Cyclic Poly(thioglycolide) and Poly(D,L-thiolactide) by Zwitterionic Polymerization of Dithiolane-2,4-diones

Hans R. Kricheldorf,* Nino Lomadze, and Gert Schwarz

Institut für Technische und Makromolekulare Chemie, Universität Hamburg, Bundesstrsse 45, D-20146 Hamburg, Germany

Received March 6, 2007; Revised Manuscript Received May 7, 2007

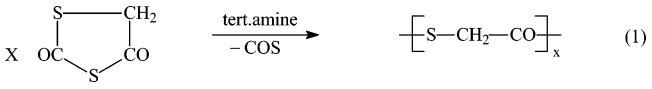
ABSTRACT: Dithiolane-2,4-dione was polymerized either by heating in bulk to 140 °C or by reacting at 20 °C using pyridine and triethylamine as catalysts. Whereas the thermal polymerization almost exclusively yielded cyclic poly(thioglycolide), the samples prepared at 20 °C by means of tertiary amines contained cyclic and linear chains. The end groups of the linear chains varied with the nonsolvent used for the workup procedure, because chains having reactive end groups were immobilized by rapid crystallization and reacted at the electrophilic CO-chain end with the nonsolvent. D,L-5-Methyldithiolane-2,4-dione proved so stable that tertiary amines did not catalyze its polymerization even at 100 °C. Thermal polymerization at 160 °C yielded oligoester mainly consisting of cyles. A zwitterionic polymerization mechanism allowing for simultaneous chain-growth and step-growth polymerization is discussed.

Introduction

In contrast to normal aliphatic polyesters, aliphatic polythioesters have not attracted much interest in previous decades. However, the recent discovery of Steinbüchel and Lüke-Eversloh[1−3] that certain microorganisms can produce homo- and copolyesters of β-mercapto carboxylic acids will certainly stimulate further research activities in this field. Since the enzymatic capabilities of microbes are limited to polycondensations of β-mercapto carboxylic acids, the polyesters of α-mercapto carboxylic acids (which are the thio analogs of polyglycolide and polylactide) need to be prepared by chemical methods.

Low molar mass poly(thioglycolide) was first prepared by Schöberl[4−7] via polycondensation of mercapto acetic acid and its methyl ester or by ring-opening polymerization (ROP) of the cyclic dimer (i.e., 1,4-dithiane-2,5-dione). Low molar mass poly(thioglycolide) and poly(thiolactide) were also prepared by ROP of oxathiolane 2,4-diones.[8,9]

Synthesis and polymerization of dithiolane-2,4-dione were first described by Kricheldorf and Schwarz[10,11] about 30 years ago. It was found that tertiary amines were the only useful catalysts, and in extremely pure dioxane high molar mass poly(thioglycolide) was obtained (eq 1). Unfortunately, this polymer



(1)

is a highly crystalline material for which only two inert solvents were found, namely dichloroacetic acid and hexafluoroacetone sesquihydrate.[8] Since 30 years ago neither deuterated dichloroacetic acid nor ^{13}C NMR spectroscopy or MALDI−TOF mass spectrometry was available, it was difficult to identify end groups and to elaborate a polymerization mechanism.

Quite recently it was found[12] that pyridine-catalyzed polymerizations of α-amino acid *N*-carboxy anhydrides (NCAs) including Sar-NCA yield cyclic polypeptides via a zwitterionic polymerization mechanism (eqs 2−5). Similar results were found for "spontaneous" polymerizations of NCAs in nucleophilic polar solvents, such as *N*-methylpyrrolidone or DMSO[13] which also play the role of catalysts in analogy to pyridine. These polymerizations are of particular interest for two reasons. First, they yield cyclic polypeptides which are difficult to prepare by other synthetic methods. Second, the polymerizations combine both chain-growth and step-growth polymerizations (eqs 4 and 5) although both chain-growth reactions are usually treated in text books as two quite different and incompatible polymerization processes. In this connection the present work had the purpose to reinvestigate thermal and pyridine-catalyzed polymerizations of dithiolane-2,4-diones by MALDI−TOF mass spectrometry to find out if these polymerization methods generate cyclic polythioesters. A positive result will have the consequence that polymerizations involving simultaneous chain-growth and step-growth reactions will represent a concept of broader validity and not just a curiosity of α-amino acid NCAs. In this context, it should be mentioned that zwitterionic polymerizations were studied by several research groups,[14−36] but in all publications which appeared before 2006 the formation of cyclic polymers was neither postulated nor war the detection of cyclic polymers in complex reaction mixtures feasible before MALDI−TOF mass spectrometer was available. Only one quite recent paper[36] which appeared just when this work was submitted for publication reported on the formation of cyclic polymers (i.e., poly-L-lactides) by zwitterionic polymerization.

Experimental Section

Materials. Carbon disulfide, chloroacetic acid, and 2-bromoacetic acid were purchased from ACROS Organics (Geel, Belgium) and used as received. Pyridine and triethylamine (ACROS Org.) were distilled over powdered calcium hydride. Dry DMSO was purchased from Aldrich Co. (Milwaukee, WI). *N*-Methylpyrrolidone was distilled over P_4O_{10} in vacuo. Pyridine was distilled over freshly powdered calcium hydride, and dioxane was distilled over sodium.

Dithiolane-2,4-dione (DTD). This monomer was prepared from xanthogen acetic acid and thionyl chloride in refluxing chloroform as described previously.[1] It was twice distilled in a vacuum of 10^{-2} mbar. A yellowish crystalline product with mp 45−46 °C was obtained.

