Synthesis and Radical Polyaddition of Optically Active Monomers Derived from Cysteine

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ABSTRACT: Synthesis and radical polyaddition behavior of *N*-methacryloyl-L-cysteine methyl ester (MA-C-M), *N*-4-pentenoyl-L-cysteine methyl ester (P-C-M), and *N*-4-vinylbenzoyl-L-cysteine methyl ester (V-C-M) were examined. Although MA-C-M afforded a cross-linked polymer and P-C-M did not polymerize at 60 °C, V-C-M polymerized satisfactorily to afford the corresponding polysulfide with M_n's in the range 7000−23 000 in good yields. The molecular weight of poly(V-C-M) increased after post-polymerization, indicating the telechelic structure with mercapto and olefin moieties at the polymer ends. The specific rotation and CD spectrospecific analysis suggested that poly(V-C-M) had some higher order structures.

Introduction

Amino acids are not only biocompatible materials but also sources of chemically functional materials, because recent remarkable progress in fermentation and organic synthetic technology has enabled us to obtain optically active amino acids with low prices. We have developed polymers based on amino acids and peptides as biocompatible materials as well as optical and chemically functional materials.[1] L-Cysteine is characterized by its mercapto group. In most cases, it forms parts of molecular frameworks of peptides through disulfide formation. Thiyl radicals are important species in redox processes and serve as intermediates in an electron- or hydrogen-donating reaction, the so-called "repair" reaction of thiols toward the targeted carbon centered radicals.[2] Glutathione is the most abundant among thiols serving as reducing agents in biological systems.[3] Other sulfur-containing polymers such as polysulfides, polysulfoxides, and polysulfones attract much attention due to the excellent thermal stability and optical properties.[4] There are many reports concerning the synthesis of polysulfides containing sulfur in the main chains by ring-opening polymerization,[5] polycondensation,[6] and polyaddition.[7] The addition reaction of thiols to unsaturated compounds can be promoted by radical initiators or UV light irradiation.[8] In this article, we describe the synthesis and radical polyaddition behavior of cysteine-based monomers having mercapto and olefin groups.

Experimental Section

Measurements. ^{1}H and ^{13}C NMR spectra were recorded on a JEOL JNM EX-400 spectrometer using tetramethylsilane (TMS) as an internal standard in chloroform-*d* ($CDCl_3$) or dimethyl-d_6 sulfoxide (DMSO-d_6). IR spectra were measured with a JASCO FTIR-5300 spectrometer. Melting points (mp) were measured on a YANACO micro-melting point apparatus. Specific rotations ($[\alpha]_D$) were measured on a JASCO DIP-1000 digital polarimeter using a sodium lamp as a light source. Circular dichroism (CD) spectra were measured on a JASCO J-720 spectropolarimeter. Molecular weights (M_n) and polydispersity ratios (M_w/M_n) were estimated by gel permeation chromatography (GPC) on a Tosoh HPLC, HLC-8020 system, equipped with three consecutive polystyrene gel columns (TSK-gels, G5000H, G4000H, and G2500H), using *N*,*N*-dimethylformamide (DMF, 5.8 mM lithium bromide solution) as an eluent at a flow rate of 1.0 mL/min, polystyrene calibration, and refractive index (RI) and ultraviolet (UV) detectors. Thermal analyses were performed on Seiko instruments TG/DTA 220 and DSC 220C. Glass transition temperatures (T_g) were taken as an inflection point on a trace at a heating rate of 10 °C/min by differential scanning calorimetry (DSC). Ten percent weight loss temperatures (T_{d10}) were determined by thermogravimetric analysis (TGA) at a heating rate of 10 °C/min under a nitrogen atmosphere.

Materials. L-Cysteine was obtained from Ajinomoto Co. The initiators 2,2′-azobis(isobutyronitrile) (AIBN) and di-*tert*-butyl peroxide (DTBP) were purchased from Tokyo Kasei Kogyo Co. and Nakarai Tesque Co., respectively. Dichloromethane, chlorobenzene, DMF, DMSO, and methacryloyl chloride were distilled over calcium hydride before use. 4-Vinylbenzoyl chloride was synthesized according to the previous report.[9]

Synthesis of Monomers: MA-C-M, P-C-M, V-C-M. L-Cysteine Methyl Ester Hydrochloride. Thionyl chloride (78 mL, 0.9 mol) was added to methanol (300 mL) dropwise at −10 °C, and the mixture was stirred for 10 min. L-Cysteine (36.35 g, 300 mmol) was added to the mixture, and it was stirred for 15 h at room temperature. The reaction mixture was concentrated by a rotary evaporator, and the residual mass was washed with ethyl ether (300 mL) several times to obtain powdery L-cysteine methyl ester hydrochloride, which was used to the next step without further purification. Yield 46.3 g (90%). ^{1}H NMR (DMSO-d_6, 400 MHz): δ = 2.96−3.09 (m, 2H, $-CH_2-S-$), 3.34 (m, 1H, −SH), 3.75 (s, 3H, $-COOCH_3$), 4.19−4.37 (m, 1H, $\rangle CH-$), 6.35−6.36 (broad, 3H, $HCl\cdot NH_2-$) ppm. ^{13}C NMR (DMSO-d_6, 400 MHz): δ = 24.15, 52.96, 53.93, 169.18 ppm.

