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Synthesis, including asymmetric synthesis, of 3-oxabicyclo[3.1.0]hexanes and bicyclo[3.1.0]hexanes by the 1,5-CH insertion of cyclopropylmagnesium carbenoids as the key reaction

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ABSTRACT

The addition reactions of α,β-unsaturated carbonyl compounds with dichloromethyl *p*-tolyl sulfoxide in the presence of NaHMDS or LDA resulted in the formation of adducts, 1-chlorocyclopropyl *p*-tolyl sulfoxides bearing a carbonyl group at the 2-position, in almost quantitative yields. The carbonyl group of the adducts was transformed to various ether groups to give 1-chlorocyclopropyl *p*-tolyl sulfoxides bearing an ether functional group at the 2-position in short steps. Treatment of these products with *i*-PrMgCl at low temperature afforded cyclopropylmagnesium carbenoids via the sulfoxide-magnesium exchange reaction. 1,5-Carbon–hydrogen insertion (1,5-CH insertion) reaction of the generated magnesium carbenoid intermediates took place to give 3-oxabicyclo[3.1.0]hexanes or bicyclo[3.1.0]hexanes bearing an ether group at the 4-position in moderate to good yields. When this procedure was carried out starting with enantiopure dichloromethyl *p*-tolyl sulfoxide, enantiopure 3-oxabicyclo[3.1.0]hexanes were obtained in good overall yields. These procedures provide a good way for the synthesis, including asymmetric synthesis, of multisubstituted 3-oxabicyclo[3.1.0]hexanes and bicyclo[3.1.0]hexanes from α,β-unsaturated carbonyl compounds and dichloromethyl *p*-tolyl sulfoxide in short steps.

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1. Introduction

The carbon–hydrogen insertion (CH insertion) reaction[1] is one of the most striking reactions of carbenes and carbenoids.[2] This reaction enables the formation of a carbon–carbon bond between non-activated carbon and the carbene (or carbenoid) carbons. Recently, formation of a chemical bond to a non-activated carbon (functionalization of inert C–H bond) has been received considerable attention.[3]

Previously, we found that the magnesium carbenoids, generated from 1-chloroalkyl *p*-tolyl sulfoxides with Grignard regents via the sulfoxide-magnesium exchange reaction,[4] gave rise to 1,3-CH insertion to give cyclopropanes in good to high yields.[5] Highly stereospecific 1,3-CH insertion was observed in the reaction and asymmetric synthesis of bicyclo[n.1.0]alkanes with high optical purity was also realized.[6] In continuation of our interest in the CH insertion reaction of magnesium carbenoids in organic synthesis, we investigated the 1,5-CH insertion reaction of cyclopropylmagnesium carbenoids derived from 1-chlorocyclopropyl *p*-tolyl sulfoxides with Grignard reagents and indeed the reaction proceeded smoothly to give 3-oxabicyclo[3.1.0]hexanes in good yields.[7] We further investigated this chemistry and some new results were obtained.

In this paper, above-mentioned chemistry and development of the chemistry to the asymmetric synthesis of 3-oxabicyclo[3.1.0]hexanes are reported in detail (Scheme 1). Thus, the reaction of α,β-unsaturated carbonyl compounds **1** with dichloromethyl *p*-tolyl sulfoxide **2**[8] in the presence of a base afforded adducts **3** in high to quantitative yields as a single isomer. The carbonyl group in adducts **3** was converted into an ether group to give **4** in high overall yields in two steps. Treatment of **4** with *i*-PrMgCl in THF resulted in the formation of cyclopropylmagnesium carbenoids **5** instantaneously at −78 °C via the sulfoxide-magnesium exchange reaction.[4] Upon warming the temperature of the reaction mixture, the magnesium carbenoids **5** gave rise to the 1,5-CH insertion reaction smoothly to give 3-oxabicyclo[3.1.0]hexanes **6** in up to 89% yield.[9] Adducts **3** were easily converted into two-carbon homologated ether **7**, from which bicyclo[3.1.0]hexanes bearing an alkoxy group at the 4-position **8** were obtained in moderate yields. By starting this procedure with enantiopure dichloromethyl *p*-tolyl sulfoxide **2**, an asymmetric synthesis of enantiopure 3-oxabicyclo[3.1.0]hexanes **6** was realized.

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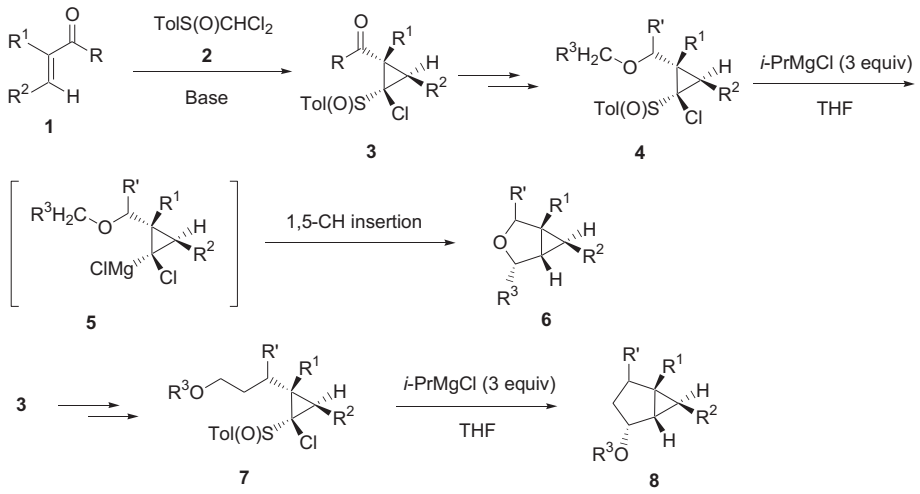


Scheme 1. Synthesis of 3-oxabicyclo[3.1.0]hexanes **6** and bicyclo[3.1.0]hexanes **8** from α,β-unsaturated carbonyl compounds **1** and dichloromethyl *p*-tolyl sulfoxide **2** by the 1,5-CH insertion reaction of cyclopropylmagnesium carbenoid intermediates **5**.

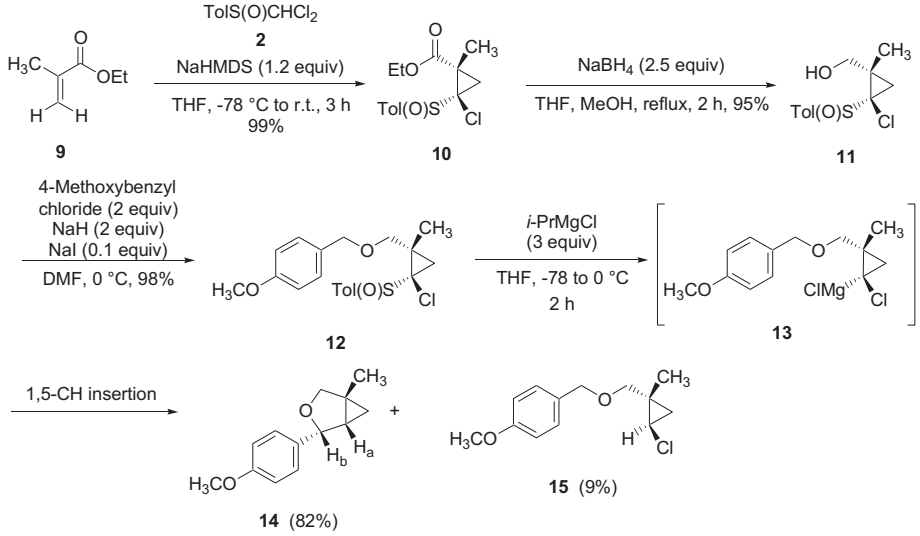
2. Results and discussion

2.1. Synthesis of 3-oxabicyclo[3.1.0]hexanes from α,β-unsaturated carbonyl compounds and dichloromethyl *p*-tolyl sulfoxide by the 1,5-CH insertion reaction of cyclopropylmagnesium carbenoids as the key reaction

We commenced our investigation with 1-chlorocyclopropyl *p*-tolyl sulfoxide bearing an ether group at the 2-position **12**. The synthesis of **12** is summarized in Scheme 2. Thus, to a solution of a mixture of ethyl methacrylate **9** and dichloromethyl *p*-tolyl sulfoxide **2**[8] in THF was added NaHMDS at −78 °C and the reaction mixture was slowly allowed to warm to room temperature to afford 1-chlorocyclopropyl *p*-tolyl sulfoxide bearing an ethoxycarbonyl group at the 2-position **10** in quantitative yield as a single isomer.[10] The ethoxycarbonyl group was reduced with $NaBH_4$ in a mixture of THF–methanol[11] to give alcohol **11** in 95% yield. Finally, the hydroxyl group was benzylated with 4-methoxybenzyl chloride under the conventional conditions to afford the desired ether **12** in 98% yield.

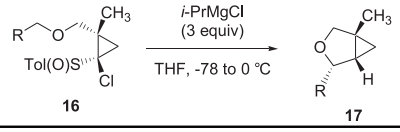
The key reactions, generation of cyclopropylmagnesium carbenoid and 1,5-CH insertion reaction, were investigated next. Based on our experiences for the generation of cyclopropylmagnesium carbenoids,[12] 1-chlorocyclopropyl *p*-tolyl sulfoxide **12** was treated with 2.5 equiv of *i*-PrMgCl in THF at −78 °C and the reaction mixture was slowly allowed to warm to room temperature. Gratifyingly, this reaction gave the desired 3-oxabicyclo[3.1.0]hexane **14** (78%) as a single isomer along with chlorocyclopropane **15** (the protonated product of the cyclopropylmagnesium carbenoid intermediate **13**; 7%). After some investigation to find the best conditions for these reactions, using 3 equiv of *i*-PrMgCl with warming from −78 to 0 °C over 2 h were proved to be the conditions of choice and **14** was obtained in 82% yield.[7] At the same time, the 1,5-CH insertion reaction was proved to proceed at around −20 °C.[7] Stereochemistry of the carbon bearing a 4-methoxyphenyl group of the product **14** was unambiguously determined as shown in Scheme 2 from the coupling constant (J=2.8 Hz) of the hydrogen on the bridgehead carbon (H_a) and the hydrogen on the carbon bearing the 4-methoxyphenyl group (H_b).[9b]

Generality of this procedure was investigated next with the substrates **16a**–**c** prepared from alcohol **11**, and the results are summarized in Table 1. As shown in entries 1 and 2, it is apparent that the 1,5-CH insertion reaction was not affected by the presence



Scheme 2. Synthesis of 3-oxabicyclo[3.1.0]hexane **14** from ethyl methacrylate **9** and dichloromethyl *p*-tolyl sulfoxide **2** via the 1,5-CH insertion reaction of cyclopropylmagnesium carbenoid intermediate **13**.

Table 1
Synthesis of 3-oxabicyclo[3.1.0]hexanes **17** by treatement of **16** with *i*-PrMgCl



16 17

Entry	16	R	17	Yield (%)
1	**16a**	F	**17a**	78
2	**16b**		**17b**	79
3	**16c**	CH_2CH_2	**17c**	89

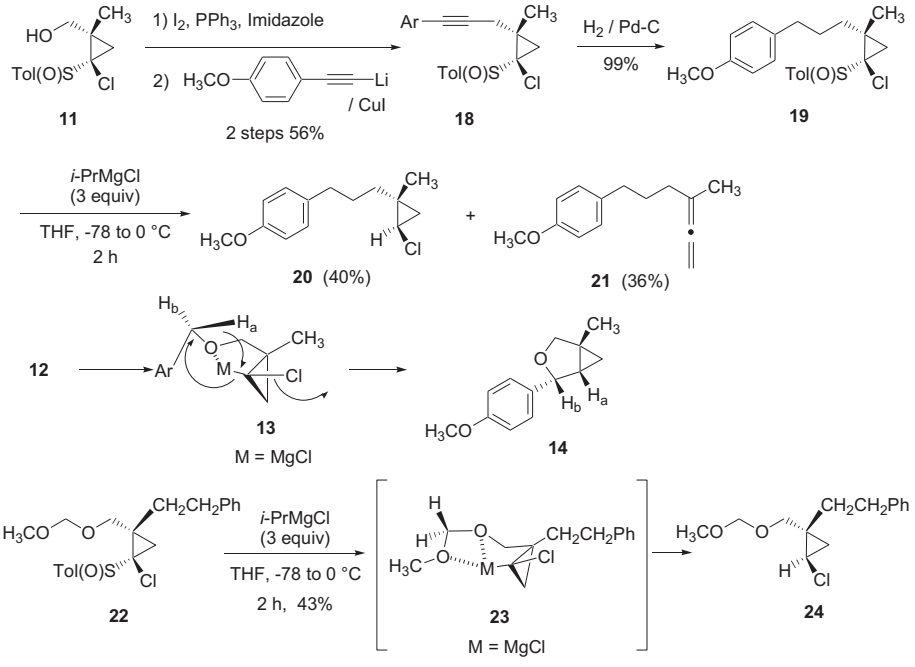
or absence of strong electron-withdrawing group on the aromatic ring at the *para* position. As shown in entry 3, 3-oxabicyclo[3.1.0] hexane bearing an alkyl group at the 4-position **17c** was obtained from the corresponding sulfoxide **16c** in high yield (89%). This result shows that the aromatic group as R is not essential for the 1,5-CH insertion reaction. From these results, generality of the 1,5-CH insertion reaction of the cyclopropylmagnesium carbenoids generated from 1-chlorocyclopropyl *p*-tolyl sulfoxides **16** was verified.

2.2. The mechanism and the role of the oxygen atom for the 1,5-CH insertion reaction

In order to clarify the mechanism and the role of the oxygen atom for the 1,5-CH insertion reaction, we synthesized 1-chlorocyclopropyl *p*-tolyl sulfoxide bearing methylene instead of the oxygen in the side chain at the 2-position of the cyclopropane ring (compound **19**) from alcohol **11** via acetylene **18** in conventional reactions as shown in Scheme 3. Quite interestingly, treatment of **19** with *i*-PrMgCl under the conditions described above gave chlorocyclopropane **20** (40%) and allene **21** (36%), and no trace of the desired bicyclo[3.1.0]hexane was observed.

