# Allylic Substitution of *meso*-1,4-Diacetoxycycloalkenes in Water with an Amphiphilic Resin-Supported Chiral Palladium Complex

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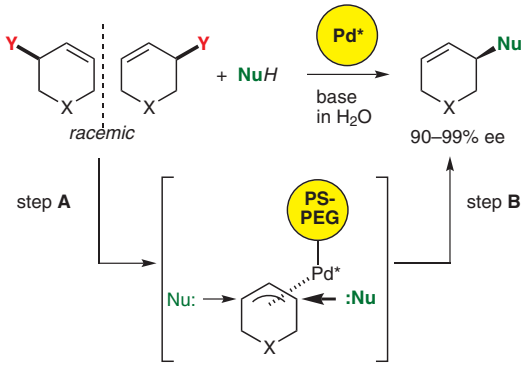
**Abstract:** Asymmetric π-allylic substitution of *meso*-1,4-diacetoxycyclopentene and *meso*-1,4-diacetoxycyclohexene with various nucleophiles was performed with an amphiphilic polystyrene-poly(ethylene glycol) (PS-PEG) resin-supported chiral imidazoindolephosphine-palladium complex in water as a single reaction medium under heterogeneous conditions to give the corresponding 1-acetoxy-4-substituted cycloalkenes with up to 99% ee.

**Key words:** π-allylpalladium, asymmetric catalysis, aqueous media, polymer support, palladium catalyst

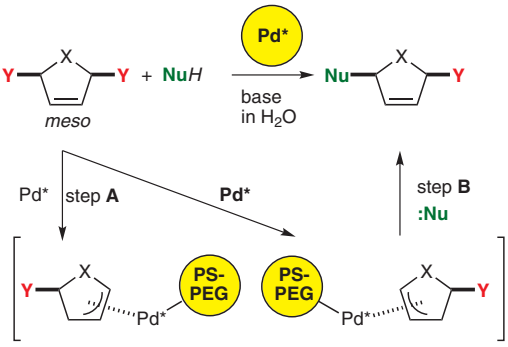
The catalytic asymmetric functionalization of carbon frameworks has become an important goal in modern synthetic organic chemistry. However, aqueous- and heterogeneous-switching of a given organic transformation is rapidly gaining importance for its ability to provide safe and green chemical processes.[1–5] If asymmetric catalysis can be achieved in water with immobilized chiral catalysts, the reaction would become what many consider an ideal organic transformation. We have recently developed amphiphilic polystyrene-poly(ethylene glycol) (PS-PEG) resin-supported chiral phosphine-palladium complexes which promote the asymmetric allylic substitution of a racemic mixture of allylic esters with various nucleophiles in water under heterogeneous conditions with excellent enantioselectivity.[6] Thus, for example, the asymmetric allylic substitution of a racemic mixture of cycloalkenyl carbonate with carbon, nitrogen, or oxygen nucleophiles was catalyzed by the amphiphilic PS-PEG resin-supported chiral palladium complex **1** in water to give the corresponding cycloalkenyl malonates, amines, or aryl ethers, respectively, with enantioselectivities of 90–99% ee, where the reactions proceeded via formation of the π-allylpalladium intermediates and subsequent enantioposition-selective nucleophilic attack (Scheme 1). Our continuing interest in the utility of the polymeric chiral catalyst under aqueous conditions led us to study its potential in the enantioselective desymmetrization of *meso*-cycloalkene-1,4-diesters where the stereoselectivity should be induced mainly at the π-allylic formation step via the enantioposition-selective oxidative addition (Scheme 2).[7,8]




X = $CH_2$, $C_2H_4$, NCOO*t*-Bu
Nu*H* = $CH_2(COOEt)_2$, *H*NBn$_2$, *H*OC$_6$H$_4$O(4-Me)

step A: formation of the π-allylpalladium intermediate,
step B: **enantio-position selective** nucleophilic attack

**Scheme 1** Asymmetric π-allylic substitution via enantioselective nucleophilic attack (representative example of previous work)




step A: **enantio-position selective** formation
of the π-allylpalladium intermediate,
step B: nucleophilic attack

**Scheme 2** Asymmetric π-allylic substitution via enantioselective π-allylpalladium formation (working hypothesis of the present work)

Here we wish to report preliminary results on the aquacatalytic asymmetric desymmetrization of the *meso*-cycloalkenyl-1,4-diacetate via π-allylic substitution with carbon, nitrogen, and oxygen nucleophiles, which was promoted by the palladium complex anchored onto the amphiphilic PS-PEG resin-supported (3*R*,9a*S*)-[2-aryl-3-(2-diphenylphosphino)phenyl]tetrahydro-1*H*-imidazo[1,5-*a*]indol-1-one in water under heterogeneous conditions to give the corresponding hemi-substituted products with up to 99% ee.

