Palladium-Catalyzed S\textsubscript{N}2'-Cyclization of Ambivalent (Bromoalkadienyl)malonates: Preparation of Medium- to Large-Membered Endocyclic Allenes

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Abstract. A palladium-catalyzed reaction of preparing various endocyclic allenes was developed. The substrates for the reaction were readily available ω-(pronucleophile-tethered)-3-bromo-1,3-alkadienes, and a palladium-catalyst facilitated their unimolecular S,2'-cyclization in the presence of potassium tert-butoxide to give the corresponding 9- to 16-membered endocyclic allenes in fair yields of up to 67% together with the dimeric 16- to 32-membered endocyclic bis-allenes and other oligomeric/polymeric intermolecular reaction products. For higher yields of the monomeric endocyclic allenes, the reaction needed to be conducted under high-dilution conditions. Using a chiral palladium-catalyst, axially chiral endocyclic allenes were obtained in up to 70% ee.
Introduction

Allenes are a class of compounds characterized by two cumulated carbon-carbon double bonds. Due to the propadiene structures, they show distinctive steric and electronic properties and have emerged as highly interesting target molecules in organic synthesis. Incorporation of an allenic substructure into a carbocycle creates a peculiar topological property. Although various endocyclic allenes have been prepared and reported so far, most of their synthetic methods construct an allenic motif within a preformed carbocycle precursor. Two of the most widely applicable methods in the synthesis of endocyclic allenes, namely the ring enlargement of cycloalkenes via the corresponding gem-dibromobicyclo[n.1.0]alkenes by the Doering-Moore-Skattebøl reaction and dehydrohalogenation of 1-halocycloalkenes, are also classified to this category. Another approach to the endocyclic allenes is cyclization of preformed acyclic allenes. This approach, however, is not applicable to the synthesis of relatively smaller-ring cyclic allenes. The third category of the endocyclic allene synthesis is simultaneous construction of both allenic and cyclic structures by a single process, but the reported examples in this category are very rare. Since 2000, we have developed a palladium-catalyzed reaction of preparing functionalized allenes starting with 2-halo-1,3-dienes and appropriate soft nucleophiles (eq 1 in Scheme 1). The reaction was extended into an asymmetric counterpart by the use of a chiral Pd catalyst, and enantiomerically enriched axially chiral allenes were obtained in up to 94% ee. We also demonstrated that the palladium-catalyzed reaction could be used for the synthesis of a series of endocyclic allenes starting with cycloalkenones.

Scheme 1. Palladium-Catalyzed Reaction of 2-Halo-1,3-dienes with Soft Nucleophile
In this report, we would like to describe a novel method of preparing various endocyclic allenes utilizing the Pd-catalyzed reaction. The two reactants of the palladium-catalyzed reaction, namely a 2-bromo-1,3-diene and a soft nucleophile, are incorporated into a single molecule and the S,2'-cyclization of the "ambivalent" substrates proceeds primarily intramolecularly to afford various endocyclic allenes in fair yields.

The allenic substructure, which is with two cumulated orthogonal carbon-carbon double bonds, suppresses the relative motion among the five consecutive atoms (marked in red; eq 2 in Scheme 1). Similarly, the relative orientation of the five atoms is fastened in the (alkylidene-π-allyl)palladium intermediate of the palladium-catalyzed reaction. These rigid substructures in the palladium-intermediates as well as in the allenic products may lead to the unusual preference/selectivity in the present cyclization reactions. Indeed, the cyclization process could provide various medium- to large-carbocycles in reasonable yields. It should be mentioned that formation of five- to seven-membered carbocycles, which are easy to be assembled in typical cyclization processes, are impractical by the present method, because thermodynamically stable endo-carbocyclic allenes are usually nine-membered or larger. Although a few kinetically stabilized eight-membered carbocyclic allenes were reported to be isolable, endocyclic allenes with a seven-membered or a smaller carbocycle exist only as transient reactive intermediates.

Results and Discussion

Preparation of Pronucleophile-Tethered 3-Bromo-1,3-diene Derivatives 3 and 4. The substrates for our endocyclic allene synthesis are pronucleophile-tethered 3-bromo-1,3-dienes (3a-h and 4f), and they are prepared from ω-bromoalkanals by the simple three-step sequence as depicted in Scheme 2. Readily available ω-bromoalkanals were converted into the corresponding 1,1,ω-tribromoalkenes 1a-i in 61-77% yields by the standard Wittig dibromoolefination (Ramirez olefination). The palladium-catalyzed cross-coupling of 1 with vinylzinc chloride proceeded at the sterically less congested alkenyl-Br (i.e., C=CBr trans to the ω-bromoalkyl group) selectively to give the corresponding (Z)-3,ω-dibromo-1,3-dienes 2a-h in 50-68% yields. Alkylation of dimethyl malonate or benzodithiole tetraoxide (BDT) with 2 furnished designed substrates 3a-h and 4f in pure form (70-95%).
Scheme 2. Preparation of Pronucleophile-Tethered 3-Bromo-1,3-dienes

\[
\begin{align*}
\text{CHO} & \quad \text{Br} \\
\text{Br} & \quad \text{Br} \\
\text{CH}_2\text{Cl}_2, 0 \, ^\circ \text{C} & \quad \text{Pd(PPh}_3)_4 \text{(cat.)} \\
\end{align*}
\]

Palladium-Catalyzed Reactions of Pronucleophile-Tethered 3-Bromo-1,3-diene Derivatives 3 and 4. Substrates 3 and 4 prepared as in Scheme 2 were subjected to the palladium-catalyzed reaction. At the outset, the conditions for the palladium-catalyzed reaction were optimized using 3e \((n = 7)\) as a model substrate, and the results of the optimization studies are summarized in Table 1. The reaction of 3e was efficiently catalyzed by 5 mol% of a palladium complex generated in situ from Pd(dba)\(_2\) and dpbb \((1.1 \text{ equiv to } \text{Pd})\) in THF in the presence of potassium tert-butoxide \((1.1 \text{ equiv to } \text{3e})\). Under the rather standard conditions, i.e. with the initial concentration of substrate 3e being \(1.4 \times 10^{-2} \text{ mol/L}\), 3e was completely consumed within 20 h at 30 °C. However, to our disappointment, yield of desired 12-membered endocyclic allene 5e was only 9\% (entry 1). Complete consumption of 3e and the low yield of 5e indicated that intermolecular processes giving oligomeric/polymeric products competed with the unimolecular cyclization reaction. Indeed, reactions under dilute conditions facilitated the desired intramolecular pathway leading to the higher yields of 5e (entries 2 and 3). When the initial concentration of 3e was \(1.4 \times 10^{-3} \text{ mol/L}\), 5e was isolated in 31\% yield (entry 3). It should be mentioned that the reactions in entries 1-3 produced dimeric endocyclic bis-allene 6e in 11-19\% yields together with 5e. Endocyclic bis-allene 6e was obtained as a mixture of dl- and meso-diastereomers with respect to the allenic axial chirality; two allenic central \(sp\)-C signals were detected at \(\delta 205.8\) and 205.9 in the \(^1\text{C-NMR spectrum (see Experimental Section).} \text{THF was the best solvent examined so far. Reactions in DMF, toluene, or dichloromethane gave 5e in much lower yields ranging 0-8\% (entries 4-6). The choice of a proper base drastically influences the yield of 5e; while the reactions with KOBu or NaOMe afforded the monomeric endocyclic allene in 31\% yield (entries 3 and 7), the yield of 5e declined to 16\% by the use of CsOBU (entry 8), and the reaction using Cs.CO. did not provide 5e at all (entry 9).} \]
On the other hand, the effects of the bisphosphine ancillary ligands were minor, and the reactions with DPEphos\(^\text{a}\) (1.1 equiv to Pd) or dppf gave 5e in 23% and 25% yields, respectively (entries 10 and 11).