D,L-5-Methyl Dithiolane-2,4-dione (MDTD). A. 2-Xanthogen Proprionic Acid. Sodium (1.0 mol) was dissolved in dry ethanol (450 mL) and carbon disulfide (1.1 mol) was added rapidly but dropwise under cooling with ice. This solution was stored for 48 h at 20−25 °C under an atmosphere of nitrogen. A 5 M aqueous

10.1021/ma0705467 CCC: $37.00
Published on Web 06/16/2007

solution of KOH (50 mL) was then added at once, and under cooling with ice, 2-chloropropionic acid (0.25 mol) was added dropwise. Addition of aqueous KOH and 2-chloropropionic acid was repeated three times. After 20 h of stirring at 20−25 °C, water (60 mL) was added and the ethanol was completely distilled off in vacuo by means of a rotating evaporator. The remaining alkaline solution was cooled with ice and acidified by dropwise addition of precooled concentrated hydrochloric acid (120 mL). The oily product was extracted with three 300 mL portions of ethyl acetate. The combined extracts were washed with water (twice), dried over Na_2SO_4, and concentrated in vacuo.

B. Silylation of 2-xanthogen Propionic Acid. The crude product was dissolved in dry tetrahydrofuran (1.2 L), chlorotrimethylsilane (1.0 mol) was added, and a mixture of triethylamine (1.0 mol) and tetrahydrofuran (100 mL) was added rapidly but dropwise. The reaction mixture was refluxed for 2 h, cooled with ice, and filtered under exclusion of moisture (the triethylamine hydrochloride was washed with ligroin). The combined filtrates were concentrated in vacuo and filtered again. Finally, the liquid product was distilled over a short-path apparatus in a vacuum of 10^{-2} mbar at a bath temperature of 60−65 °C. Yield (relative to 2-chloropropionic acid): 73%.

^{1}H NMR ($CDCl_3$/TMS): δ = 0.29 (s, 9H), 1.40 (t, 3H), 1.50 (d, 3H), 4.30 (q, 1H) 4.60 (q, 2H) ppm.

C. Cyclization. The silylated 2-xanthogen propionic acid (0.5 mol) was dissolved in dry chloroform (250 mL), and thionyl chloride (0.75 mol) was added. This mixture was stirred for 20 h at 20−25 °C and afterward refluxed for 2 h. After evaporation of the chloroform, dry chloroform was added to the residue and evaporated again to remove most of the $SOCl_2$. The residue was then dissolved in ethylacetate (200 mL), cooled with ice and washed with 300 mL portions of cold 5% aqueous $NaCO_3H$ and cold water (twice). The CH_2Cl_2 solution was dried over $CaCl_2$ and concentrated. The crude product was distilled over short-path apparatus at a bath temperature of 60−70 °C in a vacuum of 10^{-1} mbar. Three fractions were taken, and the middle fraction (yield: 41%) was found to be sufficiently pure on the basis of its 400 MHz ^{1}H NMR spectrum.

n_D^{22} = 1.5725.

Anal. Calcd. for $C_4H_4O_2S_2$ (116.09): C, 32.42; H, 2.72; S, 43.27. Found: C, 32.52; H, 2.84; S, 42.72.

^{1}H NMR ($CDCl_3$/TMS): δ = 1.77 (d, 3H), 4.77 (q, 1H).

^{13}C NMR ($CDCl_3$/TMS): δ = 19.07, 58.55, 186.96, 199.45 ppm.

Polymerizations of DTD. (1) Thermal Polymerization. DTD (20 mmol) was heated in a 20 mL glass flask having silanized glass walls to a temperature of 140 °C for 20 h, whereby the product solidified. This reaction product was characterized by MALDI−TOF mass spectroscopy without any purification or fractionation. An analogous polymerization was conducted at 120 °C for 48 h.

(2) Pyridine-Catalyzed Polymerizations. DTD (20 mmol) was dissolved in dry pyridine and stored at 20 °C for 24 h. Evolution of gas and precipitation of crystalline poly(thioglycolide) began within the first hour. This experiment was repeated three times and the reaction mixtures were worked up in four ways: (a) the reaction mixture was diluted with pyridine (10 mL) and filtered under an atmosphere of dry nitrogen. The wet polythioester was transferred into a test tube and immersed for 15 min in an oil bath preheated to 160 °C. After cooling with ice, the crude product was characterized. (b) The reaction mixture was poured into water (100 mL) and the polythioester was isolated by filtration. (c) The reaction mixture was poured into methanol (100 mL). (d) The reaction mixture was poured into dry ethanol (100 mL).

(3) Triethylamine-Catalyzed Polymerization. DTD (20 mmol) was dissolved in dry dioxane (10 mL), and triethylamine (2 mmol) was injected. After 48 h at 20 °C, the reaction mixture was poured: (a) into water (100 mL), (b) into methanol (100 mL), or (c) into ethanol (100 mL).

After isolation by filtration, the polythioester was dried in vacuo at 60 °C.

Polymerization of MDTD. (1) Thermal Polymerization. MDTD (20 mmol) was heated in a 20 mL glass flask having silanized glass walls to 160 °C for 24 h. Thereby, a viscous melt was obtained, the ^{1}H NMR spectrum of which indicated complete conversion: ^{1}H NMR ($CDCl_3$/TMS), δ = 1.54 (d, 3H), 4.38 (s, broad), 1H) ppm.

