Pergamon

Tetrahedron 58 (2002) 7065–7074

TETRAHEDRON

Unusual cyclodimerization of small cyclic ethers via neighboring carbonyl-group participation and cation transfer

Shigeyoshi Kanoh,* Tomonari Nishimura, Masashi Naka and Masatoshi Motoi

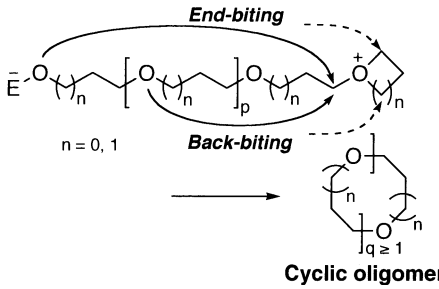
Department of Industrial Chemistry, Faculty of Engineering, Kanazawa University, Kodatsuno, Kanazawa 920-8667, Japan

Received 19 March 2002; accepted 23 May 2002

Abstract—Oxetanes having both a carbonyl functional group and a phenyl group at the 3-position bring about unusual cyclodimerization under the influence of trifluoromethanesulfonic acid, to give a *cis*/*trans*-isomer mixture of substituted 1,3-dioxanes via neighboring carbonyl-group participation, cation transfer including phenonium rearrangement, and cyclodimerization. Oxiranes having a carbonyl functional group also undergo a similar cyclodimerization to form a 1,3-dioxolane ring. No phenyl substituent is required in the cases of the oxiranes, because the cation transfer process involves a 1,2-hydride shift alone. These five- and six-membered cyclic acetals are quite different from ring-expanded cyclic ether dimers expected simply from the back-biting reaction known in the cationic ring-opening polymerization of oxiranes and oxetanes.

1. Introduction

Small cyclic ethers, such as epoxide–oxirane, oxetane, and tetrahydrofuran–oxolane, are of major interest in the field of polymer chemistry, because polyethers produced by polymerization possess the high polarizability and flexibility of their main chains. The cationic ring-opening polymerization by an active chain end mechanism (Scheme 1) is most frequently used, both academically and industrially.[1,2] In this propagation, cyclic oxonium ions at growing chain ends are repeatedly opened and regenerated by nucleophilic attack of the ether oxygen in these monomers. However, intramolecular cyclization (cyclooligomerization) could take place, if the oxonium end suffers 'back-biting' by any oxygen atom in its own polyether chain or, in a rare case, 'end-biting' by the terminal oxygen atom after growth to a long chain.[3] Consequently, various types of ring-expanded ethers from a cyclic dimer up to a cyclic macromer can be formed. The cyclooligomerization has been regarded as an undesirable side reaction for production of linear, high-molecular-weight polyethers by the cationic polymerization, but it can be available for synthesizing crown ethers, if control of the ring size is possible.[4] Such cyclization is usually less significant during the cationic processes of oxetanes, because of a great difference in basicity between four-membered cyclic ethers (pK_a=2.0) and acyclic ones (pK_a=3.6): the pK_a values of oxirane and tetrahydrofuran are 3.7 and 2.1, respectively.[2] Nevertheless, formation of cyclic oligomers from trimer to octamer has been long known in the cationic polymerization of oxetane and substituted oxetanes, especially at elevated temperatures.[5,6] Cyclic oligomers reported therein are all back-biting products.



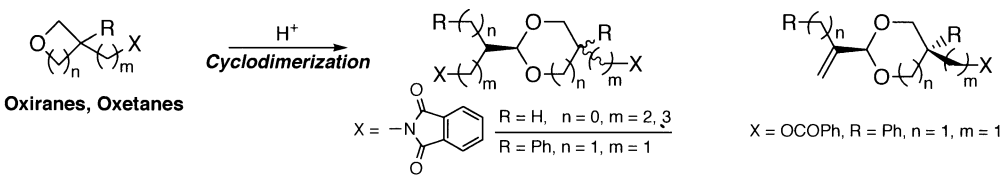
Scheme 1. Cationic cyclooligomerization of cyclic ethers.

Recently, we have communicated a quite different type of cyclodimerization:[7–9] 3-phenyloxetane (**1a**) having a phthalimidomethyl group at the 3-position is isomerized to a bicyclic acetal (**1b**) by an acid-promoted 1,6-intramolecular nucleophilic attack of the carbonyl oxygen,[10,11] and in turn **1b** undergoes a dimerization under certain cationic conditions, to give 1,3-dioxane derivatives (**1d**) in high yield.[7] Formation of the unusual cyclic dimers is not unique to **1a**. A similar dimerization has been found for 3-phenyloxetan-3-ylmethyl benzoate (**3a**).[9] However, oxiranes and oxetanes having a carbonyl functional group do not always bring about such a dimerization, which is strongly dependent on both the nature of carbonyl group and the structures of the cyclic ether and the additional substituent. This paper describes unusual cyclodimerization of oxiranes and oxetanes having a phthalimido or benzoate group, as outlined in Scheme 2. This cyclodimerization seems to be of primary interest for its curious reaction mechanism rather than its synthetic utility.

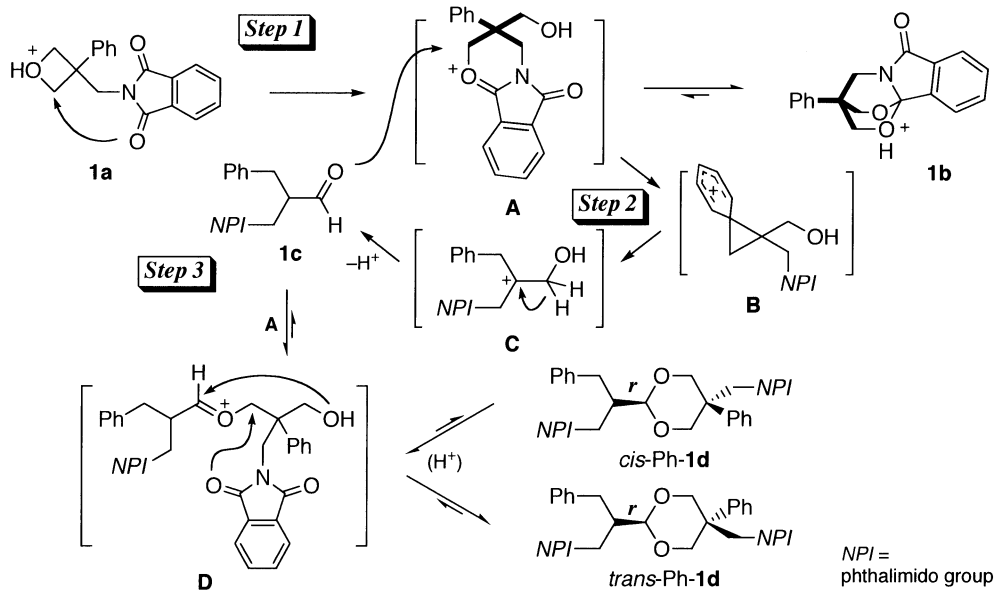
Keywords: dimerization; oxetanes; epoxides; carbonyl compounds.

* Corresponding author. Fax: +81-76-234-4800;
e-mail: kanoh@t.kanazawa-u.ac.jp

0040–4020/02/$ - see front matter
PII: S0040-4020(02)00702-0



Scheme 2. Unusual cyclodimerization of cyclic ethers having a carbonyl functional group.



Scheme 3. Cyclodimerization of oxetane phthalimide (**1a**).

2. Results and discussion

2.1. Cyclodimerization of oxetanes having a carbonyl functional group

2.1.1. Cyclodimerization of oxetane phthalimide. As reported in the preceding paper of this journal issue,[11] we have found that oxetanes having a cyclic imide group undergo tandem cyclization to bicyclic acetals under the influence of Lewis acids, Brønsted acids, and alkylating agents, regardless of the imide group as well as the additional substituent at the 3-position. In addition, when this isomerization was performed at temperatures above 80°C, these catalysts, except for weak Lewis acids such as Me_3Al and methylaluminum bis(2,6-di-*tert*-butyl-4-methylphenoxide) (MAD), caused in situ double ring-opening polymerization of the bicyclic acetal intermediates, to give polyethers having pendant imide groups.[10] The Lewis acid-promoted reactions of 3-phenyl-3-phthalimidomethyloxetane **(1a)** with Me_3Al or MAD in chlorobenzene at 120°C yielded **1b** in a nearly quantitative conversion (Scheme 3).[11] Similarly, the use of $BF_3{\cdot}Et_2O$, 1-benzyltetrahydrothiophenium hexafluoroantimonate (BnTA), and trifluoromethanesulfonic acid (TfOH) under the same conditions also yielded **1b** only at a very early stage of the reactions (vide infra). However, **1b** was rapidly converted into different products, and ultimately into oligomeric products different from the polyether mentioned above.[7,8]