**Table 1. Optimization of Reaction Conditions for Palladium-Catalyzed S,2'-Cyclization of 3e.**

<table>
<thead>
<tr>
<th>entry</th>
<th>solvent</th>
<th>base</th>
<th>ligand</th>
<th>conc. of 3e (mol/L)</th>
<th>yield of 5e (%)</th>
<th>yield of 6e (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>THF</td>
<td>KOBu</td>
<td>dpbp</td>
<td>1.4 × 10(^{-1})</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>THF</td>
<td>KOBu</td>
<td>dpbp</td>
<td>1.4 × 10(^{-1})</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>THF</td>
<td>KOBu</td>
<td>dpbp</td>
<td>4.6 × 10(^{-1})</td>
<td>31</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>DMF</td>
<td>KOBu</td>
<td>dpbp</td>
<td>1.4 × 10(^{-1})</td>
<td>8(^b)</td>
<td>n.d.(^b)</td>
</tr>
<tr>
<td>5</td>
<td>toluene</td>
<td>KOBu</td>
<td>dpbp</td>
<td>1.4 × 10(^{-1})</td>
<td>7(^b)</td>
<td>n.d.(^b)</td>
</tr>
<tr>
<td>6</td>
<td>CH(_2)Cl(_2)</td>
<td>KOBu</td>
<td>dpbp</td>
<td>1.4 × 10(^{-1})</td>
<td>0(^b)</td>
<td>n.d.(^b)</td>
</tr>
<tr>
<td>7</td>
<td>THF</td>
<td>NaOMe</td>
<td>dpbp</td>
<td>1.4 × 10(^{-1})</td>
<td>31(^b)</td>
<td>15(^b)</td>
</tr>
<tr>
<td>8</td>
<td>THF</td>
<td>CsOBu</td>
<td>dpbp</td>
<td>1.4 × 10(^{-1})</td>
<td>16(^b)</td>
<td>n.d.(^b)</td>
</tr>
<tr>
<td>9</td>
<td>THF</td>
<td>CsCO(_3)</td>
<td>dpbp</td>
<td>1.4 × 10(^{-1})</td>
<td>0(^b)</td>
<td>n.d.(^b)</td>
</tr>
<tr>
<td>10</td>
<td>THF</td>
<td>NaOMe</td>
<td>DPEphos</td>
<td>1.4 × 10(^{-1})</td>
<td>23(^b)</td>
<td>n.d.(^b)</td>
</tr>
<tr>
<td>11</td>
<td>THF</td>
<td>NaOMe</td>
<td>dppf</td>
<td>1.4 × 10(^{-1})</td>
<td>25(^b)</td>
<td>n.d.(^b)</td>
</tr>
</tbody>
</table>

\(^a\) The reaction was carried out with 3f (140 µmol) and a base (154 µmol) in the given solvent at 30 °C for 20 h in the presence of a palladium catalyst (5 mol %) generated from Pd(dba)\(_4\), and a bisphosphine ligand. \(^b\) Obtained as all/meso-diastereomeric mixtures (footnote 17). \(^c\) Isolated yield by recycle HPLC. \(^d\) Determined by GC analysis. \(^e\) Not determined.

The reaction conditions shown in entry 3 of Table 1 were selected as "optimized conditions" and they were applied to the other substrates in the same way. The results of the palladium-catalyzed reaction are summarized in Table 2.
While the substrates with more than three methylene units (i.e., 3b and the longer ones) afforded the corresponding monomeric endocyclic allenes 5b-h in moderate yields by the palladium-catalyzed reaction, the reaction of 3a did not provide eight-membered endocyclic allene 5a (entry 1). The highest yield of 5 was achieved for the reaction of 3f giving thirteen-membered monomeric endocyclic allene 5f in 52% yield (entry 6). With a longer polymethylene chain in 3g (n = 9) and 3h (n = 11), the yields of 5g (42%) and 5h (33%) were slightly lower (entries 7 and 8). Likewise, shorter substrates 3b-e afforded the corresponding monomeric endocyclic allenes 5b-e in lower yields ranging 11% to 31% (entries 2-5).

In all the cases including the reaction of 3a, substrates 3 were completely consumed under these conditions, and the formation of dimeric endocyclic bis-allenes 6, which were isolated in 10-30% yields by the HPLC separation, was observed. Homologous trimeric endocyclic tris-allenes 7a, 7c, and 7d were also isolated in 10%, 7%, and 9% yields, respectively, in the reactions giving 6 in relatively higher yields (entries 1, 3, and 4). Since bis-allenes 6 and tris-allenes 7 possess multiple allenic axially chiral elements, they were obtained as diastereomeric mixtures.

**Table 2. Influences of Ring Size in Palladium-Catalyzed S,2'-Cyclization of 3:**

<table>
<thead>
<tr>
<th>entry</th>
<th>substrate 3</th>
<th>yield of 5 (%)</th>
<th>yield of 6 (%)</th>
<th>yield of 7 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3a (n = 3)</td>
<td>0 (5a)</td>
<td>30 (6a)</td>
<td>10 (7a)</td>
</tr>
<tr>
<td>2</td>
<td>3b (n = 4)</td>
<td>23 (5b)</td>
<td>16 (6b)</td>
<td>----</td>
</tr>
<tr>
<td>3</td>
<td>3c (n = 5)</td>
<td>11 (5c)</td>
<td>24 (6c)</td>
<td>7 (7c)</td>
</tr>
<tr>
<td>4</td>
<td>3d (n = 6)</td>
<td>18 (5d)</td>
<td>27 (6d)</td>
<td>9 (7d)</td>
</tr>
<tr>
<td>5</td>
<td>3e (n = 7)</td>
<td>31 (5e)</td>
<td>19 (6e)</td>
<td>----</td>
</tr>
</tbody>
</table>
Whereas eight-membered endo-carbocyclic allenes are generally too reactive to be isolated without appropriate kinetically stabilizing bulky substituents, it was rational that 5a was not detected in the reaction of 3a. However, the absence of 5a should not be ascribed to its high reactivity. Once highly reactive 5a was generated in situ, it was expected to undergo [2+2]cycloaddition giving an isomeric mixture of homodimers such as 8, but 8 and/or related isomeric species were not detected in the reaction mixture. The key intermediate of the palladium-catalyzed reaction of 3a is (alkylidene-\(\pi\)-allyl)palladium species 9. Due to the short trimethylene chain in 9, the nucleophilic malonate moiety is not capable of attacking the CH\(_2\)\(\pi\)-allyl terminus intramolecularly, and thus the formation of 5a could not be realized (Scheme 3).

Scheme 3.

The cyclization reaction of 4f was also examined. Substrate 4f possesses a benzo[1,3]dithiole tetraoxide (BDT) substructure as a pronucleophilic moiety. The palladium-catalyzed reaction of 4f was conducted essentially in the same way as in Table 2 except for the reaction time. Due probably to the
lower nucleophilicity of BDT, the reaction took longer time (120 h) for completion, and monomeric endocyclic allene 10f was obtained in the highest yield of 67% (Scheme 4). The formation of the corresponding endocyclic dimeric bis-allene and trimeric tris-allene was minor (<5%) in this reaction. The BDT moiety in 4f is sterically more compact than the malonate moiety in 3f, which may facilitate the intramolecular cyclization in the palladium-catalyzed process.

**Scheme 4.** Palladium-Catalyzed S,2'-Cyclization of BDT-Tethered Substrate 4f.

**Palladium-Catalyzed Asymmetric Synthesis of Axially Chiral Endocyclic Allenes 5f and 10f.** Endocyclic allenes 5 and 10 obtained as in Table 2 and Scheme 4 are axially chiral but racemic. Using 3f as a representative substrate, palladium-catalyzed enantioselective synthesis of 5f was examined according to our previous studies. That is, with a palladium catalyst (5 mol %) generated from Pd(dba) and (R)-segphos ((R)-L1) in THF at 30 °C in the presence of KOtBu, (+)-5f was obtained in 50% yield with 65% ee (Table 3, entry 1). Among the various solvents and bases examined, the combination of THF and KOtBu showed the highest yield and the highest enantioselectivity for the reaction of 3f (entries 1-5). While (R)-L2, (R)-L4, and (R)-L5 showed lower enantioselectivity than (R)-L1 with 45-55% ee (entries 6, 8, and 9), the enantioselectivity was improved to 70% ee by the use of (R)-L3 although the chemical yield of (+)-5f was considerably lower (entry 7). The enantioselective reaction of 4f was conducted as in entry 7 and (+)-10f was obtained in 51% ee and 29% yield (entry 10). The absolute configurations of dextrorotatory (+)-5f and (+)-10f were deduced to be (S) by the Lowe-Brewster rule.

**Table 3.** Palladium-Catalyzed Asymmetric Synthesis of Axially Chiral Endocyclic Allenes 5f/10f.
The reaction was carried out with 3f or 4f (100 µmol) and a base (110 µmol) in a given solvent (70 mL) at 30 °C for 60 h in the presence of a palladium catalyst (5 mol %) generated from Pd(dba)\(_4\) and a chiral ligand L.  

- Isolated yield by recycle HPLC.  
- Determined by chiral HPLC analysis (see Experimental Section for details).  
- The absolute configurations were deduced by the Lowe-Brewster rule (ref 20).  
- Not determined.

