegradation accompanied by a rather small weight loss (ca. 25%) and small changes in morphology (SEM). For comparison, the random copolymer, poly[(*R*)-1-MTC-*co*-CL] (6/94), showed 60% weight loss by lipoprotein lipase over a period of 100 h. Weight loss of the polymer blend, poly[(*R*)-1-MTC]/poly-(CL)(5/95), was also considerably lower (13%) after immersion for 70 days in activated sludge as compared to that observed for the random copolymer, poly[(*R*)-1-MTC-*co*-CL] (6/94) (40%).

Similar results were obtained for a poly[(*R*,*R*)-1,3-DTC]/poly(CL) 5/95 blend in the degradation with cholesterol esterase. The remaining portion of the random copolymer, poly[(*R*,*R*)-1,3-DTC-*co*-CL] (3/97), was 19% after exposing the sample to cholesterol esterase for 100 h, while the blended polymer retained 71% of its weight.

Complete decomposition of poly(*rac*-1,3-DTC-*co*-CL) (5/95) was realized with activated sludge after 38 days, while the blended polymer, poly(*rac*-1,3-DTC)/poly(CL) (5/95), retained 40% of its original weight. Thus, good biodegradability was not achieved when the homopolymers were blended with each other.

The inefficient biodegradation of the blended polymers may be due to poor compatibility between the two polymers while random copolymerization brings about homogeneous mixing at the atomic level and allowed good biodegradation.

Table 9. Changes in Molecular Weight and Composition of Poly[(*R*)-1-MTC-*co*-CL] before and after Degradation by Lipoprotein Lipase for 150 h

before degradation				after degradation				
composition[a]	$M_n \times 10^3$	M_w/M_n	wt loss, %	composition[a]	$M_n \times 10^3$	M_w/M_n	T_m, °C	$-\Delta H_f$, J/g
6/94	180	1.45	38.2	9/91	172	1.40	60.1	73.2
18/82	139	1.53	95.0	21/79	136	1.49	55.5	68.2
29/71	112	1.68	25.6	32/68	108	1.59	50.2	56.3
46/54	106	1.67	17.5	46/54	105	1.65		38.5
65/35	68	1.70	8.2	66/34	67	1.70		
100/0	41	1.46	3.5	100/0	41	1.49		

[a] Determined by ^{1}H NMR.

6. Changes in the Properties of the Copolymers before and after Enzymatic Degradation. The molecular weight, polydispersity, and composition of poly-[(*R*)-1-MTC-*co*-CL] before and after degradation with lipoprotein lipase were examined by GPC and ^{1}H NMR analyses. Table 9 presents the results obtained after 150 h incubation (refer also Table 5). The values of M_n and M_w/M_n decreased slightly during the enzymatic degradation. Contrary to this behavior, random chain scission was dominant for poly(CL)[31] and high molecular weight poly(trimethylene carbonate),[1] which resulted in the significant broadening of the molecular weight distribution. The exception is the (*R*)-1-MTC-*co*-CL copolymer with a MTC/CL ratio of 6/94. This copolymer showed a substantial decrease in the content of CL units and M_n, and an increase in the melting point and $-\Delta H_f$ indicating preferential biodegradation of amorphous poly(CL) units. Similar results were obtained using poly[(*S*)-1-MTC-*co*-CL], poly(*rac*-1-MTC-*co*-CL), poly[(*R*,*R*)-1,3-DTC-*co*-CL],