Table 1. Calculated Masses (Including K^+ Doping) of Polythioesters Resulting from Polymerizations of DTD and MDTD[a]

DP	**C** (DTD)	**La**	**Lb**	**Lc**	**C** (MDTD)
10	780.0	798.0	812.0	826.0	920.3
11	854.1	872.1	886.1	900.1	1008.4
12	928.2	946.2	960.2	974.2	1096.6
13	1002.3	1020.3	1034.3	1048.3	1184.7
14	1076.4	1094.4	1108.4	1122.4	1272.9
15	1150.5	1168.5	1182.5	1196.5	1361.0
16	1224.6	1242.6	1256.6	1270.6	1449.1
17	1298.6	1316.6	1330.7	1344.7	1537.3
18	1372.8	1390.9	1405.0	1419.0	1625.4
19	1447.0	1465.0	1479.0	1493.0	1713.5
20	1521.1	1539.0	1554.0	1568.0	1801.6
25	1891.6	1909.6	1923.6	1937.6	2242.2

[a] These masses were calculated for DPs between 10 and 25, because this mass range was preferentially measured (or limited by the MALDI method); see Figures 1−3.

(2) 4-Dimethylaminopyridine-Catalyzed Polymerization. MDTD (20 mmol) and 4-*N*,*N*-dimethylaminopyridine (20 mmol) were mixed in a 20 mL glass flask and thermostated at 60 °C for 24 h, but no polymerization occurred. After the reaction was heated to 100 °C for 24 h, a black tar was obtained.

(3) Parallel Experiment. In a parallel experiment, the polythioester was dissolved in CH_2Cl_2 (15 mL) and precipitated into methanol.

Measurements. The inherent viscosities were measured in dichloroacetic acid with an automated Ubbelohde viscometer thermostated at 30 °C. The 400 MHz ^{1}H NMR spectra were recorded on a Bruker "Advance 400" in 5 mm o.d. sample tubes. Dichloroacetic acid containing TMS (1 vol %) and C_6D_6 (10 vol %) served as solvent for polythioglycolide. All other ^{1}H NMR spectra were measured in $CDCl_3$. The IR spectra were recorded on a Nicolet FT spectrometer Md "Impact" 410" between NaCl prisms. The MALDI−TOF mass spectra were measured with a Bruker Biflex III mass spectrometer equipped with a nitrogen laser (λ = 337 nm). All spectra were recorded in the reflection mode using an acceleration voltage of 20 kV. The irradiation targets were prepared with dithranol as matrix and potassium trifluoroacetate as dopant. Chloroform served as solvent for poly(D,L-thiolactate) and dichloroacetic acid for poly(thioglycolide). The masses calculated for the reaction products are summarized in Table 1.

Results and Discussion

Thermal Polymerization of Dithiolane-2,4-dione (DTD). In two previous publications[1,2] it was demonstrated that tertiary amines are excellent catalysts for the ring-opening polymerizations of DTD even at temperatures below 20 °C. For a proper understanding of the results obtained with tertiary amines as catalysts, it seemed to be advisable to discuss at first the outcome of thermal polymerizations. From preliminary experiments (not described here in detail) it was learned that temperatures ≥120 °C are needed for complete polymerization of DTD within 24 or 48 h. At temperatures <150 °C the thermal polymerization in bulk resulted in total solidification of the originally liquid monomer, due to the crystallization of the poly(thioglycolide). The yield depends on the loss of the monomer by volatilization in combination with the evolution of COS, and thus, does not say anything about the course of the polymerization. To avoid fractionation and chain scission, the crude product obtained after 24 h at 140 °C (no. 2, Table 2) was characterized. A relatively low inherent viscosity of 0.14 dL/g (measured at 30 °C in dichloroacetic acid) was found. The MALDI−TOF mass spectrum exclusively displayed peaks of cycles (up to a DP of

Table 2. Polymerizations of Dithiolane-2,4-dione

expt no.	reaction medium	catalyst	temp (°C)	time (d)	yield (%)	η_{inh}[a] (dL/g)	products (MALDI−TOF)
1			120	1	81	0.15	**C**
2			140	2	82	0.14	**C**
3	pyridine[b]	pyridine[b]	20	1	76	0.20	**C** + **La**
4	pyridine[c]	pyridine[c]	20	1	75	0.25	**C** + **Lb**
5	pyridine[d]	pyridine[d]	20	1	76	0.27	**C** + **Lc**
6	pyridine[e]	pyridine[e]	20	1	78	0.21	**C**
7	dioxane[b]	triethylamine	20	2	81	0.17	**C** + **La**
8	dioxane[c]	triethylamine	20	2	74	0.16	**C** + **Lb**
9	dioxane[d]	triethylamine	20	2	79	0.15	**C** + **Lc**

[a] Measured at 30 °C with $c = 2$ g/L in dichloroacetic acid. [b] Worked up with water. [c] Worked up with methanol. [d] Worked up with ethanol. [e] Heated at 170 °C for 10 min, immediately after isolation (filtration).

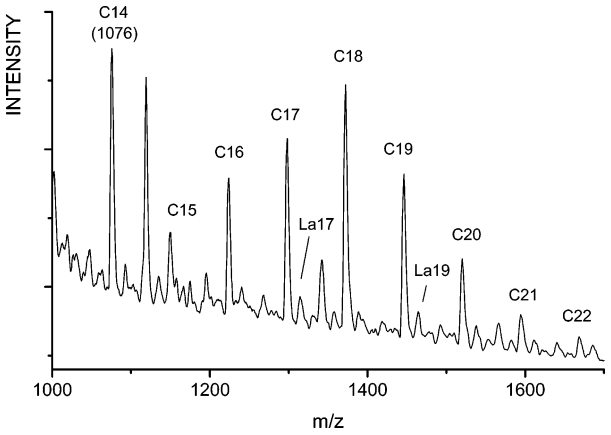


Figure 1. MALDI−TOF mass spectrum of a poly(thioglycolide) prepared in pyridine at 20 °C and washed with water.