Based on this result, we propose a plausible mechanism for the 1,5-CH insertion reaction of cyclopropylmagnesium carbenoid intermediate **13** as follows (Scheme 3). Thus, as the sulfoxide-magnesium exchange reaction is proved to take place with retention of the configuration at the carbon bearing the sulfinyl group,[13] the sulfoxide-magnesium exchange reaction of **12** must give cyclopropylmagnesium carbenoid intermediate **13**. The magnesium and the oxygen atom of the ether group are thought to make strong interaction to generate five-membered intermediate as shown in Scheme 3. In this intermediate, the hydrogen on the benzylic carbon (H_a) is located close to the backside of the chlorine atom of magnesium carbenoid carbon and the 1,5-CH insertion reaction exactly took place between C–H_a bond and the carbenoid carbon to give 3-oxabicyclo[3.1.0]hexane **14**. Thus, the interaction of the oxygen atom with the magnesium is thought to be essential to this 1,5-CH insertion reaction. As described above, the reaction of **19**, which has only methylene carbon in the side chain, with *i*-PrMgCl gave the cyclopropylmagnesium carbenoid intermediate; however, no 1,5-CH insertion reaction occurred. This result is the strong evidence for this mechanism.

We next synthesized 1-chlorocyclopropyl *p*-tolyl sulfoxide bearing an acetal group as the side chain **22** staring from 2-(2-phenylethyl)acrylic acid ethyl ester in a similar way described in Scheme 2. Protection of the hydroxyl group of the corresponding alcohol with chloromethyl methyl ether gave the desired **22** in good overall yield. Somewhat disappointingly, treatment of **22** with *i*-PrMgCl did not give any desired 3-oxabicyclo[3.1.0]hexane but chlorocyclopropane **24** in 43% yield. This result is also explained as follows. Thus, the sulfoxide-magnesium exchange reaction of **22** resulted in the formation of magnesium carbenoid intermediate **23**. The magnesium atom must interact with both oxygen atoms of the acetal group to give the fixed conformation as depicted in Scheme 3. In this conformation, the two hydrogens on the acetal carbon are too separated to react with the carbenoid carbon.

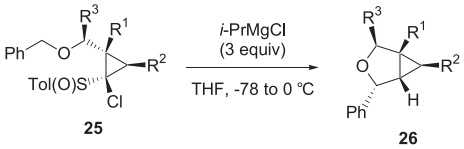


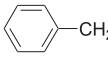
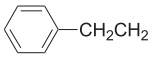
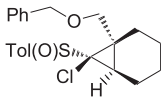
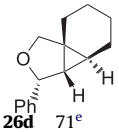
Scheme 3. A plausible mechanism and critical role of the oxygen atom for the 1,5-CH insertion reaction of cyclopropylmagnesium carbenoid intermediate **13**.

2.3. Synthesis of multisubstituted 3-oxabicyclo[3.1.0]hexanes

In order to extend this procedure to the synthesis of more substituted 3-oxabicyclo[3.1.0]hexanes **26**, 1-chlorocyclopropyl *p*-tolyl sulfoxides **25** were synthesized from α,β-disubstituted α,β-unsaturated carbonyl compounds in a similar way described in Scheme 2,[10] and the results are summarized in Table 2. Thus, **25a** was synthesized from tiglic acid ethyl ester, and **25b** was from (*E*)-4-methyl-2-(2-phenylethyl)pent-2-enoic acid ethyl ester. Synthesis of **25c** was commenced with (*E*)-4,6-dimethylhept-4-en-3-one and the adduct was reacted with $NaBH_4$[14] followed by benzyl bromide. Sulfoxide **25d** was synthesized from 1-cyclohexene-1-carboxylic acid benzyl ester in the same way as described for the synthesis of **25a** and **25b**.

Table 2
Synthesis of 3-oxabicyclo[3.1.0]hexanes **26** by treatment of **25** with *i*-PrMgCl



Entry	25				26	Yield (%)
		R^1	R^2	R^3		
1	**25a**[a]	CH_3	CH_3	H	**26a**	78
2	**25b**[b]		*i*-Pr	H	**26b**	48
3	**25c**[c]	CH_3		C_2H_5	**26c**	44
4	**25d**[d]				 **26d**	71[e]

[a] Prepared from tiglic acid ethyl ester.
[b] Prepared from (*E*)-4-methyl-2-(2-phenylethyl) pent-2-enoic acid ethyl ester.
[c] Prepared from (*E*)-4-methyl-7-phenylhept-4-en-3-one.
[d] Prepared from 1-cyclohexene-1-carboxylic acid benzyl ester.
[e] *i*-PrMgCl (5 equiv) was used.

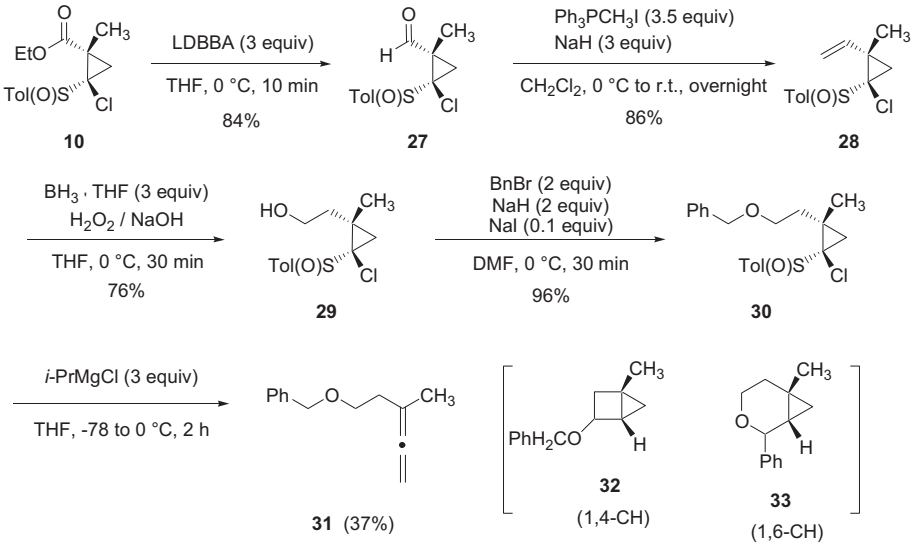
Treatment of **25a** and **25b** with *i*-PrMgCl gave the desired 1,4,6-trisubstituted 3-oxabicyclo[3.1.0]hexanes **26a** and **26b** in moderate to good yields (entries 1 and 2 in Table 2). From these results, it was anticipated that the substituents R^1 and R^2 on the cyclopropane ring have some effects on the 1,5-CH insertion reaction. On the contrary, the yield of **26c** was significantly diminished by the presence of a substituent R^3 (in this case ethyl group) on the side chain (entry 3). Quite interestingly, structurally complicated tricyclic compound **26d** was obtained from 1-cyclohexene-1-carboxylic acid benzyl ester in only four steps via **25d** without formation of diastereomers in good overall yield (entry 4).

2.4. Investigation for the 1,4-, 1,5-, 1,6-, and 1,7-CH insertion reactions: synthesis of bicyclo[3.1.0]hexanes bearing an alkoxy group at the 4-position

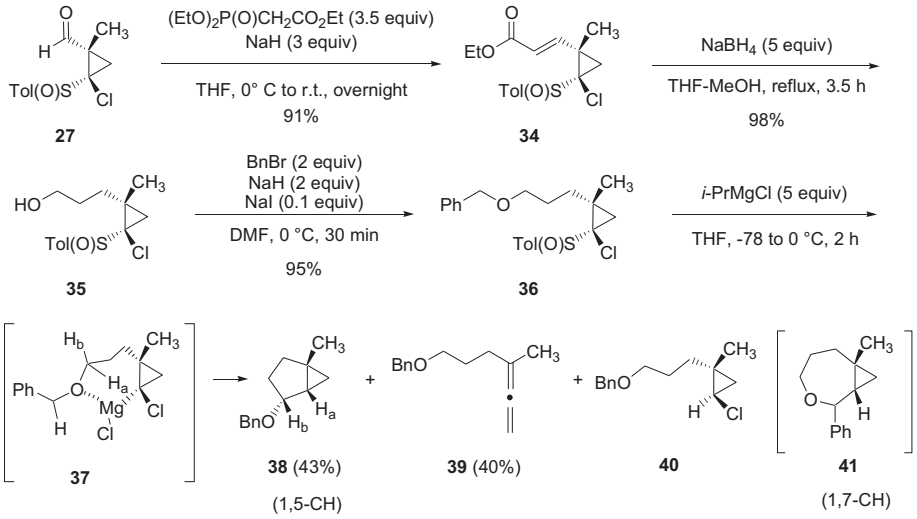
As described in the introduction, CH insertion reaction is very interesting and important reaction because it enables the formation of a carbon–carbon bond between non-activated carbon and a carbenoid carbon. In the course of our investigation reported above, we thought that there is a possibility for 1,*n*-CH insertion reaction of cyclopropylmagnesium carbenoids. We investigated this possibility by using 1-chlorocyclopropyl *p*-tolyl sulfoxides bearing a one-carbon homologated ether chain at the 2-position (compound **30** in Scheme 4; compare with compound **12** in Scheme 2) and two-carbon homologated compound (compound **36** in Scheme 5). Synthesis of these substrates and the reactions with *i*-PrMgCl are described hereinafter.

Compound **30** was synthesized from adduct **10** (Scheme 4). Thus, the ethyl ester **10** was reduced with LDBBA[15] in THF to give aldehyde **27** in good yield. Wittig olefination followed by hydroboration–oxidation of the aldehyde group of **27** gave alcohol **29** via olefin **28**. The hydroxyl group of **29** was benzylated with benzyl bromide (BnBr) to give the desired one-carbon homologated ether **30**. In expectation of producing 1,4-CH insertion product **32** or 1,6-CH insertion product **33**, 1-chlorocyclopropyl *p*-tolyl sulfoxide **30** was treated with *i*-PrMgCl under the conditions described above; however, disappointingly, only allene **31** (rearrangement product of the cyclopropylmagnesium carbenoid intermediate) was obtained in 37% yield. No cyclized product was obtained at all.

Two-carbon homologated compound **36** was synthesized from aldehyde **27** (Scheme 5). Thus, the Horner–Wadsworth–Emmons reaction of aldehyde **27** gave α,β-unsaturated ester **34** in high



Scheme 4.



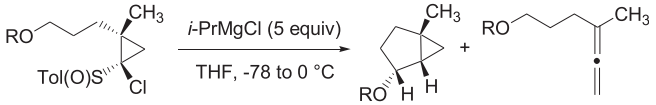
Scheme 5.

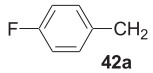
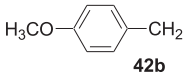
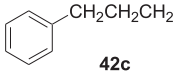
yield. The reaction of the α,β-unsaturated ester moiety with excess $NaBH_4$ resulted in the reduction of both the double bond and the ester group to afford saturated alcohol **35** in quantitative yield. Finally, the hydroxyl group of **35** was benzylated to give the desired two-carbon homologated ether **36**. In expectation of producing 1,5-CH insertion product **38** or 1,7-CH insertion product **41**, 1-chlorocyclopropyl *p*-tolyl sulfoxide **36** was treated with 5 equiv of *i*-PrMgCl under the conditions described above. This reaction gave the desired bicyclo[3.1.0]hexane bearing an alkoxy group at the 4-position **38** (43%) via the 1,5-CH insertion reaction along with allene **39** (40%) and chlorocyclopropane **40** (trace). The product from the 1,7-CH insertion reaction **41** was not observed at all.

Intermediate of this reaction is thought to be **37** as shown in Scheme 5. In this intermediate **37**, the magnesium interacts with the oxygen of the ether to give seven-membered ring, in which the benzylic hydrogen H_a is located close to the magnesium carbenoid carbon to give bicyclo[3.1.0]hexane bearing a benzyloxy group at the 4-position **38**. Stereochemistry of the carbon bearing a benzyloxy group of the product **38** was again unambiguously determined from the coupling constant (J=4.4 Hz) of the hydrogen on the bridgehead carbon (H_a) and the hydrogen on the carbon bearing the benzyloxy group (H_b).[9b]

Generality of this 1,5-CH insertion reaction giving bicyclo[3.1.0]hexanes was investigated using **42** as the substrates and the results are summarized in Table 3. 1-Chlorocyclopropyl *p*-tolyl sulfoxides **42** were synthesized from alcohol **35** with alkyl halides, TBDPSCl, and trityl chloride in conventional conditions. The reaction of **42a**–**c** with 5 equiv of *i*-PrMgCl gave the desired bicyclo[3.1.0]hexanes **43a**–**c** in up to 45% yield along with significant amount of allenes **44a**–**c**. Interestingly, TBDPS ether **42d** and trityl ether **42e** did not give the desired bicyclo[3.1.0]hexanes. This results imply that the 1,5-CH insertion reaction is hampered considerably by the steric hindrance of the ether group.

Table 3
Synthesis of bicyclo[3.1.0]hexanes **43** by treatment of **42** with *i*-PrMgCl

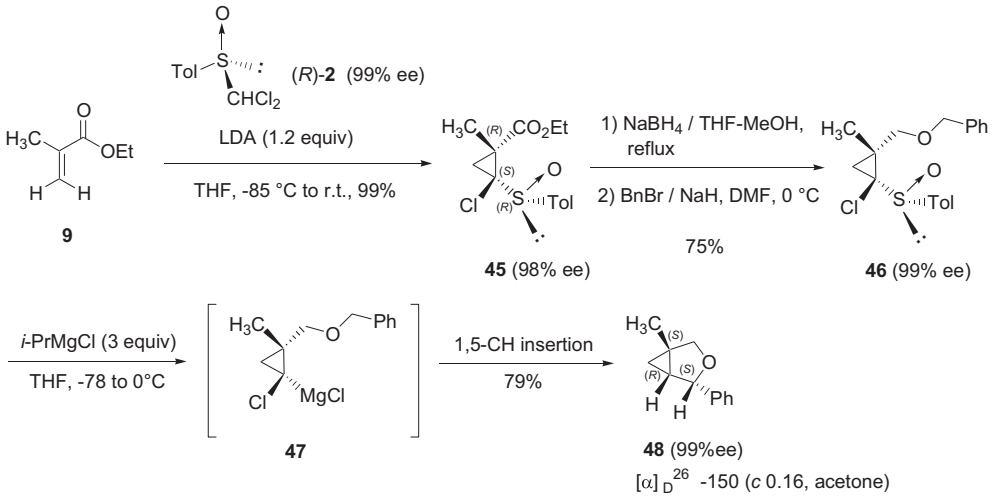


Entry	R	43	Yield (%)	44	Yield (%)
1	 **42a**	**43a**	40	**44a**	36
2	 **42b**	**43b**	45	**44b**	43
3	 **42c**	**43c**	43	**44c**	49
4	TBDPS **42d**		0	**44d**	34
5	Tr **42e**		0	**44e**	36

2.5. Asymmetric synthesis of enantiopure 3-oxabicyclo[3.1.0]hexanes

We recently reported the preparation of enantiopure aryl dichloromethyl sulfoxides[16] and application of these compounds to the asymmetric synthesis of enantiopure allenes.[14] As a further application of enantiopure aryl dichloromethyl sulfoxides in organic synthesis, we planed the asymmetric synthesis of 3-oxabicyclo[3.1.0]hexanes starting from α,β-unsaturated carbonyl compounds with enantiopure dichloromethyl *p*-tolyl sulfoxide (*R*)-**2**.