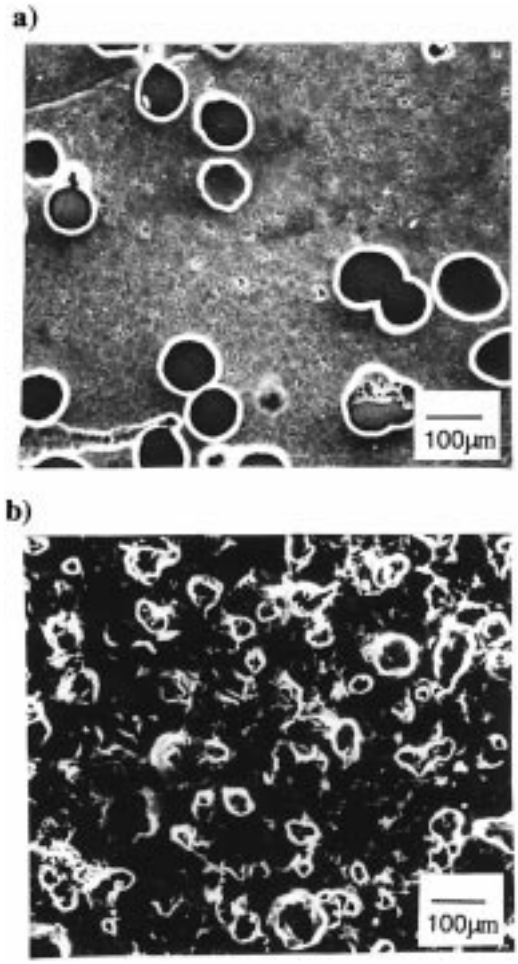


Figure 16. SEM profiles of (a) poly[(*R*)-1-MTC-*co*-CL] (18/82) film after 200 h exposure to cholesterol esterase solution and (b) that after 30 days of biodegradation in acclimated activated sludge.

poly[(*S*,*S*)-1,3-DTC-*co*-CL], and poly(*rac*-1,3-DTC-*co*-CL), regardless of whether we used films or solid masses for the tests.

Figure 16a illustrates the scanning electron micrograph (SEM) of the poly[(*R*)-1-MTC-*co*-CL] (18/82) film after 200 h enzymatic degradation with cholesterol esterase (polymer weight loss 35%). The original film had a very smooth surface with no cavities on the surface. It appears that the degraded copolymer dissolved, leaving round shaped cavities on the surface of the film (diameters of cavities, ca. 50−90 μm). Similar cavities are also seen for the poly[(*R*)-1-MTC-*co*-CL] (18/82) samples when the matrix was immersed in activated sludge for 30 days (Figure 16b). Cavities with various shapes and sizes (10−50 μm) appeared on the surface of the polymer films, presumably due to the attack by different types of microorganisms. The extent of biodegradation as a function of polymer composition is nearly the same between enzymes and activated sludge.

Biodegradation of poly(*rac*-1,3-DTC-*co*-CL) (16/84) produced large cavities (100−150 μm) with cholesterol esterase over a period of 30 days (Figure 17a). The biodegradation using activated sludge also brought about the production of cavities on the polymer surface (Figure 17b). These results clearly indicate that enzymatic degradation of copolymers with relatively high crystallinity starts from the outermost parts of films or solid masses, and the enzymes cannot diffuse into the interior of matrix.

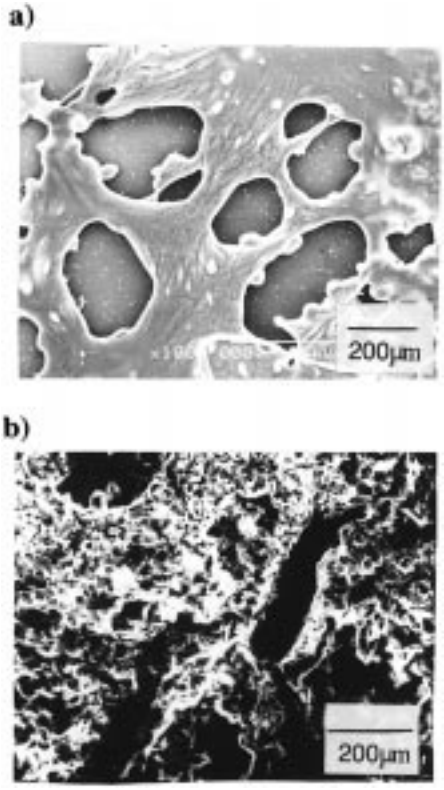


Figure 17. SEM profiles of (a) poly(*rac*-1,3-DTC-*co*-CL) (16/84) film after 200 h exposure to cholesterol esterase solution and (b) that after 75 days biodegradation in activated sludge.