***N*-Methacryloyl-L-cysteine Methyl Ester Hydrochloride (MA-C-M).** To a suspension of l-cysteine methyl ester hydrochloride (4.28 g, 25 mmol) in dichloromethane (75 mL) was added triethylamine (7.30 mL, 52.4 mmol) slowly at 0 °C under nitrogen and then a solution of methacryloyl chloride (2.61 g, 25 mmol) in dichloromethane (25 mL) slowly at 0 °C. The mixture was stirred at 0 °C for 30 min and then at room temperature overnight. The resulting mixture was concentrated by a rotary evaporator, and the residual mass was washed with ethyl acetate (200 mL). It was filtered to remove triethylamine hydrochloride, and the filtrate was concentrated by a rotary evaporator again, followed by recrystallization by ethyl acetate/*n*-hexane (2/1, volume ratio) twice to obtain a colorless solid, *N*-methacryloyl-L-cysteine methyl ester (MA-C-M). Yield 4.16 g (86%). Mp = 92−93 °C; $[\alpha]_D^{25} = -25°$ (*c* =

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1 g/dL, DMF). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 1.99 (s, 3H, $-CH_3$), 3.21−3.26 (m, 2H, $-CH_2-S$), 3.43 (t, J = 2.40 Hz, 1H, −SH), 3.78 (s, 3H, $-OCH_3$), 4.89−4.98 (m, 1H, ⟩CH−), 5.42−5.81 (m, 2H, CH_2═), 6.73−6.81 (m, 1H, −NH−) ppm. ^{13}C NMR ($CDCl_3$, 400 MHz): δ = 18.45, 40.64, 51.89, 52.81, 120.83, 139.15, 167.94, 170.88 ppm. IR (KBr): 3326, 2955, 1755, 1655, 1618, 1520, 1435, 1200, 932, 631 cm^{-1}. Anal. Calcd for $C_8H_{13}NO_3S$: C, 49.74; H, 6.96; N, 6.45; S, 14.26. Found: C, 49.70; H, 6.73; N, 6.49; S, 15.04.

4-Pentenoyl Chloride. To thionyl chloride (71.38 g, 0.6 mol) was added 4-pentenoic acid (19.62 g, 0.2 mol) at room temperature. The reaction mixture was stirred at 80 °C for 3 h. After that, residual thionyl chloride was removed from the mixture, followed by distillation to obtain 4-pentenoyl chloride. Bp = 40 °C/9 mmHg; yield 16.8 g (71%). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 2.39−2.48 (m, 2H, $-CH_2-$), 3.00 (t, J = 7.32 Hz, 2H, $-CH_2-C(O)-$), 5.07−5.14 (m, 2H, CH_2═), 5.74−5.84 (m, 1H, ═CH−) ppm. ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 28.91, 46.23, 116.92, 134.69, 173.15 ppm.

***N*-4-Pentenoyl-L-cysteine Methyl Ester (P-C-M).** P-C-M was synthesized from L-cysteine methyl ester hydrochloride (4.28 g, 25 mmol) and 4-pentenoyl chloride (2.97 g, 25 mmol) in a similar fashion with MA-C-M as mentioned above and purified by recrystallization from ethyl acetate. Yield 4.08 g (75%); mp = 93−94 °C; $[\alpha]^{25}_D$ = −11.4° (c = 1 g/dL, DMF). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 1.35 (t, J = 7.33 Hz, −SH), 2.05−2.43 (m, 4H, $-C_2H_4-$), 3.15−3.25 (m, 2H, $-CH_2-S-$), 3.77 (s, 3H, $-C(O)OCH_3$), 4.85−4.90 (m, 1H, ⟩CH−), 5.01−5.89 (m, 3H, CH_2═CH−), 6.58 (d, J = 7.2 Hz, 1H, −C(O)−NH−) ppm. ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 29.20, 35.29, 40.52, 51.49, 52.62, 115.57, 136.67, 170.82, 172.23 ppm. IR (KBr): 3333, 1743, 1657, 1612, 1442, 1205, 745, 702 cm^{-1}. Anal. Calcd for $C_9H_{15}NO_3S$: C, 47.30; H, 6.45; N, 6.89; S, 15.78. Found: C, 47.25; H, 6.35; N, 6.62; S, 16.15.