At first, to a solution of ethyl methacrylate **9** and enantiopure (*R*)-**2** in THF at −85 °C was added a solution of LDA and the temperature of the reaction mixture was slowly allowed to warm to room temperature (Scheme 6).[14,17] This reaction gave the desired (1*S*,2*R*,*Rs*)-1-chloro-2-ethoxycarbonyl-2-methylcyclopropyl *p*-tolyl sulfoxide **45** in quantitative yield and, as expected, the optical purity was proved to be 98% by HPLC with chiral stationary column. The absolute stereochemistry of **45** was determined on the basis of our previous work.[10] Ethyl ester group of **45** was reduced with $NaBH_4$, and the resultant hydroxyl group was benzylated with benzyl bromide to afford optically active ether **46** in 75% overall yield. Finally, treatment of **46** with *i*-PrMgCl under the conditions described above resulted in the formation of (1*S*,4*S*,5*R*)-1-methyl-4-phenyl-3-oxabicyclo[3.1.0]hexane **48** in 79% yield. Optical purity of the product **48** was proved to be over 99% by HPLC with chiral stationary column.



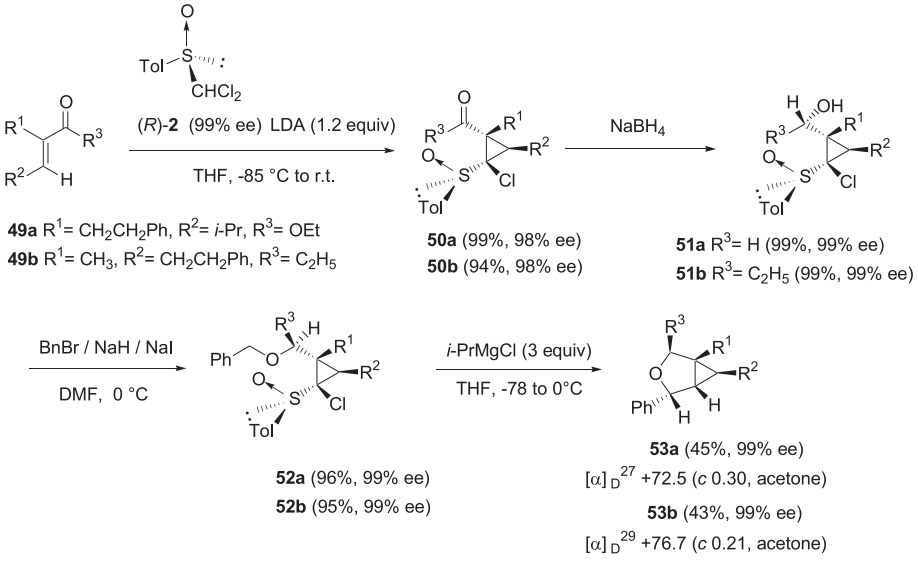
Scheme 6. Asymmetric synthesis of enantiopure (1*S*,4*S*,5*R*)-1-methyl-4-phenyl-3-oxabicyclo[3.1.0]hexane **48** from ethyl methacrylate and (*R*)-dichloromethyl *p*-tolyl sulfoxide (*R*)-**2**.

Further application of the procedure described above to the asymmetric synthesis of multisubstituted 3-oxabicyclo[3.1.0] hexanes was carried out with α,β-disubstituted α,β-unsaturated ester **49a** and ketone **49b** and the results are summarized in Scheme 7. The addition reaction of **49a** with (*R*)-**2** in the presence of LDA gave (1*R*,2*S*,3*R*,*Rs*)-1-chloro-2-ethoxycarbonyl-3-isopropyl-2-(2-phenylethyl)cyclopropyl *p*-tolyl sulfoxide **50a**[10] in quantitative yield with 98% ee. The same treatment of **49b** with (*R*)-**2** afforded (1*R*,2*S*,3*R*,*Rs*)-1-chloro-2-methyl-3-(2-phenylethyl)-2-propionylcyclopropyl *p*-tolyl sulfoxide **50b** in quantitative yield with 98% ee. The carbonyl groups in **50** were reduced to hydroxyl group,[18] which was benzylated to give **52a** and **52b** both in good overall yields. Finally, **52a** and **52b** were treated with 3 equiv of *i*-PrMgCl to give (1*R*,4*R*,5*S*,6*S*)-6-isopropyl-4-phenyl-1-(2-phenylethyl)-3-oxabicyclo[3.1.0]hexane **53a** and (1*R*,2*S*,4*R*,5*S*,6*S*)-2-ethyl-1-methyl-4-phenyl-6-(2-phenylethyl)-3-oxabicyclo[3.1.0]hexane **53b**, respectively, in moderate yield with high ee. As a result, multisubstituted 3-oxabicyclo[3.1.0] hexanes in high enantiomeric purity were synthesized from α,β-disubstituted α,β-unsaturated carbonyl compounds and enantiopure (*R*)-**2** in only four steps.

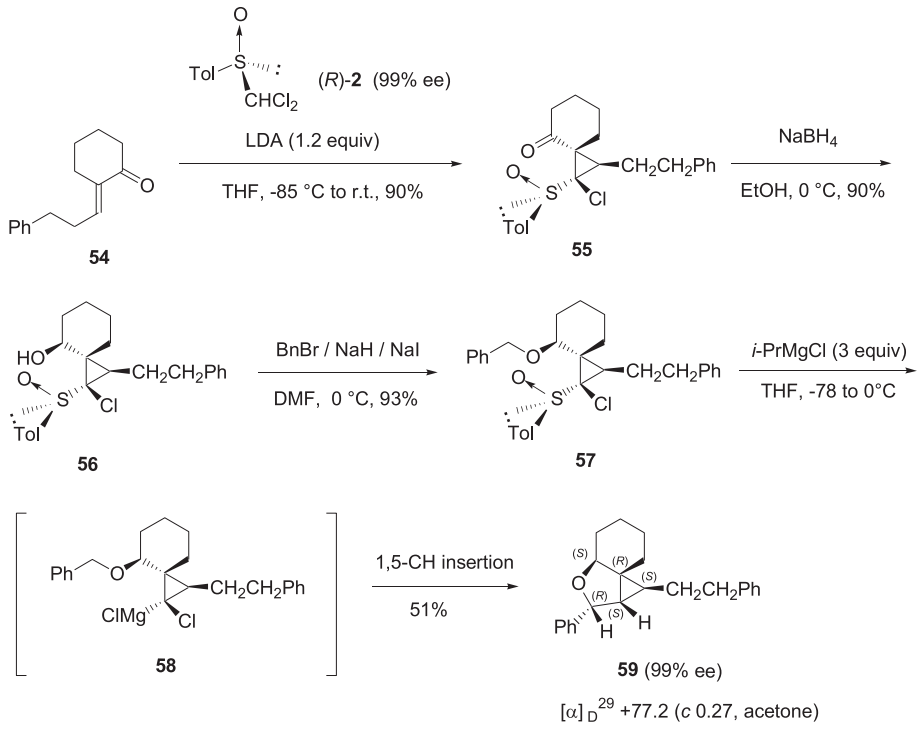
Finally, in Scheme 8, we would like to report the asymmetric synthesis of tricyclic compound bearing five stereogenic centers from (*E*)-2-(3-phenylpropylidene)cyclohexanone **54**. The addition reaction of **54** with (*R*)-**2** in the presence of LDA afforded the desired spiro-cyclopropyl sulfoxide **55** in 90% yield and the ee was found to be 99%. The ketone group was reduced with $NaBH_4$ to afford alcohol **56** in high yield. In order to confirm the absolute configuration and the stereochemistry of the hydroxyl group, X-ray crystallographic analysis of single crystal of racemic **56** was carried out, and the result was shown in Fig. 1.

Structurally confirmed alcohol **56** was benzylated with benzyl bromide under the conventional conditions to give ether **57**. Finally, **57** was treated with 3 equiv of *i*-PrMgCl under the conditions described above to give enantiopure (1*S*,3*R*,4*S*,5*S*,6*R*)-3-phenyl-5-(2-phenylethyl)-2-oxatricyclo[4.4.0.0^{4,6}]decane **59** in 51% yield.

In conclusion, we have developed a method for the synthesis of 3-oxabicyclo[3.1.0]hexanes and bicyclo[3.1.0]hexanes bearing an alkoxy group at the 4-position from various α,β-unsaturated carbonyl compounds and dichloromethyl *p*-tolyl sulfoxide **2** via the 1,5-CH insertion of cyclopropylmagnesium carbenoid intermediates as the key reaction in short steps. When the



Scheme 7. Asymmetric synthesis of multisubstituted 3-oxabicyclo[3.1.0]hexanes **53** from α,β-disubstituted α,β-unsaturated carbonyl compounds **49** with (*R*)-**2**.



Scheme 8. Asymmetric synthesis of (1*S*,3*R*,4*S*,5*S*,6*R*)-3-phenyl-5-(2-phenylethyl)-2-oxatricyclo[4.4.0.0^{4,6}]decane **59** from (*E*)-2-(3-phenylpropylidene)cyclohexanone **54** with (*R*)-**2**.

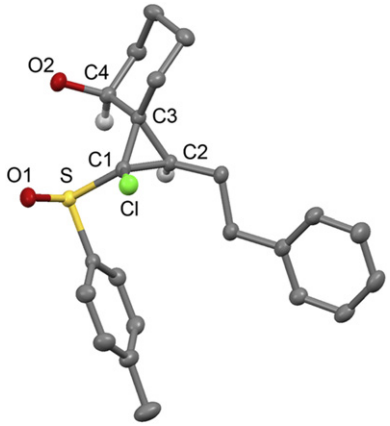


Fig. 1. ORTEP drawing of *rac*-**56** with thermal ellipsoids at the 50% probability level. Hydrogen atoms except those attached to C2 and C4 have been omitted for clarity. Selected bond lengths (Å) and angles (deg): C1–C2 1.5123(19); C2–C3 1.5190(19); C3–C1 1.5131(19); C1–C2–C3 59.89(9); C2–C3–C1 59.84(9); C3–C1–C2 60.28(9).

procedures were carried out starting from enantiopure **2**, asymmetric synthesis of 3-oxabicyclo[3.1.0]hexanes was realized. These procedures provide a good way for the synthesis, including asymmetric synthesis, of multisubstituted 3-oxabicyclo[3.1.0]hexanes from α,β-unsaturated carbonyl compounds. The chemistry presented here is unprecedented and would contribute to the chemistry of magnesium carbenoids.

3. Experimental

3.1. General

All melting points were measured on a Yanaco MP-S3 apparatus and are uncorrected. ^{1}H NMR spectra were measured in a $CDCl_3$ solution with JEOL JNM-LA 300, 500, Bruker DPX 400, and AV 600 spectrometer. Electron-impact mass spectra (MS) were obtained at 70 eV by direct insertion with HITACHI M-80B mass spectrometer. IR spectra were recorded on a Perkin–Elmer Spectrum One FTIR instrument. Silica gel 60 N (KANTO CHEMICAL) containing 0.5% fluorescence reagent 254 and a quartz column were used for column chromatography, and the products having UV absorption were detected by UV irradiation. In experiments requiring dry solvents and reagents, THF was distilled from diphenylketyl. Diisopropylamine was distilled from CaH_2. 1-Ethynyl-4-methoxybenzene was distilled before use. All reactions involving air- or water-sensitive compounds were routinely conducted in glassware, which was flame-dried under a positive pressure of argon. Sulfoxides **10**,[10] racemic **50b**,[10] and racemic **55**[10] are known compounds.

3.1.1. [(1R,2S*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]methanol (**11**).* Sodium borohydride (56.7 mg; 1.50 mmol) was added to a solution of **10** (150 mg; 0.500 mmol) in THF (3 mL) at room temperature, and the mixture was stirred under reflux for 5 min. Methanol (0.3 mL) was added dropwise to the resulting solution, and the mixture was stirred under reflux for 2 h. The reaction was quenched with satd aq NH_4Cl (5 mL), and the mixture was extracted with $CHCl_3$ (2×5 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **11** (52.0 mg; 0.48 mmol; 95%) as a colorless crystal; mp 117.0–117.5 °C (hexane/AcOEt); IR (KBr) 3326, 2986, 2901, 1499, 1096, 1031, 812 cm^{-1}; ^{1}H NMR δ 1.17 (d, *J*=7.2 Hz, 1H), 1.47 (s, 3H), 1.96 (d, *J*=7.2 Hz, 1H), 2.44 (s, 3H), 2.58–2.68 (m, 1H), 3.83 (dd, *J*=7.0, 11.9 Hz, 1H), 4.08 (dd, *J*=5.3, 11.9 Hz, 1H), 7.34 (d, *J*=8.1 Hz, 2H), 7.68 (d, *J*=8.1 Hz, 2H); Anal. Calcd for $C_{12}H_{15}ClO_2S$: C, 55.70; H, 5.84; Cl, 13.70; S, 12.39, found: C, 55.69; H, 5.78; Cl, 13.73; S, 12.44.