Fig. 1 shows a GPC curve of the product mixture obtained in the reaction with BnTA for 24 h. The curve splits into three fractions of unimer, dimer, and higher oligomers. The mass spectrum of the most abundant dimer fraction showed *m/e*=586, suggesting a dimerization of **1b** (MW=293). This fraction was composed of two geometrical isomers, which were carefully separated and purified by preparative TLC followed by repeated crystallization. The absolute structure of one was substantiated by the X-ray analysis.[7] The ORTEP view illustrated in Fig. 2 reveals that this isomer (*trans*-Ph-**1d**) has a chair-shaped 1,3-dioxane ring, and the largest, isopropyl-type, substituent at the 2-position and the phenyl group at the 5-position are in equatorial orientation. The H–H COSY spectrum of *trans*-Ph-**1d** (Fig. 3) clearly exhibits a long-range correlation between *N*-methylene protons (H13a, b) and *O*-methylene ones (axial H4b, H6b), probably due to a W-type arrangement. These observations indicate that the phenyl group at the 5-position is likely in the equatorial position, not only in the solid, but also in

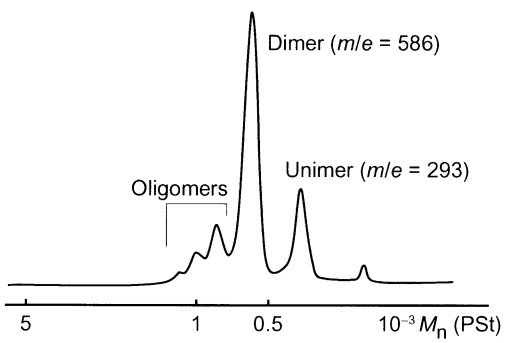


Figure 1. GPC chart of the products obtained in the reaction of **1a** with BnTA (5 mol%) in PhCl at 130°C for 24 h.

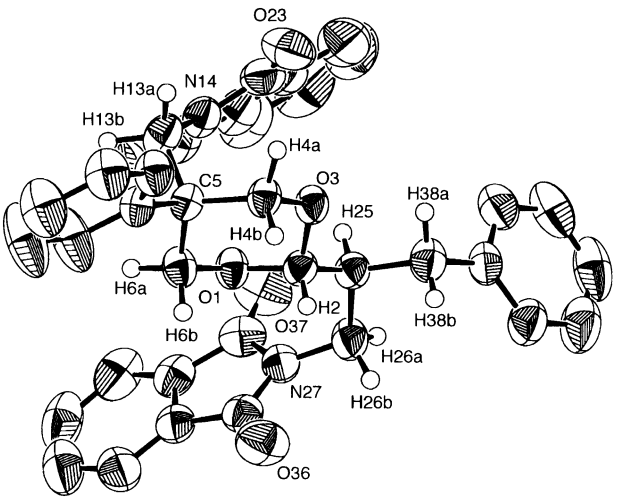


Figure 2. ORTEP view of *trans*-Ph-**1d** with 30% probability thermal ellipsoids. The numberings of carbon atoms are the same as those of the hydrogen atoms to which they are covalently bonded.

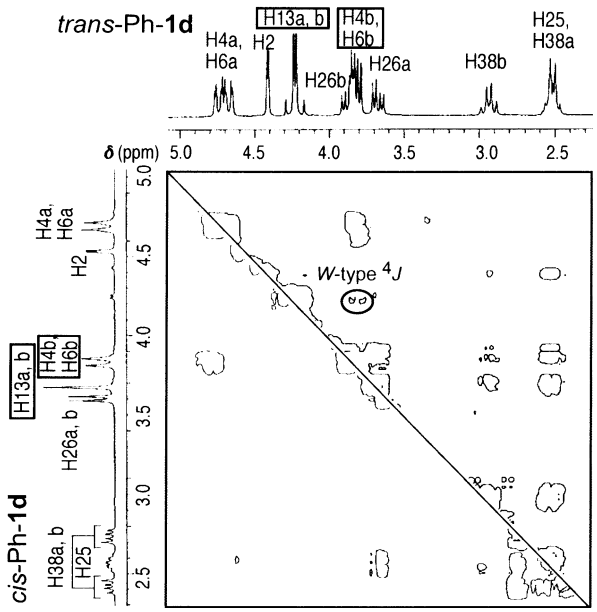


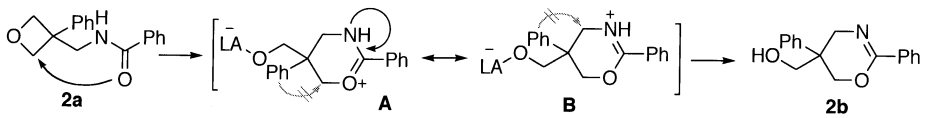
Figure 3. 270 MHz H–H COSY spectra of *trans*-Ph-**1d** (upper right) and *cis*-Ph-**1d** (lower left) in $CDCl_3$. The numberings of hydrogen atoms refer to those in Fig. 2.

$CDCl_3$ solution. The ^{13}C spectrum of the second isomer has a strong resemblance to that of *trans*-Ph-**1d**, whereas the ^1H NMR spectrum is quite different in coupling pattern (Fig. 3); the H–H COSY spectrum lacks the long-range correlation between H13a, b and H4b, H6b. Therefore, it may be deduced that the second isomer (*cis*-Ph-**1d**) is a geometrical isomer of *trans*-Ph-**1d** with respect to the substitution mode at the 5-position. Consequently, both cyclic dimers are not eight-membered cyclic ether dimers expected from the above-mentioned back-biting. In addition, we noted the presence of a small doublet with a peculiar pattern J=1.96 Hz at 9.75 ppm in ^1H NMR spectra of the reaction mixtures. This signal is characteristic of a CH–C*H*O moiety, suggesting aldehyde **1c**. However, the isolation failed, most likely due to air sensitivity.

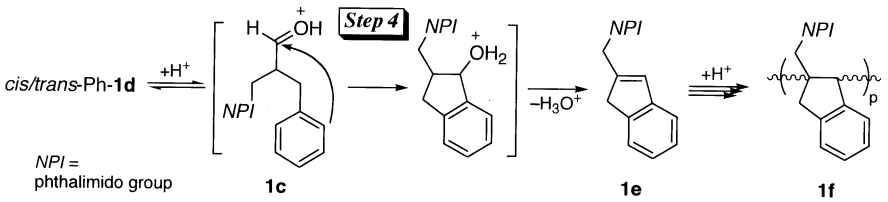
The product distribution of **1b–d** over the reaction time was re-examined in the reaction of **1a** with TfOH (5 mol%) in PhCl at 130°C. The isomerization of **1a** to **1b** was completed in a very early stage (within 8 min even at 80°C), and then **1b** was entirely converted into **1c** (1%), *trans*-Ph-**1d** (58%), *cis*-Ph-**1d** (36%), and oligomers (5%) for 10 min. After then, **1d** was gradually decreased with the formation of oligomer. The reactions with the other catalysts proceeded with a similar tendency, but the rates were remarkably more sluggish.

The overall reaction sequence of cyclodimerization would involve three consecutive elementary steps, as illustrated in Scheme 3. It is clear from the preceding reports[10,11] that step 1 is the isomerization of **1a** to **1b** via 1,3-oxazin-2-ylium cation intermediate **A** by a 1,6-intramolecular nucleophilic attack of the imide-carbonyl oxygen on the oxonium α-carbon (neighboring group assistance). The other products **1c** and **1d** have, in part, the same skeleton of an isopropyl branch that is absent from the starting **1a**. This suggests a migration of the phenyl group. It has been reported that bicyclic acetals similar to **1b** polymerize cationically in a single or double ring-opening manner.[10] Therefore, both **A** and the oxonium ion of **1b** seem to possess the potential to initiate the cationic ring-opening polymerization of **1b**. However, since these unimers carry neophyl type skeletons (shown by heavy lines in the structures) adjacent to positively charged oxygens, the steric hindrance around the electrophilic sites make the intermolecular attack of **1b** difficult. For this reason, **1b** would polymerize very reluctantly. Instead, the neighboring assistance of the phenyl group brings about self-ring opening of **A**. Taking into consideration for high susceptibility of the neophyl-type skeleton to a cation transfer,[12] the resulting phenonium ion **B** undergoes a consecutive cation transfer, i.e. phenonium rearrangement (**B** to **C**) followed by 1,2-hydride shift (**C** to **1c**). The migration of the phenyl group is the key step in this cyclodimerization, because homologous benzyl- or more bulky isopropyl-substituted oxetane phthalimide was simply isomerized to the bicyclic acetal.[11] It is most likely that the more nucleophilic **1c** compared to **1b** much more readily adds to **A** in step 3. Finally, the open oxonium dimer **D** cyclizes to cyclic dimers **1d** depending on the direction of ring closure. A tentative explanation for the stereochemical bias of **1d** is an $n-\pi$ stereoelectronic repulsion between two oxygens of the 1,3-dioxane ring and the 5-axially standing phenyl group in *cis*-Ph-**1d**. After a mixture of *cis*- and *trans*-Ph-**1d** in a mole ratio of 57:43 was similarly treated with TfOH in PhCl at 130°C for 96 h, the ratio changed to 38:62. In addition, a very small quantity of **1c** was detected from this reaction mixture. These results indicate not only that *trans*-Ph-**1d** is a more thermodynamically favorable product but also that the interconversion between the isomers of **1d** passes through **D**.