7. Analysis of Degraded Products. The HPLC profiles of water-soluble degraded products from *rac*-1-MTC/CL (8/92) random copolymers exhibited three peaks in a 3:78:19 ratio. The fractions are readily assigned to a repeating unit of polymers. The lowest fraction was assigned to 1,3-butanediol, and the second lowest fraction is assigned to 6-hydroxycaproic acid, since the structures of the isolated products agreed well with those of the commercially available 1,3-butanediol and 6-hydroxycaproic acid. The third lowest peak is assigned to caproic acid dimer, which has already been assigned to the product from the (*R*)-MOHEL/CL copolymer.[31] The formation of a 1-MTC/CL or 1,3-DTC/CL 1:l addition compound was not detected, because the starting polymer contains only a small amount of 1-MTC or 1,3-DTC units.

8. Conclusions. ^{1}H NMR of poly(*rac*-1-MTC) indicated the presence of a (*R*)−(*R*) or (*S*)−(*S*) diad sequence in combination with (*R*)−(*S*) or (*S*)−(*R*) sequence (ca. 1:1 ratio). ^{13}C NMR revealed that 2% of the homopolymer is bonded through head-to-head or tail-to-tail structures. When the 1-MTC content of the 1-MTC/CL copolymers increased to more than 45−46%, T_m and $-\Delta H_f$ disappeared, indicating that the resulting copolymer is completely amorphous. T_m values and the crystallinity of the 1,3-DTC/CL copolymer increased with increasing CL content of the copolymer. The exact values of specific rotation tell us that any helical structure is absent for the resulting 1-MTC/CL copolymers.

The homopolymers, poly(CL) and poly[(*R*)-1-MTC], degraded unexpectedly slowly in lipoprotein lipase and were unaffected by molecular weight, storage temperature, and shaking motions. The weight of homopolymers remaining after 200 h immersion were 74% and 92%, respectively.

Biodegradation tests using lipoprotein lipase and activated sludge indicated that the copolymers, poly-[(*R*)-1-MTC-*co*-CL], with 1-MTC/CL ratios of 18/82 and 6/94 were rapidly biodegraded while the copolymers containing more than 30 mol % (*R*)-1-MTC unit showed extremely low degradability. This fast degradation for 18/82 and 6/94 copolymers originated from the reduction of crystallinity as indicated by the heat of fusion [e.g., $-\Delta H_f$ of poly(CL) = 118 J/g; $-\Delta H_f$ of poly[(*R*)-1-MTC-*co*-CL](18/82) = 24.3 J/g]. The good degradability of 1-MTC/CL copolymers was realized by adding a small amount of *rac*-carbonate and does not require the use of expensive optically active carbonates. The ϵ-caprolactone copolymers containing small amounts of 1,3-DTC units also show high enzymatic degradation and high decomposition by activated sludge.

The *rac*-1,3-DTC monomer is composed of (*R*,*R*)- or (*S*,*S*)-1,3-DTC and *meso*-1,3-DTC in a ca. 1:1 ratio as evidenced from ^{1}H NMR spectrum. On the basis of the NMR measurement, the resulting 1,3-DTC copolymer contains *meso*-1,3-DTC units in ca. 50 mol %, which shows a higher enzymatic degradability than (*R*,*R*)- or (*S*,*S*)-1,3-DTC units due to the lack of crystallinity and the repulsion between neighboring methyl groups in the order *RR*/*SR* sequence > *RR*/*RS*, and *RR*/*SS* sequence > *RR*/*RR* or *SS*/*SS*.