**Conclusions**

In summary, we have developed a general method of preparing various endocyclic allenes of a nine- to sixteen-membered carbocycle utilizing the palladium-catalyzed reaction. Readily available \(\text{o-}(\text{pronucleophile-tethered})-3\)-bromo-1,3-alkadienes 3 and 4 undergo the unimolecular S,2'-cyclization in the presence of an appropriate palladium catalyst to give the corresponding endocyclic allenes 5/10 in fair yields together with the dimeric endocyclic bis-allenes and higher oligomers/polymers. The highest yield of 67% was achieved for the preparation of the thirteen-membered cyclic allene. Due probably to
the rigid substructures in the allenic C=C=C products as well as in the (alkylidene-\(\pi\)-allyl)palladium intermediates, the medium- to large-membered carbocyclic compounds are accessible in reasonable yields by the present cyclization reaction. By the use of a chiral palladium-catalyst, axially chiral endocyclic allenes were obtained in up to 70% ee.

**Experimental Section**

**General.** All anaerobic and/or moisture sensitive manipulations were carried out with standard Schlenk techniques under predried nitrogen or with glovebox techniques under prepurified argon. H NMR (at 400 MHz) and \(^{13}\)C NMR (at 100 MHz) chemical shifts are reported in ppm downfield of internal tetramethylsilane. The HRMS measurements were carried out by the EI method with a TOF analyzer. Tetrahydrofuran (from benzophenone-ketyl) and dichloromethane (from CaH\(_2\)) were distilled under nitrogen prior to use. Pd(PPh\(_3\))\(_4\), Pd\(_2\)(dba)\(_4\), dpbp, \((R)\)-L\(_1\), \((R)\)-L\(_2\), \((R)\)-L\(_4\), \((R)\)-L\(_5\), and 1,3-benzodithiole-1,1,3,3-tetraoxide (BDT) were prepared according to the reported methods. All the other chemicals were obtained from commercial sources and used as received unless otherwise noted.

**Preparation of \(\omega\)-Bromoalkanals.** The \(\omega\)-bromoalkanals were prepared from the corresponding commercially available \(\omega\)-bromo-1-alkanols according to the reported procedure,\(^2\) in which the preparation of 8-bromoocatanal (\(n = 7\) in Scheme 2) was described in detail. All the \(\omega\)-bromoalkanals used in this study are known compounds and were characterized by comparison of their NMR spectra with those reported previously (\(n = 3\),\(^n\) \(n = 4\),\(^n\) \(n = 5\),\(^v\) \(n = 6\),\(^n\) \(n = 7\),\(^v\) \(n = 8\),\(^v\) \(n = 9\),\(^v\) \(n = 11\)).

**Preparation of 1,1,\(\omega\)-Tribromo-1-alkenes (1a-h).** To a CH\(_2\)Cl\(_2\) (ca. 2 mL/\(\omega\)-bromoalkanal 1 mmol) solution of CBr\(_4\) (1.5 equiv to \(\omega\)-bromoalkanal) was added PPh\(_3\) (3.0 equiv to \(\omega\)-bromoalkanal) portionwise at 0 °C, and the solution was kept stirring at this temperature for 20 min. A solution of \(\omega\)-bromoalkanal (1 equiv) in CH\(_2\)Cl\(_2\) (ca. 1 mL/\(\omega\)-bromoalkanal 2 mmol) was added dropwise at 0 °C, and the mixture was stirred at the same temperature for 10 min. After quenching the reaction mixture with a small amount of water (ca. 1 mL), the mixture was concentrated under reduced pressure. Addition of hexane (ca. 5 mL/\(\omega\)-bromoalkanal 1 mmol) to the concentrated solution precipitated triphenylphosphine oxide as pale yellow solid, which was removed by filtration. The filtrate was evaporated, and the
residue was purified by silica gel column chromatography (with hexane). The characterization data of 1a-h are given below.

1,1,5-Tribromo-1-pentene (1a; \( n = 3 \)). Colorless liquid. Yield: 6.27 g (63\%) starting with 4-bromobutanal (4.90 g; 32.5 mmol). \(^1\)H NMR (CDCl\( _3 \)): \( \delta \) 1.96-2.03 (m, 2H), 2.25-2.31 (m, 2H), 3.42 (t, \( J = 6.6 \) Hz, 2H), 6.40 (t, \( J = 7.3 \) Hz, 1H). \(^1\)C\{H\} NMR (CDCl\( _3 \)): \( \delta \) 30.8, 31.7, 32.5, 90.5, 136.7. EI-HRMS Calcd for C\(_{11}\)H\(_6\)Br\(_3\): 303.8098. Found: 303.8101.

1,1,6-Tribromo-1-hexene (1b; \( n = 4 \)). Colorless liquid. Yield: 5.78 g (61\%) starting with 5-bromopentanal (4.90 g; 29.7 mmol). \(^1\)H NMR (CDCl\( _3 \)): \( \delta \) 1.56-1.64 (m, 2H), 1.86-1.93 (m, 2H), 2.12-2.17 (m, 2H), 3.42 (t, \( J = 6.7 \) Hz, 2H), 6.39 (t, \( J = 7.2 \) Hz, 1H). \(^1\)C\{H\} NMR (CDCl\( _3 \)): \( \delta \) 26.3, 31.9, 32.1, 33.3, 89.5, 137.9. EI-HRMS Calcd for C\(_{12}\)H\(_6\)Br\(_3\): 317.8254. Found: 317.8251.

1,1,7-Tribromo-1-heptene (1c; \( n = 5 \)). Colorless liquid. Yield: 3.96 g (65\%) starting with 6-bromohexanal (3.26 g; 18.2 mmol). \(^1\)H NMR (CDCl\( _3 \)): \( \delta \) 1.41-1.52 (m, 4H), 1.84-1.91 (m, 2H), 2.09-2.14 (m, 2H), 3.41 (t, \( J = 6.8 \) Hz, 2H), 6.39 (t, \( J = 7.3 \) Hz, 1H). \(^1\)C\{H\} NMR (CDCl\( _3 \)): \( \delta \) 27.0, 27.6, 32.5, 32.8, 33.6, 89.1, 138.3. EI-HRMS Calcd for C\(_{13}\)H\(_6\)Br\(_3\): 331.8411. Found: 331.8405.

1,1,8-Tribromo-1-octene (1d; \( n = 6 \)). Colorless liquid. Yield: 1.78 g (61\%) starting with 7-bromohexanal (1.62 g; 8.39 mmol). \(^1\)H NMR (CDCl\( _3 \)): \( \delta \) 1.31-1.38 (m, 2H), 1.41-1.49 (m, 4H), 1.83-1.90 (m, 2H), 2.07-2.13 (m, 2H), 3.41 (t, \( J = 6.8 \) Hz, 2H), 6.38 (t, \( J = 7.3 \) Hz, 1H). \(^1\)C\{H\} NMR (CDCl\( _3 \)): \( \delta \) 27.6, 27.9, 28.2, 32.7, 32.9, 33.9, 88.8, 138.6. EI-HRMS Calcd for C\(_{14}\)H\(_6\)Br\(_3\): 345.8567. Found: 345.8570.

1,1,9-Tribromo-1-nonene (1e; \( n = 7 \)). Colorless liquid. Yield: 5.64 g (77\%) starting with 8-bromooctanal (4.18 g; 20.2 mmol). \(^1\)H NMR (CDCl\( _3 \)): \( \delta \) 1.31-1.47 (m, 8H), 1.82-1.89 (m, 2H), 2.07-2.12 (m, 2H), 3.41 (t, \( J = 6.8 \) Hz, 2H), 6.38 (t, \( J = 7.2 \) Hz, 1H). \(^1\)C\{H\} NMR (CDCl\( _3 \)): \( \delta \) 27.7, 28.1, 28.5, 28.8, 32.7, 32.9, 34.0, 88.7, 138.7. EI-HRMS Calcd for C\(_{15}\)H\(_6\)Br\(_3\): 359.8724. Found: 359.8718.