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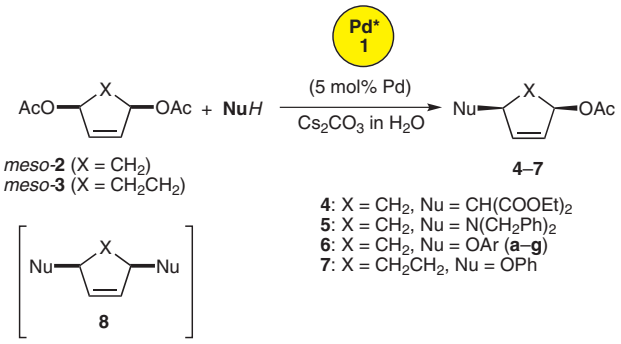


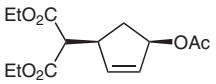
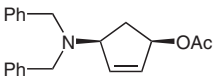
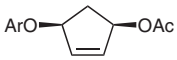
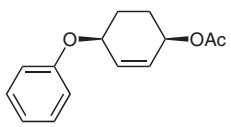

**Scheme 3**

The aquacatalytic asymmetric desymmetrization of the *meso*-cycloalkene-1,4-diesters via π-allylic substitution was examined for alkylation and amination of *cis*-1,4-diacetoxycyclopentene (*meso*-**2**) (Table 1, entries 1 and 2). Thus, a mixture of the cyclopentene diacetate *meso*-**2** and diethyl malonate (1.0 equiv to **2**) in water was shaken at 0 °C for 18 hours in the presence of 5 mol% palladium of the amphiphilic resin-supported chiral imidazoindole-phosphine-palladium complex **1** (average diameter = ca. 100 μm, Pd loading = 0.28 mmol/g, 1% DVB cross-linked)[9] and cesium carbonate as base (entry 1).[10] The reaction mixture was filtered and the resin beads were rinsed with a small portion of ethyl acetate. The combined extract was concentrated and the resulting crude residue was chromatographed on silica gel to give 56% isolated yield of the hemialkylated product (1*R*,4*S*)-**4** along with the dialkylated product **8** (4%).[11] We were pleased to find that the enantiomeric purity of (1*R*,4*S*)-**4** was 91% ee as determined by GC analysis using a chiral stationary phase column (Cyclodex CB). Amination of *meso*-**2** was carried out with dibenzylamine (2 equiv) in water at 0 °C for 18 hours to give 91% ee of the hemiaminated **5** in 62% isolated yield (entry 2).

With this highly enantioselective desymmetrization protocol in hand, we turned our attention to demonstrating the catalytic as well as stereoselective potential of the asymmetric aquacatalysis in the hemietherification of the *meso*-diacetate **2** with phenolic nucleophiles. Though quite a few reports on the palladium-catalyzed asymmetric π-allylic hemi-substitution of *meso*-cyclic 1,4-diesters with carbon and nitrogen nucleophiles have appeared so far, research on the asymmetric hemietherification with oxygen nucleophiles has been limited to isolated reports,[12] and therefore still remains a challenging target. The reaction of 1,4-diacetoxycyclopentene, *meso*-**2**, with phenol as a nucleophile under similar water-based conditions at 0 °C gave 99% ee of **6a** in 64% isolated yield where the disubstituted product **8** was obtained in 14% yield (Table 1, entry 3).[13] The enantiomeric excess of the phenol ether **6a** was slightly decreased (98% ee) when the reaction was carried out at 25 °C (entry 4). The etherification took place smoothly in water at 25 °C with phenols bearing *ortho* substituents. Thus, 2-benzyloxyphenol (**b**), 2-chlorophenol (**c**), and 2-bromophenol (**d**) reacted with *meso*-**2** to afford the corresponding hemiethers **6b**, **6c**, and **6d** in 45, 52, and 53% yields with 97, 94, and 95% enantiomeric purities, respectively (entries 5–7). Sterically hindered 2,6-dimethylphenol (**e**) gave 90% ee of **6e** in 59% yield under similar conditions (entry 8). The reactions with 3-methoxyphenol (**f**) and 4-*tert*-butylphenol (**g**) also gave the desired hemiethers **6f** and **6g** in 43 and 52% isolated yields with 96 and 94% ee values, respectively (entries 9 and 10). The cyclohexenyl ester *meso*-**3** also underwent etherification with phenol to give 95% ee of **7** in 37% yield (entry 11).