3.1.2. 1-({[(1R,2S*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]methoxy}methyl)-4-methoxybenzene (**12**).* Sodium hydride (55% oil suspension; 26.2 mg; 0.60 mmol) was added to a solution

of **11** (77.7 mg; 0.300 mmol), 4-methoxybenzyl chloride (104 mg; 0.600 mmol), and sodium iodide (4.50 mg; 0.0300 mmol) in DMF (3 mL) at 0 °C, and the mixture was stirred at that temperature for 30 min. The reaction was quenched with satd aq NH_4Cl (1 mL), and the mixture was extracted with benzene (2×1 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **12** (111 mg; 0.294 mmol; 98%) as a pale yellow oil; IR (neat) 2933, 2862, 1612, 1514, 1248, 1086, 813 cm^{-1}; ^1H NMR δ 1.30 (d, J=7.2 Hz, 1H), 1.45 (s, 3H), 1.95 (d, J=7.2 Hz, 1H), 2.40 (s, 3H), 3.67 (d, J=9.8 Hz, 1H), 3.82 (d, J=9.8 Hz, 1H), 3.82 (s, 3H), 4.49 (d, J=11.6 Hz, 1H), 4.51 (d, J=11.6 Hz, 1H), 6.88 (d, J=8.7 Hz, 2H), 7.27 (m, 4H), 7.68 (d, J=8.7 Hz, 2H); MS (EI) m/z (%) 378 (M^+, 0.2), 361 (8), 225 (32), 121 (100); HRMS (EI) calcd for $C_{20}H_{23}ClO_3S$: 378.1056, found: 378.1055.

3.1.3. (1R,4R*,5S*)-4-(4-Methoxyphenyl)-1-methyl-3-oxabicyclo [3.1.0]hexane (**14**).* A solution of isopropylmagnesium chloride in THF (2.0 mol/L; 0.15 mL; 0.30 mmol) was added dropwise to a solution of **12** (37.9 mg; 0.100 mmol) in THF (1 mL) at −78 °C. The mixture was allowed to warm to 0 °C over 2 h. The reaction was quenched with satd aq NH_4Cl (0.5 mL), and the mixture was extracted with $CHCl_3$ (2×3 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **14** (16.8 mg; 0.0822 mmol; 82%) as a colorless oil; IR (neat) 2956, 2836, 1614, 1513, 1247, 1173, 1087, 1034, 819 cm^{-1}; ^1H NMR δ 0.42 (m, 1H), 0.74 (m, 1H), 1.30 (s, 3H), 1.47 (m, 1H), 3.71 (d, J=8.1 Hz, 1H), 3.81 (s, 3H), 3.92 (d, J=8.1 Hz, 1H), 5.00 (d, J=2.8 Hz, 1H), 6.86 (d, J=8.8 Hz, 2H), 7.31 (d, J=8.8 Hz, 2H); MS (EI) m/z (%) 204 (M^+, 48), 175 (100), 149 (36), 147 (14), 135 (53), 121 (27), 108 (17); HRMS (EI) calcd for $C_{13}H_{16}O_2$: 204.1150, found: 204.1150.

3.1.4. 1-{[((1R,2S*)-2-Chloro-1-methylcyclopropyl)methoxy] methyl}-4-methoxybenzene (**15**).* Colorless oil; IR (neat) 2934, 2857, 1613, 1513, 1248, 1088, 1036, 821 cm^{-1}; ^1H NMR δ 0.60 (dd, J=4.1, 6.2 Hz, 1H), 1.04 (dd, J=6.2, 7.7 Hz, 1H), 1.29 (s, 3H), 3.03 (dd, J=4.1, 7.7 Hz, 1H), 3.20 (d, J=9.8 Hz, 1H), 3.31 (d, J=9.8 Hz, 1H), 3.80 (s, 3H), 4.40 (d, J=11.7 Hz, 1H), 4.44 (d, J=11.7 Hz, 1H), 6.88 (d, J=8.7 Hz, 2H), 7.23 (d, J=8.7 Hz, 2H); MS (EI) m/z (%) 240 (M^+, 7), 121 (100); HRMS (EI) calcd for $C_{13}H_{17}ClO_2$: 240.0917, found: 240.0914.

3.1.5. 1-({[(1R,2S*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]methoxy}methyl)-4-fluorobenzene (**16a**).* Yield (99%); colorless oil; IR (neat) 2930, 2866, 1603, 1514, 1222, 1054, 813, 760 cm^{-1}; ^1H NMR δ 1.30 (d, J=7.2 Hz, 1H), 1.47 (s, 3H), 1.97 (d, J=7.2 Hz, 1H), 2.41 (s, 3H), 3.72 (d, J=9.9 Hz, 1H), 3.86 (d, J=9.9 Hz, 1H), 4.51 (d, J=11.6 Hz, 1H), 4.56 (d, J=11.6 Hz, 1H), 7.04 (t, J=8.7 Hz, 2H), 7.25–7.37 (m, 4H), 7.67 (d, J=8.2 Hz, 2H); MS (EI) m/z (%) 366 (M^+, 0.1), 349 (0.2), 109 (100); HRMS (EI) calcd for $C_{19}H_{20}ClFO_2S$: 366.0857, found: 366.0858.

3.1.6. 1-{[(1R,2S*)-2-(Benzyloxymethyl)-1-chloro-2-methylcyclopropyl]sulfinyl}-4-methylbenzene (**16b**).* Yield (99%); colorless oil; IR (neat) 2930, 2863, 1495, 1455, 1363, 1087, 812 cm^{-1}; ^1H NMR δ 1.31 (d, J=7.1 Hz, 1H), 1.47 (s, 3H), 1.95 (d, J=7.1 Hz, 1H), 2.40 (s, 3H), 3.71 (d, J=10.0 Hz, 1H), 3.86 (d, J=10.0 Hz, 1H), 4.55 (d, J=11.8 Hz, 1H), 4.60 (d, J=11.8 Hz, 1H), 7.20–7.39 (m, 7H), 7.69 (d, J=8.2 Hz, 2H); MS (EI) m/z (%) 348 (M^+, 0.1), 331 (0.2), 91 (100); HRMS (EI) calcd for $C_{19}H_{21}ClO_2S$: 348.0951, found: 348.0950.

3.1.7. 1-({(1R,2S*)-1-Chloro-2-methyl-2-[(3-phenylpropoxy)methyl] cyclopropyl}sulfinyl)-4-methylbenzene (**16c**).* Yield (90%); colorless oil; IR (neat) 2932, 2864, 1496, 1455, 1112, 1065, 751 cm^{-1}; ^1H NMR δ 1.32 (d, J=7.1 Hz, 1H), 1.47 (s, 3H), 1.87–2.06 (m, 2H), 1.96 (d, J=7.1 Hz, 1H), 2.42 (s, 3H), 2.72 (t, J=7.0 Hz, 2H), 3.42–3.55 (m, 2H), 3.67 (d, J=10.0 Hz, 1H), 3.78 (d, J=10.0 Hz, 1H), 7.12–7.36 (m, 7H), 7.74 (d, J=8.2 Hz, 2H); MS (EI) m/z (%) 376 (M^+, 1), 359 (1), 119 (34), 91 (100); HRMS (EI) calcd for $C_{21}H_{25}ClO_2S$: 376.1264, found: 376.1263.

3.1.8. (1R,4R*,5S*)-4-(4-Fluorophenyl)-1-methyl-3-oxabicyclo[3.1.0] hexane (**17a**).* Colorless oil; IR (neat) 2958, 2845, 1608, 1510, 1221, 1086, 1033, 823 cm^{-1}; ^1H NMR δ 0.42 (dd, J=4.4, 7.6 Hz, 1H), 0.68 (t, J=4.4 Hz, 1H), 1.31 (s, 3H), 1.49 (ddd, J=2.9, 4.4, 7.6 Hz, 1H), 3.73 (d, J=8.2 Hz, 1H), 3.93 (d, J=8.2 Hz, 1H), 5.02 (d, J=2.9 Hz, 1H), 7.01 (t, J=8.6 Hz, 2H), 7.34 (dd, J=5.5, 8.6 Hz, 2H); MS (EI) m/z (%) 192 (M^+, 52), 191 (31), 174 (23), 163 (82), 146 (23), 135 (65), 123 (100), 109 (79), 95 (31), 68 (18), 67 (24), 53 (13); HRMS (EI) calcd for $C_{12}H_{13}FO$: 192.0950, found: 192.0950.

3.1.9. (1R,4R*,5S*)-1-Methyl-4-phenyl-3-oxabicyclo[3.1.0]hexane (**17b**).* Colorless oil; IR (neat) 2926, 2854, 1733, 1455, 1093, 1032, 698 cm^{-1}; ^1H NMR δ 0.41 (dd, J=4.7, 7.7 Hz, 1H), 0.72 (t, J=4.7 Hz, 1H), 1.31 (s, 3H), 1.52 (ddd, J=2.9, 4.7, 7.7 Hz, 1H), 3.74 (d, J=8.2 Hz, 1H), 3.95 (d, J=8.2 Hz, 1H), 5.56 (d, J=2.9 Hz, 1H), 7.24–7.44 (m, 5H); MS (EI) m/z (%) 174 (M^+, 61), 145 (81), 117 (59), 105 (100), 91 (59), 77 (35); HRMS (EI) calcd for $C_{12}H_{14}O$: 174.1045, found: 174.1047.

3.1.10. (1R,4S*,5S*)-1-Methyl-4-(2-phenylethyl)-3-oxabicyclo[3.1.0] hexane (**17c**).* Colorless oil; IR (neat) 2928, 2840, 1604, 1497, 1455, 1091, 1033, 699 cm^{-1}; ^1H NMR δ 0.34 (dd, J=4.3, 7.7 Hz, 1H), 0.61 (t, J=4.3 Hz, 1H), 1.19 (ddd, J=2.9, 4.3, 7.7 Hz, 1H), 1.23 (s, 3H), 1.66–1.80 (m, 1H), 1.80–1.95 (m, 1H), 2.60–2.79 (m, 2H), 3.53 (d, J=8.2 Hz, 1H), 3.75 (d, J=8.2 Hz, 1H), 3.97 (dt, J=2.9, 6.5 Hz, 1H), 7.14–7.33 (m, 5H); MS (EI) m/z (%) 202 (M^+, 22), 97 (81), 91 (100), 41 (37); HRMS (EI) calcd for $C_{14}H_{18}O$: 202.1358, found: 202.1355.

3.1.11. 1-{3-[(1R,2R*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]prop-1-ynyl}-4-methoxybenzene (**18**).* Imidazole (264 mg; 3.00 mmol) was added to a solution of **11** (389 mg; 1.50 mmol), triphenylphosphine (788 mg; 3.00 mmol), and iodine (762 mg; 3.00 mmol) in $CHCl_3$ (1.5 mL) at 0 °C, and the mixture was stirred at room temperature for 5 min. The reaction was quenched with satd aq Na_2SO_3 (10 mL), and the mixture was extracted with $CHCl_3$ (2×3 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give 1-{[(1*R**,2*R**)-1-chloro-2-(iodomethyl)-2-methylcyclopropyl]sulfinyl}-4-methylbenzene (504 mg) as a colorless crystal. A solution of BuLi in hexane (1.67 mol/L; 1.88 mL; 3.1 mmol) was added to a solution of 1-ethynyl-4-methoxybenzene (415 mg; 3.14 mmol) and copper(I) iodide (19.0 mg; 0.100 mmol) in THF (12.9 mL) at 0 °C, and the mixture was stirred at that temperature for 10 min. A solution of 1-{[(1*R**,2*R**)-1-chloro-2-(iodomethyl)-2-methylcyclopropyl]sulfinyl}-4-methylbenzene (504 mg; 1.37 mmol) in THF (0.8 mL) was added to the resulting solution at −78 °C. The mixture was allowed to warm to room temperature over 2.5 h, and the mixture was stirred at that temperature overnight. The reaction was quenched with satd aq NH_4Cl (7 mL), and the mixture was extracted with $CHCl_3$ (2×7 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **18** (343 mg; 0.920 mmol; 56% yield for two steps) as a pale yellow crystal; mp 126.5–127.0 °C (hexane/AcOEt); IR (KBr) 2964, 2926, 1509, 1245, 1059, 827, 714 cm^{-1}; ^1H NMR δ 1.32 (d, J=7.3 Hz, 1H), 1.55 (s, 3H), 2.03 (d, J=7.3 Hz, 1H), 2.41 (s, 3H), 2.93 (d, J=17.2 Hz, 1H), 3.05 (d, J=17.2 Hz, 1H), 3.83 (s, 3H), 6.85 (d, J=8.9 Hz, 2H), 7.28 (d, J=8.2 Hz, 2H), 7.37 (d, J=8.9 Hz, 2H), 7.71 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 373 ([M+H]$^+$,

11), 233 (21), 135 (100); HRMS (FAB$^+$) calcd for $C_{21}H_{22}ClO_2S$: 373.1029, found: 373.1031.

3.1.12. 1-{3-[(1R,2R*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]propyl}-4-methoxybenzene (**19**).* Pd/C (20% wt; 28.0 mmg; 0.053 mmol) was added to a solution of **18** (112 mg; 0.300 mmol) in THF (0.75 mL) at room temperature, and the mixture was stirred at that temperature under H_2 atmosphere (1 atm; balloon) overnight. The mixture was passed through a pad of Celite®545, and the filtrate was concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **19** (112 mg; 0.297 mmol; 99%) as a colorless crystal; mp 64.0–64.5 °C (hexane/AcOEt); IR (KBr) 2935, 2917, 1610, 1513, 1250, 1055, 805 cm^{-1}; ^{1}H NMR δ 1.21 (d, J=6.9 Hz, 1H), 1.31 (s, 3H), 1.69–1.92 (m, 5H), 2.43 (s, 3H), 2.62 (t, J=6.9 Hz, 2H), 3.80 (s, 3H), 6.85 (d, J=8.6 Hz, 2H), 7.11 (d, J=8.6 Hz, 2H), 7.32 (d, J=8.2 Hz, 2H), 7.53 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 377 ([M+H]$^+$, 80), 201 (18), 147 (16), 121 (100), 93 (20); HRMS (FAB$^+$) calcd for $C_{21}H_{26}ClO_2S$: 377.1342, found: 377.1343.

3.1.13. 1-[3-((1R,2R*)-2-Chloro-1-methylcyclopropyl)propyl]-4-methoxybenzene (**20**).* Colorless oil; IR (neat) 2933, 2856, 1612, 1513, 1461, 1301, 1246, 1177, 1036, 830 cm^{-1}; ^{1}H NMR δ 0.52 (dd, J=4.0, 6.1 Hz, 1H), 0.83 (dd, J=6.1, 7.5 Hz, 1H), 1.18–1.30 (m, 5H), 1.67 (quint, J=7.9 Hz, 2H), 2.48–2.56 (m, 2H), 2.84 (dd, J=4.0, 7.5 Hz, 1H), 3.79 (s, 3H), 6.82 (d, J=8.7 Hz, 2H), 7.07 (d, J=8.7 Hz, 2H); MS (EI) m/z (%) 238 (M$^+$, 19), 176 (16), 147 (51), 134 (22), 121 (100), 91 (10); HRMS (EI) calcd for $C_{14}H_{19}ClO$: 238.1124, found: 238.1123.