1,1,10-Tribromo-1-decene (1f; \( n = 8 \)). Colorless liquid. Yield: 4.66 g (63\%) starting with 9-bromononanal (4.34 g; 19.6 mmol). \(^1\)H NMR (CDCl\( _3 \)): \( \delta \) 1.28-1.47 (m, 10H), 1.82-1.89 (m, 2H), 2.06-2.12 (m, 2H), 3.41 (t, \( J = 6.8 \) Hz, 2H), 6.39 (t, \( J = 7.3 \) Hz, 1H). \(^1\)C\{H\} NMR (CDCl\( _3 \)): \( \delta \) 27.8, 28.1, 28.7, 28.9, 29.2, 32.8, 33.0, 34.1, 88.6, 138.9. EI-HRMS Calcd for C\(_{16}\)H\(_6\)Br\(_3\): 373.8880. Found: 373.8881.
**1,1,11-Tribromo-1-undecene (1g; n = 9).** Colorless liquid. Yield: 3.06 g (66%) starting with 10-bromodecanal (2.79 g; 11.9 mmol). 1H NMR (CDCl₃): δ 1.26-1.43 (m, 12H), 1.82-1.89 (m, 2H), 2.06-2.12 (m, 2H), 3.41 (t, J = 6.9 Hz, 2H), 6.38 (t, J = 7.2 Hz, 1H). 13C{¹H} NMR (CDCl₃): δ 27.8, 28.1, 28.7, 29.0, 29.2, 29.3, 32.8, 33.0, 34.1, 88.5, 138.9. EI-MS Calcd for C₁₁H₁₉Br₃: 387.9037. Found: 387.9037.

**1,1,13-Tribromo-1-tridecene (1h; n = 11).** Colorless liquid. Yield: 4.68 g (68%) starting with 12-bromododecanal (4.32 g; 16.4 mmol). 1H NMR (CDCl₃): δ 1.26-1.46 (m, 16H), 1.82-1.89 (m, 2H), 2.06-2.11 (m, 2H), 3.41 (t, J = 6.9 Hz, 2H), 6.38 (t, J = 7.2 Hz, 1H). 13C{¹H} NMR (CDCl₃): δ 27.8, 28.2, 28.8, 29.1, 29.3, 29.4, 29.49, 29.50, 32.9, 33.0, 34.1, 88.5, 138.9. EI-MS Calcd for C₁₃H₂₃Br₃: 415.9350. Found: 415.9356.

**Preparation of (Z)-3,ω-Dibromo-1,3-alkadienes (2a-h).** To a suspension of (CH=CH)ZnCl in THF, prepared from dry ZnCl₂ (28 mmol) and vinlylmagnesium chloride (2.0 M THF solution; 12 mL; 24 mmol), was added a solution of 1,1,ω-tribromo-1-alkene 1 (8.0 mmol) and Pd(PPh₃)₄ (0.20 mmol) in THF (16 mL) at 0 °C. After stirring the mixture for 4.5 h at room temperature, the reaction mixture was diluted with hexane, filtered, and evaporated to dryness. The residue was purified by silica gel chromatography (with hexane), and further purified by recycle HPLC to give the title compound. The characterization data of 2a-h are given below.

**(Z)-3,7-Dibromo-1,3-heptadiene (2a; n = 3).** Colorless liquid. Yield: 1.10 g (54%). 1H NMR (CDCl₃): δ 1.99-2.06 (m, 2H), 2.46-2.52 (m, 2H), 3.43 (t, J = 6.8 Hz, 2H), 5.20 (d, J = 10.4 Hz, 1H), 5.56 (d, J = 16.3 Hz, 1H), 5.98 (t, J = 7.2 Hz, 1H), 6.32 (dd, J = 16.3 and 10.4 Hz, 1H). 13C{¹H} NMR (CDCl₃): δ 30.3, 31.5, 32.9, 118.2, 127.4, 132.7, 135.7. EI-MS Calcd for C₇H₁₀Br₂: 251.9149. Found: 251.9144.

**(Z)-3,8-Dibromo-1,3-octadiene (2b; n = 4).** Colorless liquid. Yield: 1.16 g (54%). 1H NMR (CDCl₃): δ 1.58-1.66 (m, 2H), 1.87-1.94 (m, 2H), 2.34-2.39 (m, 2H), 3.43 (t, J = 6.7 Hz, 2H), 5.19 (d, J = 10.5 Hz, 1H), 5.55 (d, J = 16.3 Hz, 1H), 5.97 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.5 Hz, 1H). 13C{¹H} NMR (CDCl₃): δ 26.9, 30.6, 32.2, 33.6, 117.7, 126.6, 134.0, 135.7. EI-MS Calcd for C₈H₁₂Br₂: 265.9306. Found: 265.9303.
(Z)-3,9-Dibromo-1,3-nonadiene (2c; n = 5). Colorless liquid. Yield: 1.17 g (52%). 1H NMR (CDCl₃): δ 1.47-1.50 (m, 4H), 1.85-1.92 (m, 2H), 2.31-2.36 (m, 2H), 3.41 (t, J = 6.8 Hz, 2H), 5.17 (d, J = 10.5 Hz, 1H), 5.54 (d, J = 16.3 Hz, 1H), 5.98 (t, J = 7.2 Hz, 1H), 6.31 (dd, J = 16.3 and 10.5 Hz, 1H).


(Z)-3,10-Dibromo-1,3-decadiene (2d; n = 6). Colorless liquid. Yield: 1.21 g (51%). 1H NMR (CDCl₃): δ 1.32-1.51 (m, 6H), 1.83-1.90 (m, 2H), 2.30-2.35 (m, 2H), 3.41 (t, J = 6.9 Hz, 2H), 5.17 (d, J = 10.5 Hz, 1H), 5.53 (d, J = 16.3 Hz, 1H), 5.97 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.5 Hz, 1H).


(Z)-3,11-Dibromo-1,3-undecadiene (2e; n = 7). Colorless liquid. Yield: 1.56 g (63%). 1H NMR (CDCl₃): δ 1.31-1.49 (m, 8H), 1.82-1.89 (m, 2H), 2.29-2.34 (m, 2H), 3.41 (t, J = 6.9 Hz, 2H), 5.16 (d, J = 10.5 Hz, 1H), 5.53 (d, J = 16.3 Hz, 1H), 5.98 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.5 Hz, 1H).


(Z)-3,12-Dibromo-1,3-dodecadiene (2f; n = 8). Colorless liquid. Yield: 1.30 g (50%). 1H NMR (CDCl₃): δ 1.26-1.46 (m, 10H), 1.82-1.89 (m, 2H), 2.28-2.34 (m, 2H), 3.41 (t, J = 6.8 Hz, 2H), 5.16 (d, J = 10.5 Hz, 1H), 5.53 (d, J = 16.3 Hz, 1H), 5.98 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.5 Hz, 1H). 13C{H} NMR (CDCl₃): δ 28.2, 28.3, 28.7, 29.15, 29.24, 31.5, 32.8, 34.1, 117.2, 125.9, 135.2, 135.9. El-HRMS Calcd for C₈H₈Br₂: 321.9932. Found: 321.9931.

(Z)-3,13-Dibromo-1,3-tridecadiene (2g; n = 9). Colorless liquid. Yield: 1.84 g (68%). 1H NMR (CDCl₃): δ 1.30-1.34 (m, 8H), 1.39-1.46 (m, 4H), 1.82-1.89 (m, 2H), 2.28-2.34 (m, 2H), 3.41 (t, J = 6.9 Hz, 2H), 5.16 (d, J = 10.5 Hz, 1H), 5.53 (d, J = 16.3 Hz, 1H), 5.98 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.5 Hz, 1H). 13C{H} NMR (CDCl₃): δ 28.1, 28.3, 28.7, 29.2, 29.28, 29.32, 31.5, 32.8, 34.1, 117.1, 125.8, 135.2, 135.9. El-HRMS Calcd for C₁₀H₉Br₂: 336.0088. Found: 336.0091.

(Z)-3,15-Dibromo-1,3-pentadecadiene (2h; n = 11). Colorless liquid. Yield: 1.64 g (56%). 1H NMR (CDCl₃): δ 1.28-1.47 (m, 16H), 1.82-1.89 (m, 2H), 2.28-2.34 (m, 2H), 3.41 (t, J = 6.9 Hz, 2H), 5.15 (d,
J = 10.5 Hz, 1H), 5.52 (d, J = 16.3 Hz, 1H), 5.98 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.5 Hz, 1H). 1H NMR (CDCl3): δ 28.2, 28.4, 28.8, 29.3, 29.450, 29.455, 29.53 (2C), 31.6, 32.9, 34.1, 117.1, 125.8, 135.3, 135.9. EI-HRMS Calcd for C15H26Br2: 364.0401. Found: 364.0404.

Preparation of Malonate-Tethered Bromodienes 3a-h. A general procedure is given below. To a solution of NaH (4.9 mmol) in DMF (10 mL) was added dimethyl malonate (4.9 mmol) at 0 °C. After gas evolution was ceased, dibromoalkadiene 2 (4.0 mmol) was added to the solution by means of syringe under nitrogen. The mixture was stirred at room temperature for 20 h. After quenching with saturated NH4Cl, the reaction mixture was extracted with Et2O twice and the combined organic layer was washed with H2O and NaCl, dried over MgSO4, filtered, and evaporated under reduced pressure. The residue was purified by silica gel chromatography (hexane/ethyl acetate = 4/1) to afford the malonate-tethered bromodiene 3. The characterization data of 3a-h are given below.