In the asymmetric etherification of *meso*-**2** with phenol (**a**) it was found that the enantiomeric purity of the hemiether **6a** was dependent on the yield of the disubstituted product **8** (Scheme 4). Thus, in order to decrease the formation of the diether **8**, the asymmetric etherification was carried out with a fivefold excess of *meso*-**2** at 25 °C to give the hemiether **6a** and the diether **8** in 72% and 5% yields, re-

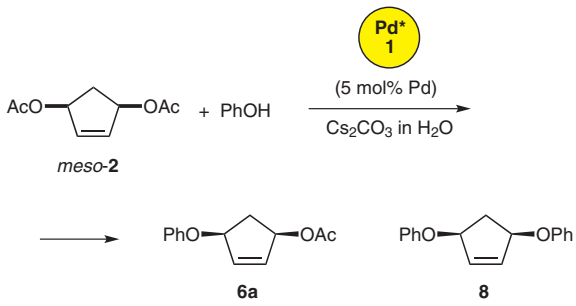
**Table 1** Asymmetric π-Allylic Substitution of *meso*-1,4-Diacetoxycycloalkenes in Water[a,14]

| Entry | Product | | Yield (%)[b] | ee (%) |
|---|---|---|---|---|
| 1 | **4** |  | 56 (**8**: 4%) | 91 |
| 2[c] | **5** |  | 62 (**8**: –[d]) | 91 |
| | **6a–g** |  | | |
| 3 | **6a** | Ar = Ph (at 0 °C) | 64 (**8**: 14%) | 99 |
| 4 | **6a** | Ar = Ph (at 25 °C) | 55 (**8**: 12%) | 98 |
| 5 | **6b** | Ar = 2-BnOC$_6$H$_4$ | 45 (**8**: –[d]) | 97 |
| 6 | **6c** | Ar = 2-ClC$_6$H$_4$ | 52 (**8**: 17%) | 94 |
| 7 | **6d** | Ar = 2-BrC$_6$H$_4$ | 53 (**8**: 16%) | 95 |
| 8 | **6e** | Ar = 2,6-diMeC$_6$H$_3$ | 59 (**8**: 4%) | 90 |
| 9 | **6f** | Ar = 3-MeOC$_6$H$_4$ | 43 (**8**: 14%) | 96 |
| 10 | **6g** | Ar = 4-*t*-BuC$_6$H$_4$ | 52 (**8**: 11%) | 94 |
| 11 | **7** |  | 37 (**8**: 11%) | 95 |

[a] All reactions were carried out in $H_2O$ at 0 °C for 18 h (entries 1–3) or 25 °C for 6 h (entries 4–11) with 5 mol% Pd of **1**. The ratio of **2** (or **3**) (mol)/nucleophile (mol)/Pd (mol)/$Cs_2CO_3$ (mol)/$H_2O$ (L) = 1:1.0:0.05:0.9:1.0, unless otherwise noted.
[b] Isolated yield.
[c] Reaction was carried out with amine (2 equiv) without $Cs_2CO_3$.
[d] Not isolated.

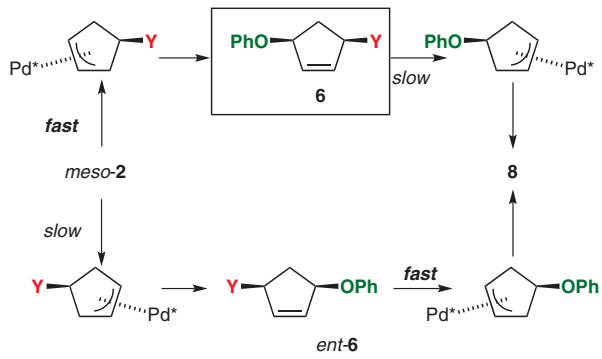
spectively, where the enantiomeric purity of **6a** was 84% ee. The reaction with *meso*-**2** and phenol in an equimolar ratio gave 98% ee of **6a** in 55% yield along with 12% of **8**. A similar trend was also observed at 0 °C; the reaction in a 1:1 mol ratio of *meso*-**2**/phenol gave **6a** in 64% yield (99% ee) and **8** (14%), and that in a 5:1 mol ratio gave **6a** in 72% yield (93% ee) and **8** (5%). Though the detailed kinetic study on asymmetric induction steps is not clear because of the complication of the side reactions (e.g., hydrolysis of acetate, oxidative addition of allyl phenyl ether), the kinetic resolution at the second etherification forming **8**, preferentially via *ent*-**6**, must contribute to the increase of the enantiomeric excess of the hemiether **6a** (Scheme 5).