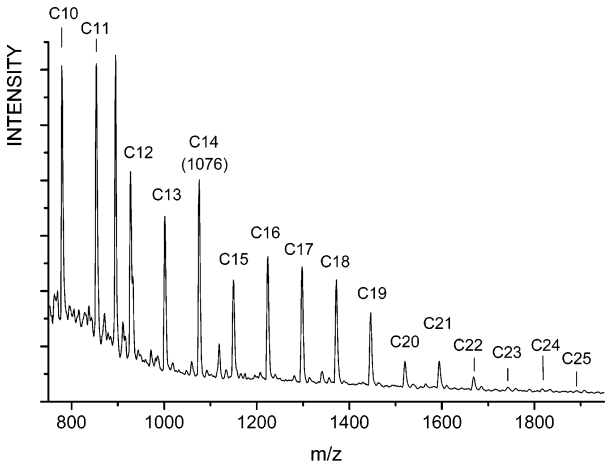


Figure 2. MALDI−TOF mass spectrum of a poly(thioglycolide) prepared in pyridine at 20 °C and heated to 160 °C for 10 min.

28) (the mass spectrum was quite similar to that presented in Figure 2). This finding allowed for two important conclusions. First, warm dichloroacetic acid used as solvent for the preparation of the irradiation targets of the mass spectroscometric measurements did not cleave the polythioester chains and, thus, allowed us to continue this study. Second, the thermal polymerization of DTD proceeds most likely by a zwitterionic polymerization which enables cyclization by a charge-cancellation step. This mechanism outlined in Scheme 2 resembles largely the pyridine-catalyzed polymerization of sarcosine NCA formulated in Scheme 1. In this mechanism, a monomer plays the role of pyridine with its most nucleophilic site, the carbonyl oxygen, and stabilizes the positive charge by delocalization (eq 6). Quite analogous to Scheme 1 the chain-growth combines ring-opening steps (eqs 7 and 8), obeying a chain-growth kinetic and condensation steps (eq 9).

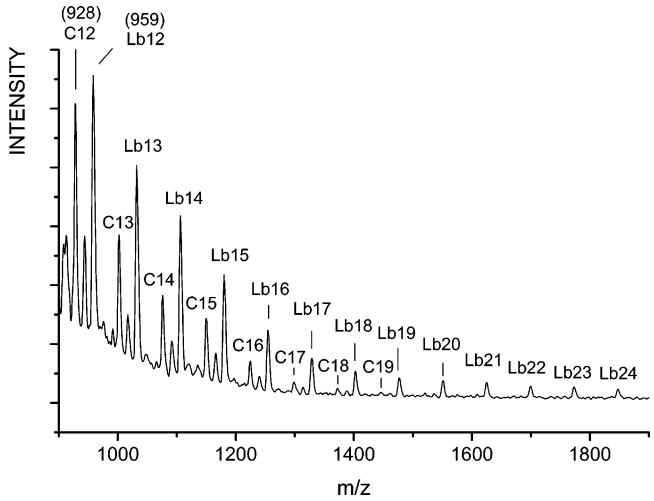
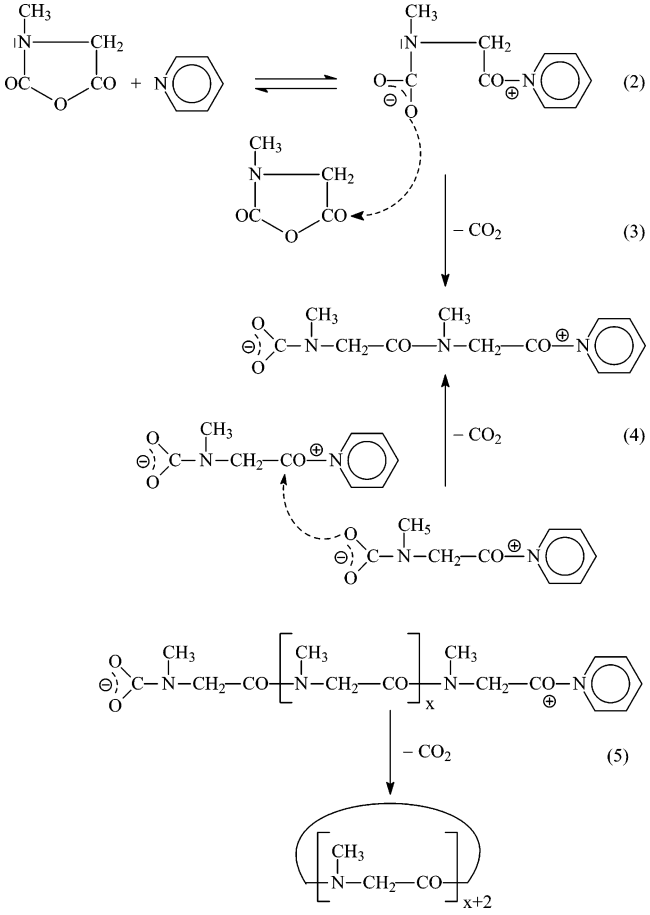


Figure 3. MALDI−TOF mass spectrum of a poly(thioglycolide) prepared with triethylamine in dioxyne at 20 °C and washed with methanol.