Dimethyl 2-((Z)-5-Bromo-4,6-heptadienyl)-1,3-propanedioate (3a; n = 3). Colorless liquid. Yield: 854 mg (70%). 1H NMR (CDCl3): δ 1.43-1.53 (m, 2H), 1.92-1.98 (m, 2H), 2.33-2.38 (m, 2H), 3.39 (t, J = 7.5 Hz, 1H), 3.74 (s, 6H), 5.18 (d, J = 10.4 Hz, 1H), 5.54 (d, J = 16.3 Hz, 1H), 5.96 (t, J = 7.1 Hz, 1H), 6.30 (dd, J = 16.3 and 10.4 Hz, 1H). 13C{1H} NMR (CDCl3): δ 26.1, 28.4, 31.1, 51.5, 52.6, 117.7, 126.6, 133.8, 135.7, 169.8. Anal. Calcd for C12H17BrO4: C, 47.23; H, 5.61. Found: C, 47.23; H, 5.57. ESI-HRMS Calcd for C12H17BrO4Na: 327.0208 (M+Na). Found: 327.0220.

Dimethyl 2-((Z)-6-Bromo-5,7-octadienyl)-1,3-propanedioate (3b; n = 4). Colorless liquid. Yield: 1.02 g (80%). 1H NMR (CDCl3): δ 1.32-1.40 (m, 2H), 1.45-1.52 (m, 2H), 1.90-1.96 (m, 2H), 2.30-2.35 (m, 2H), 3.37 (t, J = 7.5 Hz, 1H), 3.74 (s, 6H), 5.18 (d, J = 10.4 Hz, 1H), 5.54 (d, J = 16.3 Hz, 1H), 5.96 (t, J = 7.1 Hz, 1H), 6.30 (dd, J = 16.3 and 10.4 Hz, 1H). 13C{1H} NMR (CDCl3): δ 27.0, 27.9, 28.7, 31.2, 51.6, 52.6, 117.5, 126.3, 134.5, 135.8, 169.9. Anal. Calcd for C13H19BrO4: C, 48.92; H, 6.00. Found: C, 48.77; H, 5.97. ESI-HRMS Calcd for C13H19BrO4Na: 318.0467. Found: 318.0468.

Dimethyl 2-((Z)-7-Bromo-6,8-nonadienyl)-1,3-propanedioate (3c; n = 5). Colorless liquid. Yield: 1.00 g (75%). 1H NMR (CDCl3): δ 1.29-1.50 (m, 6H), 1.88-1.93 (m, 2H), 2.28-2.33 (m, 2H), 3.36 (t, J = 7.6 Hz, 1H), 3.74 (s, 6H), 5.16 (d, J = 10.6 Hz, 1H), 5.52 (d, J = 16.3 Hz, 1H), 5.96 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.6 Hz, 1H). 13C{1H} NMR (CDCl3): δ 27.1, 27.9, 28.69, 28.71, 31.3, 51.6, 52.4,
Yield: 1.01 g (73%). 1H NMR (CDCl3): δ 1.29-1.34 (m, 6H), 1.40-1.47 (m, 2H), 1.87-1.93 (m, 2H), 2.28-2.33 (m, 2H), 3.36 (t, J = 7.5 Hz, 1H), 3.74 (s, 6H), 5.16 (d, J = 10.3 Hz, 1H), 5.53 (d, J = 16.3 Hz, 1H), 5.97 (t, J = 7.2 Hz, 1H), 6.31 (dd, J = 16.3 and 10.3 Hz, 1H). 13C{1H} NMR (CDCl3): δ 27.3, 28.2, 28.8, 28.9, 29.0, 31.5, 51.7, 52.5, 117.2, 126.0, 135.0, 135.9, 170.0. Anal. Calcd for C21H27BrO4: C, 51.88; H, 6.68. Found: C, 51.72; H, 6.60. EI-MS Calcd for C21H27BrO4: 346.0780. Found: 346.0781.

Dimethyl 2-((Z)-8-Bromo-7,9-decadienyl)-1,3-propanedioate (3d; n = 6). Colorless liquid. Yield: 1.37 g (95%). 1H NMR (CDCl3): δ 1.26-1.32 (m, 8H), 1.39-1.47 (m, 2H), 1.87-1.92 (m, 2H), 2.28-2.33 (m, 2H), 3.36 (t, J = 7.6 Hz, 1H), 3.74 (s, 6H), 5.16 (d, J = 10.4 Hz, 1H), 5.53 (d, J = 16.3 Hz, 1H), 5.97 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.4 Hz, 1H). 13C{1H} NMR (CDCl3): δ 27.3, 28.3, 28.8, 29.09, 29.11 (2C), 31.5, 51.7, 52.5, 117.2, 125.9, 135.2, 135.9, 170.0. Anal. Calcd for C23H29BrO4: C, 53.19; H, 6.97. Found: C, 52.66; H, 6.91. EI-MS Calcd for C23H29BrO4: 360.0936. Found: 360.0936.

Dimethyl 2-((Z)-9-Bromo-10,10-undecadienyl)-1,3-propanedioate (3e; n = 7). Colorless liquid. Yield: 1.20 g (80%). 1H NMR (CDCl3): δ 1.26-1.33 (m, 10H), 1.39-1.47 (m, 2H), 1.87-1.92 (m, 2H), 2.28-2.33 (m, 2H), 3.36 (t, J = 7.6 Hz, 1H), 3.74 (s, 6H), 5.16 (d, J = 10.5 Hz, 1H), 5.53 (d, J = 16.4 Hz, 1H), 5.98 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.4 and 10.5 Hz, 1H). 13C{1H} NMR (CDCl3): δ 27.4, 28.3, 28.9, 29.18, 29.21, 29.22, 29.3, 31.5, 51.8, 52.5, 117.2, 125.9, 135.2, 135.9, 170.0. Anal. Calcd for C25H31BrO4: C, 54.41; H, 7.25. Found: C, 54.48; H, 7.27. EI-MS Calcd for C25H31BrO4: 374.1093. Found: 374.1093.

Dimethyl 2-((Z)-10-Bromo-9,11-dodecadienyl)-1,3-propanedioate (3f; n = 8). Colorless liquid. Yield: 1.42 g (91%). 1H NMR (CDCl3): δ 1.28-1.33 (m, 12H), 1.40-1.47 (m, 2H), 1.87-1.92 (m, 2H), 2.28-2.33 (m, 2H), 3.36 (t, J = 7.6 Hz, 1H), 3.74 (s, 6H), 5.15 (d, J = 10.4 Hz, 1H), 5.52 (d, J = 16.3 Hz, 1H), 5.98 (t, J = 7.3 Hz, 1H), 6.31 (dd, J = 16.3 and 10.4 Hz, 1H). 13C{1H} NMR (CDCl3): δ 27.3, 28.3, 28.8, 29.16, 29.21, 29.25, 29.34, 29.38, 31.5, 51.7, 52.4, 117.1, 125.8, 135.2, 135.9, 170.0. Anal. Calcd

**Dimethyl 2-((Z)-13-Bromo-12,14-pentadecadienyl)-1,3-propanedioate (3h; n = 11).** Colorless liquid. Yield: 1.29 g (77%). <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 1.26-1.35 (m, 16H), 1.40-1.47 (m, 2H), 1.87-1.92 (m, 2H), 2.28-2.34 (m, 2H), 3.36 (t, J = 7.6 Hz, 1H), 3.74 (s, 6H), 5.15 (d, J = 10.4 Hz, 1H), 5.52 (d, J = 16.3 Hz, 1H), 5.98 (t, J = 7.1 Hz, 1H), 6.31 (dd, J = 16.3 and 10.4 Hz, 1H). <sup>13</sup>C{<sup>1</sup>H} NMR (CDCl<sub>3</sub>): δ 27.4, 28.4, 28.9, 29.2, 29.29, 29.32, 29.4, 29.51, 29.54, 29.6, 31.6, 51.8, 52.5, 117.1, 125.8, 135.3, 135.9, 170.0. Anal. Calcd for C<sub>20</sub>H<sub>33</sub>BrO<sub>4</sub>: C, 57.55; H, 7.97. Found: C, 57.69; H, 7.84.