In summary, the asymmetric palladium-catalyzed π-allylic substitution of *meso*-cycloalkenyl-1,4-diacetates was achieved with carbon, nitrogen, and oxygen nucleophiles in water with an amphiphilic polymeric chiral palladium complex to give the corresponding hemi-substituted products with high enantioselectivity of up to 99% ee. A detailed kinetic study and synthetic application are currently under investigation in our lab and will be reported in due course.




| conditions | | **6a** yield; % ee | **8** yield |
|---|---|---|---|
| **2**/PhOH = 1:1 | 25 °C | 55%; 98% ee | 12% |
| **2**/PhOH = 5:1 | | 72%; 84% ee | 5% |
| **2**/PhOH = 1:1 | 0 °C | 64%; 99% ee | 14% |
| **2**/PhOH = 5:1 | | 72%; 93% ee | 5% |

**Scheme 4**




**Scheme 5**

## Acknowledgment

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## References and Notes

(1) For reviews on aqueous-switching of organic transformations, see: (a) Li, C.-J.; Chan, T.-H. *Organic Reactions in Aqueous Media*; Wiley: New York, **1997**. (b) Grieco, P. A. *Organic Synthesis in Water*; Kluwer Academic Publishers: Dordrecht, **1997**. (c) Herrmann, W. A.; Kohlpaintner, C. W. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1524. (d) Lindström, U. M. *Chem. Rev.* **2002**, *102*, 2751.

(2) For reviews on heterogeneous-switching of organic transformations, see: (a) Bailey, D. C.; Langer, S. H. *Chem. Rev.* **1981**, *81*, 109. (b) Shuttleworth, S. J.; Allin, S. M.; Sharma, P. K. *Synthesis* **1997**, 1217. (c) Shuttleworth, S. J.; Allin, S. M.; Wilson, R. D.; Nasturica, D. *Synthesis* **2000**, 1035. (d) Dörwald, F. Z. *Organic Synthesis on Solid Phase*; Wiley-VCH: Weinheim, **2000**. (e) Leadbeater, N. E.; Marco, M. *Chem. Rev.* **2002**, *102*, 3217. (f) Ley, S. V.; Baxendale, I. R.; Bream, R. N.; Jackson, P. S.; Leach, A. G.; Longbottom, D. A.; Nesi, M.; Scott, J. S.; Storer, R. I.; Taylor, S. J. *J. Chem. Soc., Perkin Trans. 1* **2000**, 3815. (g) McNamara, C. A.; Dixon, M. J.; Bradley, M. *Chem. Rev.* **2002**, *102*, 3275. (h) *Chiral Catalyst Immobilization and Recycling*; De Vos, D. E.; Vankelecom, I. F. J.; Jacobs, P. A., Eds.; Wiley-VCH: Weinheim, **2000**. (i) Fan, Q.-H.; Li, Y.-M.; Chan, A. S. C. *Chem. Rev.* **2002**, *102*, 3385.

(3) For recent reviews on solid-phase reactions using palladium catalysts, see: (a) Uozumi, Y.; Hayashi, T. *Solid-Phase Palladium Catalysis for High-Throughput Organic Synthesis, In Handbook of Combinatorial Chemistry*; Nicolaou, K. C.; Hanko, R.; Hartwig, W., Eds.; Wiley-VCH: Weinheim, **2002**, Chap. 19. (b) Uozumi, Y. *Top. Curr. Chem.* **2004**, *242*, 77.