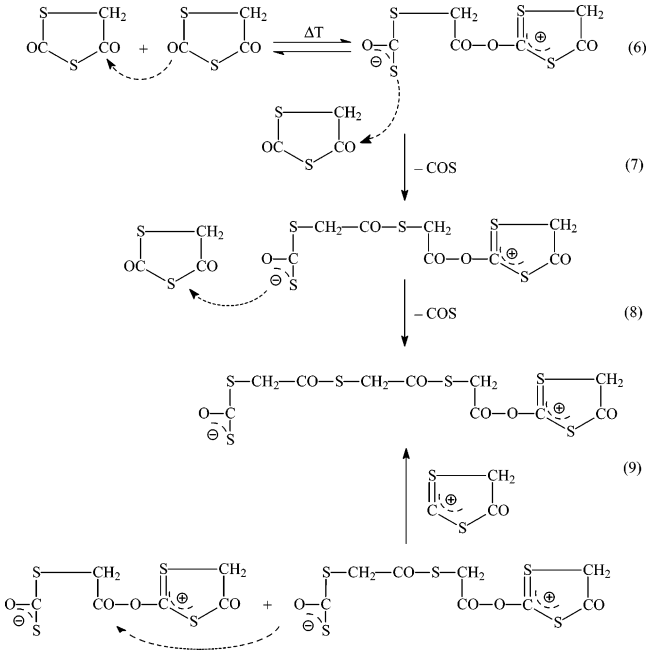
Nearly identical results were obtained from a polymerization of DTD at 120 °C in bulk (no. 1, Table 2). In principle, cyclic oligoesters may be formed by "backbiting" degradation of polyesters, but it is highly unlikely that intensive transesterification occurred at 120 °C in the absence of catalysts. Model reactions conducted up to 150 °C with OH-terminated telechelic aliphatic polyesters (described in ref 6) did not give any indication of "backbiting" in the absence of transesterification catalysts. Even in the presence of bismuth-based catalysts, cyclization by "backbiting" is avoidable up to 220 °C.[37,38]

***tert*-Amine-Catalyzed Polymerizations of DTD.** Since pyridine is a nucleophilic base of low basicity and triethylamine a less nucleophilic base of relatively high basicity, both amines were used as catalysts. All pyridine-catalyzed polymerizations were performed in neat pyridine at 20 °C, but the workup procedure was varied (nos. 2−6, Table 2), because it was found that the pattern of mass peaks in the MALDI−TOF mass spectra varied with the nonsolvent used for the precipitation and washing of the poly(thioglycolide). In all mass spectra the peaks of cyclic poly(thioglycolide)s were present. Yet, when the reaction mixture was worked up with water, small peaks of H_2O-terminated chains (**La** in Scheme 3) were also detectable as illustrated in Figure 1. When the reaction mixture was washed with methanol, mass peaks of chains having methyl ester end groups (**Lb** in Scheme 3) were present, whereas washing with dry ethanol yielded a product the mass spectrum of which displayed the mass peaks of **Lc** chains. A fourth experiment was conducted in such a way that the reaction mixture was diluted with dry pyridine, filtered under exclusion of moisture and the polythioester placed for 10 min in an oil bath preheated to 160 °C. The resulting melt was quenched with ice and immediately subjected to mass spectrometry (no. 6, Table 2).

Scheme 1. Pyridine-Catalyzed Zwitterionic Polymerization of Sarcosine NCA

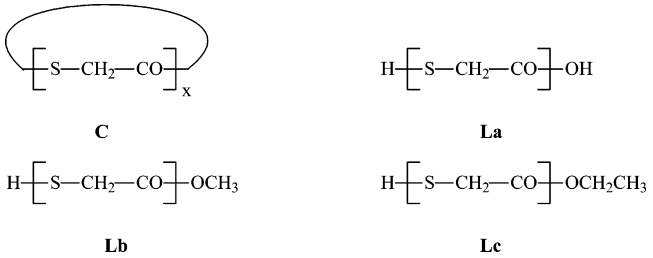


Scheme 2. Mechanism of the Thermal Polymerization of DTD



The mass spectrum obtained in this way exclusively displayed peaks of cycles as illustrated in Figure 2. ^{1}H NMR spectra measured in dichloroacetic acid containing 10 vol % of deuterated benzene were not very informative. They displayed the CH_3 signal (0.86 ppm) of the ethyl ester end groups, when ethanol was used for the workup procedure. Yet, the OCH_2 signal and the OCH_3 signal of methyl ester end groups were obscured by the S−CH_2-signal.

Scheme 3. Potential Reaction Product of Pyridine-Catalyzed Polymerization of Dithiolane-2,4-dione