***N*-4-Vinylbenzoyl-L-cysteine Methyl Ester (V-C-M).** V-C-M was synthesized from L-cysteine methyl ester hydrochloride (4.28 g, 25 mmol) and 4-vinylbenzoyl chloride (4.17 g, 25 mmol) in a similar fashion with MA-C-M and P-C-M as mentioned above. Yield 4.16 g (86%); mp = 105−106 °C; $[\alpha]^{25}_D$ = −9.8° (c = 1 g/dL, DMF); $[\alpha]^{25}_D$ = −2.4° (c = 1 g/dL, acetone); $[\alpha]^{25}_D$ = −2.9° (c = 1 g/dL, CH_2Cl_2); $[\alpha]^{25}_D$ = −5.2° (c = 1 g/dL, $CHCl_3$). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 1.41 (t, J = 9.2 Hz, 1H, −SH), 3.12−3.16 (m, 2H, $-CH_2-$), 3.80 (s, 3H, $-OCH_3$), 5.07−5.10 (m, 1H, −CH⟨), 5.36−6.79 (m, 3H, CH_2═CH−), 7.08 (d, J = 6.4 Hz, 1H, −C(O)−NH−), 7.40−7.86 (m, 4H, $-C_6H_4-$) ppm. ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 27.01, 52.96, 53.93, 116.29, 126.43, 127.49, 132.55, 135.88, 141.20, 166.55, 170.74 ppm. IR (KBr): 3297, 2575, 1736, 1644, 1535, 1333, 1221, 1188, 996, 924, 858, 779, 694 cm^{-1}. Anal. Calcd for $C_{13}H_{15}O_3NS$: C, 58.84; H, 5.70; N, 5.28; S, 12.09. Found: C, 59.06; H, 5.77; N, 5.15; S, 11.83.

Radical Polyaddition. *Typical procedure*: To a monomer (0.5 mmol) in a polymerization tube was introduced AIBN (2.5 mg, 0.015 mmol) and subsequently a dry solvent (1 or 0.5 mL). The tube was cooled, degassed, sealed off, and heated at 60 °C for 20 h. The reaction mixture was poured into ethyl ether to precipitate the polymer. The ethyl ether-insoluble polymer was filtered with a membrane filter (Millipore LAWPO 4700 pore size 0.45 μm) and then dried in vacuo at 40 °C for 12 h.

Poly(MA-C-M). ^{1}H NMR (DMSO-d_6, 400 MHz): δ = 0.80−1.63 (broad m, 3H, CH_3-), 1.99 (s, 3H, CH_3-, polymer end), 1.71−2.46 (broad m, 3H, $-CH_2-CH⟨$), 2.83−3.60 (broad m, 4H, $-CH_2-S-CH_2-$), 3.45−3.51 (d, J = 13.8 Hz, 2H, $-CH_2-S$, polymer end), 3.78 (broad s, 3H, $-OCH_3$), 4.90 (broad s, 1H, −CH⟨), 5.38−5.70 (m, 2H, CH_2═, polymer end), 7.90−8.52 (broad s, 1H, −NH−) ppm. IR (KBr): 3409, 2955, 1740, 1655, 1657, 1522, 1439, 1213, 1024, 978, 542 cm^{-1} (run 3 in Table 1).

Poly(P-C-M). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 2.35−2.53 (m, 6H, $-C_3H_6-$), 2.98−3.00 (m, 4H, $-CH_2-S-CH_2-$), 3.77 (s, 3H, $-C(O)OCH_3$), 4.82−4.89 (m, 1H, ⟩CH−), 5.83−5.85 (m, 3H, CH_2═CH−, polymer end), 6.41−6.83 (m, 1H, −NH−) ppm. IR (KBr): 3332, 1745, 1655, 1612, 1442, 1206, 744, 701 cm^{-1}.

Poly(V-C-M). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 1.42 (broad s, 1H, −SH, polymer end), 1.91−2.44 (m, 2H, $-CH_2-Ph$), 2.81−3.33 (m, 4H, $-CH_2-S-CH_2-$), 3.78 (s, 3H, $-C(O)OCH_3$), 5.05 (broad s, 1H, ⟩CH−), 5.33−6.78 (m, 3H, CH_2═CH−, polymer end), 7.11−7.71 (broad m, 5H, $-C_6H_4-$, −NH−) ppm. IR (KBr): 3366, 2951, 1742, 1649, 1611, 1535, 1499, 1310, 1215, 1019, 858, 855, 710 cm^{-1} (run 1 in Table 2).

Table 1. Radical Polyaddition of MA-C-M[a]

run	solvent (M)	conv[b] (%)	yield[c] (%)	M_n (M_w/M_n)[d]	$[M]_D$[e] (deg)
1	Ph−Cl (0.5 M)	h	85	16800 (2.27)/ 2900 (1.03)[g]	*h*
2	Ph−Cl (1.0 M)	f	quant	*h*	*h*
3	DMF (1.0 M)	quant	87	46000 (4.45)	−144.8
4	DMF (2.0 M)	f	quant	*h*	*h*
5	DMSO (1.0 M)	quant	quant	43200 (4.28)	−61.1

[a] Conditions: initiator AIBN (3 mol %), 60 °C, 20 h. [b] Determined by ^{1}H NMR. [c] Ether-insoluble part. [d] Estimated by GPC based on polystyrene standards; eluent: LiBr solution (5.8 mM) in DMF. [e] $[M]_D = [\alpha]_D \times MW/100$, where MW represents the formula weight of the polymer repeating unit, $[\alpha]_D$ was measured by a polarimeter at 25 °C (c = 1.00 g/dL, DMF). [f] Not determined, solvent-insoluble polymer was obtained. [g] Bimodal peak, yield of the low molecular weight part 18%. [h] Not measured.