2.1.2. Isomerization of oxetane benzamide. The above observation stimulated our interest in the reaction mode of oxetane benzamide (**2a**), which resembles **1a** in structure (Scheme 4). The reactions of **2a** with Me_3Al, $BF_3{\cdot}Et_2O$, or TfOH as the acid catalysts were examined in PhCl at 130°C. The use of TfOH gave oligomeric products showing an ester carbonyl stretching band (1720 cm^{-1}), but no further



Scheme 4. Isomerization of oxetane benzamide (**2a**).



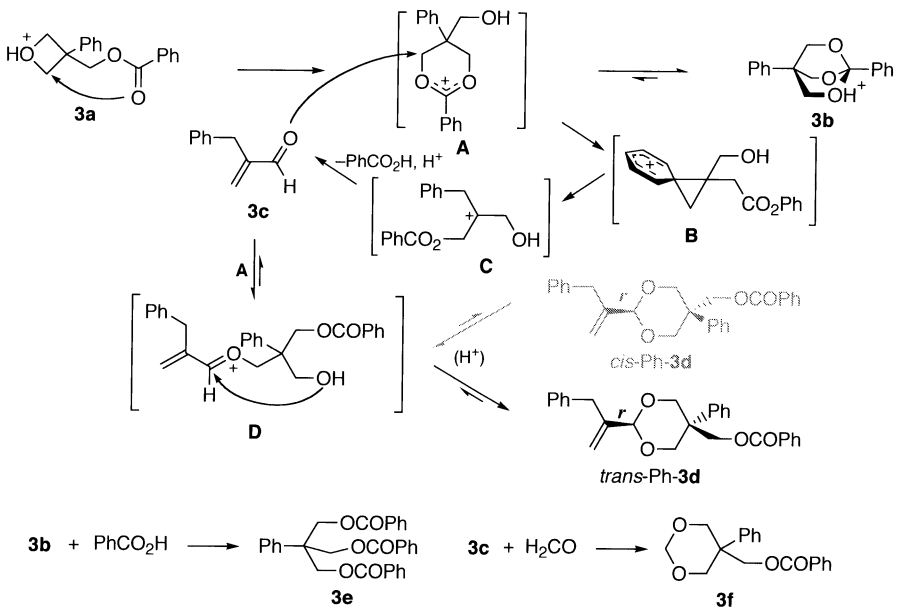
Scheme 5. Formation of poly(indene) (**1f**) from **1d**.

analysis was done. The other two catalysts gave a 5,6-dihydro-4*H*-1,3-oxazine derivative (**2b**) as the only product. This result is consistent with the isomerization mode of *sec*-amide-substituted oxetanes.[11,13] The nitrogen in a cation intermediate leading to **2b** possesses more amine character, unlike the amide nitrogen in the cation formed from **1a**. The contribution of carbeoxonium ion **A** to the cation intermediate would be negligibly small, compared with that of more stable imidate cation **B**. For this reason, the phenyl group misses a chance to migrate and, consequently, no cyclodimerization takes place.

2.1.3. Polymerization of oxetane phthalimide with quantitative dehydration. When the reaction of **1a** with TfOH was forced into completion, oligomers were obtained as the final product. The structure of the oligomers was confirmed by matrix-assisted laser desorption ionization time of flight mass (MALDI-TOF-MS) analysis. Crests of peak clusters appeared at regular intervals separated by approximately 275 mass units.[8] This indicates that the repeating monomer units have FW=275 and can be derived by release of one molecule of water from **1a** (MW=293). From the reaction mixtures obtained after more than 72 h, 2-(phthalimidomethyl)indene (**1e**: MW=275 corresponding to FW of the repeating unit) was isolated, but the yield was less than 10% throughout the reaction (Scheme 5).

To explain the mechanism for the above polymerization in the presence of a proton source (Scheme 5), an additional step 4 should be required besides steps 1–3 shown in Scheme 3. As already mentioned, the interconversion between **1c** and the isomers of **1d** is an equilibrium process. Protonated aldehyde **1c** brings about an intramolecular aromatic electrophilic substitution, which is a type of Bischler–Napieralski reaction[14] with a proton as a condensing agent. Therefore, the cyclodimerization can be promoted with some Lewis acids, while the polymerization is accelerated only with TfOH. Finally, the olefinic monomer **1e** produced by dehydration undergoes proton-initiated polymerization to give **1f**.

2.1.4. Cyclodimerization of oxetane benzoate. Oxetane benzoate (**3a**) also has a bulky neophyl group, like **1a**. We have reported that **3a** is isomerized to bicyclic orthoester (**3b**) by Lewis acids[11] but **3b** undergoes little or no polymerization due to the steric hindrance of the phenyl group at the 4-position.[9] Besides **3b**, however, quite unexpected products **3c–f** were formed in the reaction of



Scheme 6. Cyclodimerization of oxetane benzoate (**3a**).

3a with TfOH in PhCl at 130°C, as shown in Scheme 6. From spectroscopic data, it was concluded that **3e** is a tribenzoate. The other two are possibly 1,3-dioxane derivatives, and it seemed that **3d** was also a cyclic dimer of **3a**. However, the high-resolution mass spectroscopic peak appeared at *m*/*e*=414.1832, which was lower than that for an exact dimer (MW=268×2) by 122 mass units, probably corresponding to a molecule of benzoic acid. Although it was difficult to isolate analytically pure **3d**, the NMR spectra were satisfactory to determine its structure precisely, as shown in Fig. 4. The H–H COSY spectrum of **3d** clearly shows allyl-type long-range correlations between benzylic protons (H^C) and terminal vinyl protons (H^A and H^B) connected by a geminal correlation. This indicates that **3d** has an allylbenzene moiety. Inspecting other NOE correlations, we propose the most reasonable stereostructure of **3d**, as shown in Fig. 4. Similarly, the structure of **3f**, which was obtained in a poor yield, was determined to be the 2-unsubstituted analogue of **3d**. In order to elucidate the above proton-promoted reaction pathway, GPC change in the reaction accelerated with 20 mol% of TfOH at 80°C was examined. As in the reaction of **1a**, **3b** was predominately produced within 10 min (curve A in Fig. 5). The initial product **3b** had been consumed after 1 h (curve B), and new products **3d** and **3e** were formed. When the reaction was allowed to proceed for 30 h (curve C), **3e** remained intact but **3d** was converted into oligomers. However, the structure of the oligomers formed is not clear yet.

The cyclodimerization sequence of **3a** can be explained by analogy of that of **1a**, as illustrated in Scheme 6. Initially, **3a** is isomerized to **3b**,[15] and hence the other products are formed through **3b**. Probably, the self-ring opening of cation **A** formed thermally from **3b** is caused by the neighboring assistance of the phenyl group, and then the resulting cation **B** undergoes phenonium rearrangement to another cation **C**, followed by 1,2-hydride shift and elimination of benzoic acid (or transformation to an enol and elimination of benzoic acid), to give an aldehyde intermediate **3c**. This elimination step is the only difference between the reactions of **1a** and **3a**, and it probably arises from the leaving ability of benzoate group. The conjugated enal structure of **3c** is supported from the presence of a very weak singlet at 9.56 ppm in ^{1}H NMR spectra taken in a middle stage of the reaction. This peak is assignable to the aldehydic proton without any vicinal proton. Attack of **3c** on **A** gives open oxonium dimer **D**, which cyclizes to cyclic dimer(s) **3d**. On the other hand, a minor product **3f** would be formed due to participation of formaldehyde in place of **3c** in the above sequence. The formaldehyde could be generated by a side reaction such as eliminative collapse of cations **A**, **B**, or **D**. It is clear that **3e** is a double adduct of **3b** with the liberated benzoic acid. The NOE correlation (Fig. 4) has revealed that **3d** is stereochemically uniform, i.e. *trans*-Ph-isomer. However, even though the *cis*-isomer is formed depending on the direction of ring closure in **D**, it would be transformed to the thermodynamically stable *trans*-Ph-**3d** through a rapid ring-opening, ring-closure equilibrium with the aid of the resonance stability of **D**.

2.2. Cyclodimerization of oxirane phthalimides

As mentioned above, a common key to the cyclodimerization of **1a** and **3a** lies in the migration of the phenyl group at the 3-position. Phthalimide-substituted oxiranes (**4a**, **5a**) are three-membered analogues of **1a**, but have no phenyl group as a migrating group. Contrary to our impression that the cyclodimerization of **4a** and **5a** might be impossible, the reactions with TfOH or BF_3·Et_2O in PhCl at 130°C gave initially bicyclic acetals (**4b**, **5b**), which were converted into 1,3-dioxolane derivatives (**4d**, **5d**) through a similar cyclodimerization (Scheme 7). As reported in our preceding paper,[11] **4b** and **5b** are the products formed by the acid-promoted isomerization of **4a** and **5a**: the 1,6- or 1,7-intramolecular nucleophilic attack of the imide-carbonyl

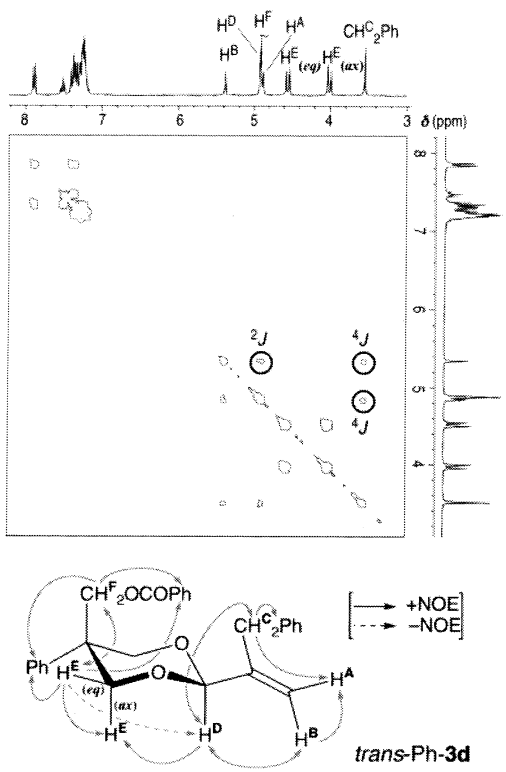


Figure 4. 270 MHz H–H COSY spectrum of *trans*-Ph-**3d** in $CDCl_3$ and the NOE correlation.