(4) For studies on polymer-supported catalysts from the author's group, see: (a) Cross-coupling: Uozumi, Y.; Danjo, H.; Hayashi, T. *J. Org. Chem.* **1999**, *64*, 3384. (b) Carbonylation reaction: Uozumi, Y.; Watanabe, T. *J. Org. Chem.* **1999**, *64*, 6921. (c) Michael addition: Shibatomi, K.; Nakahashi, T.; Uozumi, Y. *Synlett* **2000**, 1643. Suzuki–Miyaura coupling: (d) Uozumi, Y.; Nakai, Y. *Org. Lett.* **2002**, *4*, 2997. (e) Uozumi, Y.; Kikuchi, M. *Synlett* **2005**, 1775. (f) Heck reaction: Uozumi, Y.; Kimura, T. *Synlett* **2002**, 2045. (g) Rhodium catalysis: Uozumi, Y.; Nakazono, M. *Adv. Synth. Catal.* **2002**, *344*, 274. (Wacker cyclization): (h) Hocke, H.; Uozumi, Y. *Synlett* **2002**, 2049. (i) Hocke, H.; Uozumi, Y. *Tetrahedron* **2003**, *59*, 619. (j) Sonogashira reaction: Uozumi, Y.; Kobayashi, Y. *Heterocycles* **2003**, *59*, 71. Oxidation: (k) Uozumi, Y.; Nakao, R. *Angew. Chem. Int. Ed.* **2003**, *42*, 194. (l) Uozumi, Y.; Nakao, R. *Angew. Chem.* **2003**, *115*, 204. (m) Yamada, Y. M. A.; Arakawa, T.; Hocke, H.; Uozumi, Y. *Angew. Chem. Int. Ed.* **2007**, *46*, 704. (n) Reduction: Nakao, R.; Rhee, H.; Uozumi, Y. *Org. Lett.* **2005**, *7*, 163. (o) Alkylation: Yamada, Y. M. A.; Uozumi, Y. *Org. Lett.* **2006**, *8*, 1375.

(5) For studies on π-allylic transformations with polymer-supported complex catalysts in water, see: (a) Uozumi, Y.; Danjo, H.; Hayashi, T. *Tetrahedron Lett.* **1997**, *38*, 3557. (b) Danjo, H.; Tanaka, D.; Hayashi, T.; Uozumi, Y. *Tetrahedron* **1999**, *55*, 14341. (c) Uozumi, Y.; Suzuka, T.; Kawade, R.; Takenaka, H. *Synlett* **2006**, 2109.

(6) For studies on heterogeneous aquacatalytic asymmetric π-allylic transformations with polymer-supported complex catalysts in water, see: (a) Alkylation: Uozumi, Y.; Danjo, H.; Hayashi, T. *Tetrahedron Lett.* **1998**, *39*, 8303. (b) Reduction with monodentate phosphine (MOP): Hocke, H.; Uozumi, Y. *Tetrahedron* **2004**, *60*, 9297. (c) Alkylation: Uozumi, Y.; Shibatomi, K. *J. Am. Chem. Soc.* **2001**, *123*, 2919. (d) Amination: Uozumi, Y.; Tanaka, H.; Shibatomi, K. *Org. Lett.* **2004**, *6*, 281. (e) Cyclization: Nakai, Y.; Uozumi, Y. *Org. Lett.* **2005**, *7*, 291. (f) Etherification: Uozumi, Y.; Kimura, M. *Tetrahedron: Asymmetry* **2006**, *17*, 161. (g) Nitromethylation: Uozumi, Y.; Suzuka, T. *J. Org. Chem.* **2006**, *71*, 8644. (h) Kobayashi, Y.; Tanaka, D.; Danjo, H.; Uozumi, Y. *Adv. Synth. Catal.* **2006**, *348*, 1561. (i) Uozumi, Y. *Pure Appl. Chem.* **2007**, *79*, 1481.

(7) For recent reviews on asymmetric π-allylic substitution, see: (a) Acemoglu, L.; Williams, J. M. J. *Handbook of Organopalladium Chemistry for Organic Synthesis*; Negishi, E.; de Meijere, A., Eds.; Wiley: New York, **2002**. (b) Trost, B. M.; Crawley, M. L. *Chem. Rev.* **2003**, *103*, 2921.

(8) (a) Taniimori, S.; Tsuji, Y.; Kirihara, M. *Biosci., Biotechnol., Biochem.* **2002**, *66*, 660. (b) Song, E. S.; Yang, J. W.; Roh, E. J.; Lee, S.-G.; Han, H. *Angew. Chem. Int. Ed.* **2002**, *41*, 3852. (c) Trost, B. M.; Van Vranken, D. L.; Bingel, C. *J. Am. Chem. Soc.* **1992**, *114*, 9327.

(9) Trost B. M., Pulley S. R., Bingel C.; *Tetrahedron Lett.;* **1995**, *36*: 8737.

(10) Tenta Gel $SNH_2$ (purchased from Rapp Polymere) was used as the polymer support.

(11) Chemical yield of the monosubstituted product **4** was lowered to <30% with $Li_2CO_3$, $NaHCO_3$, $Na_2CO_3$, or $K_2CO_3$.

(12) The absolute configuration of **4** was determined by chemical correlation with (1*R*,4*S*)-*cis*-1-acetoxy-4-[bis(methoxycarbonyl)methyl]-2-cyclopentene (see ref. 8a).