**2-((Z)-10-Bromo-9,11-dodecadienyl)-1,3-benzodithiole-1,1,3,3-tetraoxide (4f).** To a mixture of NaH (26 mg, 1.1 mmol) and BDT (240 mg, 1.1 mmol) in DMF (4.5 ml) was added dibromododecadiene 2f (274 mg, 844 µmol) by means of syringe under nitrogen. After stirring the mixture for 16 h at 80 °C, the reaction mixture was extracted with ethyl acetate twice and the combined organic layer was washed with H<sub>2</sub>O and NaCl<sub>aq</sub>, dried over MgSO<sub>4</sub>, filtered, and evaporated under reduced pressure. The residue was purified by recycle HPLC to afford 4f (263 mg, 570 µmol, 68%) as a white solid. m. p., 67-69 °C. <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 1.33-1.50 (m, 10H), 1.75-1.80 (m, 2H), 2.30-2.34 (m, 4H), 4.36 (t, J = 7.1 Hz, 1H), 5.16 (d, J = 10.4 Hz, 1H), 5.53 (d, J = 16.3 Hz, 1H), 5.99 (t, J = 7.0 Hz, 1H), 6.32 (dd, J = 16.3 and 10.4 Hz, 1H) 7.91-7.94 (m, 2H), 8.02-8.05 (m, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (CDCl<sub>3</sub>): δ 22.1, 25.8, 28.2, 28.8, 29.00, 29.04, 29.1, 31.4, 73.7, 117.1, 122.5, 125.8, 135.1, 135.78, 135.79, 137.6. Anal. Calcd for C<sub>19</sub>H<sub>25</sub>BrO<sub>4</sub>S<sub>2</sub>: C, 49.46; H, 5.46. Found: C, 49.80; H, 5.40. EI-MS calcd for C<sub>19</sub>H<sub>25</sub>BrO<sub>4</sub>S<sub>2</sub>: 460.0378. Found: 460.0367.

**Palladium-Catalyzed Reaction of Malonate-Tethered Bromodiienes 3a-h.** A general procedure is given below. To a mixture of Pd(dba) (17.5 µmol), dpbp (19.2 µmol), and KOtBu (385 µmol) in THF (250 mL) was added malonate-tethered bromodiene 3 (350 µmol, 1.4 mM) by means of syringe under nitrogen. After stirring the mixture for 20 h at 30 °C, the reaction mixture was concentrated, filtered through a short pad of silica gel, and evaporated to dryness. The crude product was purified by recycle HPLC to afford the corresponding endocyclic allenes 5, 6, and 7. The characterization data of the cyclic allenic products (5, 6, and 7) are listed below.
Dimethyl 2,2-(2,3-Octadien-1,8-diyl)-1,3-propanedioate (5b; n = 4). Colorless liquid. Yield: 19.2 mg (23%). H NMR (CDCl3): δ 1.42-1.58 (m, 4H), 1.93-2.06 (m, 3H), 2.36-2.46 (m, 1H), 2.57-2.63 (m, 1H), 2.81-2.87 (m, 1H), 3.71 (s, 3H), 3.72 (s, 3H), 4.94-5.01 (m, 2H). 13C{1H} NMR (CDCl3): δ 18.9, 24.1, 24.8, 28.4, 31.6, 52.5, 52.6, 57.0, 85.3, 87.4, 172.2, 172.6, 209.8. ESI-HRMS Calcd for C11H16O4Na: 261.1103 (M+Na). Found: 261.1106.

Dimethyl 2,2-(2,3-Nonadien-1,9-diyl)-1,3-propanedioate (5c; n = 5). Colorless liquid. Yield: 9.7 mg (11%). H NMR (CDCl3): δ 1.29-1.84 (m, 7H), 1.88-1.96 (m, 1H), 2.04-2.11 (m, 1H), 2.32-2.41 (m, 1H), 2.61-2.72 (m, 2H), 3.72 (s, 3H), 3.73 (s, 3H), 4.98-5.05 (m, 1H), 5.29-5.32 (m, 1H). 13C{1H} NMR (CDCl3): δ 20.0, 20.6, 28.3, 29.7, 29.8, 32.6, 52.5, 52.6, 55.5, 87.0, 92.9, 172.0, 172.7, 205.9. EI-HRMS Calcd for C14H20O4: 252.1362. Found: 252.1363.

Dimethyl 2,2-(2,3-Decadien-1,10-diyl)-1,3-propanedioate (5d; n = 6). Colorless liquid. Yield: 16.8 mg (18%). H NMR (CDCl3): δ 1.18-1.62 (m, 8H), 1.78-1.96 (m, 2H), 2.04-2.15 (m, 2H), 2.59 (dd, J = 14.1 and 11.6 Hz, 1H), 2.79 (dt, J = 14.1 and 4.4 Hz, 1H), 3.71 (s, 3H), 3.74 (s, 3H), 5.01-5.08 (m, 1H), 5.26-5.31 (m, 1H). 13C{1H} NMR (CDCl3): δ 20.4, 26.0, 26.1, 26.4, 26.8, 30.9, 34.0, 52.5, 52.6, 57.2, 87.4, 91.4, 171.8, 172.2, 206.0. EI-HRMS Calcd for C15H22O4: 266.1518. Found: 266.1516.

Dimethyl 2,2-(2,3-Undecadien-1,11-diyl)-1,3-propanedioate (5e; n = 7). Colorless liquid. Yield: 30.4 mg (31%). H NMR (CDCl3): δ 0.97-1.59 (m, 10H), 1.74-1.82 (m, 1H), 1.93-2.17 (m, 3H), 2.55 (dd, J = 13.9 and 11.6 Hz, 1H), 2.68-2.73 (m, 1H), 3.71 (s, 3H), 3.74 (s, 3H), 4.61-4.67 (m, 1H), 4.89-4.96 (m, 1H). 13C{1H} NMR (CDCl3): δ 19.1, 21.4, 22.3, 25.9, 26.48, 26.54, 27.3, 32.1, 52.5, 52.6, 56.8, 83.8, 89.2, 171.7, 171.8, 208.4. Anal. Calcd for C16H24O4: C, 68.54; H, 8.63. Found: C, 68.28; H, 8.74. EI-HRMS Calcd for C16H24O4: 280.1675. Found: 280.1675.

Dimethyl 2,2-(2,3-Dodecadien-1,12-diyl)-1,3-propanedioate (5f; n = 8). Colorless liquid. Yield: 53.6 mg (52%). H NMR (CDCl3): δ 1.06-1.15 (m, 1H), 1.26-1.62 (m, 11H), 1.90-2.12 (m, 4H), 2.55 (dd, J = 14.6 and 11.4 Hz, 1H), 2.77 (dt, J = 14.6, 4.4, and 1.2 Hz, 1H), 3.71 (s, 3H), 3.73 (s, 3H), 4.74-4.81 (m, 1H), 5.12-5.17 (m, 1H). 13C{1H} NMR (CDCl3): δ 21.7, 25.0, 26.1, 26.9, 27.2, 27.9, 28.6, 30.8, 31.7, 52.45, 52.51, 57.4, 85.7, 91.4, 171.8 (2C), 206.1. Anal. Calcd for C17H26O4: C, 69.36; H, 8.90. Found: C, 69.28; H, 9.05. EI-HRMS Calcd for C17H26O4: 294.1831. Found: 294.1824.
**Dimethyl 2,2-(2,3-Tridecaadien-1,13-diyl)-1,3-propanedioate (5g; n = 9).** Colorless liquid. Yield: 45.3 mg (42%). \(^1\)H NMR (CDCl\(_3\)): \(\delta\) 0.73-0.90 (m, 1H), 1.14-1.57 (m, 13H), 1.87-2.04 (m, 4H), 2.58 (dd, \(J = 14.5\) and 11.6 Hz, 1H), 2.78 (tdd, \(J = 14.5, 4.4,\) and 0.9 Hz, 1H), 3.72 (s, 3H), 3.73 (s, 3H), 4.63-4.70 (m, 1H), 5.02-5.08 (m, 1H). \(^{13}\)C{\(^1\)H} NMR (CDCl\(_3\)): \(\delta\) 20.7, 23.2, 23.9, 26.0, 26.37, 26.40, 27.16, 27.18, 31.6, 32.4, 52.5, 52.6, 57.2, 84.5, 91.3, 171.8, 171.9, 206.1. Anal. Calcd for C\(_{18}\)H\(_{28}\)O\(_4\): C, 70.10; H, 9.15. Found: C, 70.00; H, 9.11. Ei-HRMS Calcd for C\(_{18}\)H\(_{28}\)O\(_4\): 308.1988. Found: 308.1989.