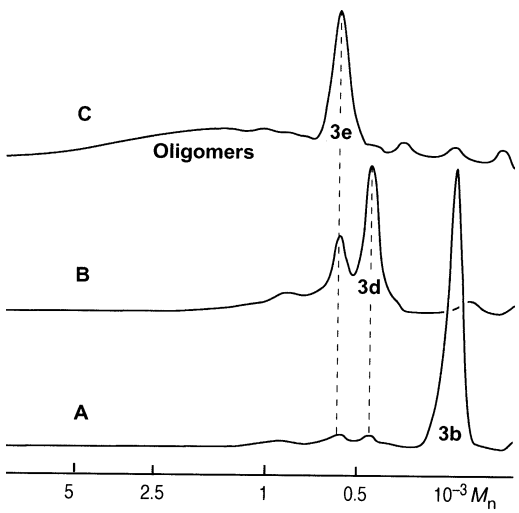
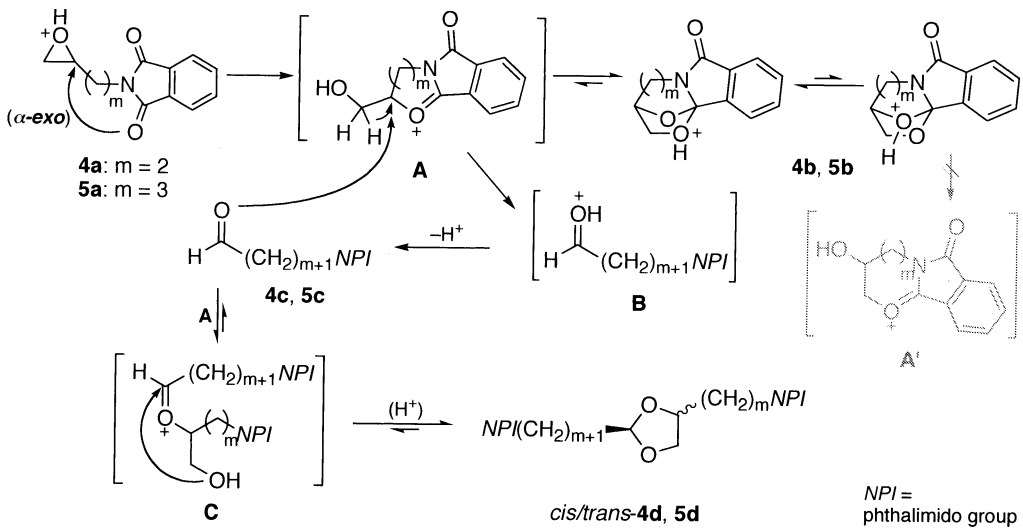


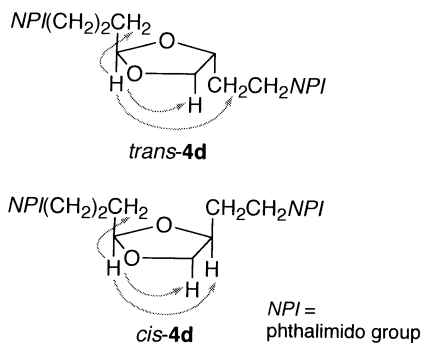
Figure 5. Change of RI-detected GPC curves in the reaction of **3a** with TfOH (20 mol%) in PhCl at 80°C: (A) 10 min; (B) 1 h; (C) 30 h.



Scheme 7. Cyclodimerization of oxirane phthalimides (**4a** and **5a**).

oxygen leads to the regioselective α-exo cyclization, in accord with Baldwin's rules.[16] The other products **4d** and **5d** are 1,3-dioxolane derivatives showing *cis*/*trans* isomerism with respect to the 2- and 3-substituents. Although the complete separation of the isomers failed, **4d** was separated into fractions enriched with each isomer by preparative TLC (89 and 73% enrichment of *cis*- and *trans*-isomer, respectively). The precise stereostructures were confirmed from NOE difference spectra under irradiation of the C2-methine proton, as shown in Scheme 8. The isomeric structures of **5d** were similarly determined. The *cis*/*trans*-isomer ratios of **4d** and **5d** obtained after 72 h were 59:41 and 51:49, respectively. The stereochemical biases were not so large compared to those of **1d** and **3d**, probably because of the lack of stereoelectronic effect due to a phenyl group. To confirm the formation of aldehyde intermediates (**4c**, **5c**), the ^{1}H NMR spectra of the reaction mixtures were inspected. The characteristic, but very weak triplet signals were spotted, which were ascribed to the aldehydic protons of CH_2–C*H*O moieties: 9.77 ppm (J=1.3 Hz) and 9.75 ppm (J=1.6 Hz) for **4c** and **5c**, respectively. More prolonged reaction gave substantial amounts of oligomers, which were not identified.

The cyclodimerization of **4a** and **5a** fundamentally resembles that of **1a**, as outlined in Scheme 7. Cation intermediate **A** can be isomerized into aldehydes (**4c** and **5c**) even without the aid of phenyl group: the isomerization step



Scheme 8. Plus NOE correlation of *cis*- and *trans*-**4d**.

is completed by a simple 1,2-hydride shift from the exo-methylene to the electron-deficient methine carbon neighboring carbeoxonium oxygen. Finally, the coupling of the aldehydes with **A** finishes the cyclodimerization. In contrast to **1b** and **3b**, the two acetal oxygens in **4b** and **5b** are not equivalent to each other, namely either a five- or six-membered carbeoxonium intermediate (**A** and **A′**) can be formed depending on which oxygen is protonated. However, the protonation would occur preferentially at the oxygen in an oxymethylene-bridge, rather than an oxy-bridge of **4b** and **5b**, because the lone pairs of acetal oxygen with a less strained bond angle are more basic due to the higher *p*-character.[17]

3. Conclusion

Oxetanes having both a carbonyl functional group and a phenyl group at the 3-position underwent an unusual cyclodimerization in the presence of TfOH, to give a *cis*/*trans*-isomer mixture of substituted 1,3-dioxanes. It is proposed that this occurred via neighboring carbonyl-group participation, cation transfers including a phenonium rearrangement, and cyclodimerization. The cyclodimerization products appear to exist in equilibrium with aldehyde intermediates. In the case of phthalimido-substituted oxetane, the aldehyde further underwent an intramolecular aromatic electrophilic substitution of the Bischler–Napieralski type, followed by dehydration and polymerization. Ultimately, a poly(indene) having a carbon–carbon backbone was formed. Oxiranes having a carbonyl functional group also underwent a similar cyclodimerization to form a 1,3-dioxolane ring. No phenyl substituent was required, most likely because the cation transfer process involved 1,2-hydride shifts alone. These five- and six-membered cyclic acetals are quite different from ring-expanded cyclic ether dimers expected simply from back-biting reactions known in the cationic ring-opening polymerization of oxiranes and oxetanes. It is surprising that in the cyclodimerization and related reactions a sequence of complicated processes proceeded in an extremely ordered manner.

4. Experimental

4.1. General

All melting points are uncorrected, and all boiling ranges denote bath temperatures. NMR spectra were measured on JEOL EX-270 NMR spectrometers using $CDCl_3$ as the solvent. The chemical shifts were determined with respect to TMS (δ 0.00 ppm) for ^1H nuclei and $CDCl_3$ (δ 77.00 ppm) for ^{13}C nuclei as internal standards. IR spectra were recorded on a JASCO FT/IR-3 infrared spectrometer. High resolution mass spectroscopic analyses (HRMS) and microanalyses were accomplished at the Center for Instrumental Analysis, Kanazawa University, using a JEOL JMS-SX102A mass spectrometer (ionization potential, 70 eV for EIMS) and a YANAKO CHN Corder MT-5, respectively. GPC was performed on a Shimadzu LC-10A high-speed liquid chromatography system equipped with a differential refractometer, using THF as an eluent with a flow rate of 1.0 mL/min at rt. Number-average molecular weights ($M_{n\ GPC}$) were determined on the basis of the molecular weight calibration curve obtained using polystyrene standards. MALDI-TOF-MS analysis was performed on a PerSeptive Biosystems Voyager-DE RP, equipped with a 337 nm nitrogen laser. The measurement was done using no salt additive at an accelerating potential of 20 kV. To a matrix layer, deposited by evaporation of 0.3 μL of 0.1% dithranol solution in THF, was added 0.3 μL of a sample solution in THF (2.0 mg/mL). A mixture of angiotensin and ACTH 7-38 was used for calibration.