Experimental Part

General Data. All operations were conducted with standard Schlenk techniques under an argon atmosphere. Gas chromatographic analysis was carried out on a GL Science Model GC 390 instrument using a column packed with Silicone DC 550.^{1}H and ^{13}C NMR spectra were recorded on a JEOL Model Rambda 400 or a JEOL Model EX 270 instruments. ^{1}H NMR chemical shifts were calibrated by using chloroform (δ 7.26 ppm) in chloroform-*d* and ^{13}C NMR chemical shifts by the carbon resonance of chloroform-*d* (δ 77.0 ppm). The number and weight average molecular weights were determined by a gel permeation chromatograph on a Tosoh Model SC 8010 chromatograph equipped with columns TSK gel $G1000_{HR}$, $G2500_{HR}$, $G4000_{HR}$, and $G7000_{HR}$ using chloroform as eluent at 40 °C. The flow rate was 1.0 mL min^{-1}. The molecular weights were determined by using universal curve plotted with standard polystyrene, whose M_w values were measured by a light-scattering method. The absolute molecular weights were measured on a GPC instrument attached to DAWAN DSC laser photometer (Whyatt Tech.). The optical rotations of polymers were measured on a JASCO Model DIP-181 digital polarimeter attached to the constant temperature controller, using chloroform as solvent. Morphological changes concerning T_g (glass transition temperature), T_m (melting point), and $-\Delta H_f$ (heat of fusion) were measured on a Seiko SSC 5100-DSC 22C apparatus for the second heating. The samples (ca. 6 mg each) were heated at a rate of 10 °C/min from −100 to +200 °C in a nitrogen stream. Topological changes of the polymer surface were measured on a scanning electron microscope Hitachi Model S-2150R after Pt + Pd coating of the films using an ion coater (Denton Vacuum Desc II).

Materials. Tetrahydrofuran and toluene were dried over CaH_2 and then over Na metal and distilled before use. Commercially available ϵ-caprolactone was dried over CaH_2 and then over activated molecular sieve 3A and distilled under the reduced pressure. (*R*)-1,3-Butanediol and (*S*)-1,3-butanediol were purchased from Azmax Co. Ltd. and Across Co. Ltd., respectively. (*R*,*R*)-Pentanediol and (*S*,*S*)-2,4-pentanediol were purchased from Azmax Co. Ltd. and dried over a small amount of sodium metal. Cholesterol esterase from *Pseudomonas* sp. (Wako Pure Chem. Ind. Ltd.) with TES buffer at pH 7.4 at 37 °C, Proteinase K from *Tritirachium album* with Tricine buffer at pH 8.0, and lipoprotein lipase (Merck) with Tricine buffer at pH 8.0 at 37 °C were used without further purification. Ion-exchanged water was used for biodegradation tests. $Sm(C_5Me_5)_2(THF)_2$ and $SmMe(C_5Me_5)_2(THF)$ were prepared according to the literature.[33,34] $AlEt_3-H_2O$ system was prepared by adding a 0.8 equimolar amount of water to $AlEt_3$ (5 mL) at 0 °C in toluene (100 mL) with stirring, and the mixture was heated to 80 °C for 2 h. Tin(II) 2-ethylhexanoate, $Sn(Oct)_2$, and $Zr(OBu)_4$ were purchased from Aldrich.

(*R*)-1-Methyltrimethylene Carbonate. Triethylamine (100 mL, 0.72 mol) was added dropwise to a stirred solution of (*R*)-1,3-butanediol (36 mL, 0.36 mol) and ethylchloroformate (68.8 mL, 0.72 mol) in THF (500 mL) at 0 °C over a period of 30 min. The mixture was warmed to room temperature and stirred there overnight. The precipitated triethylammonium chloride was filtered off, and the filtrate was concentrated under reduced pressure. The crude product was dried over Na_2SO_4 in THF and recrystallized from THF three times at −25 °C. Then the resulting solid was distilled under reduced pressure (90−92 °C/1 mmHg) and dried over activated molecular sieve 3A to give (*R*)-1-methyltrimethylene carbonate (1-MTC) in 50.4% yield (7.3 g, 62.5 mmol). Mp: 30.5 °C. $[\alpha]^{25}$ = +31.4° (*c* = 0.5 g/L, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.39 (d, 3H, CH_3), 1.89−2.07 (m, 2H, CH_2), 4.36 (m, 2H, OCH_2), 4.58 (m, 1H, OCH). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.1 (CH_3), 28.6 (CH_2), 66.9 (OCH_2), 75.7 (OCH), 148.9 (CO). In a similar manner, (*S*)-1-methyltrimethylene carbonate and *rac*-1-methyltrimethylene carbonate were prepared starting from (*S*)-1,3-butanediol and *rac*-1,3-butanediol, respectively.