*3.1.14. 1-Methoxy-4-(4-methylhexa-4,5-dienyl)benzene (**21**).* Colorless oil; IR (neat) 2935, 2857, 1959, 1612, 1513, 1442, 1300, 1246, 1177, 1039, 844 cm^{-1}; ^{1}H NMR δ 1.65–1.78 (m, 5H), 1.89–2.00 (m, 2H), 2.57 (t, J=7.6 Hz, 2H), 3.78 (s, 3H), 4.60 (sextet, J=3.2 Hz, 2H), 6.82 (d, J=8.7 Hz, 2H), 7.10 (d, J=8.7 Hz, 2H); MS (EI) m/z (%) 202 (M$^+$, 21), 134 (100), 121 (33); HRMS (EI) calcd for $C_{14}H_{18}O$: 202.1358, found: 202.1355.

3.1.15. 1-({(1R,2S*)-1-Chloro-2-[(methoxymethoxy)methyl]-2-(2-phenylethyl)cyclopropyl}sulfinyl)-4-methylbenzene (**22**).* Yield (71%); colorless oil; IR (neat) 2928, 1496, 1455, 1092, 1040, 700 cm^{-1}; ^{1}H NMR δ 1.36 (d, J=7.3 Hz, 1H), 1.94–2.08 (m, 2H), 2.14 (ddd, J=6.8, 10.9, 14.1 Hz, 1H), 2.43 (s, 3H), 2.62–2.82 (m, 2H), 3.44 (s, 3H), 3.88 (d, J=10.6 Hz, 1H), 4.03 (d, J=10.6 Hz, 1H), 4.71 (s, 2H), 7.10–7.39 (m, 5H), 7.34 (d, J=8.2 Hz, 2H), 7.68 (d, J=8.2 Hz, 2H); MS (EI) m/z (%) 392 (M$^+$, 0.3), 295 (15), 184 (26), 139 (25), 91 (74), 45 (100); HRMS (EI) calcd for $C_{21}H_{25}ClO_3S$: 392.1213, found: 392.1212.

3.1.16. (2-{(1R,2S*)-2-Chloro-1-[(methoxymethoxy)methyl]cyclopropyl}ethyl)benzene (**24**).* Colorless oil; IR (neat) 2930, 1454, 1150, 1108, 1047, 699 cm^{-1}; ^{1}H NMR δ 0.67 (dd, J=4.2, 6.3 Hz, 1H), 1.07 (dd, J=6.3, 7.6 Hz, 1H), 1.86–2.04 (m, 2H), 2.73 (ddd, J=7.1, 10.0, 17.2 Hz, 1H), 2.87 (ddd, J=6.8, 10.0, 17.2 Hz, 1H), 3.13 (dd, J=4.2, 7.6 Hz, 1H), 3.38 (s, 3H), 3.38 (d, J=10.4 Hz, 1H), 3.50 (d, J=10.4 Hz, 1H), 4.60 (d, J=7.2 Hz, 1H), 4.62 (d, J=7.2 Hz, 1H), 7.12–7.34 (m, 5H); MS (FAB$^+$) m/z (%) 277 ([M+Na]$^+$, 7), 193 (14), 157 (49), 129 (31), 91 (100), 45 (53); HRMS (FAB$^+$) calcd for $C_{14}H_{19}ClNaO_2$: 277.0971, found: 277.0972.

3.1.17. 1-{[(1R,2S*,3R*)-2-(Benzyloxymethyl)-1-chloro-2,3-dimethylcyclopropyl]sulfinyl}-4-methylbenzene (**25a**).* Yield (97%); colorless oil; IR (neat) 2931, 2864, 1496, 1455, 1086, 1059, 813 cm^{-1}; ^{1}H NMR δ 1.18 (d, J=6.4 Hz, 3H), 1.27 (s, 3H), 2.01 (q, J=6.4 Hz, 1H), 2.40 (s, 3H), 3.70 (d, J=9.8 Hz, 1H), 3.83 (d, J=9.8 Hz, 1H), 4.53 (d, J=11.8 Hz, 1H), 4.60 (d, J=11.8 Hz, 1H), 7.23 (d, J=8.2 Hz, 2H), 7.28–7.41 (m, 5H), 7.67 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 363 ([M+H]$^+$, 43), 255 (6), 231 (7), 198 (3), 154 (2), 139 (22), 91 (100), 77 (3); HRMS (FAB$^+$) calcd for $C_{20}H_{24}ClO_2S$: 363.1187, found: 363.1189.

3.1.18. 1-{[(1R,2S*,3R*)-2-(Benzyloxymethyl)-1-chloro-3-isopropyl-2-(2-phenylethyl)cyclopropyl]sulfinyl}-4-methylbenzene (**25b**).* Yield (99%); colorless oil; IR (neat) 2964, 2869, 1601, 1454, 1090, 1064, 699 cm^{-1}; ^{1}H NMR δ 0.49 (d, J=6.5 Hz, 3H), 0.97 (d, J=6.5 Hz, 3H), 1.34 (d, J=10.5 Hz, 1H), 1.56–1.73 (m, 2H), 2.22 (ddd, J=6.5, 11.3, 14.0 Hz, 1H), 2.42 (s, 3H), 2.64–2.83 (m, 2H), 3.77 (d, J=10.0 Hz, 1H), 4.04 (d, J=10.0 Hz, 1H), 4.58 (d, J=12.2 Hz, 1H), 4.65 (d, J=12.2 Hz, 1H), 7.13–7.26 (m, 4H), 7.27–7.47 (m, 8H), 7.56 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 481 ([M+H]$^+$, 31), 233 (10), 139 (14), 91 (100); HRMS (FAB$^+$) calcd for $C_{29}H_{34}ClO_2S$: 481.1968, found: 481.1968.

3.1.19. 1-({(1R,2S*,3R*)-2-[(S*)-1-(Benzyloxy)propyl]-1-chloro-2-methyl-3-(2-phenylethyl)cyclopropyl}sulfinyl)-4-methylbenzene (**25c**).* Yield (99%); colorless crystal; mp 142.5–143.0 °C (hexane/AcOEt); IR (KBr) 2967, 2932, 1599, 1495, 1455, 1087, 1059, 747 cm^{-1}; ^{1}H NMR δ 1.05 (t, J=7.4 Hz, 3H), 1.21 (t, J=6.9 Hz, 1H), 1.25 (s, 3H), 1.39–1.57 (m, 2H), 1.63–1.94 (m, 2H), 2.12 (ddd, J=6.1, 10.4, 14.0 Hz, 1H), 2.35 (ddd, J=5.7, 10.4, 14.0 Hz, 1H), 2.42 (s, 3H), 3.61 (dd, J=4.1, 9.0 Hz, 1H), 4.61 (d, J=11.4 Hz, 1H), 4.79 (d, J=11.4 Hz, 1H), 7.09 (d, J=7.2 Hz, 2H), 7.15–7.25 (m, 2H), 7.26–7.38 (m, 6H), 7.48 (d, J=7.2 Hz, 2H), 7.55 (d, J=8.2 Hz, 2H); ^{13}C NMR δ 10.4, 11.3, 21.6, 25.4, 26.4, 27.6, 34.3, 37.5, 71.6, 73.3, 82.0, 125.8, 126.2, 127.4, 127.9, 128.1, 128.2, 128.5, 129.5, 137.9, 138.8, 140.1, 142.3; MS (FAB$^+$) m/z (%) 481 ([M+H]$^+$, 13), 373 (9), 233 (17), 139 (42), 91 (100); HRMS (FAB$^+$) calcd for $C_{29}H_{34}ClO_2S$: 481.1968, found: 481.1967.

3.1.20. (1R,6S*,7S*)-1-(Benzyloxymethyl)-7-chloro-7-(p-tolylsulfinyl)bicyclo[4.1.0]heptane (**25d**).* Yield (78%); colorless oil; IR (neat) 2942, 2857, 1494, 1454, 1091, 1064, 698 cm^{-1}; ^{1}H NMR δ 1.19–1.52 (m, 5H), 1.74 (dd, J=1.6, 8.5 Hz, 1H), 1.76–1.99 (m, 2H), 2.04–2.21 (m, 1H), 2.41 (s, 3H), 3.79 (d, J=10.0 Hz, 1H), 3.84 (d, J=10.0 Hz, 1H), 4.58 (d, J=12.2 Hz, 1H), 4.62 (d, J=12.2 Hz, 1H), 7.28–7.44 (m, 7H), 7.51 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 389 ([M+H]$^+$, 100), 281 (9), 185 (10), 154 (14), 139 (17), 136 (11), 123 (5), 107 (6), 91 (53), 77 (5); HRMS (FAB$^+$) calcd for $C_{22}H_{26}ClO_2S$: 389.1342, found: 389.1340.

3.1.21. (1R,4R*,5S*,6S*)-1,6-Dimethyl-4-phenyl-3-oxabicyclo[3.1.0]hexane (**26a**).* Colorless oil; IR (neat) 2954, 2842, 1451, 1055, 1021, 698 cm^{-1}; ^{1}H NMR δ 0.94–1.05 (m, 4H), 1.16 (t, J=3.1 Hz, 1H), 1.26 (s, 3H), 3.74 (d, J=8.2 Hz, 1H), 3.90 (d, J=8.2 Hz, 1H), 5.03 (d, J=2.9 Hz, 1H), 7.21–7.42 (m, 5H); MS (EI) m/z (%) 188 (M$^+$, 50), 173 (35), 131 (83), 120 (63), 105 (100), 91 (61), 82 (62), 77 (46), 67 (83), 41 (35); HRMS (EI) calcd for $C_{13}H_{16}O$: 188.1201, found: 188.1202.

3.1.22. (1R,4R*,5S*,6S*)-6-Isopropyl-1-(2-phenylethyl)-4-phenyl-3-oxabicyclo[3.1.0]hexane (**26b**).* Colorless oil; IR (neat) 2956, 2864, 1604, 1454, 1052, 698 cm^{-1}; ^{1}H NMR δ 0.74–0.84 (m, 4H), 0.99 (d, J=6.6 Hz, 3H), 1.15–1.31 (m, 2H), 1.86–2.05 (m, 2H), 2.68 (ddd, J=7.2, 10.3, 16.8 Hz, 1H), 2.87 (ddd, J=6.8, 10.3, 16.8 Hz, 1H), 3.90 (d, J=8.2 Hz, 1H), 3.94 (d, J=8.2 Hz, 1H), 4.95 (d, J=2.8 Hz, 1H), 7.17–7.25 (m, 4H), 7.26–7.40 (m, 6H); MS (EI) m/z (%) 306 (M$^+$, 60), 263 (39), 249 (31), 159 (38), 129 (20), 117 (22), 105 (67), 91 (100); HRMS (EI) calcd for $C_{22}H_{26}O$: 306.1984, found: 306.1979.

3.1.23. (1R,2S*,4R*,5S*,6S*)-2-Ethyl-1-methyl-6-(2-phenylethyl)-4-phenyl-3-oxabicyclo[3.1.0]hexane (**26c**).* Colorless oil; IR (neat) 2929, 2875, 1604, 1495, 1453, 1099, 698 cm^{-1}; ^{1}H NMR δ 0.94–1.07 (m, 4H), 1.17 (s, 3H), 1.25 (t, J=3.3 Hz, 1H), 1.43–1.73 (m, 4H), 2.41–2.62 (m, 2H), 3.81 (dd, J=3.4, 9.8 Hz, 1H), 5.05 (d, J=2.7 Hz, 1H), 6.96–7.04 (m, 2H), 7.09–7.41 (m, 8H); ^{13}C NMR δ 10.6, 10.7, 22.8, 25.1, 30.3, 30.9, 35.2, 36.0, 78.0, 85.8, 125.7, 126.4, 127.1, 128.1,

128.2, 128.5, 141.2, 142.3; MS (EI) *m/z* (%) 306 (M^+, 25), 277 (23), 117 (35), 91 (100), 77 (13), 57 (13); HRMS (EI) calcd for $C_{22}H_{26}O$: 306.1984, found: 306.1988.

3.1.24. (1R,4R*,5S*,6S*)-4-Phenyl-3-oxatricyclo[4.4.0.0^{1,5}]decane (**26d**).* *i*-PrMgCl (5 equiv) was used. Colorless oil; IR (neat) 2926, 2850, 1450, 1061, 1028, 698 cm^{-1}; ^1H NMR δ 1.05–1.12 (m, 1H), 1.16–1.32 (m, 3H), 1.36–1.50 (m, 3H), 1.66–1.97 (m, 3H), 3.75 (d, *J*=8.1 Hz, 1H), 3.92 (d, *J*=8.1 Hz, 1H), 5.02 (d, *J*=3.0 Hz, 1H), 7.21–7.41 (m, 5H); ^{13}C NMR δ 15.7, 22.1, 22.5, 23.0, 23.2, 28.3, 33.1, 74.9, 81.4, 126.4, 127.2, 128.1, 140.9; MS (EI) *m/z* (%) 214 (M^+, 89), 171 (21), 157 (42), 120 (59), 105 (100), 91 (57), 77 (48); HRMS (EI) calcd for $C_{15}H_{18}O$: 214.1358, found: 214.1360.

3.1.25. (1R,2S*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropanecarbaldehyde (**27**).* Lithium diisobutyl-*tert*-butoxyaluminum hydride (LDBBA) was prepared according to the procedure described in the literature.[15] A solution of BuLi in hexane (1.67 mol/L; 1.31 mL; 2.2 mmol) was added to a solution of *tert*-butyl alcohol (163 mg, 2.20 mmol) in THF (1 mL) at 0 °C, and the mixture was stirred at room temperature for 1 h. A solution of DIBALH in hexane (1.03 mol/L; 1.94 mL; 2.0 mmol) was then added dropwise to the resulting solution at 0 °C, and the mixture was stirred at room temperature for 2 h. The resulting solution containing LDBBA was added dropwise to a solution of **10** (60.2 mg; 0.200 mmol) in THF (2 mL) at 0 °C, and the mixture was stirred at that temperature for 10 min. The reaction was quenched with 10% hydrochloric acid (0.5 mL), and the mixture was extracted with Et_2O (2×5 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **27** (43.3 mg; 0.169 mmol; 84%) as a colorless crystal; mp 92.0–92.5 °C (hexane/AcOEt); IR (KBr) 3068, 2981, 2842, 1711, 1454, 1056, 805 cm^{-1}; ^1H NMR δ 1.47 (s, 3H), 1.73 (d, *J*=7.6 Hz, 1H), 2.43 (s, 3H), 2.75 (d, *J*=7.6 Hz, 1H), 7.34 (d, *J*=8.2 Hz, 2H), 7.49 (d, *J*=8.2 Hz, 2H), 9.61 (s, 1H); MS (FAB^+) *m/z* (%) 257 ($[M+H]^+$, 100), 185 (18), 154 (28), 139 (16), 137 (28), 93 (37); HRMS (FAB^+) calcd for $C_{12}H_{14}ClO_2S$: 257.0403, found: 257.0403.