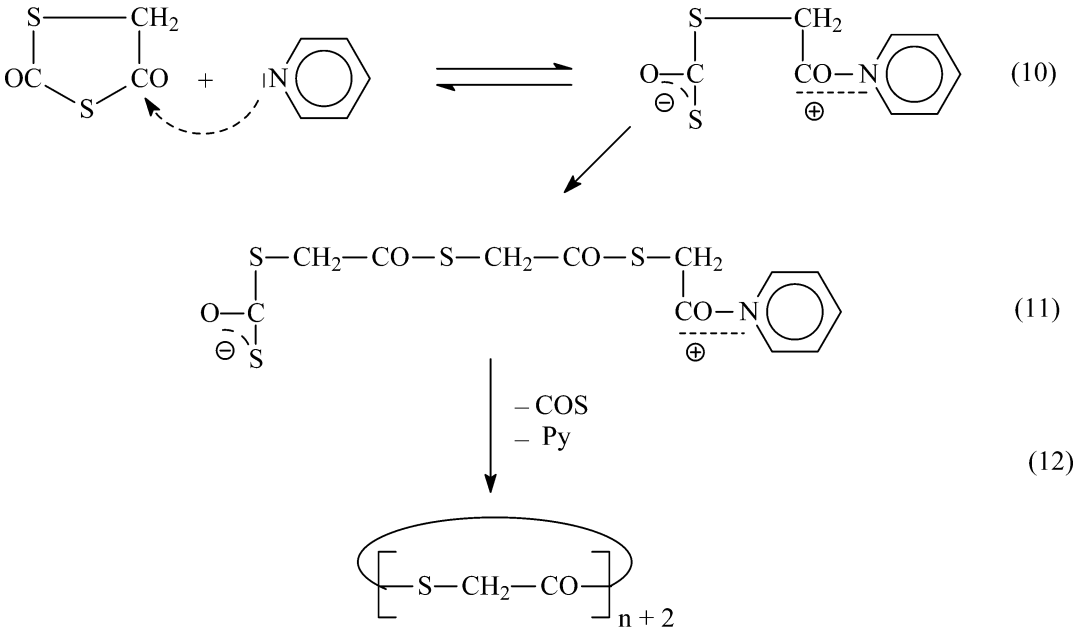
These results suggest the following interpretation: Pyridine activates monomers via formation of zwitterions (eq 10, Scheme 4). These zwitterions can initiate an anionic ring-opening polymerization and in a parallel reaction, all zwitterionic species can react with each other by condensation steps obeying a step-growth kinetic as formulated in Scheme 1 for sarcosine NCA. With decreasing monomer concentrations the contribution of chain-growth steps will decrease and the influence of step-growth reactions will increase. Regardless of the chain-growth/step-growth ration which is difficult to determine, the total chain-growth (eq 11) will be terminated by cyclization (eq 12).

The formation of **La**, **Lb**, and **Lc** chains can be explained by the rapid crystallization of poly(thioglycolide) chains which hinders cyclization by immobilization. Since the ionic end groups do not fit into the crystal lattice, they will preferentially sit on the surface of the crystallites and react with the nonsolvents used for washing of the reaction product. When the active chains regain their mobility by melting prior to the reaction with a nucleophilic species, complete cyclization may take place. A close analogy was found for polymerizations of L-alanine NCA. The rapid zwitterionic polymerizations catalyzed with pyridine in *N*-methylpyrrolidone (or in neat NMP) exclusively yielded cycles. Yet, during the slow polymerizations initiated by imidazole oligo(L-alanine)s precipitated from the reaction mixture and buried linear chains with active end groups on the surface of β-sheet lamellae. Washing with water then yielded poly(L-alanine)s having CO_2H end groups, and washing with methanol gave CO_2CH_3 end groups.[40]

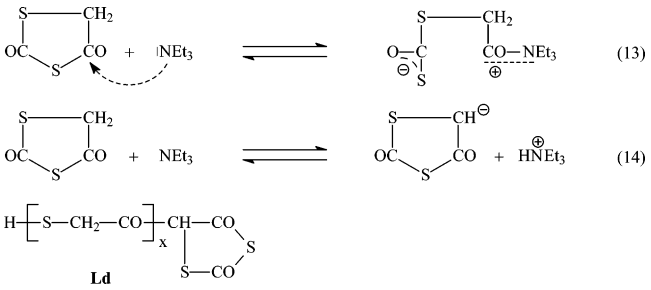
Three polymerizations were performed in dioxane at 20 °C using triethylamine as catalyst at monomer-catalyst ration of 20/1 (nos. 7−9, Table 2). In analogy to the experiments with pyridine these polymerizations were faster than the thermal polymerizations at 120 or 140 °C. Furthermore, the three experiments were worked up with three different nonsolvents, water, methanol and ethanol. Again all mass spectra displayed the peaks of cycles together with the peaks of linear chains which had the structures **La**, **Lb**, or **Lc** depending on the nonsolvent used for the workup. Figure 3 presents the product isolated after precipitation into methanol.

These results allow the conclusion that triethylamine also reacted with DTD by formation of zwitterions (eq 13, Scheme 5) and initiation of a zwitterionic polymerization. This mechanism is in contradiction to the mechanism speculatively formulated in a previous publication.[11] Previously it was assumed that triethylamine can deprotonate DTD (eq 14), so that the resulting carbanion initiates a ring-opening polymerization yielding polymer chains of structure **Ld**. In summary, all tertiary amine-catalyzed polymerizations of DTD yielded cyclic polythioesters under condition which certainly do not involve "backbiting" equilibration and, thus, require a zwitterionic polymerization mechanism as the most plausible explana-