Preparation of Poly[(*R*)-1-methyltrimethylene carbonate]. All of the experiments were operated under argon atmosphere. $AlEt_3-H_2O$ (1:08) (0.51 mL, 3.3×10^{-2} mmol) dissolved in toluene was added to the toluene solution (3.5 mL) of (*R*)-1-methyltrimethylene carbonate (0.87 g, 7.7 mmol) in a 20 mL Schlenk tube. Then the Schlenk tube was sealed off and heated to 60 °C in a thermostated oil bath. After being allowed to stand for a fixed time, the reaction product was dissolved in chloroform, and the solution was poured into excess methanol to produce the polymer as a white solid in 28−62% yield.

Synthesis of (*R*,*R*)-1,3-Dimethyltrimethylene Carbonate. Triethylamine (70 mL, 0.5 mol) was added dropwise to a stirred solution of (*R*,*R*)-2,4-pentanediol (26.2 g, 0.25 mol) and ethylchloroformate (145 mL, 1.52 mol) in THF (300 mL) at 0 °C over a 1 h period. The solution was warmed to room temperature and stirred there for 2 days. The precipitated triethylammonium chloride was filtered off, and the filtrate was concentrated under reduced pressure. The crude product was distilled under reduced pressure (98 °C/1 mmHg) and dried over activated molecular sieve 3A to give (*R*,*R*)-1,3-dimethyltrimethylene carbonate in 36% yield (11.7 g, 90 mmol). $[\alpha]^{25}$ = +85° (*c* = 0.5 g/L, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.42 (d, 6H, CH_3), 1.92 (t, 2H, CH_2), 4.69 (m, 2H, OCH). ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.8 (CH_3), 33.9 (CH_2), 72.5 (OCH), 148.9 (CO). In a similar manner, (*S*,*S*)-1,3-dimethyltrimethylene carbonate and *rac*-1,3-dimethyltrimethylene carbonate were prepared starting from (*S*,*S*)-2,4-pentanediol and *rac*-2,4-pentanediol, respectively.

Preparation of Poly[(*R*,*R*)-1,3-dimethyltrimethylene Carbonate. All the procedure was operated under an argon atmosphere. To a toluene solution (0.8 mL) of (*R*,*R*)-1,3-dimethyltrimethylene carbonate (0.2 g, 1.5 mmol) was added a solution of $SmMe(C_5Me_5)_2(THF)$ (0.77×10^{-2} mmol) in toluene (0.3 mL) in a 20 mL Schlenk tube. Then the Schlenk tube was sealed off and heated to 25 °C in a thermostated oil bath. After the reaction was allowed to stand for a fixed time, the solvent was removed under reduced pressure. Then the reaction product was dissolved in chloroform, and the solution was poured into excess methanol to induce the precipitation of a white polymer solid in 75−96% yield. $[\alpha]^{25}$ = −68°. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.24 (d, 6H, CH_3), 1.76 (t, 2H, CH_2), 4.80 (m, 2H, OCH). ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.3 (CH_3), 42.3 (CH_2), 71.1 (OCH), 154.2 (CO).

Preparation of (*R*)-1-MTC/CL Random Copolymer (1:1). (*R*)-1-Methyltrimethylene carbonate (0.87 g, 7.5 mmol), ϵ-caprolactone (0.8 g, 7.5 mmol), $AlEt_3-H_2O$ (1.0 mL, $7.5 \times$