Table 2. Radical Polyaddition of V-C−M in Several Solvents[a]

run	monomer conc (M)	solvent	yield[b] (%)	M_n (M_w/M_n)[c]	$[M]_D$[d] (deg)
1	0.5	DMF	85	7100 (1.21)	−25.2
2	0.5	MeOH	62	7300 (1.50)	−21.2
3	0.5	CH_2Cl_2	88	7000 (1.45)	−25.2
4	0.5	PhCl	91	6900 (1.43)	−27.3
5	1.0	DMF	quant	14000 (1.95)	−26.5
6	1.0	MeOH[e]	quant	10000 (1.44)	−9.3[g]
7	1.0	CH_2Cl_2[f]	95	17000 (2.07)	−14.3[g]
8	1.0	PhCl[f]	quant	16000 (2.15)	−9.6[g]

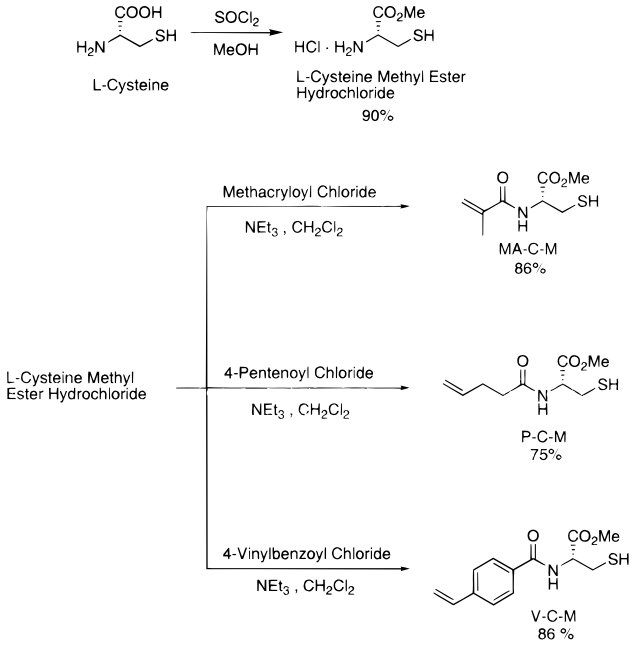
[a] Conditions: V-C-M (0.5 mmol), initiator AIBN (3 mol %), 60 °C, 20 h. [b] Ether-insoluble part. [c] Estimated by GPC based on polystyrene standards; eluent: LiBr solution (5.8 mM) in DMF. [d] $[M]_D = [\alpha]_D \times MW/100$, where MW represents the formula weight of the polymer repeating unit, $[\alpha]_D$ was measured by a polarimeter at 25 °C (c = 1.00 g/dL, DMF). [e] Became heterogeneous after 3 h. [f] Became heterogeneous after 12 h. [g] The obtained polymer was partially insoluble in DMF.

Results and Discussion

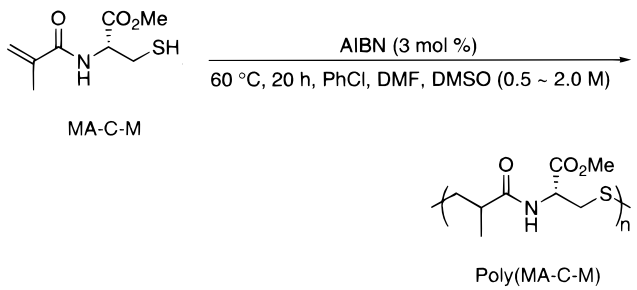
Monomer Synthesis. The monomers *N*-methacryloyl-L-cysteine methyl ester (MA-C-M), *N*-4-pentenoyl-L-cysteine methyl ester (P-C-M), and *N*-4-vinylbenzoyl-L-cysteine methyl ester (V-C-M) were synthesized in satisfactory yields by the reaction of L-cysteine methyl ester hydrochloride with methacryloyl chloride, 4-pentenoyl chloride, and 4-vinylbenzoyl chloride, in the presence of triethylamine in CH_2Cl_2, respectively (Scheme 1). The structures of the monomers were confirmed by ^{1}H, ^{13}C NMR, and IR spectroscopy, besides elemental analysis. We can expect that the monomers easily and efficiently undergo radical polyaddition, because the unit ratio of the two functional groups is automatically equal in the polyaddition. Nuyken et al. have reported that mercaptostyrenes spontaneously undergo self-polyaddition, but the polymerization has not been fully characterized, because the monomers cannot be isolated due to the unstability.[10] In this work, the novel mercapto-olefin monomers could be isolated by recrystallization, were stable at room temperature, and easy to handle.