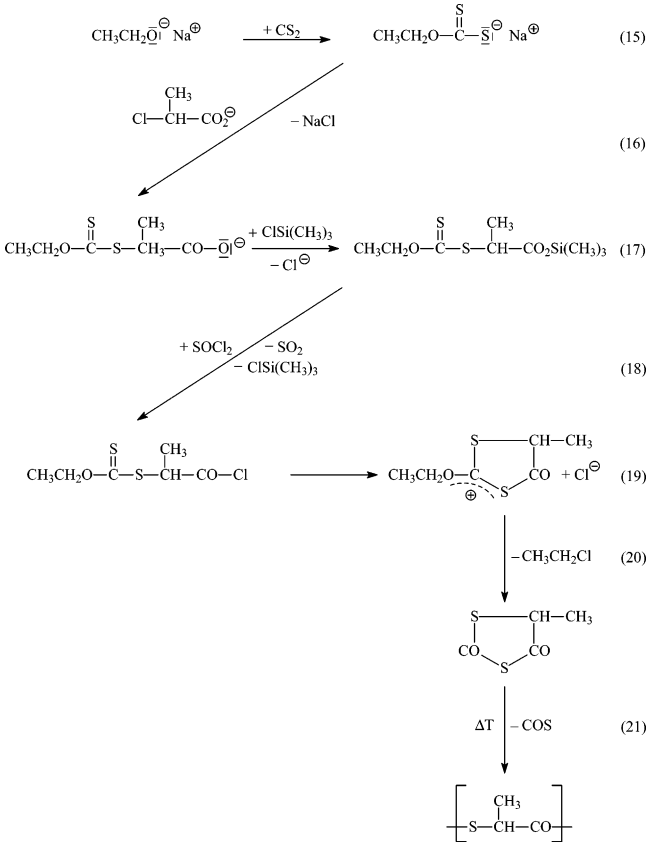
Scheme 4. Mechanism of Pyridine-Catalyzed Formation of Cyclic Poly(thioglycolide)



Scheme 5. Hypothetical Initiation Mechanisms and Reaction Product of Triethylamine-Initiated Polymerizations of Dithiolane-2,4-dione



Scheme 6. Synthesis and Thermal Polymerization of D,L-5-Methyl Dithiolane-2,4-dione (MDTD)



tion. This interpretation perfectly agrees with our previous studies of α-amino acid NCAs which can certainly not undergo transamidation and "backbiting" at temperatures ≤60 °C.

Synthesis and Polymerization of 5-Methyldithiolane-2,4-dione (MDTD). In contrast to DTD, D,L-5-methyldithiolane-2,5-dione (MDTD) has not been described before. The polymerization of this new monomer was of interest, because the resulting poly(D,L-thiolactide) should be amorphous and soluble in the reaction medium, so that not interference of chain-growth and cyclization with crystallization should occur.

MDTD was prepared according to the reaction sequence outlined in Scheme 6. It is important that the preparation of the ethyl xanthogenate (eq 15) is performed with an excess of CS_2, and long reaction time, to avoid that unreacted ethoxide can react with 2-chloropropionate during the following step (eq 16). The 2-xanthogen propionic acid did not crystallize and decomposed partially upon distillation in vacuo. Therefore, it was silylated with chlorotrimethylsilane and triethylamine. The resulting trimethylsilyl ester (eq 17) was then distilled without decomposition. Its reaction with thionyl chloride directly yielded the monomer via the reaction sequence in eqs 18−20.

MDTD proved to be chemically and thermally considerably more stable than DTD itself. A temperature of 160 °C and a long reaction time of 24 h was required to achieve complete thermal polymerization (eq 21) which was checked by ^{1}H NMR spectroscopy. The amorphous transparent poly(D,L-thiolactide) was soluble in $CHCl_2$ and the inherent viscosity (η_{inh} = 0.08 g/L) measured in CH_2Cl_2 at 20 °C was low. The MALDI−TOF mass spectrum mainly displayed peaks of cyclic polythiolactides. Therefore, it may be assumed that the polymerization mechanism was, in principle, the same as that formulated for DTD in Scheme 2. However, four weak peaks were also detectable, indicating that in addition to the polymerization process a complex decomposition had occurred. The reproducibility of both thermal polymerization and mass spectrum were checked. In contrast to DTD, MDTD did not polymerize in pyridine even when the temperature was raised to 60 or 100 °C. When mixed with 4-(*N*,*N*-dimethylamino)pyridine

(monomer-catalyzed ratio 20/1) in toluene, again no polymerization occurred at 20, 60 or 100 °C. With an equimolar amount of 4-*N*,*N*-dimethylamino pyridine a black tar was obtained at 120 °C. Furthermore, no polymerization occurred with triethylamine (monomer−catalyst ratio 20/1) in dioxane at 20 or 60 °C. In summary, MDTD proved to be useless as a monomer for the preparation of high molar mass polythiolactide due to its unexpectedly high chemical stability.

Conclusion

The experiments of this work prove that dithiolane-2,4-diones polymerize upon heating above 120 °C without addition of catalysts. These thermal polymerizations and the tertiary amine-catalyzed polymerizations have in common that cyclic oligo- and polythioesters are formed. From these observations, it may be concluded that dithiolane-2,4-diones like sarcosine NCA may polymerize via a zwitterionic polymerization involving cyclization by a charge cancellation step. An unusual aspect of these zwitterionic polymerizations is the coexistence of chain-growth and step-growth propagation steps. The formation of cyclic polymers is typical for the step-growth character of this polymerization process. However, it should be emphasized that, on the one hand, zwitterionic polymerizations do not necessarily yield cyclic polymers as demonstrated for poly(pivalolactone)[39] and, on the other hand, combined chain-growth and step-growth polymerizations involving cyclization are not limited to zwitterionic polymerizations.[40]