(13) Nishiyama, H.; Sakata, N.; Sugimoto, H.; Motoyama, Y.; Wakita, H.; Nagase, H. *Synlett* **1998**, 930.

(14) The absolute configuration of **6a** was determined to be 1*R*,4*S* by measurement of the specific rotation (see, ref. 12). The configurations of **6b–g** were tentatively assigned on the basis of the mechanistic similarity of the asymmetric induction, as depicted in Table 1.

(15) **Palladium-Catalyzed Asymmetric Desymmetrization of *meso*-Cycloalkene-1,4-diacetate**: Reaction conditions and results are shown in Table 1. A typical procedure is given for the reaction with *cis*-1,4-diacetoxycyclopentene (*meso*-**2**) and phenol (**a**) in $H_2O$ (entry 3).

To a mixture of the catalyst **1** (89 mg, 0.025 mmol) and *meso*-**2** (92 mg, 0.5 mmol) in $H_2O$ (2.5 mL) was added phenol (48 mg, 0.5 mmol), and the mixture was shaken at 0 °C for 18 h. The reaction mixture was filtered and the recovered resin beads were rinsed with EtOAc (3 ×). The combined filtrate was dried over anhyd $Na_2SO_4$. The solvent was evaporated and the residue was chromatographed on silica gel (hexane–EtOAc, 10:1) to give 1-acetoxy-4-phenoxycyclopentene (**6a**; 70 mg, 64% yield) and 1,4-diphenoxycyclopentene (**8**; 18 mg). The enantiomeric excess was determined to be 99% ee by GC analysis using a chiral stationary phase capillary column (Cyclodex CB). Spectral and analytical data for compounds **6** are shown below, where the enantiomeric excesses were determined by GC (Cyclodex CB), unless otherwise noted: 1-Acetoxy-4-phenoxycyclopentene (**6a**): $[\alpha]_D^{23}$ +63.8 (*c* = 1.0, $CHCl_3$). $^1H$ NMR ($CDCl_3$): δ = 7.29 (t, *J* = 7.8 Hz, 2 H), 6.96 (t, *J* = 7.3 Hz, 1 H), 6.92 (d, *J* = 7.8 Hz, 2 H), 6.24 (d, *J* = 5.8 Hz, 1 H), 6.12 (d, *J* = 5.3 Hz, 1 H), 5.61 (br, 1 H), 5.17 (br, 1 H), 2.97 (dt, *J* = 7.3, 14.6 Hz, 1 H), 2.05 (s, 3 H), 1.89 (dt, *J* = 4.0, 14.6 Hz, 1 H). $^{13}C$ NMR ($CDCl_3$): δ = 170.77, 157.77, 135.05, 134.06, 129.53, 115.34, 79.55, 76.74, 37.94, 21.08. IR (ATR): 1733, 1493, 1366, 1228, 1087, 889, 754, 692, 628 $cm^{-1}$. MS (EI): *m*/*z* (%rel intensity) = 218 (0.7) [$M^+$], 43 (base peak). Anal. Calcd for $C_{13}H_{14}O_3$: C, 71.54; H, 6.47. Found: C, 71.49; H, 6.53. CAS registry number: 210701-09-0.

1-Acetoxy-4-(2-benzyloxyphenoxy)-2-cyclopentene (**6b**): $[\alpha]_D^{28}$ –20.5 (*c* = 1.0, $CHCl_3$); 97% ee. $^1H$ NMR ($CDCl_3$): δ = 7.43–7.27 (m, 4 H), 6.89–6.98 (m, 5 H), 6.26 (br d, *J* = 4.8 Hz, 1 H), 6.09 (br d, *J* = 4.8 Hz, 1 H), 5.57 (br, 1 H), 5.17 (br, 1 H), 5.12 (s, 2 H), 2.93 (dt, *J* = 7.3, 14.6 Hz, 1 H), 2.04 (s, 3 H), 1.98 (dt, *J* = 4.3, 14.6 Hz, 1 H). $^{13}C$ NMR ($CDCl_3$): δ = 170.88, 149.49, 148.28, 137.32, 134.67, 133.73, 128.45, 127.78, 127.29, 122.21, 121.70, 117.09, 115.60, 81.72, 76.79, 71.31, 38.08, 21.13. IR (ATR): 1732, 1499, 1452, 1366, 1236, 1212, 1083, 1012, 896, 742, 697, 627 $cm^{-1}$. MS (EI): *m*/*z* (%rel intensity) = 324 (1) [$M^+$], 91 (base peak). Anal Calcd for $C_{20}H_{20}O_4$: C, 74.06; H, 6.21. Found: C, 73.94; H, 6.28.