Radical Polyaddition. Radical polyaddition of MA-C-M was carried out at 60 °C for 20 h in the presence of AIBN (3 mol %) in chlorobenzene, DMF, and DMSO to afford the polymers as summarized in Scheme

Scheme 1



Scheme 2



2 and Table 1. The polymers were isolated by precipitation with ether. The polymerization in chlorobenzene (0.5 M) afforded the DMF-soluble polymer in 85% yield along with a small amount of DMF-insoluble polymer (run 1 in Table 1). Increase of the monomer concentration resulted in the insolubility of the obtained polymer in the polymerization in both chlorobenzene and DMF (runs 2 and 4 in Table 1). The DMF-soluble polymers obtained by polymerization in DMF (1 M) and DMSO (1 M) showed large polydispersity ratios (4.28−4.45) (runs 3 and 5 in Table 1). These results suggest that the produced polymers contained branched and partially cross-linked structures, formed by vinyl polymerization of the methacryloyl group of MA-C-M along with the polyaddition.

Next, we examined the radical polyaddition of P-C-M in the presence of AIBN and DTBP at 60 and 120 °C (Scheme 3). We expected to obtain the polymer via selective polyaddition because the olefin group of P-C-M is less reactive compared with the methacryloyl group of MA-C-M.[11] However, P-C-M afforded no polymer in the polyaddition in chlorobenzene, DMF, and DMSO at 60 °C. However, a low molecular weight oligomer with the M_n of 1600 was obtained in 31% yield in the presence of DTBP (10 mol %) in the bulk at 120 °C for 20 h.

The radical polyaddition of V-C-M was carried out in the presence of AIBN (3 mol %) in DMF, MeOH, chlorobenzene, and CH_2Cl_2 (1 M) at 60 °C for 20 h as summarized in Scheme 4 and Table 2. Polyaddition with monomer concentration of 1.0 M (runs 5−8 in Table 2) afforded polymer with M_n of 10 000−17 000 in quantitative yield. This was higher than the polymer obtained in the polymerization with the monomer concentration of 0.5 M (runs 1−4 in Table 2). Polymers obtained by polymerization in MeOH, CH_2Cl_2, and chlorobenzene were partially insoluble in DMF (runs 6, 7, and 8 in Table 2), which would result in the absolute values of the specific rotations smaller than that obtained in DMF (run 5 in Table 2).[12]

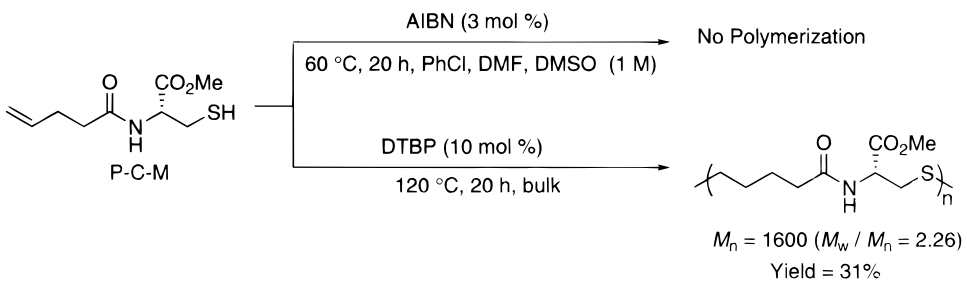
Figure 1 illustrates the ^{1}H NMR spectrum of poly(V-C-M) along with that of V-C-M. The figure shows signals assignable to vinyl and mercapto groups of the polymer ends at 5.35, 5.82 ppm and 1.42 ppm as well as the signals assignable to the polysulfide unit. Poly(V-C-M) seems to be a telechelic polymer. The degree of polymerization is calculated to be 12 by ^{1}H NMR integration of the signal for the olefin protons, of the polymer ends at 5.35 ppm and the methyl ester protons at 3.78 ppm.

To confirm the telechelic structure of the polymer, postreaction was carried out in the presence of AIBN (10 mol %) in DMF (1 M) at 60 °C for 20 h. Figure 2 illustrates the GPC profiles before and after the post-radical polyaddition, showing the increase of the M_n from 7100 to 15 700. This result indicates that the original telechelic polymer has been converted into a higher molecular weight polymer.

The radical polyaddition of V-C-M was carried out in the presence of AIBN ranging from 1 to 30 mol % as summarized in Table 3. The polymer yield and M_n increased with the amount of AIBN in most cases. The absolute value of $[M]_D$ slightly increased with the M_n.

Mechanism of Radical Polyaddition of V-C-M. Scheme 5 illustrates a plausible mechanism of the radical polyaddition of V-C-M. In the initiation step, the radical initiator abstracts the thiol hydrogen atom of V-C-M to produce a thiyl radical species. The second step is the addition of the thiyl radical to another monomer followed by the chain transfer, i.e., abstraction of hydrogen from another mercapto group. Consequently, radical polyaddition proceeds to afford the polysulfide.