3.1.26. 1-[((1R,2S*)-1-Chloro-2-methyl-2-vinylcyclopropyl)sulfinyl]-4-methylbenzene (**28**).* Sodium hydride (55% oil suspension; 26.2 mg; 0.60 mmol) was added to a solution of methyltriphenylphosphonium iodide (283 mg; 0.700 mmol) in THF (1.5 mL) at 0 °C, and the mixture was stirred at room temperature for 1 h. A solution of **27** (51.4 mg; 0.200 mmol) in THF (0.5 mL) was added to the resulting solution at 0 °C, and the mixture was stirred at room temperature overnight. The reaction was quenched with satd aq NH_4Cl (10 mL), and the mixture was extracted with $CHCl_3$ (2×7 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **28** (43.9 mg; 0.172 mmol; 86%) as a colorless crystal; mp 103.0–103.3 °C (hexane/AcOEt); IR (KBr) 3070, 2988, 1635, 1621, 1081, 1054, 517 cm^{-1}; ^1H NMR δ 1.45 (s, 3H), 1.61 (d, *J*=7.2 Hz, 1H), 2.23 (d, *J*=7.2 Hz, 1H), 2.42 (s, 3H), 5.34 (dd, *J*=0.4, 17.2 Hz, 1H), 5.36 (dd, *J*=0.4, 10.6 Hz, 1H), 6.02 (dd, *J*=10.6, 17.2 Hz, 1H), 7.30 (d, *J*=8.2 Hz, 2H), 7.55 (d, *J*=8.2 Hz, 2H); MS (FAB^+) *m/z* (%) 255 ($[M+H]^+$, 100), 115 (26), 79 (12); HRMS (FAB^+) calcd for $C_{13}H_{16}ClOS$: 255.0610, found: 255.0613.

3.1.27. 2-[(1R,2R*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]ethanol (**29**).* A solution of borane–tetrahydrofuran complex in THF (0.95 mmol/L; 4.5 mL; 4.3 mmol) was added dropwise to a solution of **28** (410 mg; 1.61 mmol) in THF (8 mL) at 0 °C, and the mixture was stirred at that temperature for 1 h. The reaction mixture was quenched with aq NaOH (3 mol/L; 4.1 mL) and 35% H_2O_2 (3.7 mL), and the mixture was extracted $CHCl_3$ (2×10 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **29** (332 mg; 1.22 mmol; 76%) as a colorless crystal; mp 100.0–100.5 °C (hexane/AcOEt); IR (KBr) 3391, 2865, 1429, 1173, 1048, 808 cm^{-1}; ^1H NMR δ 1.16 (d, *J*=7.0 Hz, 1H), 1.39 (s, 3H), 1.74–1.84 (m, 1H), 1.96 (d, *J*=7.0 Hz, 1H), 2.10 (td, *J*=6.4, 13.7 Hz, 1H), 2.20 (td, *J*=6.4, 13.7 Hz, 1H), 2.43 (s, 3H), 3.87 (q, *J*=6.4 Hz, 2H), 7.33 (d, *J*=8.2 Hz, 2H), 7.60 (d, *J*=8.2 Hz, 2H); MS (FAB^+) *m/z* (%) 273 ($[M+H]^+$, 100), 141 (17); HRMS (FAB^+) calcd for $C_{13}H_{18}ClO_2S$: 273.0716, found: 273.0715.

3.1.28. 1-({(1R,2R*)-2-[2-(Benzyloxy)ethyl]-1-chloro-2-methylcyclopropyl}sulfinyl)-4-methylbenzene (**30**).* Colorless crystal; mp 33.8–34.3 °C (hexane/AcOEt); IR (KBr) 2925, 2864, 1597, 1494, 1454, 1085, 1062 cm^{-1}; ^1H NMR δ 1.22 (d, *J*=7.0 Hz, 1H), 1.35 (s, 3H), 2.00 (d, *J*=7.0 Hz, 1H), 2.15 (td, *J*=6.6, 13.9 Hz, 1H), 2.21 (td, *J*=6.0, 13.9 Hz, 1H), 2.42 (s, 3H), 3.68 (m, 2H), 4.55 (s, 2H), 7.30–7.36 (m, 3H), 7.36–7.39 (m, 4H), 7.56 (d, *J*=8.1 Hz, 2H); MS (FAB^+) *m/z* (%) 363 ($[M+H]^+$, 100), 91 (68); HRMS (EI) calcd for $C_{20}H_{24}ClO_2S$: 363.1186, found: 363.1185.

*3.1.29. [(3-Methylpenta-3,4-dienyloxy)methyl]benzene (**31**).* Colorless oil; IR (neat) 2981, 2858, 1961, 1454, 1364, 1103, 849, 736, 697 cm^{-1}; ^1H NMR δ 1.71 (t, *J*=3.2 Hz, 3H), 2.27 (tt, *J*=3.2, 6.9 Hz, 2H), 3.58 (t, *J*=6.9 Hz, 2H), 4.52 (s, 2H), 4.60 (sextet, *J*=3.2 Hz, 2H), 7.26–7.39 (m, 5H); MS (EI) *m/z* (%) 188 (M^+, 4), 91 (100); HRMS (EI) calcd for $C_{13}H_{16}O$: 188.1201, found: 188.1197.

3.1.30. (E)-Ethyl 3-[(1R,2S*)-2-chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]acrylate (**34**).* Sodium hydride (55% oil suspension; 65.5 mg; 1.50 mmol) was added to a solution of triethyl phosphonoacetate (392 mg; 1.75 mmol) in THF (1.5 mL) at 0 °C, and the mixture was stirred at room temperature for 1 h. A solution of **27** (129 mg; 0.502 mmol) in THF (1 mL) was then added to the resulting solution at 0 °C, and the mixture was stirred at room temperature overnight. The reaction was quenched with satd aq NH_4Cl (1 mL), and the mixture was extracted with $CHCl_3$ (2×5 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **34** (149 mg; 0.456 mmol; 91%) as a colorless crystal; mp 112.0–112.5 °C (hexane/AcOEt); IR (KBr) 2982, 2935, 1715, 1645, 1239, 1096, 1050, 812 cm^{-1}; ^1H NMR δ 1.33 (t, *J*=7.2 Hz, 3H), 1.48 (s, 3H), 1.72 (d, *J*=7.4 Hz, 1H), 2.37 (d, *J*=7.4 Hz, 1H), 2.42 (s, 3H), 4.26 (q, *J*=7.2 Hz, 2H), 6.02 (d, *J*=15.7 Hz, 1H), 7.10 (d, *J*=15.7 Hz, 1H), 7.30 (d, *J*=8.2 Hz, 2H), 7.98 (d, *J*=8.2 Hz, 2H); Anal. Calcd for $C_{16}H_{19}ClO_3S$: C, 58.80; H, 5.86; Cl, 10.85; S, 9.81, found: C, 58.75; H, 5.79; Cl, 10.78; S, 9.79.

3.1.31. 3-[(1R,2R*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]propan-1-ol (**35**).* $NaBH_4$ (5 equiv) was used. Colorless crystal; mp 57.5–58.0 °C (hexane/AcOEt); IR (KBr) 3419, 2931, 2870, 1456, 1085, 1059, 810, 755 cm^{-1}; ^1H NMR δ 1.19 (d, *J*=7.0 Hz, 1H), 1.36 (s, 3H), 1.70–2.09 (m, 6H), 2.43 (s, 3H), 3.64–3.80 (m, 2H), 7.33 (d, *J*=8.1 Hz, 2H), 7.58 (d, *J*=8.1 Hz, 2H); MS (EI) *m/z* (%) 286 (M^+, 0.7), 269 (7), 201 (24), 140 (100), 123 (10), 92 (35), 85 (19), 77 (16), 65 (8); HRMS (EI) calcd for $C_{14}H_{19}ClO_2S$: 286.0794, found: 286.0796.

3.1.32. 1-({(1R,2R*)-2-[3-(benzyloxy)propyl]-1-chloro-2-methylcyclopropyl}sulfinyl)-4-methylbenzene (**36**).* Colorless oil; IR (neat) 2930, 2861, 1455, 1095, 1063, 739 cm^{-1}; ^1H NMR δ 1.23 (d, *J*=6.9 Hz, 1H), 1.32 (s, 3H), 1.72–1.97 (m, 5H), 2.43 (s, 3H), 3.48–3.56 (m, 2H), 4.53 (s, 2H), 7.27–7.41 (m, 7H), 7.55 (d, *J*=8.2 Hz, 2H); MS (FAB^+) *m/z* (%) 377 ($[M+H]^+$, 100), 269 (8), 231 (9), 201 (4), 154 (2),

123 (11), 91 (80), 77 (3); HRMS (FAB$^+$) calcd for $C_{21}H_{26}ClO_2S$: 377.1342, found: 377.1343.

3.1.33. (1R,4R*,5S*)-4-(Benzyloxy)-1-methylbicyclo[3.1.0]hexane (**38**).* *i*-PrMgCl (5 equiv) was used. Colorless oil; IR (neat) 2926, 2862, 1454, 1096, 1075, 697 cm^{-1}; ^{1}H NMR δ 0.31 (dd, J=5.0, 7.8 Hz, 1H), 0.80 (t, J=5.0 Hz, 1H), 1.62 (s, 3H), 1.20–1.29 (m, 2H), 1.55 (dt, J=8.2, 12.6 Hz, 1H), 1.75 (dd, J=8.2, 12.6 Hz, 1H), 1.89 (td, J=8.2, 12.6 Hz, 1H), 4.28 (dt, J=4.4, 8.2 Hz, 1H), 4.49 (d, J=11.9 Hz, 1H), 4.58 (d, J=11.9 Hz, 1H), 7.22–7.39 (m, 5H); MS (EI) m/z (%) 202 (M$^+$, 1), 158 (19), 111 (17), 91 (100), 79 (13), 65 (11), 55 (12); HRMS (EI) calcd for $C_{14}H_{18}O$: 202.1358, found: 202.1359.

*3.1.34. [(4-Methylhexa-4,5-dienyloxy)methyl]benzene (**39**).* Colorless oil; IR (neat) 2939, 2855, 1960, 1454, 1104, 847, 735 cm^{-1}; ^{1}H NMR δ 1.68 (t, J=3.1 Hz, 3H), 1.72–1.81 (m, 2H), 1.98–2.06 (m, 2H), 3.50 (t, J=6.5 Hz, 2H), 4.50 (s, 2H), 4.58 (sextet, J=3.1 Hz, 2H), 7.26–7.36 (m, 5H); MS (EI) m/z (%) 202 (M$^+$, 5), 111 (23), 105 (30), 91 (100), 79 (17), 77 (22), 65 (12), 55 (11), 43 (11); HRMS (EI) calcd for $C_{14}H_{18}O$: 202.1358, found: 202.1356.

3.1.35. {[3-((1R,2R*)-2-Chloro-1-methylcyclopropyl)propoxy]methyl}benzene (**40**).* Colorless oil; IR (neat) 2941, 2855, 1455, 1102, 1029, 697 cm^{-1}; ^{1}H NMR δ 0.53 (dd, J=4.0, 6.0 Hz, 1H), 0.86 (t, J=6.0 Hz, 1H), 1.21 (s, 3H), 1.26–1.38 (m, 2H), 1.64 (quint, J=6.4 Hz, 2H), 2.88 (dd, J=4.0, 7.6 Hz, 1H), 3.45 (t, J=6.4 Hz, 2H), 4.89 (s, 2H), 7.26–7.36 (m, 5H); MS (ESI$^+$) m/z (%) 263 (35), 261 ([M+Na]$^+$ 100), 225 ([M−HCl+Na]$^+$ 32); HRMS (ESI$^+$) calcd for $C_{14}H_{19}ClONa$: 261.1022, found: 261.1017.

3.1.36. 1-({3-[(1R,2R*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]propoxy}methyl)-4-fluorobenzene (**42a**).* Yield (95%); colorless oil; IR (neat) 2930, 2863, 1509, 1221, 1091, 1062, 810 cm^{-1}; ^{1}H NMR δ 1.22 (d, J=6.9 Hz, 1H), 1.33 (s, 3H), 1.72–1.98 (m, 5H), 2.43 (s, 3H), 3.52 (m, 2H), 4.83 (s, 2H), 7.03 (t, J=8.6 Hz, 2H), 7.28–7.36 (m, 4H), 7.55 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 395 ([M+H]$^+$, 100), 269 (6), 185 (16), 154 (17), 137 (19), 109 (90), 93 (28); HRMS (EI) calcd for $C_{21}H_{25}FO_2S$: 395.1248, found: 395.1247.

3.1.37. 1-({3-[(1R,2R*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]propoxy}methyl)-4-methoxybenzene (**42b**).* Yield (96%); colorless oil; IR (neat) 2933, 2861, 1612, 1513, 1247, 1091, 1035, 811 cm^{-1}; ^{1}H NMR δ 1.23 (d, J=6.9 Hz, 1H), 1.31 (s, 3H), 1.70–1.96 (m, 5H), 2.43 (s, 3H), 3.45–3.53 (m, 2H), 3.80 (s, 3H), 4.45 (s, 2H), 6.88 (d, J=8.3 Hz, 2H), 7.29 (d, J=8.2 Hz, 2H), 7.32 (d, J=8.3 Hz, 2H), 7.55 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 407 ([M+H]$^+$, 17), 121 (100); HRMS (FAB$^+$) calcd for $C_{22}H_{28}ClO_3S$: 407.1448, found: 407.1449.