1-Acetoxy-4-(2-chlorophenoxy)-2-cyclopentene (**6c**): $[\alpha]_D^{26}$ –58.0 (*c* = 1.0, $CHCl_3$). $^1H$ NMR ($CDCl_3$): δ = 7.37 (dd, *J* = 1.8, 7.9 Hz, 1 H), 7.20 (dt, *J* = 1.8, 7.9 Hz, 1 H), 6.95 (d, *J* = 7.9 Hz, 1 H), 6.92 (t, *J* = 7.9 Hz, 1 H), 6.26 (d, *J* = 5.5 Hz, 1 H), 6.14 (*J* = 5.5 Hz, 1 H), 5.60 (br, 1 H), 5.17 (br, 1 H), 2.99 (dt, *J* = 7.3, 14.6 Hz, 1 H), 2.06 (s, 3 H), 1.96 (dt, *J* = 4.3, 14.6 Hz, 1 H). $^{13}C$ NMR ($CDCl_3$): δ = 170.84, 153.65, 134.65, 134.46, 130.57, 127.66, 123.71, 121.94, 115.26, 81.33, 76.61, 38.02, 21.11. IR (ATR): 1237, 1090, 902, 730, 649, 630 $cm^{-1}$. MS (EI): *m*/*z* (%rel intensity): = 252 (0.02) [$M^+$], 43 (base peak).

1-Acetoxy-4-(2-bromophenoxy)-2-cyclopentene (**6d**): $[\alpha]_D^{25}$ –100.8 (*c* = 1.1, $CHCl_3$); 95% ee. $^1H$ NMR ($CDCl_3$): δ = 7.55 (dd, *J* = 1.2, 7.9 Hz, 1 H), 7.25 (td, *J* = 1.2, 7.3 Hz, 1 H), 6.94 (d, *J* = 1.2 Hz, 1 H), 6.85 (td, *J* = 1.2, 7.9 Hz, 1 H), 6.26 (d, *J* = 5.5 Hz, 1 H), 6.14 (d, *J* = 5.5 Hz, 1 H), 5.60 (br t, *J* = 5.5 Hz, 1 H), 5.17 (br t, *J* = 5.5 Hz, 1 H), 2.07 (s, 3 H), 2.00 (dt, *J* = 7.3, 14.6 Hz, 1 H), 1.96 (dt, *J* = 4.2, 14.6 Hz, 1 H). $^{13}C$ NMR ($CDCl_3$): δ = 170.79, 154.52, 134.60, 134.39, 133.61, 128.37, 122.34, 114.99, 113.00, 81.34, 76.55, 38.00, 21.07. IR (ATR): 1733, 1584, 1573, 1474, 1442, 1366, 1085, 1029, 895, 748, 627 $cm^{-1}$. MS (EI): *m*/*z* (%rel intensity) = 296 (0.02) [$M^+$], 43 (base peak). Anal. Calcd for $C_{13}H_{13}BrO_3$: C, 52.55; H, 4.41. Found: C, 52.37; H, 4.37.

1-Acetoxy-4-(2,6-dimethylphenoxy)-2-cyclopentene (**6e**): $[\alpha]_D^{27}$ –41.4 (*c* = 1.1, $CHCl_3$). $^1H$ NMR ($CDCl_3$): δ = 7.02 (d, *J* = 7.3 Hz, 2 H), 6.92 (t, *J* = 7.3 Hz, 1 H), 6.16 (d, *J* = 5.4 Hz, 1 H), 6.05 (d, *J* = 5.4 Hz, 1 H), 5.52 (br t, *J* = 4.4 Hz, 1 H), 4.81 (br t, *J* = 6.3 Hz, 1 H), 2.88 (dt, *J* = 7.3, 14.6 Hz, 1 H), 2.30 (s, 6 H), 2.09 (s, 3 H), 2.06 (dt, *J* = 4.4, 14.6 Hz, 1 H). $^{13}C$ NMR ($CDCl_3$): δ = 171.09, 155.79, 136.60, 133.37, 131.06, 129.16, 123.95, 84.66, 76.73, 38.51, 21.39, 17.46. IR (ATR): 1730, 1365, 1237, 1198, 1091, 903, 730, 649, 630 $cm^{-1}$. MS (EI): *m*/*z* (%rel intensity) = 246 (0.09) [$M^+$], 43 (base peak). HRMS (EI): *m*/*z* [$M^+$] calcd for $C_{15}H_{18}O_3$: 246.1256; found: 246.1251. The enantiomeric excess was determined by HPLC analysis using a chiral stationary phase column [Chiralcel OD-H, eluent: *n*-hexane–2-propanol, 50:1; flow rate: 0.5 mL/min; $t_R$ (major isomer) = 14.73 min and $t_R$ (minor isomer) = 13.98 min] to be 90% ee.