Scheme 3



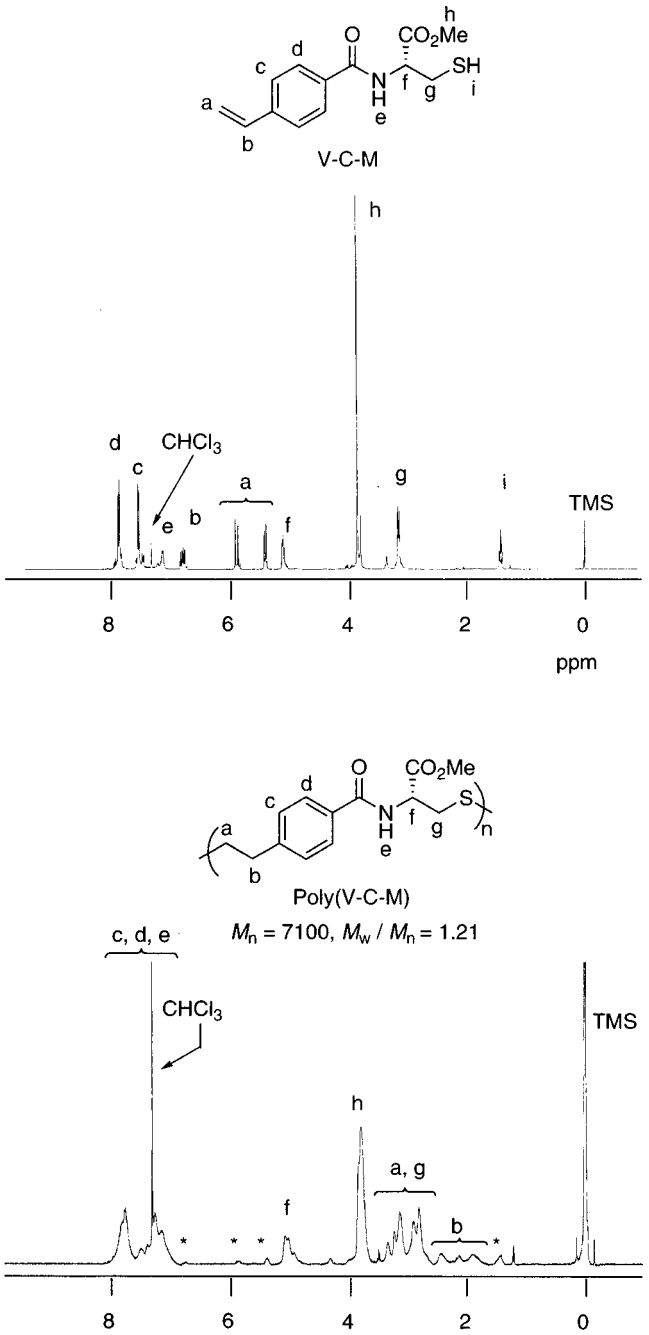
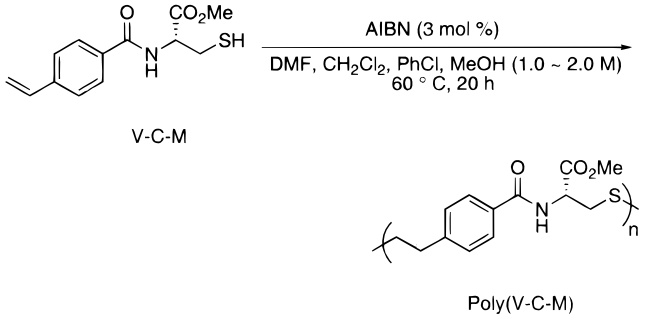


Figure 1. ^{1}H NMR spectra (400 MHz, $CDCl_3$) of V-C-M and poly(V-C-M) obtained in the radical polyaddition with AIBN (3 mol %) in DMF (0.5 M) at 60 °C for 20 h (run 1 in Table 2). *: signal derived from the polymer end.

Scheme 4



Specific Rotations of V-C-M and Poly(V-C-M). Figure 3 illustrates the relationships between the specific rotations of V-C-M and poly(V-C-M) and DMF content of the measuring mixed solvent of DMF and $CHCl_3$. Poly(V-C-M) was insoluble in the mixed solvent whose DMF content was less than 50%. The specific rotation of V-C-M and DMF content showed a linear relationship as shown in Figure 3, while that of poly(V-C-M) showed a minimum at the DMF content of 86% independent of M_n. The polymer with M_n of 18 000 showed smaller $[M]_D$ than that with M_n of 7100. We previously examined the solvent effect on the specific rotation of *N*-pivaloyl-L-leucine methyl ester to find it decreased as the relative dielectric constant of the measuring solvent increased.[13] From the conformational analysis of *N*-pivaloyl-L-leucine methyl ester by molecular orbital calculation, it was suggested that the compound changed its conformation according to the solvent resulting in the change of $[M]_D$. The similar conformational change of V-C-M appeared to cause the change of $[M]_D$ of V-C-M according to the measuring solvent content. A possible reason for these interesting results concerning specific rotations is a higher order structure of the polymer constructed by hydrogen bonding between the carbonyl groups and amide hydrogen. Lotz et al. have reported that a polysulfide with asymmetric carbons in the main chain, poly(*tert*-butylethylene sulfide), is one of several isotactic polymers and forms one-handed helices of one hand.[14] Poly(V-C-M) seems to take some helical structures due to its asymmetric carbons.