Chlorobenzene (PhCl) and triethylamine (Et_3N) were freshly distilled from powdered CaH_2. 1-Benzyltetrahydrothiophenium hexafluoroantimonate (BnTA)[18] as a thermally latent Lewis acid was prepared by Endo's method: 60% yield, mp 112–113°C (lit.[18] mp 121.5–122°C). Throughout this work, products were purified by preparative column chromatography and preparative thin-layer chromatography using Merck Art. 101097 aluminum oxide 90 (70–230 mesh ASTM) and Merck Art. 1104 aluminum oxide 90 $PF_{254+366}$ (type E), respectively. R_f values were determined using Merck precoated TLC aluminum sheets aluminum oxide 60 F_{254} neutral. 'NPI' refers to phthalimido group. X-Ray crystallographic data for the structure have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 186848.

4.2. Preparation and reaction of oxetane phthalimide

4.2.1. 2-(3-Phenyloxetan-3-ylmethyl)isoindole-1,3-dione (1a). 2-Hydroxymethyl-2-phenylpropane-1,3-diol was prepared from excess formalin and phenylacetaldehyde in 51% yield.[19] The alcohol and diethyl carbonate (2.20 g, 12.1 mmol) were heated in the presence of alcoholic KOH (0.014 g, 0.5 mL) at 95–100°C for 5 h. Distillation at 180–200°C under ca. 20 mmHg gave (3-phenyloxetan-3-yl)methanol (**6**) in 51% yield. A solution of *p*-toluenesulfonyl chloride (1.30 g, 6.83 mmol) in THF (10 mL) was added dropwise to a mixture of **6** (1.02 g, 6.83 mmol) in THF (5 mL) and NaOH (1.37 g, 34.2 mmol) in water (10 mL) at 5–10°C. After stirring at rt for 2.5 h, a large amount of water was added to the mixture to deposit (3-phenyloxetan-3-yl)methyl *p*-toluenesulfonate. The crude product, obtained in 94% yield, was used in the next step without further purification. A DMF (20 mL) solution of the tosylate (2.53 g, 7.96 mmol) and potassium phthalimide (2.21 g, 11.92 mmol) was stirred at 80°C for 2 h, and then a large amount of water was added. The precipitates deposited were filtered, and dissolved in $CHCl_3$. The organic layer was washed with 5% aq NaOH and water, dried over Na_2SO_4, and evaporated in vacuo. The residue was recrystallized from $CHCl_3$–hexane to give **1a** (1.36 g, 58%). Colorless needles; mp 138.5–139.5°C; IR (KBr) 1771, 1718, 1708, 979, 850 cm^{-1}; ^1H NMR δ 4.17 (s, 2H, NCH_2), 5.05 (s, 4H, OCH_2), 7.02–7.12 (m, 2H, *o*-Ar*H* of 3-Ph), 7.18–7.38 (m, 3H, *m*- and *p*-Ar*H* of 3-Ph), 7.65–7.75, 7.75–7.87 (both m, 2H, carbonyl *m*- and *o*-Ar*H* of *NPI*); ^{13}C NMR δ 46.3, 48.8, 80.1, 123.4, 125.9, 127.1, 128.6, 131.7, 134.1, 142.4, 168.6. EI HRMS calcd for $C_{18}H_{15}NO_3$: 293.1053. Found: 293.1031. Anal. calcd for $C_{18}H_{15}NO_3$: C, 73.71; H, 5.15; N, 4.78. Found: C, 73.75; H, 5.16; N, 4.75.

4.2.2. 2,3-Benzo-7-phenyl-9,10-dioxa-5-azatricyclo-[5.2.2.0^{1,5}]undec-2-en-4-one (1b). Anhydrous PhCl (3.5 mL) containing TfOH (0.09 mmol, 5 mol%) was added to **1a** (0.504 g, 1.72 mmol) under dry nitrogen. The mixture was allowed to stand at 80°C for 10 min, quenched by adding anhydrous Et_3N (0.2 mL), and then evaporated in vacuo to dryness. The residue was recrystallized from CH_2Cl_2–hexane to give **1b** (0.413 g, 82%). Colorless needless; mp 198.5–199.5°C; IR (KBr) 1703, 1115, 1064–963 cm^{-1}; ^1H NMR δ 4.16 (s, 2H, NCH_2), 4.35, 4.63 (both d, J=8.6 Hz, 2H, *equatorial* and *axial* OCH_2 with respect to a boat-type 1,3-dioxane ring), 7.23–7.33 (m, 2H, *o*-Ar*H* of 7-Ph), 7.33–7.49 (m, 3H, *m*- and *p*-Ar*H* of 7-Ph), 7.51–7.68 (m, 3H, carbonyl *m*- and *o*-Ar*H* of *NPI*), 7.82 (dd, J_1=5.8, 1.8 Hz, 1H, carbonyl *o*-Ar*H* of *NPI*); ^{13}C NMR δ 37.8, 48.6, 73.4, 102.0, 122.1, 123.6, 125.4, 128.5, 129.4, 130.9, 132.4, 133.1, 135.5, 139.7, 164.4. EI HRMS calcd for $C_{18}H_{15}NO_3$: 293.1053. Found: 293.1054. Anal. calcd for $C_{18}H_{15}NO_3$: C, 73.70; H, 5.15; N, 4.78. Found: C, 73.93; H, 5.16; N, 4.82.

4.2.3. *trans*/*cis*-5-Phenyl-*cis*/*trans*-5-phthalimidomethyl-*r*-2-(1-benzyl-2-phthalimidoethyl)-1,3-dioxane (*trans*/*cis*-Ph-1d). In the same procedure as above except using $BF_3{\cdot}Et_3O$ (5 mol%), the reaction of **1a** was carried out at 130°C for 132 h, to give a mixture of **1c**, *trans*- and *cis*-Ph-**1d**, and oligomers in 2, 60, 28, and 10% NMR conversions, respectively. The crude products were fractionated by preparative TLC on alumina with AcOEt–hexane=1:1. The dimer fraction (R_f=0.61) was carefully separated into upper and lower halves, which were desorbed with a mixture of MeOH–CH_2Cl_2=1:1. Repeated crystallization of the upper and lower parts from MeOH–CH_2Cl_2–hexane gave *trans*- and *cis*-Ph-**1d**, respectively.

trans-Ph-**1d**. Colorless needles; mp 204–206°C (MeOH–CH_2Cl_2–hexane); IR (KBr) 1780, 1710, 1140, 1095–1025 cm^{-1}; ^1H NMR δ 2.43–2.61 (m, 1H, H25), 2.51, 2.93 (both dd, J=17.6, 9.2 Hz, 1H, *H*38a, b), 3.67, 3.87 (both dd, J=14.1, 6.6 Hz, 1H, *H*26a, b), 3.80, 3.83 (both d, J=11.6 Hz, 1H, *H*4b, *H*6b), 4.21, 4.25 (both d, J=14.4 Hz, 1H, *H*13a, b), 4.54 (d, J=2.9 Hz, 1H, *H*2), 4.67, 4.74 (both

dd, J=11.2, 2.9 Hz, 1H, *H*4a, *H*6a), 6.97–7.27 (m, 10H, Ar*H* of Ph), 7.73–7.80 (m, 8H, Ar*H* of *NPI*); ^{13}C NMR δ 33.5, 37.9, 39.6, 42.2, 44.5, 73.5, 102.0, 123.0, 123.2, 125.2, 125.8, 127.5, 128.2, 128.6, 128.8, 132.0, 132.1, 133.6, 133.7, 139.2, 139.3, 168.2, 168.4. EI HRMS calcd for $C_{36}H_{30}N_2O_6$: found 586.2101. Anal. calcd for $C_{36}H_{30}N_2O_6$: C, 73.70; H, 5.15; N, 4.78. Found: C, 73.76; H, 5.26; N, 4.67. Crystal data: monoclinic, space group *C*2/*c*, Z=8 with a=32.598(9) Å, b=11.517(2) Å, c=19.118(4) Å; V=5958(2) Å^3, and D_{calc}=1.308 g/cm^3, 9558 measured, 4683 independent reflections, of which 6153 were considered as observed [$I>3.00\sigma(I)$]. R=0.048, R_w=0.056.

cis-Ph-**1d**. Colorless needles; mp 192–193°C ($MeOH–CH_2Cl_2$–hexane); IR (KBr) 1780, 1710, 1140, 1095–1025 cm^{-1}; ^{1}H NMR δ 2.40, 2.72 (both dd, J=13.9, 6.9 Hz, 1H, *H*38a, b), 2.50–2.61 (m, 1H, *H*25), 3.58 (d, J=7.3 Hz, 1H, *H*26a, b), 3.65 (s, 2H, *H*13a, b), 3.81 (d, J=11.6 Hz, 2H, *H*4b, *H*6b), 4.51 (d, J=2.3 Hz, 1H, *H*2), 4.67 (d, J=11.6 Hz, 2H, *H*4a, *H*6a), 6.90–7.37 (m, 10H, Ar*H* of Ph), 7.56–7.84 (m, 8H, Ar*H* of *NPI*); ^{13}C NMR δ 33.5, 37.8, 42.4, 42.9, 43.2, 72.8, 101.5, 122.9, 123.5, 125.6, 126.8, 127.9, 128.1, 128.3, 128.7, 131.7, 132.0, 133.6, 134.2, 139.6, 139.9, 168.4. EI HRMS calcd for $C_{36}H_{30}N_2O_6$: 586.2105. Found: 586.2104. Anal. calcd for $C_{36}H_{30}N_2O_6$: C, 73.70; H, 5.15; N, 4.78. Found: C, 73.75; H, 5.19; N, 4.72.