References and Notes

(1) Lüke-Eversloh, T.; Bergander, K.; Luftmann, H.; Steinbüchel, A. *Microbiol. (Reading, U.K.)* **2001**, *147*, 11.
(2) Lüke-Eversloh, T.; Steinbüchel, A. *Microbiol. Lett.* **2005**, *221*, 191.
(3) Kim, D. Y.; Lüke-Eversloh, T.; Elbana, K.; Thakor, N.; Steinbüchel, A. *Biomacromolecules* **2005**, *6*, 897.
(4) Schöberl, A.; Krumey, F. *Ber. Dtsch. Chem. Ges.* **1944**, *77*, 1.
(5) Schöberl, A. *Angew. Chem.* **1948**, *60*, 7.
(6) Schöberl, A.; Wrekler, G. *Angew. Chem.* **1954**, *66*, 273.
(7) Schöberl, A. *Macromol. Chem.* **1960**, *64*, 37.
(8) Elias, H.-G.; Buhrer, H. G. *Makromol. Chem.* **1970**, *140*, 21.
(9) Buhrer, H. G.; Elias, H.-G. *Makromol. Chem.* **1970**, *141*, 41.
(10) Kricheldorf, H. R.; Bösinger, K.; Schwarz, G. *Makromol. Chem. Phys.* **1973**, *173*, 43.
(11) Kricheldorf, H. R.; Bösinger, K. *Makromol. Chem. Phys.* **1973**, *173*, 67. Elias, H.-G.; Bührer, H. G. *Makromol. Chem.* **1970**, *140*, 21.
(12) Kricheldorf, H. R.; von Lossow, C.; Schwarz, G. *J. Polym. Sci., Part, A. Polym. Chem.* **2006**, *44*, 4680.
(13) Kricheldorf, H. R.; von Lossow, C.; Schwarz, G. *Macromolecules* **2005**, *38*, 5513.
(14) Gresham, T. L.; Janssen, J. E.; Shaver, W.; Bankert, R. A.; Fiedrorek, F. T. *J. Am. Chem. Soc.* **1951**, *73*, 3168.
(15) Etienne, Y. P.; Soulas, R. M.; Thiebaut, R. J. *Polym. Sci. C* **1963**, *4*, 1061.
(16) Yamashitu, Y.; Ito, K.; Nakakita, F. *Makromol. Chem.* **1969**, *127*, 292.
(17) Boehlke, K.; Hans, M. J.; Jaacks, V.; Mathes, N.; Zimmerschied, K. *Angew. Chem.* **1969**, *81*, 336.
(18) Mathes, N.; Jaacks, V. *Makromol. Chem.* **1971**, *142*, 209.
(19) Eisenbach, C. D.; Schnecko, H.; Kern, W. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.*) **1975**, *16*, 13.
(20) Eisenbach, C. D.; Schnecko, H.; Kern, W. *Chem. Z.* **1975**, *99*, 241.
(21) Saegusa, T.; Ikeda, H.; Fuju, H. *Macromolecules* **1972**, *5*, 354.
(22) Saegusa, T.; Kobayashi, S.; Kimura, Y. *Macromolecules* **1974**, *7*, 1.
(23) Saegusa, T.; Kobayashi, S.; Kimura, Y.; Ikeda, H. J. *Macromol. Sci. Chem.* **1975**, *A9* (5), 641.
(24) Saegusa, T.; Kimura, Y.; Kobayashi, S. *Macromolecules* **1977**, *10*, 236.
(25) Wilson, D. R.; Beaman, R. G. *J. Polym. Sci., Part A, Polym. Chem.* **1970**, *8*, 2161.
(26) Johnston, D. S. *Adv. Polym. Sci.* **1982**, *42*, 51.
(27) Han, M. J.; Chang, J. Y.; Lee, Y. Y. *Macromolecules* **1982**, *15*, 255.
(28) McEwen, I. J. *Prog. Polym. Sci.* **1984**, *10*, 317.
(29) Odian, G.; Gunatillake, P. A. *Macromolecules* **1984**, *17*, 1297.
(30) Endo, T.; Fukuda, H.; Hirota, M. *J. Am. Chem. Soc.* **1984**, *106*, 4035.
(31) Miura, M.; Akutsu, F.; Kunimoto, F.; Ito, H.; Nagakubo, K. *Makromol. Chem. Rapid Commun.* **1984**, *5*, 109.
(32) Tijsma, E. J.; Van der Does, L.; Bantjes, A. *J. Macromol. Sci.—Rev. Macrom. Chem. Phys.* **1994**, *34*, 515.
(33) Eromosele, I. C.; Pepper, D. C. *Macromol. Rapid Commun.* **1096**, *7*, 531.
(34) Cronin, J. P.; Pepper, D. C. *Macromol. Chem.* **1989**, *189*, 85.
(35) Arsu, N.; Oenen, A.; Yagei, Y. *Macromolecules* **1996**, *29*, 8973.
(36) Culkin, D. A.; Jeong, W.; Csikony, S.; Gomoz, E. D.; Balsano, N. P.; Hedrick, J. L.; Weymouth, R. M. *Angew. Chem.* **2007**, *119*, 2681; *Angew. Chem., Int. Ed.* **2007**, *46*, 2627.
(37) Kricheldorf, H. R.; Behnken, G.; Schwarz, G. *Polymer* **2005**, *46*, 11219.
(38) Kricheldorf, H. R.; Al-Masri, M.; Lomadze, N.; Schwarz, G. *Macromolecules* **2005**, *38*, 9085.
(39) Kricheldorf, H. R.; Garaleh, M.; Schwarz, G. *J. Macromol. Sci., Pure Appl. Chem.* **2005**, *A42*, 139.
(40) Kricheldorf, H. R.; von Lossow, C.; Schwarz, G. *J. Polym. Sci., Part, A. Polym. Chem.* **2005**, *43*, 5690.

MA0705467