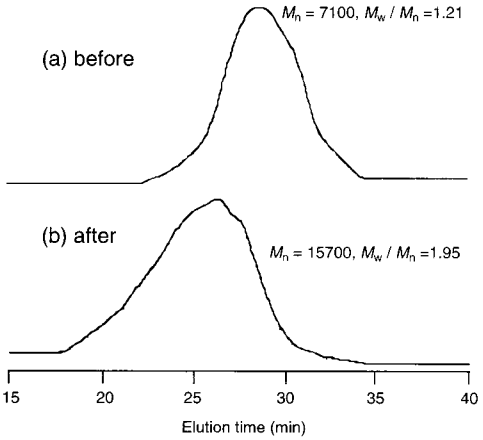


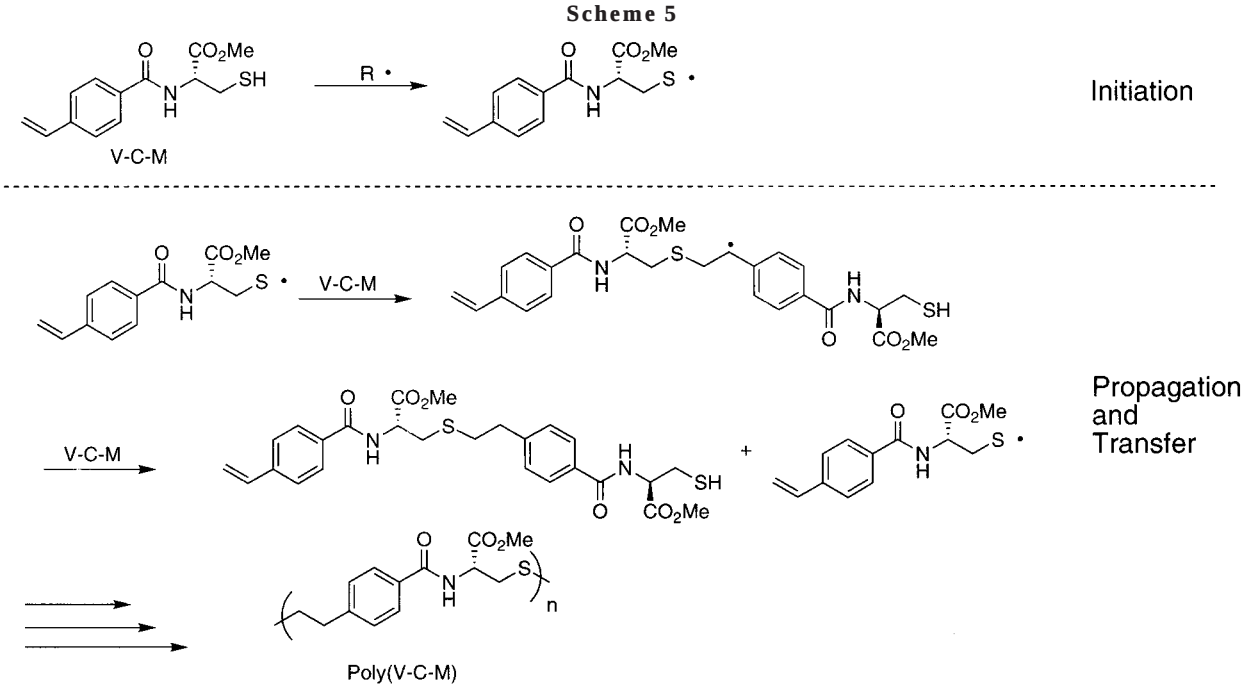
Figure 2. GPC profiles [eluent: LiBr (5.8 mM) in DMF] before and after the post-radical polyaddition of poly(V-C-M) obtained in the radical polyaddition with AIBN (3 mol %) in DMF (0.5 M) at 60 °C for 20 h (run1 in Table 2). (a) Before post-radical polyaddition of poly(V-C-M); M_n = 7100, M_w/M_n = 1.21. (b) After post-radical polyaddition of poly(V-C-M). M_n = 15 700; M_w/M_n = 1.95.