4.2.4. 2-(1*H*-Inden-2-ylmethyl)isoindole-1,3-dione (1e). Similarly, the reaction of **1a** with TfOH (5 mol%) was carried out at 130°C for 3 days. The crude products were separated by preparative TLC on alumina with AcOEt–hexane=1:1, to give **1e** in 9% (R_f=0.95). The analytical sample was further purified by recrystallization from CH_2Cl_2–hexane. Colorless needles; mp 192–193°C; IR (KBr) 1770, 1708, 1615 cm^{-1}; ^{1}H NMR δ 3.41 (s, 2H, 1-C*H*$_2$), 4.73 (s, 2H, NC*H*$_2$), 6.77 (s, 1H, 3-C*H*), 7.13 (td, J=7.3, 1.7 Hz, 1H, either 5- or 6-Ar*H*), 7.21 (t, J=6.9 Hz, 1H, either 5- or 6-Ar*H*), 7.29 (d, J=6.9 Hz, 1H, either 4- or 7-Ar*H*), 7.37 (d, J=7.3 Hz, 1H, either 4- or 7-Ar*H*), 7.73, 7.87 (both dd, J=5.3, 3.0 Hz, 2H, carbonyl *m*- and *o*-Ar*H* of *NPI*); ^{13}C NMR δ 37.8, 40.1, 121.0, 123.4, 123.6, 124.7, 126.4, 130.0, 132.1, 134.1, 142.9, 143.2, 144.3, 168.0. EI HRMS calcd for $C_{18}H_{13}NO_2$: 275.0946. Found: 275.0947. Anal. calcd for $C_{18}H_{13}NO_2$: C, 78.53; H, 4.76; N, 5.09. Found: C, 78.48; H, 4.81; N, 5.04.

4.2.5. Poly(2-phthalimidomethyl-1,2-indanylene) (1f). The above reaction was continued for 11 days to give **1f**. The crude oligomer was dissolved in THF, and precipitated by adding Et_2O, to separate it into lower- and higher-molecular-weight fractions: M_n (polydispersity)=916 (1.14) and 1730 (1.18), isolated yield=28 and 41%, respectively. The latter part was used for analytical purposes. IR (KBr) 1780, 1710 cm^{-1}; ^{1}H NMR δ 2.0–3.4 (m, 3H, C*H*$_2$ and C*H* in indane moiety), 3.4–4.8 (m, 2H, NC*H*$_2$), 6.0–7.3 (m, 4H, Ar*H* of indane moiety), 7.3–8.1 (m, 4H, Ar*H* of *NPI*); ^{13}C NMR δ 36.2, 41.4, 47.7, 55.6, 122.9, 124.0, 126.6, 128.3, 141.7, 131.8, 133.8, 147.1, 168.2. Anal. calcd for $C_{18}H_{13}NO_2$: C, 78.53; H, 4.76; N, 5.09. Found: C, 78.93; H, 4.60; N, 4.50.

4.3. Preparation and reaction of oxetane benzamide

4.3.1. *N*-(3-Phenyloxetan-3-ylmethyl)benzamide (2a). Hydrazine hydrate (2.58 g, 51.6 mmol) was added dropwise to an EtOH (200 mL) solution of **1a** (2.52 g, 8.60 mmol) with stirring. The mixture was refluxed for 3 h, and the resulting precipitates were filtered off. Small portions of Raney Ni (W-2)[20] were added to the filtrate under vigorous refluxing in order to decompose unreacted hydrazine.[21] The inorganic materials were filtered off, and the filtrate was concentrated by distillation at atmospheric pressure. The residue was distilled in vacuo to give 3-phenyl-3-aminomethyloxetane in 54% yield: bp 110–130°C (10 mmHg). Benzoic anhydride (1.16 g, 5.11 mmol) was added to a $CHCl_3$ solution of the above amine (0.757 g, 4.64 mmol) and Et_3N (0.516 g, 5.11 mmol) at 5°C, and then the mixture was stirred at rt for 4 h. The organic layer was washed with 5% aq NaOH and brine, dried over Na_2SO_4, and evaporated in vacuo. The residue was recrystallized from $CHCl_3$–Et_2O to give **2a** (0.786 g, 63%). Colorless powder; mp 125–127°C; IR (KBr) 3300, 1640, 1310, 1180, 980, 830 cm^{-1}; ^{1}H NMR δ 4.04 (d, J=5.9 Hz, 2H, NC*H*$_2$), 4.84, 5.03 (both d, J=6.1 Hz, 2H, OC*H*$_2$ *trans* and *cis* to 3-C*H*$_2$NH), 6.22 (br s, 1H, N*H*), 7.04–7.69 (m, 10H, Ar*H*); ^{13}C NMR δ 47.9, 48.1, 79.7, 125.6, 126.7, 127.1, 128.5, 128.9, 131.5, 134.2, 142.5, 167.8. EI HRMS calcd for $C_{17}H_{17}NO_2$: 267.1260. Found: 267.1263.

4.3.2. (2,5-Diphenyl-5,6-dihydro-4*H*-1,3oxazin-5-yl)-methanol (2b). A hexane solution of Me_3Al (0.02 mL, 0.98 mol/L, 0.02 mmol) was added to a PhCl (1.0 mL) solution of **2a** (100 mg, 0.374 mmol). The resulting solution was allowed to react at 120°C for 30 h and quenched by adding Et_3N (0.1 mL) followed by MeOH (3.0 mL). The mixture was evaporated in vacuo and purified by alumina chromatography with AcOEt, to give **2b** (63 mg, 63%). Colorless semi-solid; IR (KBr) 3300, 1650, 1150–1020 cm^{-1}; ^{1}H NMR δ 1.88 (br s, 1H, O*H*), 3.93–3.79 (m, 4H, NC*H*$_2$ and C*H*$_2$OH), 4.51, 4.77 (both d, J=10.9 Hz, 1H, OC6*H*$_2$), 7.30–7.45 (m, 8H, Ar*H* of 5-Ph and *m*- and *p*-Ar*H* of 2-Ph), 7.95 (d, J=6.9 Hz, 2H, *o*-Ar*H* of 2-Ph); ^{13}C NMR δ 40.3, 50.1, 65.8, 68.2, 126.0, 127.0, 127.3, 128.0, 128.9, 130.5, 132.9, 140.2, 155.1. FAB HRMS calcd for $C_{17}H_{18}NO_2$ (M^++H): 268.1338. Found: 268.1336.

On the other hand, the reaction with TfOH (5 mol%) in PhCl at 130°C for 48 h gave oligomeric products ($M_{n\ GPC}$=522), which showed an ester carbonyl stretching band (1720 cm^{-1}).

4.4. Preparation and reaction of oxetane benzoate

4.4.1. 3-Phenyloxetan-3-ylmethyl benzoate (3a). Benzoic anhydride (7.00 g, 31.0 mmol) was added to a CH_2Cl_2 (20 mL) solution of **6** (1.00 g, 6.10 mmol) and Et_3N (4.00 g, 40.0 mmol) at 5°C, and then the mixture was stirred at rt for 5 h. Ordinary extractive work-up, followed by distillation in vacuo, gave the crude ester, which was purified by recrystallization from Et_2O–hexane to give **1a** (1.12 g, 69%). Colorless needles; mp 76–77°C; bp 130–140°C (1 mmHg); IR (KBr) 1720, 1270, 1120, 990, 850 cm^{-1}; ^{1}H NMR δ 4.70 (s, 2H, 3-C*H*$_2$O), 4.92, 5.07 (both d, J=6.4 Hz, 2H, *cis*- and *trans*-OC*H*$_2$ to 3-Ph), 7.17 (dd, J=8.3, 1.0 Hz,

2H, *o*-Ar*H* of 3-Ph), 7.29 (t-like, *J*=7.3 Hz, 1H, *p*-Ar*H* of 3-Ph), 7.38, 7.43 (both t-like, *J*=7.8 Hz, 2H, *m*-Ar*H* of $PhCO_2$ and 3-Ph), 7.56 (t-like, *J*=7.6 Hz, 1H, *p*-Ar*H* of $PhCO_2$), 8.01 (dd, *J*=8.3, 1.5 Hz, 1H, *o*-Ar*H* of $PhCO_2$); ^{13}C NMR δ 47.1, 69.8, 79.1, 126.0, 127.2, 128.5, 128.7, 129.6, 129.8, 133.2, 142.0, 166.4. EI HRMS calcd for $C_{17}H_{16}O_3$: 268.1100. Found: 268.1104. Anal. calcd for $C_{17}H_{16}O_3$: C, 75.95; H, 6.07. Found: C, 76.10; H, 6.10.