1-Acetoxy-4-(3-methoxyphenoxy)-2-cyclopentene (**6f**): $[\alpha]_D^{26}$ +57.5 (*c* = 1.1, $CHCl_3$); 96% ee. $^1H$ NMR ($CDCl_3$): δ = 7.18 (t, *J* = 8.5 Hz, 1 H), 6.52 [td, *J* = 2.4, 8.5 Hz (overlapped), 2 H], 6.48 (t, *J* = 2.4 Hz, 1 H), 6.24 (d, *J* = 5.5 Hz, 1 H), 6.13 (d, *J* = 5.5 Hz, 1 H), 5.60 (br, 1 H), 5.16 (br, 1 H), 3.78 (s, 3 H), 2.96 (dt, *J* = 7.3, 14.6 Hz, 1 H), 2.05 (s,

3 H), 1.88 (dt, *J* = 3.9, 14.6 Hz, 1 H). $^{13}$C NMR ($CDCl_3$): δ = 170.77, 160.87, 158.99, 134.98, 134.12, 129.95, 107.35, 106.54, 101.88, 79.62, 55.24, 37.90, 21.04. IR (ATR): 1733, 1602, 1491, 1366, 1235, 1199, 1150, 1087, 1015, 891, 837, 765, 687, 629 cm$^{-1}$. MS (EI): *m*/*z* (%rel intensity) = 248 (1) [M$^+$], 43 (base peak). Anal. Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.50. Found: C, 67.51; H, 6.45.

1-Acetoxy-4-(4-*tert*-buthylphenoxy)-2-cyclopentene (**6g**): $[\alpha]_D^{27}$ +148.7 (*c* = 1.4, $CHCl_3$); 94% ee. $^1$H NMR ($CDCl_3$): δ = 7.30 (d, *J* = 8.5 Hz, 2 H), 6.85 (d, *J* = 8.5 Hz, 2 H), 6.24 (d, *J* = 5.5 Hz, 1 H), 6.11 (d, *J* = 5.5 Hz, 1 H), 5.60 (s, 1 H), 5.14 (s, 1 H), 2.96 (dt, *J* = 7.3, 14.6 Hz, 1 H), 2.05 (s, 3 H), 1.89 (dt, *J* = 3.9, 14.6 Hz, 1 H), 1.37 (s, 9 H). $^{13}$C NMR ($CDCl_3$): δ = 170.79, 155.51, 143.66, 135.25, 133.90, 126.30, 114.78, 79.61, 76.79, 37.98, 34.05, 31.48, 21.08. IR (ATR): 1736, 1511, 1365, 1232, 1185, 1087, 1013, 898, 829, 732, 630 cm$^{-1}$. MS (EI): *m*/*z* (%rel intensity) = 274 (0.2) [M$^+$], 43 (base peak). Anal. Calcd for $C_{17}H_{22}O_3$: C, 74.42; H, 8.08. Found: C, 74.56; H, 8.22.

1-Acetoxy-4-phenoxy-2-cyclohexene (**7**): $^1$H NMR ($CDCl_3$): δ = 7.26–7.31 (m, 2 H), 6.92–6.97 (m, 3 H), 6.08 (ddd, *J* = 1.2, 3.7, 10.0 Hz, 1 H), 6.07 (ddd, *J* = 1.2, 3.0, 10.0 Hz, 1 H), 5.25 (br s, 1 H), 4.76 (br s, 1 H), 2.07 (s, 3 H), 1.87–2.02 (m, 4 H). $^{13}$C NMR ($CDCl_3$): δ = 170.72, 157.52, 131.10, 129.59, 121.06, 115.84, 70.27, 67.38, 24.92, 24.75, 21.27. IR (ATR): 1730, 1597, 1492, 1371, 1226, 1079, 1035, 958, 903, 754, 692 cm$^{-1}$. MS (EI): *m*/*z* = 232 [M$^+$]. The enantiomeric excess was determined by HPLC analysis using a chiral stationary phase column [Chiralcel OD-H, eluent: *n*-hexane–2-propanol, 50:1; flow rate: 0.5 mL/min; $t_R$ (major isomer) = 21.33 min and $t_R$ (minor isomer) = 18.48 min] to be 95% ee.