Table 3. Radical Polyaddition of V-C-M in the Presence of AIBN[a]

run	amount of AIBN (mol %)	yield[b] (%)	M_n (M_w/M_n)[c]	$[M]_D$[d] (deg)
1	1	62	8900 (1.38)	−24.4
2	3	76	7100 (1.21)	−25.2
3	5	83	18000 (1.76)	−30.8
4	10	88	23000 (1.43)	−32.9
5	30	97	19000 (1.95)	−32.1

[a] Conditions: V-C-M (0.5 mmol), initiator AIBN (3 mol %), 60 °C, 20 h in DMF (1.0 mL). [b] Ether-insoluble part. [c] Estimated by GPC based on polystyrene standards; eluent: LiBr solution (5.8 mM) in DMF. [d] $[M]_D = [\alpha]_D \times MW/100$, where MW represents the formula weight of the polymer repeating unit, $[\alpha]_D$ was measured by a polarimeter at 25 °C (c = 1.00 g/dL, DMF).

Scheme 5



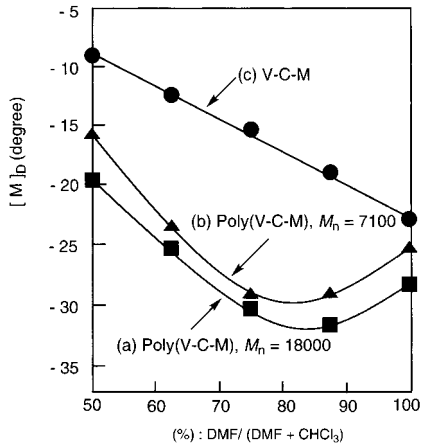


Figure 3. Specific rotation ($[M]_D$) of V-C-M and poly(V-C-M) vs DMF content of the mixed solvent of DMF and $CHCl_3$. $[M]_D = [\alpha]_D \times MW/100$ where MW represents the formula weight of the polymer repeating unit; $[\alpha]_D$ was measured by a polarimeter at 25 °C (c = 1.00 g/dL, DMF/$CHCl_3$). (a) Poly(V-C-M) (M_n = 18 000, M_w/M_n = 1.76) obtained in the radical polyaddition with AIBN (5 mol %) in DMF (0.5 M) at 60 °C for 20 h (run 3 in Table 3). (b) Poly(V-C-M) (M_n = 7100, M_w/M_n = 1.21) obtained in the radical polyaddition with AIBN (3 mol %) in DMF (0.5 M) (run 1 in Table 2). (c) V-C-M.

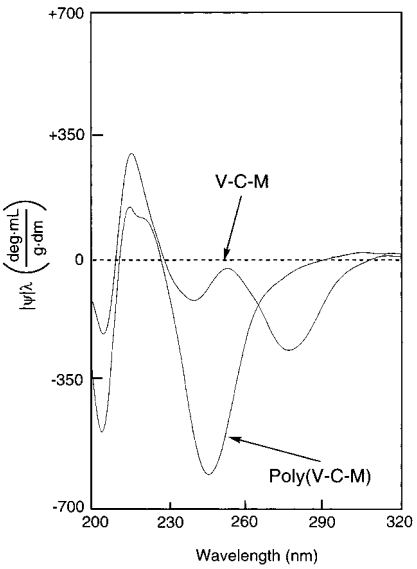


Figure 4. CD spectra (c = 0.01 g/dL, $CHCl_3$) of V-C-M and poly(V-C-M). Poly(V-C-M) (M_n = 7100, M_w/M_n = 1.21) was obtained in the radical polyaddition with AIBN (3 mol %) in DMF (0.5 M) (run 1 in Table 2).

Circular Dichroism (CD) Spectra of V-C-M and Poly(V-C-M). Figure 4 illustrates the CD spectra of poly(V-C-M) with M_n of 7100 and V-C-M measured in chloroform (0.01 g/mL). The polymer with M_n of 18 000 was insoluble in chloroform. The Cotton effect of poly(V-C-M) at 245 nm much larger than that of V-C-M, and the results of specific rotations suggested that poly(V-C-M) had some regulated higher order structures such as a helical conformation to some extent. Poly(V-C-M) did not show an apparent T_g up to 200 °C and showed T_{d10}'s in the range 264−275 °C.

In summary, we examined the synthesis and radical polyaddition of the novel three monomers having olefin and mercapto groups derived from cysteine. The radical polyaddition of *N*-4-vinylbenzoyl-L-cysteine methyl ester (V-C-M) proceeded satisfactorily to afford the corresponding polysulfide with M_n in the range 7000−23 000 in good yields. The specific rotation and CD spectrospecific analysis suggested that poly(V-C-M) had some higher order structures. It is expected that poly(V-C-M) shows interesting functions, because it has wide variety of functional groups, i.e., amide and sulfide moieties, and asymmetric carbons in the main chain, besides ester groups in the side chain as well as olefin and mercapto groups in the polymer ends.

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(12) This means that the real reagent concentrations of the solutions in runs 6−8 in Table 2 were smaller than $c = 1$ g/dL. Possible reasons of formation of the DMF-insoluble part is incorporation of cross-linked structures, which may be formed by coupling of polymer end thiyl radicals.

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