Typically, anhydrous PhCl (0.6 mL) containing TfOH (0.02 mmol) was added to an evacuated tube containing **3a** (0.100 g, 0.37 mmol) by a syringe under dry nitrogen. The resulting solution was allowed to react under the designated conditions, and then the reaction was quenched by addition of anhydrous Et_3N (0.05 mL). After dilution with CH_2Cl_2, the organic layer was washed with 5% NaOH followed by water, dried over Na_2SO_4, and then evaporated. The crude products obtained in different reaction times were separated by means of recrystallization or preparative TLC on alumina with toluene. The following yields refer to mol% yields based on **3a**, and hence the stoichiometric yields of **3b**, **3d**, **3e**, and **3f** can be estimated assuming a reaction mechanism proposed in Scheme 6 to be 100, 50, 33, and 50%, respectively.

4.4.2. 1,4-Diphenyl-2,6,7-trioxabicyclo[2.2.2]octane (3b). The crude product, obtained in the reaction at 80°C for 10 min, was purified by recrystallization from $CHCl_3$–hexane, to give **3b** (0.072 g, 72%). Colorless needles; mp 170–172°C; IR (KBr) 1115–970 cm^{-1}; ^{1}H NMR δ 4.50 (s, 6H, OCH_2), 7.20 (dd-like, *J*=8.6, 1.2 Hz, 2H, *o*-Ar*H* of 4-Ph), 7.32–7.45 (m, 6H, *m*- and *p*-Ar*H* of 1- and 4-Ph), 7.68 (dd-like, *J*=6.6, 3.2 Hz, 2H, *o*-Ar*H* of 1-Ph); ^{13}C NMR δ 36.9, 72.1, 108.1, 125.3, 125.7, 128.1, 128.1, 129.2, 129.3, 136.0, 137.3. EI HRMS calcd for $C_{17}H_{16}O_3$: 268.1100. Found: 268.1097. Anal. calcd for $C_{17}H_{16}O_3$: C, 76.04; H, 6.03. Found: C, 76.10; H, 6.01.

4.4.3. *r*-2-(1-Benzylvinyl)-*trans*-5-phenyl-1,3-dioxan-*cis*-5-ylmethyl benzoate (3d). This compound was separated in 29% yield from the crude products obtained in the reaction at 130°C for 72 h. Analytically pure **3d** failed to isolate, because partial decomposition (probably hydrolysis) happened during recrystallization. Colorless needles; mp 104–109°C (Et_2O–hexane); IR (KBr) 1710, 1270, 1110, 1090–915 cm^{-1}; ^{1}H NMR δ 3.54 (s, 2H, CH_2Ph), 4.01, 4.55 (both d, *J*=11.7 Hz, 2H, CH_2 of dioxane ring), 4.88 (d, *J*=1.32 Hz, 1H, *trans*-H_2C=C), 4.90 (s, 2H, 5-CH_2-OCOPh), 4.92 (s, 1H, C2*H*), 5.37 (s-like, 1H, *cis*-H_2C=C), 7.18–7.36 (m, 10H, Ar*H* of Ph except for OCOPh), 7.37 (t-like, *J*=7.81 Hz, 2H, *m*-Ar*H* of OCOPh), 7.51 (t-like, *J*=7.33 Hz, 1H, *p*-Ar*H* of OCOPh), 7.88 (d-like, *J*=8.30 Hz, 2H, *o*-Ar*H* of OCOPh); ^{13}C NMR δ 37.4, 39.8, 66.5, 71.6, 102.4, 115.3, 125.5, 126.1, 127.5, 128.3, 128.3, 128.8, 129.5, 130.1, 132.9, 138.9, 139.2, 145.4, 166.2. EI HRMS calcd for $C_{27}H_{26}O_4$: 414.1832. Found: 414.1832.

4.4.4. Diphenyl 3-phenoxycarbonylmethyl-3-phenylpentanedioate (3e). This compound was isolated in 14% yield from the crude products obtained in the reaction at 130°C for 144 h. Colorless liquid; IR (liquid film) 1710, 1270, 1100 cm^{-1}; ^{1}H NMR δ 4.92 (s, 6H, CH_2OCOPh), 7.31 (t-like, *J*=6.5 Hz, 1H, *p*-Ar*H* of 3-Ph), 7.36 (t-like, *J*=7.8 Hz, 6H, *m*-Ar*H* of OCOPh), 7.41 (t-like, *J*=7.3 Hz, 3H, *p*-Ar*H* of OCOPh), 7.52 (t-like, *J*=7.3 Hz, 2H, *m*-Ar*H* of 3-Ph), 7.56 (d-like, *J*=8.3 Hz, 2H, *o*-Ar*H* of 3-Ph), 7.92 (d-like, *J*=8.3 Hz, 6H, *o*-Ar*H* of OCOPh); ^{13}C NMR δ 46.2, 65.9, 126.5, 127.7, 128.4, 128.9, 129.6, 129.6, 133.2, 138.2, 166.2. EI HRMS calcd for $C_{31}H_{26}O_6$: 494.1730. Found: 414.1732.

4.4.5. 5-Phenyl-1,3-dioxan-5-ylmethyl benzoate (3f). This compound was isolated in 5% yield from the crude products obtained in the reaction at 130°C for 72 h. Colorless needles; mp 92–94°C (hexane); IR (liquid film) 1715, 1260, 1110, 1090–915 cm^{-1}; ^{1}H NMR δ 4.01, 4.44 (both d, *J*=11.7 Hz, 2H, OCH_2 of dioxane ring), 4.75, 5.13 (both d, *J*=6.3 Hz, 1H, C2H_2), 7.26–7.29 (m, 3H, *m*- and *p*-Ar*H* of 5-Ph), 7.35–7.40 (m, 4H, *m*-Ar*H* of OCOPh and *o*-Ar*H* of 5-Ph), 7.52 (t-like, *J*=7.6 Hz, 1H, *p*-Ar*H* of OCOPh), 7.88 (d-like, *J*=8.3 Hz, 1H, *o*-Ar*H* of OCOPh); ^{13}C NMR δ 40.7, 66.6, 71.6, 94.2, 125.6, 127.4, 128.3, 128.8, 129.5, 130.0, 132.9, 139.4, 166.1. EI HRMS calcd for $C_{18}H_{18}O_4$: 298.1205. Found: 298.1208.

4.5. Preparation and reaction of oxirane phthalimides

Oxirane phthalimides **4a** and **5a**, and the bicyclic acetals **4b** and **5b** were prepared as described in the preceding paper,[11] and the spectroscopic properties and analytical data were reported therein.

4.5.1. 2-(3-Phthalimidopropyl)-4-*cis*/*trans*-(2-phthalimidoethyl)-1,3-dioxolane (4d). The reaction of **4a** (0.200 g, 0.922 mmol) with BF_3·Et_2O (5 mol%) was carried out in anhydrous PhCl (2.0 mL) at 130°C for 72 h. The crude product was purified by alumina column chromatography with AcOEt–hexane=2:1, to give a *cis*/*trans*-isomer mixture of **4d** (0.172 g, 86%). Assignment of *cis*- and *trans*-isomers was made on the basis of the NOE difference spectra on irradiating the respective 2-methine protons, and the isomer ratio was determined based on the ^{1}H NMR spectrum. Colorless oil (*cis*/*trans*=59:41); IR (KBr) 1768, 1724, 1710, 1156, 1087–1003 cm^{-1}. EI HRMS calcd for $C_{24}H_{22}N_2O_6$: 434.1479. Found: 434.1481. Anal. calcd for $C_{24}H_{22}N_2O_6$: C, 66.35; H, 5.10; N, 6.45. Found: C, 66.08; H, 5.05; N, 6.41. The isomer mixture was subjected to repeated alumina chromatography using the same eluent, and the fraction of R_f=0.58–0.67 (AcOEt–hexane=1:1) was separated into the upper and lower parts abundant in *cis*- and *trans*-isomers, respectively.

cis-**4d** (89% *enrichment of cis-isomer*). Colorless needles; mp 92–95°C; ^{1}H NMR for the isomer mixture δ 1.58–1.81 (m, 4H, 2-CH_2CH_2CH_2N), 1.90 (dq, *J*=14.4, 6.4 Hz, 1H, 4-CH_2CH_2N), 2.01 (dq, *J*=14.4, 7.2 Hz, 1H, 4-CH_2CH_2N), 3.55 (t, *J*=6.8 Hz, 1H, OC5H_2 *cis* to 2-propyl), 3.67 (t, *J*=6.6 Hz, 2H, 2-CH_2CH_2CH_2N), 3.81, 3.83 (both dt, *J*=13.5, 6.8 Hz, 1H, 4-CH_2CH_2N,), 3.93 (t, *J*=7.1 Hz, 1H, OC5H_2 *trans* to 2-propyl), 4.08 (qui, *J*=6.2 Hz, 1H, OC4*H*), 4.89 (t, *J*=3.6 Hz, 1H, C2*H*), 7.63–7.75 (m, 4H, *m*-Ar*H*), 7.78–7.88 (m, 4H, *o*-Ar*H*); ^{13}C NMR for the *cis*-isomer δ 22.7, 31.1, 32.3, 35.1, 37.8, 69.5, 74.6, 104.2, 123.2, 123.2, 132.2, 133.9, 168.3.