3.1.38. 1-({(1R,2R*)-1-Chloro-2-methyl-2-[3-(3-phenylpropoxy)propyl]cyclopropyl}sulfinyl)-4-methylbenzene (**42c**).* Yield (87%); colorless oil; IR (neat) 2933, 2861, 1495, 1455, 1116, 1063, 701 cm^{-1}; ^{1}H NMR δ 1.25 (d, J=6.9 Hz, 1H), 1.34 (s, 3H), 1.70–1.98 (m, 7H), 2.42 (s, 3H), 2.70 (t, J=7.7 Hz, 2H), 3.44 (t, J=6.4 Hz, 2H), 3.46 (t, J=6.3 Hz, 2H), 7.16–7.22 (m, 3H), 7.26–7.30 (m, 2H), 7.32 (d, J=8.2 Hz, 2H), 7.57 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 405 ([M+H]$^+$, 100), 269 (10), 119 (20), 91 (59); HRMS (FAB$^+$) calcd for $C_{23}H_{30}ClO_2S$: 405.1655, found: 405.1650.

3.1.39. tert-Butyl{3-[(1R,2R*)-2-chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]propoxy}diphenylsilane (**42d**).* A solution of **35** (172 mg; 0.600 mmol) in DMF (0.5 mL) was added to a solution of imidazole (61.2 mmg; 0.900 mmol) and *tert*-butylchlorodiphenylsilane (247 mmg; 0.900 mmol) in DMF (0.7 mL) at room temperature, and the mixture was stirred at that temperature for 4 h. The reaction was quenched with satd aq NH_4Cl (1 mL), and the mixture was extracted with benzene (2×3 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **42d** (246 mg; 0.468 mmol; 78%) as a colorless oil; IR (neat) 2931, 2858, 1428, 1111, 1063, 703 cm^{-1}; ^{1}H NMR δ 1.07 (s, 9H), 1.24 (d, J=7.1 Hz, 1H), 1.29 (s, 3H), 1.60–1.96 (m, 5H), 2.43 (s, 3H), 3.72 (t, J=6.0 Hz, 2H), 7.28–7.48 (m, 8H), 7.52 (d, J=8.2 Hz, 2H), 7.60 (dd, J=1.4, 7.5 Hz, 4H); MS (FAB$^+$) m/z (%) 525 ([M+H]$^+$, 23), 467 (35), 447 (75), 199 (51), 135 (93), 93 (100), 77 (27); HRMS (FAB$^+$) calcd for $C_{30}H_{38}ClO_2SSi$: 525.2050, found: 525.2051.

3.1.40. ({3-[(1R,2R*)-2-Chloro-1-methyl-2-(p-tolylsulfinyl)cyclopropyl]propoxy}methanetriyl)tribenzene (**42e**).* 4-Dimethylaminopyridine (2.4 mg; 0.020 mmol) and triethylamine (60.7 mmg; 0.600 mmol) were added to a solution of trityl chloride (167 mg; 0.600 mmol) and **35** (57.4 mg; 0.200 mmol) in $CHCl_3$ (0.4 mL) at room temperature, and the mixture was stirred at that temperature overnight. The reaction was quenched with satd aq NH_4Cl (0.5 mL), and the mixture was extracted with $CHCl_3$ (2×3 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **42e** (87.6 mmg; 0.166 mmol; 83%) as a colorless crystal; mp 106.0–106.5 °C (hexane/AcOEt); IR (KBr) 3058, 2930, 1491, 1449, 1063, 756 cm^{-1}; ^{1}H NMR δ 1.19 (d, J=6.9 Hz, 1H), 1.29 (s, 3H), 1.68–1.96 (m, 5H), 2.42 (s, 3H), 3.08–3.22 (m, 2H), 7.20–7.26 (m, 3H), 7.26–7.34 (m, 8H), 7.38–7.50 (m, 6H), 7.54 (d, J=8.2 Hz, 2H); MS (FAB$^+$) m/z (%) 551 ([M+Na]$^+$, 100), 243 (73), 165 (24); HRMS (FAB$^+$) calcd for $C_{33}H_{33}ClO_2SNa$: 551.1787, found: 551.1788.

3.1.41. (1R,4R*,5S*)-4-(4-Fluorobenzyloxy)-1-methylbicyclo[3.1.0]hexane (**43a**).* Colorless oil; IR (neat) 2927, 2863, 1510, 1223, 1102, 1087, 824 cm^{-1}; ^{1}H NMR δ 0.31 (dd, J=4.8, 7.7 Hz, 1H), 0.79 (t, J=4.8 Hz, 1H), 1.17 (s, 3H), 1.18–1.31 (m, 2H), 1.49–1.62 (m, 1H), 1.76 (dd, J=8.3, 12.9 Hz, 1H), 1.89 (td, J=8.0, 12.9 Hz, 1H), 4.27 (dt, J=4.4, 8.0 Hz, 1H), 4.44 (d, J=11.6 Hz, 1H), 4.54 (d, J=11.6 Hz, 1H), 7.01 (t, J=8.8 Hz, 2H), 7.32 (dd, J=5.6, 8.8 Hz, 2H); MS (EI) m/z (%) 220 (M$^+$, 0.6), 202 (1), 109 (100), 93 (7); HRMS (EI) calcd for $C_{14}H_{17}FO$: 220.1263, found: 220.1262.

3.1.42. (1R,4R*,5S*)-4-(4-Methoxybenzyloxy)-1-methylbicyclo[3.1.0]hexane (**43b**).* Colorless oil; IR (neat) 2955, 2861, 1613, 1514, 1248, 1087, 820 cm^{-1}; ^{1}H NMR δ 0.30 (dd, J=4.5, 7.8 Hz, 1H), 0.79 (t, J=4.5 Hz, 1H), 1.16 (s, 3H), 1.19–1.29 (m, 2H), 1.54 (dt, J=8.0, 12.5 Hz, 1H), 1.75 (dd, J=8.2, 12.5 Hz, 1H), 1.87 (td, J=8.0, 12.5 Hz, 1H), 3.78 (s, 3H), 4.26 (dt, J=4.4, 8.0 Hz, 1H), 4.42 (d, J=11.4 Hz, 1H), 4.51 (d, J=11.4 Hz, 1H), 6.87 (d, J=8.6 Hz, 2H), 7.28 (d, J=8.6 Hz, 2H); MS (EI) m/z (%) 232 (M$^+$, 13), 147 (11), 121 (100); HRMS (EI) calcd for $C_{15}H_{20}O_2$: 232.1463, found: 232.1463.

3.1.43. (1R,4R*,5S*)-1-Methyl-4-(3-phenylpropoxy)bicyclo[3.1.0]hexane (**43c**).* Colorless oil; IR (neat) 2942, 2860, 1454, 1342, 1106, 1073, 699 cm^{-1}; ^{1}H NMR δ 0.29 (dd, J=4.6, 7.7 Hz, 1H), 0.76 (t, J=4.6 Hz, 1H), 1.09–1.27 (m, 5H), 1.48–1.61 (m, 1H), 1.75 (dd, J=8.3, 12.5 Hz, 1H), 1.81–1.96 (m, 3H), 2.69 (t, J=7.7 Hz, 2H), 3.38 (td, J=6.5, 9.3 Hz, 1H), 3.50 (td, J=6.6, 9.3 Hz, 1H), 4.17 (dt, J=4.4, 8.0 Hz, 1H), 7.13–7.31 (m, 5H); MS (EI) m/z (%) 230 (M$^+$, 1), 215 (1), 135 (12), 118 (54), 91 (100); HRMS (EI) calcd for $C_{16}H_{22}O$: 230.1671, found: 230.1666.

*3.1.44. 1-Fluoro-4-[(4-methylhexa-4,5-dienyloxy)methyl]benzene (**44a**).* Colorless oil; IR (neat) 2940, 2858, 1960, 1604, 1509, 1223, 1093, 824 cm^{-1}; ^{1}H NMR δ 1.68 (t, J=3.2 Hz, 3H), 1.70–1.81 (m, 2H), 1.95–2.06 (m, 2H), 3.49 (t, J=6.5 Hz, 2H), 4.46 (s, 2H), 4.58 (sextet, J=3.2 Hz, 2H), 7.02 (t, J=8.8 Hz, 2H), 7.30 (dd, J=5.5, 8.8 Hz, 2H); MS

(EI) *m*/*z* (%) 220 (M^+, 2), 123 (9), 109 (100); HRMS (EI) calcd for $C_{14}H_{17}FO$: 220.1263, found: 220.1261.

*3.1.45. 1-Methoxy-4-[(4-methylhexa-4,5-dienyloxy)methyl]benzene (**44b**).* Colorless oil; IR (neat) 2937, 2856, 1960, 1514, 1248, 1100, 847 cm^{-1}; ^1H NMR δ 1.68 (t, *J*=2.9 Hz, 3H), 1.74 (quint, *J*=6.8 Hz, 2H), 1.96–2.05 (m, 2H), 3.46 (t, *J*=6.8 Hz, 2H), 3.80 (s, 3H), 4.43 (s, 2H), 4.58 (sextet, *J*=2.9 Hz, 2H), 6.67 (d, *J*=8.5 Hz, 2H), 7.26 (d, *J*=8.5 Hz, 2H); MS (EI) *m*/*z* (%) 232 (M^+, 0.7), 135 (22), 121 (100); HRMS (EI) calcd for $C_{15}H_{20}O_2$: 232.1463, found: 232.1466.

*3.1.46. [3-(4-Methylhexa-4,5-dienyloxy)propyl]benzene (**44c**).* Colorless oil; IR (neat) 2941, 2858, 1960, 1604, 1455, 1116, 699 cm^{-1}; ^1H NMR δ 1.65–1.78 (m, 5H), 1.82–1.96 (m, 2H), 1.96–2.07 (m, 2H), 2.69 (t, *J*=7.7 Hz, 2H), 3.42 (t, *J*=6.5 Hz, 2H), 3.43 (t, *J*=6.6 Hz, 2H), 4.60 (sextet, *J*=3.2 Hz, 2H), 7.16–7.31 (m, 5H); MS (EI) *m*/*z* (%) 230 (M^+, 1), 118 (63), 112 (20), 91 (100), 79 (16).

*3.1.47. tert-Butyl(4-methylhexa-4,5-dienyloxy)diphenylsilane (**44d**).* Colorless oil; IR (neat) 2932, 2858, 1960, 1428, 1112, 702 cm^{-1}; ^1H NMR δ 1.04 (s, 9H), 1.63–1.76 (m, 5H), 1.97–2.07 (m, 2H), 3.68 (t, *J*=6.4 Hz, 2H), 4.55 (sextet, *J*=3.2 Hz, 2H), 7.32–7.46 (m, 6H), 7.67 (dd, *J*=1.7, 7.7 Hz, 4H); MS (EI) *m*/*z* (%) 350 (M^+, 0.1), 293 (77), 281 (13), 215 (46), 199 (100), 183 (18), 123 (13); HRMS (EI) calcd for $C_{23}H_{30}OSi$: 350.2066, found: 350.2064.

*3.1.48. [(4-Methylhexa-4,5-dienyloxy)methanetriyl]tribenzene (**44e**).* Colorless oil; IR (neat) 2939, 2870, 1959, 1490, 1448, 1072, 706 cm^{-1}; ^1H NMR δ 1.66 (t, *J*=3.2 Hz, 3H), 1.76 (quint, *J*=6.8 Hz, 2H), 1.95–2.06 (m, 2H), 3.08 (t, *J*=6.8 Hz, 2H), 4.53 (sextet, *J*=3.2 Hz, 2H), 7.21–7.25 (m, 3H), 7.25–7.31 (m, 6H), 7.41–7.44 (m, 6H); MS (EI) *m*/*z* (%) 354 (M^+, 0.5), 243 (100), 183 (6), 165 (23), 105 (9), 77 (3), 67 (2); HRMS (EI) calcd for $C_{26}H_{26}O$: 354.1984, found: 354.1980.

*3.1.49. (1R,2S)-Ethyl 2-chloro-1-methyl-2-((R$_S$)-p-tolylsulfinyl)cyclopropanecarboxylate (**45**).* Colorless oil; $[\alpha]_D^{27}$ +3.6 (*c* 0.38, acetone); HPLC: DAICEL CHIRALCEL AD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/9, flow rate=0.50 mL/min, detection at 254 nm, retention time=26.7 min (major), 31.0 min (minor), 98% ee.

*3.1.50. 1-{(R$_S$)-[(1S,2R)-2-(Benzyloxymethyl)-1-chloro-2-methylcyclopropyl]sulfinyl}-4-methylbenzene (**46**).* Colorless oil; $[\alpha]_D^{28}$ +38.9 (*c* 0.26, acetone); HPLC: DAICEL CHIRALCEL AD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/9, flow rate=0.50 mL/min, detection at 254 nm, retention time=24.6 min (major), 26.4 min (minor), 99% ee.

*3.1.51. (1S,4S,5R)-1-Methyl-4-phenyl-3-oxabicyclo[3.1.0]hexane (**48**).* Colorless oil; $[\alpha]_D^{26}$ −150 (*c* 0.16, acetone); HPLC: DAICEL CHIRALCEL IA (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/200, flow rate=0.25 mL/min, detection at 254 nm, retention time=23.4 min (minor), 24.5 min (major), 99% ee.

*3.1.52. (1S,2R,3R)-Ethyl 2-chloro-3-isopropyl-1-(2-phenylethyl)-2-((R$_S$)-p-tolylsulfinyl)cyclopropanecarboxylate (**50a**).* Colorless oil; IR (neat) 2967, 2934, 1727, 1597, 1495, 1454, 1367, 1265, 1246, 1191, 1092, 1067, 1038, 811, 752, 734 cm^{-1}; ^1H NMR δ 0.43 (d, *J*=6.6 Hz, 3H), 1.05 (d, *J*=6.6 Hz, 3H), 1.40 (t, *J*=7.1 Hz, 3H), 1.57–1.67 (m, 1H), 1.94 (d, *J*=10.5 Hz, 1H), 1.97–2.09 (m, 1H), 2.13–2.25 (m, 1H), 2.40 (s, 3H), 2.85 (t, *J*=8.6 Hz, 2H), 4.35 (q, *J*=7.1 Hz, 1H), 4.37 (q, *J*=7.1 Hz, 1H), 7.15–7.33 (m, 7H), 7.60 (d, *J*=8.2 Hz, 2H); MS (EI) *m*/*z* (%) 432 (M^+, 0.3), 416 (0.2), 387 (0.2), 325 (0.2), 293 (45), 265 (15), 149 (24), 91 (100); HRMS (EI) calcd for $C_{24}H_{29}ClO_3S$: 432.1526, found: 432.1529; $[\alpha]_D^{29}$ −54.4 (*c* 0.41, acetone); HPLC: DAICEL CHIRALCEL OD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/9, flow rate=0.50 mL/min, detection at 254 nm, retention time=16.8 min (minor), 19.5 min (major), 98% ee.