10^{-2} mmol), and 7.5 mL of toluene were added into a 20 mL Schlenk tube via a syringe at 0 °C. Then the tube was sealed off and heated to 60 °C in an oil bath for 24 h. The resulting product was dissolved in chloroform and the solution was poured into excess methanol to induce the precipitation of white rubbery solid in 90−93% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.30 (t, 3H, CH_3), 1.35 (m, 2H, $CH_2CH_2CH_2$), 1.63 (m, 4H, $CH_2CH_2CH_2$), 1.94 (m, 2H, OCH_2CH_2), 2.28 (m, 2H, $COCH_2$), 4.03 (t, 2H, OCH_2), 4.10 (m, 2H, OCH_2), 4.86 (m, 1H, OCH). ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.03 (CH_3), 24.49 ($CH_2CH_2CH_2$), 25.51 ($CH_2CH_2CH_2$), 28.34 (OCH_2CH_2), 34.06 (COCH2), 34.81 (OCH_2CH_2), 154.66 (CO), 173.53 (CO). In the same manner, copolymerization of (*S*)- or *rac*-1-methyltrimethylene carbonate with CL was carried out.

Preparation of (*R*,*R*)-1,3-DTC/CL Random Copolymer (1:1). To a toluene solution (7.5 mL) of (*R*,*R*)-1,3-dimethyltrimethylene carbonate (0.99 g, 7.5 mmol) were added ϵ-caprolactone (0.8 g, 7.5 mmol) and $SmMe(C_5Me_5)_2(THF)$ (toluene solution 1.0 mL, 7.5×10^{-2} mmol) via a syringe at 0 °C. After being stirred for 24 h, the resulting reaction mixture was poured into excess methanol to induce the precipitation of the polymer as a white powder in 80−90% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.24 (d, 6H, CH_3), 1.36 (m, 2H, $CH_2CH_2CH_2$), 1.62 (m, 2H, $CH_2CH_2CH_2$), 1.76 (t, 2H, CH_2), 2.28 (t, 2H, $COCH_2$), 4.03 (t, OCH_2), 4.80 (m, 2H, OCH). ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.31 (CH_3), 24.54 ($COCH_2CH_2$), 25.50 ($CH_2CH_2CH_2$), 28.32 (OCH_2CH_2), 34.09 ($COCH_2$), 42.32 (CH_2), 64.12 (OCH_2), 71.12 (OCH), 154.46 (CO), 173.51 (CO). In the same manner, the copolymerization of (*S*,*S*)- or *rac*-1,3-dimethyltrimethylene carbonate with CL took place under the argon atmosphere.

Enzymatic Degradation. The enzymatic degradations of polymers by lipoprotein lipase and Proteinase K were carried out at 37 °C in Tricine buffer (pH 8.0). The degradation test by cholesterol esterase in TES buffer (pH 7.4) was conducted by exposing the polymer samples and determining the weight loss gravimetrically after recovering the samples at intervals. The polymer disks were prepared by solvent casting method. The size and weight of the films used were 10 × 10 mm (thickness 50−70 μm) and 10−15 mg, respectively. The enzyme and the buffer solution were replaced every 15 h so that the enzyme activities maintain at a desired level throughout the experiment. The bottle (50 mL volume) containing the sample, enzyme and buffer solution were warmed to 37 °C with stirring. After a fixed time, the samples were removed from the bottle, washed with 99.5% ethanol, and then dried to constant weight (5 h) in vacuo before weighing. The molecular weight, the composition, and the surface morphology of the copolymers before and after degradation were determined by GPC, NMR, and SEM observations, respectively.

Degradation in Activated Sludge. The polymer films (thickness 50−70 μm, 5 × 5 mm) were stored in a polyethylene net (15 × 15 mm, mesh 1 mm), and the net was allowed to settle in the activated sludge (obtained from the Higashi-Hiroshima water purification center) at 25 °C, pH 8−9 under aerobic conditions. The DO value was ca. 5 ppm, and MLSS was 3500 mg/L. Weight loss of the film was measured every 5 days.

Analysis of Biodegradation Products. Water-soluble fractions of the biodegradation products (by enzymes) were filtered and lyophilized. Resulting solid masses were washed with a mixture of THF/diethyl ether to remove the enzyme and buffer and then transferred to $CHCl_3$ to enable identification. The products were separated using preparative HPLC (JASCO 800, column TSKgel ($G1000_{HR} \times 2 + G2000_{HR} \times 2$, column temperature 40 °C, detector differential refractometer).

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