trans-**4d** (*73% enrichment of trans-isomer*). Colorless oil; ^{1}H NMR for the isomer mixture δ 1.62–1.79 (m, 4H, 2-CH_2CH_2CH$_2$N), 1.81–2.03 (m, 2H, 4-CH_2CH$_2$N), 3.44 (t, J=10.1 Hz, 1H, OC5H_2 *cis* to 2-propyl), 3.66 (t, J=6.8 Hz, 2H, 2-CH$_2$CH$_2$CH_2N), 3.78, 3.87 (both dt, J=13.7, 6.5 Hz, 1H, 4-CH_2CH$_2$N), 4.09–4.15 (m, 1H, OC4H), 4.13 (dd, J=10.9, 4.5 Hz, 1H, OC5H_2 *trans* to 2-propyl), 4.98 (t, J=4.1 Hz, 1H, C2H), 7.65–7.72 (m, 4H, *m*-ArH), 7.81–7.85 (m, 4H, *o*-ArH); ^{13}C NMR for the *trans*-isomer δ 22.8, 31.3, 31.7, 35.2, 37.7, 70.3, 74.1, 103.4, 123.2, 123.2, 132.2, 133.9, 168.3.

4.5.2. 2-(4-Phthalimidobutyl)-4-*cis*/*trans*-(2-phthalimidopropyl)-1,3-dioxolane (5d). Similarly, the reaction of **5a** (0.147 g, 0.636 mmol) with BF_3·Et_2O (10 mol%) was carried out in PhCl (1.5 mL) at 130°C for 72 h. The crude product was purified by alumina column chromatography with AcOEt–hexane=2:3, to give a *cis*/*trans*-isomer mixture of **5d** (0.100 g, 68%). Assignment of *cis*- and *trans*-isomers was made on the basis of the NOE difference spectra on irradiating the respective 2-methin protons, and the isomer ratio was determined based on the ^{1}H NMR spectrum. Colorless oil (*cis*/*trans*=55:45); IR (KBr) 1770, 1710, 1130, 1090–1020 cm^{-1}; ^{1}H NMR for the isomer mixture δ 1.41–1.93 (m, 10H, 2-CH_2CH_2CH_2CH$_2$N and 4-CH_2CH_2CH$_2$N), 3.41 (pseudo t, J=5.6 Hz, 1H, OC5H_2 of *trans*-**5d**), 3.48 (t, J=7.1 Hz, 1H, OC5H_2 of *cis*-**5d**), 3.64–3.79 (m, 4H, 2-CH$_2$CH$_2$CH$_2$CH_2N and 4-CH$_2$CH$_2$CH_2N), 3.89 (t, J=7.3 Hz, 1H, OC5H_2 of *cis*-**5d**), 4.01–4.11 (m, 2H, OC4H and OC5H_2 of *trans*-**5d**), 4.86 (t, J=4.6 Hz, 1H, OC2H of *cis*-**5d**), 4.94 (t, J=4.6 Hz, 1H, OC2H of *trans*-**5d**), 7.69–7.73 (m, 4H, *m*-ArH), 7.81–7.85 (m, 4H, *o*-ArH); ^{13}C NMR for the isomer mixture δ 21.2 (*trans*), 21.3 (*cis*), 24.9 (*cis*), 25.1 (*trans*), 28.5 (*cis*), 28.5 (*trans*), 30.5 (*trans*), 30.7 (*cis*), 33.5 (*cis*), 33.6 (*trans*), 37.7, 37.9, 69.4 (*cis*), 70.3 (*trans*), 75.4 (*trans*), 76.0 (*cis*), 103.6 (*trans*), 104.4 (*cis*), 123.1, 123.2, 132.1, 132.2, 133.8, 133.9, 133.9, 133.9, 168.4. EI HRMS calcd for $C_{26}H_{26}N_2O_6$: 462.1792. Found: 462.1796.

Acknowledgments

The authors would like to thank Professor Amy Howell, University of Connecticut, for carefully proofreading the manuscript and also for her many valuable suggestions that were important to clarifying the presentation.

References

1. (a) Kodera, Y.; Kanoh, S.; Ueyama, A.; Motoi, M. *Bull. Chem. Soc. Jpn* **1998**, *71*, 433–442. (b) Hiruma, T.; Kanoh, K.; Yamamoto, T.; Kanoh, S.; Motoi, M. *Polym. J.* **1995**, *27*, 78–89. (c) Motoi, M.; Sekizawa, S.; Asakura, K.; Kanoh, S. *Polym. J.* **1993**, *25*, 1283–1294. (d) Motoi, M.; Saito, E.; Kyoda, S.; Takahata, N.; Nagai, S.; Arano, A. *Polym. J.* **1991**, *23*, 1225–1241. (e) Motoi, M.; Nagahara, S.; Akiyama, H.; Horiuchi, M.; Kanoh, S. *Polym. J.* **1989**, *21*, 987–1001.
2. Penczek, S.; Kubisa, P. Cationic Ring-opening Polymerization: Ethers. *Comprehensive Polymer Science*, Allen, G., Bevington, J. C., Eastmond, G. C., Ledwith, A., Russo, S., Sigwalt, P., Eds.; Pergamon Press: Oxford, 1989; Vol. 3, pp 751–786.
3. Penczek, S.; Slomkowski, S. Cationic Ring-opening Polymerization: Formation of Cyclic Oligomers. *Comprehensive Polymer Science*, Allen, G., Bevington, J. C., Eastmond, G. C., Ledwith, A., Russo, S., Sigwalt, P., Eds.; Pergamon Press: Oxford, 1989; Vol. 3, pp 725–750.
4. Dale, J. *Tetrahedron* **1993**, *49*, 8707–8725.
5. Rose, J. B. *J. Chem. Soc.* **1956**, 542–546.
6. (a) Dreyfuss, P.; Dreyfuss, M. P. *Polym. J.* **1976**, *8*, 81–87. (b) Arimatsu, Y. *J. Polym. Sci. A1* **1966**, *4*, 728–729. (c) Bucquoye, M. R.; Goethals, E. J. *Makromol. Chem.* **1978**, *179*, 1681–1688. (d) Bucquoye, M. R.; Goethals, E. J. *Makromol. Chem.* **1981**, *182*, 3379–3386.
7. Kanoh, S.; Nishimura, T.; Ando, K.; Senda, H.; Motoi, M. *Macromolecules* **1998**, *31*, 7988–7991.
8. Kanoh, S.; Nishimura, T.; Motoi, M. *Macromolecules* **1999**, *32*, 1301–1303.
9. Kanoh, S.; Naka, M.; Yokozuka, T.; Itoh, S.; Nishimura, T.; Honda, M.; Motoi, M.; Matsuura, N. *Macromol. Chem. Phys.* **2002**, *203*, 511–521.
10. (a) Kanoh, S.; Nishimura, T.; Senda, H.; Motoi, M.; Tanaka, T.; Kano, K. *Macromolecules* **1999**, *32*, 2438–2448. (b) Kanoh, S.; Nishimura, T.; Tsuchida, T.; Senda, H.; Motoi, M.; Takani, M.; Matsuura, N. *Macromol. Chem. Phys.* **2001**, *202*, 2489–2503.
11. Kanoh, S.; Naka, M.; Nishimura, T.; Motoi, M. *Tetrahedron*, **2002**, *58*, 7049–7064.
12. Fujio, M.; Goto, M.; Funatsu, K.; Yoshino, T.; Saeki, Y.; Yatsugi, K.; Tsuno, Y. *Bull. Chem. Soc. Jpn* **1992**, *65*, 46–54.
13. Nishimura, T.; Kanoh, S.; Senda, H.; Tanaka, T.; Ando, K.; Motoi, M. *J. Chem. Soc., Chem. Commun.* **1998**, 43–44.
14. Bischler, A.; Napieralski, B. *Ber.* **1893**, *26*, 1903–1908.
15. Greene, T. W.; Wuts, P. G. M. *Protective Groups in Organic Synthesis*. 3rd ed. Wiley: New York, 1999; pp 437–440.
16. Baldwin, J. E. *J. Chem. Soc., Chem. Commun.* **1976**, 734–736.
17. Yokoyama, Y.; Padias, A. B.; De Blauwe, F.; Hall, Jr. H. K. *Macromolecules* **1980**, *13*, 252–261.
18. Endo, T.; Uno, H. *J. Polym. Sci., Polym. Lett. Ed.* **1985**, *23*, 359–363.
19. Derfer, J. M.; Greenlee, K. W.; Boord, C. E. *J. Am. Chem. Soc.* **1949**, *71*, 175–182.
20. Mozingo, R. *Organic Synthesis*, Horning, E. C., Allen, C. F. H., Shriner, R. L., Drake, N. L., Smith, L. I., Hamilton, C. S., Snyder, H. R., Eds.; Wiley: New York, 1955; Collect. Vol. 3, pp 181–184.
21. Moore, R. E.; Furst, A. *J. Org. Chem.* **1958**, *23*, 1504–1506.