*3.1.53. [(1S,2R,3R)-2-Chloro-1-methyl-3-(2-phenylethyl)-2-((R$_S$)-p-tolylsulfinyl)cyclopropyl]-propan-1-one (**50b**).* Colorless crystal; mp 72.5–73.0 °C (hexane/AcOEt); $[\alpha]_D^{28}$ −11.1 (*c* 0.42, acetone); HPLC: DAICEL CHIRALCEL OD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/9, flow rate=0.50 mL/min, detection at 254 nm, retention time=26.7 min (minor), 29.7 min (major), 98% ee.

*3.1.54. [(1S,2R,3R)-2-Chloro-3-isopropyl-1-(2-phenylethyl)-2-((R$_S$)-p-tolylsulfinyl)cyclopropyl]methanol (**51a**).* Colorless crystal; mp 162.0–162.5 °C (hexane/AcOEt); IR (KBr) 3380, 2961, 1602, 1494, 1455, 1425, 1085, 1065, 1036, 1014, 813, 762, 739, 702, 513 cm^{-1}; ^1H NMR δ 0.68 (d, *J*=6.5 Hz, 3H), 1.00 (d, *J*=6.6 Hz, 3H), 1.49 (d, *J*=10.5 Hz, 1H), 1.55–1.72 (m, 1H), 1.85–2.07 (m, 2H), 2.43 (s, 3H), 2.77 (dd, *J*=4.8, 8.6 Hz, 1H), 2.80–2.91 (m, 2H), 4.03 (dd, *J*=4.8, 12.7 Hz, 1H), 4.16 (dd, *J*=8.6, 12.7 Hz, 1H), 7.14–7.30 (m, 5H), 7.34 (d, *J*=8.1 Hz, 2H), 7.58 (d, *J*=8.2 Hz, 2H); Anal. Calcd for $C_{22}H_{27}ClO_2S$: C, 67.59; H, 6.96; Cl, 9.07; S, 8.20, found: C, 67.42; H, 6.98; Cl, 9.04; S, 8.15; $[\alpha]_D^{29}$ −50.1 (*c* 0.47, acetone); HPLC: DAICEL CHIRALCEL OD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/9, flow rate=0.50 mL/min, detection at 254 nm, retention time=26.8 min (major), 42.2 min (minor), 99% ee (after recrystallization).

*3.1.55. (S)-1-[(1S,2R,3R)-2-Chloro-1-methyl-3-(2-phenylethyl)-2-((R$_S$)-p-tolylsulfinyl)cyclopropyl]propan-1-ol (**51b**).* Sodium borohydride (136 mg; 3.60 mmol) was added to a solution of **50b** (475 mg; 1.22 mmol) in ethanol (12 mL) at 0 °C, and the mixture was stirred at that temperature for 30 min. The reaction was quenched with satd aq NH_4Cl (7 mL), and the mixture was extracted with $CHCl_3$ (2×10 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography on silica gel using hexane/AcOEt as the eluent to give **51b** (471 mg; 1.20 mmol; 99%) as a colorless crystal; mp 168.5–169.0 °C (hexane/AcOEt); IR (KBr) 3454, 2925, 2879, 1599, 1496, 1452, 1321, 1114, 1084, 1031, 814, 746, 700 cm^{-1}; ^1H NMR δ 1.02 (t, *J*=7.5 Hz, 3H), 1.27 (s, 3H), 1.48–1.65 (m, 2H), 1.65–1.86 (m, 3H), 2.36–2.59 (m, 2H), 2.43 (s, 3H), 3.04–3.08 (m, 1H), 3.82–3.90 (m, 1H), 7.11 (d, *J*=7.7 Hz, 2H), 7.17–7.32 (m, 3H), 7.34 (d, *J*=8.2 Hz, 2H), 7.46 (d, *J*=8.2 Hz, 2H); MS (FAB^+) *m*/*z* (%) 391 ($[M+H]^+$, 100), 233 (55), 154 (28), 139 (87), 91 (58), 57 (34); HRMS (FAB^+) calcd for $C_{22}H_{28}ClO_2S$: 391.1499, found: 391.1498; $[\alpha]_D^{27}$ +22.9 (*c* 0.38, acetone); HPLC: DAICEL CHIRALCEL OD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/9, flow rate=0.50 mL/min, detection at 254 nm, retention time=23.2 min (minor), 26.6 min (major), 99% ee (after recrystallization).

*3.1.56. 1-{(R$_S$)-[(1R,2S,3R)-2-(Benzyloxymethyl)-1-chloro-3-isopropyl-2-(2-phenylethyl)cyclopropyl]sulfinyl}-4-methylbenzene (**52a**).* Colorless oil; $[\alpha]_D^{29}$ −31.8 (*c* 0.27, acetone); HPLC: DAICEL CHIRALCEL OD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/10, flow rate=0.30 mL/min, detection at 254 nm, retention time=47.4 min (major), 50.4 min (minor), 99% ee.

*3.1.57. 1-((R$_S$)-{(1R,2S,3R)-2-[(S)-1-(Benzyloxy)propyl]-1-chloro-2-methyl-3-(2-phenylethyl)cyclopropyl}sulfinyl)-4-methylbenzene (**52b**).* Colorless crystal; mp 62.5–63.0 °C (hexane/AcOEt); $[\alpha]_D^{29}$ +14.9 (*c* 0.27, acetone); HPLC: DAICEL CHIRALCEL OD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/9, flow rate=0.50 mL/min, detection at 254 nm, retention time=21.0 min (major), 31.8 min (minor), 99% ee (after recrystallization).

*3.1.58. (1R,4R,5S,6S)-6-Isopropyl-1-(2-phenylethyl)-4-phenyl-3-oxabicyclo[3.1.0]hexane (**53a**).* Colorless oil; $[\alpha]_D^{27}$ +72.5 (*c* 0.30, acetone); HPLC: DAICEL CHIRALCEL IA (ϕ 0.46 cm×25 cm), 2-

propanol/hexane=1/200, flow rate=0.24 mL/min, detection at 254 nm, retention time=28.2 min (major), 31.1 min (minor), 99% ee.

*3.1.59. (1R,2S,4R,5S,6S)-2-Ethyl-1-methyl-6-(2-phenylethyl)-4-phenyl-3-oxabicyclo[3.1.0]hexane (**53b**).* Colorless oil; $[\alpha]_D^{29}$ +76.7 (*c* 0.21, acetone); HPLC: DAICEL CHIRALCEL IA (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/200, flow rate=0.15 mL/min, detection at 254 nm, retention time=28.1 min (minor), 34.5 min (major), 99% ee.

*3.1.60. (1R,2R,3S)-1-Chloro-2-(2-phenylethyl)-1-((R$_S$)-p-tolylsulfinyl)spiro[2.5]octan-4-one (**55**).* Colorless oil; $[\alpha]_D^{28}$ −52.8 (*c* 0.43, acetone). Enantiomeric excess of compound **55** could not be determined by chiral HPLC analysis because the enantiomers were inseparable on chiral HPLC.

*3.1.61. (1R,2R,3S,4S)-1-Chloro-2-(2-phenylethyl)-1-((R$_S$)-p-tolylsulfinyl)spiro[2.5]octan-4-ol (**56**).* Colorless crystal; mp 108.5–109.0 °C (hexane/AcOEt); IR (KBr) 3409, 2914, 1603, 1595, 1495, 1450, 1404, 1294, 1157, 1120, 1088, 1057, 1009, 810, 767, 716 cm^{-1}; ^{1}H NMR δ 1.14–1.31 (m, 1H), 1.40–1.49 (m, 1H), 1.49–1.59 (m, 2H), 1.59–1.70 (m, 1H), 1.71 (q, *J*=3.9 Hz, 1H), 1.73–1.86 (m, 2H), 1.86–1.98 (m, 1H), 1.98–2.08 (m, 1H), 2.15 (dt, *J*=3.5, 13.5 Hz, 1H), 2.43 (s, 3H), 2.34–2.46 (m, 1H), 2.58 (ddd, *J*=5.8, 9.9, 13.6 Hz, 1H), 3.17 (t, *J*=2.0 Hz, 1H), 4.10 (s, 1H), 7.12 (d, *J*=7.2 Hz, 2H), 7.18–7.31 (m, 3H), 7.35 (d, *J*=8.2 Hz, 2H), 7.45 (d, *J*=8.2 Hz, 2H); MS (FAB$^+$) *m*/*z* (%) 403 ([M+H]$^+$, 82), 385 (24), 245 (48), 209 (55), 154 (51), 139 (79), 91 (100); HRMS (FAB$^+$) calcd for $C_{23}H_{28}ClO_2S$: 403.1499, found: 403.1506; $[\alpha]_D^{29}$ +25.2 (*c* 0.28, acetone); HPLC: DAICEL CHIRALCEL AD (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/9, flow rate=0.50 mL/min, detection at 254 nm, retention time=28.6 min (major), 41.3 min (minor), 99% ee (after recrystallization).

*3.1.62. (1R,2R,3S,4S)-4-(Benzyloxy)-1-chloro-2-(2-phenylethyl)-1-((R$_S$)-p-tolylsulfinyl)spiro[2.5]octane (**57**).* Colorless crystal; mp 142.2–142.7 °C (hexane/AcOEt); IR (KBr) 2930, 2862, 1598, 1455, 1088, 1061, 696 cm^{-1}; ^{1}H NMR δ 1.15–1.29 (m, 1H), 1.34 (dd, *J*=5.9, 7.5 Hz, 1H), 1.40–1.57 (m, 4H), 1.66–1.87 (m, 3H), 1.99–2.23 (m, 3H), 2.32 (ddd, *J*=5.5, 10.1, 13.7 Hz, 1H), 2.39 (s, 3H), 3.63 (d, *J*=2.5 Hz, 1H), 4.58 (d, *J*=11.4 Hz, 1H), 4.85 (d, *J*=11.4 Hz, 1H), 6.97–7.08 (m, 2H), 7.15–7.40 (m, 8H), 7.48–7.54 (m, 4H); ^{13}C NMR δ 20.0, 21.5, 24.3, 24.9, 25.5, 28.0, 29.4, 34.5, 40.1, 70.4, 72.7, 78.1, 125.7, 126.2, 127.4, 128.1, 128.2, 128.3, 128.5, 129.3, 138.4, 138.5, 141.3, 141.9; MS (FAB$^+$) *m*/*z* (%) 493 ([M+H]$^+$, 38), 385 (19), 245 (32), 209 (29), 139 (41), 91 (100); HRMS (FAB$^+$) calcd for $C_{30}H_{34}ClO_2S$: 493.1968, found: 493.1966; $[\alpha]_D^{29}$ +69.8 (*c* 0.31, acetone); HPLC: DAICEL CHIRALCEL IA (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/5, flow rate=0.30 mL/min, detection at 254 nm, retention time=33.4 min (major), 64.9 min (minor), 99% ee (after recrystallization).

*3.1.63. (1S,3R,4S,5S,6R)-3-Phenyl-5-(2-phenylethyl)-2-oxatricyclo[4.4.0.0^{4,6}]decane (**59**).* Colorless oil; IR (neat) 2930, 2854, 1603, 1496, 1449, 1082, 1042, 699 cm^{-1}; ^{1}H NMR δ 0.94–1.03 (m, 1H), 1.20–1.52 (m, 5H), 1.54–1.87 (m, 5H), 1.90–2.02 (m, 1H), 2.38–2.60 (m, 2H), 3.90 (dd, *J*=6.1, 10.2 Hz, 1H), 5.16 (d, *J*=2.7 Hz, 1H), 6.94–7.00 (m, 2H), 7.08–7.26 (m, 3H), 7.27–7.42 (m, 5H); ^{13}C NMR δ 20.9, 23.5, 25.1, 29.4, 30.8, 33.5, 33.9, 36.0, 78.3, 80.2, 125.6, 126.2, 127.1, 128.1, 128.2, 128.4, 141.0, 142.3; MS (EI) *m*/*z* (%) 318 (M$^+$, 60), 227 (15), 213 (33), 117 (63), 105 (33), 91 (100); HRMS (EI) calcd for $C_{23}H_{26}O$: 318.1984, found: 318.1979; $[\alpha]_D^{29}$ +77.2 (*c* 0.27, acetone); HPLC: DAICEL CHIRALCEL IA (ϕ 0.46 cm×25 cm), 2-propanol/hexane=1/100, flow rate=0.30 mL/min, detection at 254 nm, retention time=16.6 min (major), 50.0 min (minor), 99% ee.

3.2. X-ray crystallographic analysis of *rac*-56

Single crystals of *rac*-**56** suitable for an X-ray diffraction study were grown by slow diffusion of hexane into the ethyl acetate solution of *rac*-**56** at room temperature. A colorless block crystal of *rac*-**56** having approximate dimensions of 0.26×0.33×0.35 mm was mounted on a glass fiber. Diffraction data were collected on a Bruker AXS SMART APEX CCD diffractometer at 173 K with graphite-monochromated Mo Kα radiation (λ=0.71073 Å).[19] The data reduction and integration were performed using the program SAINT.[20] An empirical absorption correction was applied using the program SADABS.[21] The structure was solved by direct methods with SHELXS-97[22] and refined by full-matrix least squares techniques against F^2 using SHELXL-97.[23] All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were placed in calculated positions and refined using the riding model. Crystal data for *rac*-**56**: $C_{23}H_{27}ClO_2S$, *M*=402.96, triclinic, space group *P*−1, *a*=9.8624 (4) Å, *b*=9.8812 (4) Å, *c*=11.4540 (5) Å, α=76.5840 (10)°, β=86.8140 (10)°, γ=70.6580 (10)°, *V*=1024.20 (7) Å^3, *Z*=2, D_{calcd}=1.307 g cm^{-3}, μ(Mo Kα)=0.304 mm^{-1}, *F*(000)=428, 4437 reflections, 246 parameters, R_1=0.0345 [$I>2\sigma(I)$], R_w=0.0911 (all data), GOF=1.030. Crystallographic data (excluding structure factors) for *rac*-**56** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC 837286. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK, [fax: +44 (0)1223 336,033 or e-mail: deposit@ccdc.cam.ac.Uk].

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