**Dimethyl 2,2-(2,3-Pentadecadien-1,15-diyl)-1,3-propanedioate (5h; n = 11).** Colorless liquid. Yield: 38.9 mg (33%). \(^1\)H NMR (CDCl\(_3\)): \(\delta\) 1.07-1.43 (m, 18H), 1.82-2.03 (m, 4H), 2.56 (dd, \(J = 14.2\) and 9.8 Hz, 1H), 2.71 (tdd, \(J = 14.2, 6.0,\) and 3.2 Hz, 1H), 3.72 (s, 3H), 3.73 (s, 3H), 4.69-4.71 (m, 1H), 5.07-5.13 (m, 1H). \(^{13}\)C{\(^1\)H} NMR (CDCl\(_3\)): \(\delta\) 23.6, 24.2, 24.4, 25.9, 26.0, 26.2, 26.3, 27.4, 27.5, 29.0, 31.9, 32.9, 52.41, 52.44, 57.3, 84.6, 91.2, 171.81, 171.84, 206.2. Ei-HRMS Calcd for C\(_{20}\)H\(_{32}\)O\(_4\): 336.2301. Found: 336.2302.

**5,5,13,13-Tetra(methoxycarbonyl)cyclohexadecaa-1,2,9,10-tetraene (6a; n = 3).** Diastereomeric mixture (\(^1\)C NMR signals not completely resolved). Colorless liquid. Yield: 23.5 mg (30%). \(^1\)H NMR (CDCl\(_3\)): \(\delta\) 1.02-1.10 (m, 1H), 1.17-1.41 (m, 3H), 1.79-2.12 (m, 8H), 2.49-2.55 (m, 2H), 2.66-2.72 (m, 2H), 3.70-3.72(s, 12H), 4.63-4.81 (m, 2H), 4.97-5.10 (m, 2H). \(^{13}\)C{\(^1\)H} NMR (CDCl\(_3\)): \(\delta\) 23.9, 24.8, 29.7, 31.0, 31.1, 31.5, 31.8, 32.1, 52.5, 52.57, 52.64, 57.0, 84.3, 84.8, 90.5, 90.6, 171.51, 171.55, 171.60, 171.62, 205.7, 206.0. Anal. Calcd for C\(_{24}\)H\(_{32}\)O\(_8\): C, 64.27; H, 7.19. Found: C, 64.08; H, 7.25. Ei-HRMS Calcd for C\(_{24}\)H\(_{32}\)O\(_8\): 448.2097. Found: 448.2098.

**5,5,14,14-Tetra(methoxycarbonyl)cyclooctadecaa-1,2,10,11-tetraene (6b; n = 4).** Diastereomeric mixture (\(^1\)C NMR signals not completely resolved). Colorless liquid. Yield: 13.3 mg (16%). \(^1\)H NMR (CDCl\(_3\)): \(\delta\) 0.94-1.70 (m, 8H), 1.82-2.08 (m, 8H), 2.50-2.57 (m, 2H), 2.68-2.73 (m, 2H), 3.72-3.75 (m, 12H), 4.65-4.80 (m, 2H), 5.04-5.15 (m, 2H). \(^{13}\)C{\(^1\)H} NMR (CDCl\(_3\)): \(\delta\) 23.7, 24.1, 28.4, 29.0, 30.2, 30.8, 31.7, 31.9, 32.6, 32.9, 52.50, 52.54, 52.6, 52.64, 57.0, 57.1, 84.6, 85.5, 90.7, 90.9, 171.6, 171.7, 205.7, 206.0. Anal. Calcd for C\(_{26}\)H\(_{36}\)O\(_8\): C, 65.53; H, 7.61. Found: C, 65.81; H, 7.77. Ei-HRMS Calcd for C\(_{26}\)H\(_{36}\)O\(_8\): 476.2410. Found: 476.2414.

**5,5,15,15-Tetra(methoxycarbonyl)cycloeicosa-1,2,11,12-tetraene (6c; n = 5).** Diastereomeric mixture (\(^1\)C NMR signals not completely resolved). Colorless liquid. Yield: 21.2 mg (24%). \(^1\)H NMR
(CDCl₃): δ 0.96-1.12 (m, 2H), 1.16-1.45 (m, 10H), 1.82-2.07 (m, 8H), 2.51-2.56 (m, 2H), 2.68-2.72 (m, 2H), 3.72-3.73 (m, 2H), 4.65-4.75 (m, 2H), 5.01-5.09 (m, 2H). ¹³C{¹H} NMR (CDCl₃): δ 24.0, 24.1, 29.3, 29.5, 29.8, 30.1, 30.6, 30.7, 31.6, 31.7, 32.18, 32.22, 52.55, 52.60, 57.1, 57.2, 84.4, 84.8, 90.8, 90.9, 171.7, 205.8, 205.9. Anal. Calcd for C₃₈H₇₆O₈: C, 66.65; H, 7.99. Found: C, 66.49; H, 8.12. EI-HRMS Calcd for C₂₈H₄₀O₈: 504.2723. Found: 504.2724.

5,5,16,16-Tetra(methoxycarbonyl)cyclodocosa-1,2,12,13-tetraene (6d; n = 6). Diastereomeric mixture (¹³C NMR signals not completely resolved). Colorless liquid. Yield: 25.2 mg (27%). ¹H NMR (CDCl₃): δ 0.96-1.12 (m, 16H), 1.84-2.02 (m, 8H), 2.50-2.56 (m, 2H), 2.68-2.74 (m, 2H), 3.72-3.73 (m, 12H), 4.65-4.77 (m, 2H), 5.03-5.13 (m, 2H). ¹³C{¹H} NMR (CDCl₃): δ 24.3, 24.4, 29.0, 29.6, 29.87, 29.92, 30.3, 30.4, 30.6, 31.9, 32.6, 32.7, 52.50, 52.54, 57.11, 57.13, 84.6, 85.0, 90.99, 91.04, 171.8, 205.78, 205.82. Anal. Calcd for C₃₈H₇₆O₈: C, 66.49; H, 8.12. EI-HRMS Calcd for C₂₈H₄₀O₈: 504.2723. Found: 504.2724.

5,5,17,17-Tetra(methoxycarbonyl)cycloctetrahepta-1,2,13,14-tetraene (6e; n = 7). Diastereomeric mixture (¹³C NMR signals not completely resolved). Colorless liquid. Yield: 18.6 mg (19%). ¹H NMR (CDCl₃): δ 0.97-1.43 (m, 20H), 1.83-2.05 (m, 8H), 2.51-2.57 (m, 2H), 2.66-2.72 (m, 2H), 3.72 (s, 6H), 3.73(s, 6H), 4.66-4.75 (m, 2H), 5.02-5.10 (m, 2H). ¹³C{¹H} NMR (CDCl₃): δ 24.1, 24.3, 29.4, 29.7, 29.75, 29.82, 29.9, 30.3, 30.38, 30.43, 30.8, 31.6, 31.7, 31.8, 32.3, 52.5, 52.6, 57.18, 57.23, 84.5, 84.6, 91.0, 91.1, 171.8, 205.8, 205.9. Anal. Calcd for C₃₈H₇₆O₈: C, 66.49; H, 8.12. EI-HRMS Calcd for C₂₈H₄₀O₈: 504.2723. Found: 504.2724.

5,5,18,18-Tetra(methoxycarbonyl)cyclooctacosa-1,2,14,15-tetraene (6f; n = 8). Diastereomeric mixture (¹³C NMR signals not completely resolved). Colorless liquid. Yield: 14.4 mg (14%). ¹H NMR (CDCl₃): δ 1.02-1.37 (m, 24H), 1.86-2.03 (m, 8H), 2.50-2.57 (m, 2H), 2.67-2.72 (m, 2H), 3.71-3.73 (m, 12H), 4.68-4.76 (m, 2H), 5.04-5.11 (m, 2H). ¹³C{¹H} NMR (CDCl₃): δ 24.2, 24.3, 29.2, 29.6, 29.8, 30.0, 30.17, 30.21, 30.3, 30.4, 30.5, 30.6, 31.9, 32.6, 52.49, 52.52, 57.2, 84.6, 84.8, 91.1, 171.8, 205.8. Anal. Calcd for C₃₈H₇₆O₈: C, 66.49; H, 8.12. EI-HRMS Calcd for C₂₈H₄₀O₈: 504.2723. Found: 504.2724.

5,5,19,19-Tetra(methoxycarbonyl)cyclooctacosa-1,2,14,15-tetraene (6g; n = 9). Diastereomeric mixture (¹³C NMR signals not completely resolved). Colorless liquid. Yield: 22.7 mg (21%). ¹H NMR
(CDCl₃): δ 1.01-1.37 (m, 28H), 1.86-2.05 (m, 8H), 2.56 (dd, J = 14.3 and 9.8 Hz, 2H), 2.68 (ddd, J = 14.3, 6.1, and 3.3 Hz, 2H), 3.71 (s, 6H), 3.72(s, 6H), 4.68-4.76 (m, 2H), 5.04-5.10 (m, 2H). 'C{H} NMR (CDCl₃): δ 24.0, 24.1, 29.3, 29.5, 29.67, 29.72, 29.8, 29.97, 30.03, 30.1, 30.2, 30.3, 30.5, 31.8, 32.4, 52.5, 57.2, 84.58, 84.64, 91.1, 171.8, 205.8. Anal. Calcd for C₃₆H₅₆O₈: C, 70.10; H, 9.15. Found: C, 70.08; H, 9.01. EI-HRMS Calcd for C₃₆H₅₆O₈: 616.3975. Found: 616.3978.

5,5,21,21-Tetra(methoxycarbonyl)cyclodotriaconta-1,2,17,18-tetraene (6h; n = 11). Diastereomeric mixture ('C NMR signals not completely resolved). Colorless liquid. Yield: 11.8 mg (10%). 'H NMR (CDCl₃): δ 1.04-1.41 (m, 36H), 1.86-2.05 (m, 8H), 2.55 (ddd, J = 14.3, 9.6, and 1.2 Hz, 2H), 2.67 (ddd, J = 14.3, 6.2, and 3.3 Hz, 2H), 3.71 (s, 6H), 3.72(s, 6H), 4.70-4.78 (m, 2H), 5.04-5.10 (m, 1H). 'C{H} NMR (CDCl₃): δ 24.0, 29.20, 29.24, 29.57, 29.63, 29.7, 29.8, 29.85, 29.94, 30.02, 30.07, 30.2, 30.3, 31.8, 32.4, 52.5, 57.3, 84.7, 91.1, 171.9, 205.8. Anal. Calcd for C₄₀H₆₄O₈: C, 71.39; H, 9.59. Found: C, 70.96; H, 9.56. EI-HRMS Calcd for C₄₀H₆₄O₈: 672.4601. Found: 672.4602.

5,5,13,13,21,21-Hexa(methoxycarbonyl)cycloctetracosapenta,1,2,9,10,17,18-hexaene (7a; n = 3). Diastereomeric mixture ('C NMR signals not completely resolved). Colorless liquid. Yield: 7.8 mg (10%). 'H NMR (CDCl₃): δ 1.19-1.35 (m, 6H), 1.86-2.08 (m, 12H), 2.56-2.67 (m, 6H), 3.71-3.74 (m, 18H), 4.79-4.871 (m, 3H), 4.98-5.06 (m, 3H). 'C{H} NMR (CDCl₃): δ 23.9, 29.4, 31.4, 32.6, 52.5, 57.3, 84.8, 90.3, 171.6, 205.8, 205.9, 206.0. EI-HRMS Calcd for C₃₆H₄₈O₁₂: 672.3146. Found: 672.3148.

5,5,15,15,25,25-Hexa(methoxycarbonyl)cyclotriaconta-1,2,11,12,21,22-hexaene (7c; n = 5). Diastereomeric mixture ('C NMR signals not completely resolved). Colorless liquid. Yield: 6.2 mg (7%). 'H NMR (CDCl₃): δ 1.11-1.43 (m, 18H), 1.86-1.98 (m, 12H), 2.55-2.66 (m, 6H), 3.71-3.72 (m, 18H), 4.78-4.85 (m, 3H), 5.03-5.08 (m, 3H). 'C{H} NMR (CDCl₃): δ 23.6, 28.7, 28.9, 29.2, 31.8, 32.5, 52.5, 57.5, 84.9, 90.8, 171.8, 205.8. EI-HRMS Calcd for C₄₂H₆₀O₁₂: 756.4085. Found: 756.4085.

5,5,16,16,27,27-Hexa(methoxycarbonyl)cyclotritriaconta-1,2,12,13,23,24-hexaene (7d; n = 6). Diastereomeric mixture ('C NMR signals not completely resolved). Colorless liquid. Yield: 8.4 mg (9%). 'H NMR (CDCl₃): δ 1.10-1.41 (m, 24H), 1.86-1.98 (m, 12H), 2.55-2.66 (m 6H), 3.715 (s, 9H), 3.718 (s, 9H), 4.79-4.86 (m, 3H), 5.03-5.09 (m, 3H). 'C{H} NMR (CDCl₃): δ 23.8, 28.7, 28.8, 29.1,
29.6, 31.9, 32.5, 57.5, 84.9, 90.9, 171.8, 205.8. EI-HRMS Calcd for C_{45}H_{66}O_{12}: 798.4554. Found: 798.4552.

2,2-(Dodecadien-1,12-diyl)-1,3-benzodithiole-1,1,3,3-tetraoxide (10f). To a mixture of Pd(dba), (5.5 mg, 11 μmol), dpbp (6.0 mg, 12 μmol), KOBu (23.6 mg, 210 μmol) in THF (150 ml) was added 4f (96.9 mg, 210 μmol, 1.4 mM) by means of syringe under nitrogen. After stirring the mixture for 120 h at 30 °C, the reaction mixture was concentrated, filtered through a short pad of silica gel, and evaporated to dryness. The crude product was purified by recycle HPLC to afford 10f (53.2 mg, 140 μmol, 67%) as colorless liquid. \( ^1H \) NMR (CDCl\(_3\)): \( \delta \) 1.21-1.86 (m, 12H), 2.02-2.15 (m, 2H), 2.26-2.38 (m, 2H), 2.88 (dt, \( J = 15.3 \) and 4.3 Hz, 1H), 2.99 (dd, \( J = 15.3 \) and 10.6 Hz, 1H), 5.22-5.28 (m, 1H), 5.43-5.50 (m, 1H) 7.88-7.93 (m, 2H), 7.98-8.04 (m, 2H). \( ^{13}C\)\{\( ^1H \)\} NMR (CDCl\(_3\)): \( \delta \) 21.1, 25.3, 25.7, 26.1, 26.6, 26.7, 27.5, 29.0, 29.7, 79.5, 83.4, 92.6, 123.1, 123.2, 135.1, 135.2, 135.8, 136.3, 207.1. Anal. Calcd for C_{19}H_{24}O_{4}S_{2}: C, 59.97; H, 6.36. Found: C, 60.04; H, 6.36. EI-HRMS Calcd for C_{19}H_{24}O_{4}S_{2}: 380.1116. Found: 380.1121.

Palladium-Catalyzed Asymmetric Synthesis of Axially Chiral 5f and 10f. The asymmetric reactions were conducted in the same way as with the non-asymmetric reaction described above except for using a chiral ligand instead of achiral dpbp (see Table 3 for details). (S)-5f (entry 7, Table 3): [\( \alpha \)]\(^D\) = +93.1 (c 0.73, CHCl\(_3\) for the sample of (S)-70% ee). Chiral HPLC Analysis Conditions: Chiralpak IC; eluent, hexane/PrOH = 200/1; flow rate, 1.0 mL/min; \( t \) [(R)-enantiomer] = 20.8 min, \( t \) [(S)-enantiomer] = 40.7 min. (S)-10f (entry 10, Table 3): [\( \alpha \)]\(^D\) = +56.9 (c 0.37, CHCl\(_3\) for the sample of (S)-51% ee). Chiral HPLC Analysis Conditions: Chiralpak IC; eluent, hexane/PrOH = 9/1; flow rate, 1.0 mL/min; \( t \) [(S)-enantiomer] = 20.0 min, \( t \) [(R)-enantiomer] = 31.9 min.

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Supporting Information. The Supporting Information is available free of charge on the ACS Publications website at DOI: **********. \( ^1H \)- and \( ^{13}C \)-NMR spectra for all the new compounds and chiral HPLC chromatograms of (+)-5f and (+)-10f (PDF).

References and Footnotes.


(16) dpbp = 2,2'-bis(diphenylphosphino)-1,1'-biphenyl. See, Ogasawara, M.; Yoshida, K.; Hayashi, T. Organometallics 2000, 19, 1567, and references cited therein.

(17) The dl/meso-diastereomeric ratios could not be determined due to the incomplete separation of their NMR signals.


HNu\(_n\) – \(\text{Br}\)

\(n = 3-9, 11\)

\(\text{Nu} = \text{C(CO}_2\text{Me)}_2\)

\(\text{Pd-cat. base}\)

\((\text{CH}_2)_n\) \(\text{Nu}^-\)

\((\text{CH}_2)\_n\text{Nu}^{\text{n+5}}\) + \((\text{Nu}\text{S}_n\text{SO}_2\text{C}_2\text{CO}_2\text{Me})_n\)

+ oligomers/polymers