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A Sulfinyl Trialkoxycarbonyl Ethene as a New Enantiopure Dienophile in Asymmetric Diels-Alder Reactions

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Abstract: The synthesis and the asymmetric Diels-Alder reactions of the enantiomerically pure (S)-p-tolylsulfinyl trialkoxycarbonyl ethene **3** with cyclic and acyclic dienes are reported. π -Facial selectivity and regioselectivity are very high in all studied cases. Reactions with cyclopentadiene exhibit moderated or high *exo*-selectivity, which disappears with acyclic dienes. The use of high pressure improves the π -facial selectivity but does not substantially modify the *endo-exo* selectivity.

During the last two decades the asymmetric Diels-Alder reaction from enantiopure dienophiles has known an impressive development, showing that several types of chiral dienophiles react in a highly and predictable stereoselective manner.¹ In particular, the use of vinylsulfoxides in asymmetric Diels-Alder reactions is receiving an increasing attention due to the potential ability of the sulfinyl group, directly joined to the dienophilic double bond, to control efficiently the stereoselectivity of the cycloadditions. However, the low dienophilic reactivity of vinylsulfoxides determines that other activating groups must be attached to the double bond.¹ In this field, we have recently described that the Diels-Alder reactions of mono- and diactivated vinylsulfoxides², (S)-ptolylsulfinyl-2-cyclopentenone $(1)^3$ and (S)-2-p-tolylsulfinyl maleates 2^4 , catalyzed by Lewis acids, take place with very high regioselectivity, endo selectivity and π -facial selectivity. The cyclohexenes resulting from the reactions of diesters 2 with acyclic dienes evolve quickly at rt into cyclohexadienes by pyrolytic elimination of the sulfinyl group. The problems associated to the use of these diesters derive from its moderated reactivity (they require acid catalysts) and mainly from the fact that the pyrolytic elimination is not regioselective in the case of the adducts resulting from 1-substituted dienes (scheme 1). In order to avoid these problems, we decide to study the behavior as a dienophile of a triactivated enantiopure vinylsulfoxide, the (S)-p-tolylsulfinyl trialkoxycarbonyl ethene 3, the adducts of which could only evolve into the conjugated cyclohexadienes. In this paper we report the results obtained from this study.





Dienophile **3** was readily prepared in two steps (scheme 2). Deprotonation of (*R*)-benzyl *p*-tolylsulfinyl acctate^{4b} with Li-HMDS (1.2 equiv) in THF and further reaction at -78°C with diethyl oxomalonate furnished quantitatively the corresponding alcohol **4**. Dehydration of crude **4** was performed by reaction with MsCl/Et₃N in CH₂Cl₂ at rt, affording pure olefin **3** in 69% yield after flash chromatography. The optical purity of **3** (ee> 97%) was established by ¹H-NMR analysis of both **3** and its racemic (±)-**3** (prepared from the corresponding racemic sulfinyl acetate) in the presence of 0.2 equiv of Yb(hfc)₃.



In Table 1 are shown the results obtained in the reaction of 3 with an excess of cyclopentadiene under different conditions. We have also included the results obtained from diester 2 under similar conditions taken from reference 4b. The *endo* or *exo* denominations used in this paper are related to the stereochemistry of the two ester groups displaying a *cis*-arrangement in the dienophile, which is valid for the adducts resulting from both dienophiles 2 and 3.

All the cycloadditions occurred in high yields (76-89%), affording mixtures of three adducts: the two possible *exo* adducts, *exo*-**6a** and *exo*-**6'a**, and only one *endo* adduct, *endo*-**5'a**. After flash chromatography, the *endo*-**5'a** adduct could be conveniently separated and its absolute configuration was unequivocally determined by X-ray diffraction (Fig 1).⁵

Table 1. Diels Alder reactions of dienophiles 3 and 2 (values in brackets taken from reference 4b) with cyclopentadiene.

3 (<i>2</i>)	catalyst, CH ₂ Cl ₂ end	sotol CO ₂ Et (H) + CO ₂ Et (CO ₂ Me) endo-5a		D_2 Et (<i>H</i>) Tol + 2 t (<i>CO</i> ₂ <i>Me</i>) e	CO ₂ Et CO ₂ Bn CO ₂ Et (<i>H</i>) SOTO	$(CO_2Me) + CO_2Bn + CO_2Et (CO_2Me) + CO_2Et (CO_2Me) + CO_2Et (CO_2Me) + CO_2Et (H) + CO_2Et $		
					13011011	<u>ano</u>	,	
Entry	Catalyst (equiv)	Conditions	Yield $(\%)^a$	endo-5a	endo-5'a	exo-6a	exo- 6'a	
1		20°C, 72h	83	(73)	30 (8)	8 (19)	62 ()	
2	$Eu(fod)_3(1.2)$	0°C, 2h	77	(66)	30 (3)	8 (31)	62 ()	
3	$ZnBr_2$ (1.8)	-10°C, 2h	89	(6)	45 (91)	(3)	55 ()	
4	TiCl ₄ (1.2)	-78°C, 1h	76	(83)	6 (13)	4 (4)	90 ()	

^a In pure product after chromatographic purification. ^bDetermined by ¹H-NMR.

The mixture 6a+6'a was oxidized with MCPBA into their corresponding sulfones 8 and 8', which exhibit the same ¹H-NMR spectrum (only one set of signals was observed). This demonstrates that both sulfones are enantiomers, and therefore they, as well as the starting sulfoxides 6a and 6'a, must exhibit the same *endo*- or *exo*-configuration. As the stereochemistry of 5'a had been unequivocally established as *endo*, the *exo* configuration must be assigned to 6a and 6'a, as well as the enantiomeric sulfones 8 and 8'. This was

confirmed by oxidation of the sulfoxide *endo*-5'a into the sulfone *endo*-7, which shows ¹H-NMR spectrum different to that of the sulfone *exo*-8. Finally, the results obtained from compounds 2 and 3 allowed us the stereochemical assignment of the exo adducts 6a and 6a'. As it can be seen in Table 1, both dienophiles showed an opposite π -facial selectivity for the *endo* approach, (starting from 3 the adduct 5'a is exclusively formed, whereas in the reactions from dienophile 2 the *endo* adduct with similar stereochemistry to that of 5'a is the minor, except in reaction catalyzed by ZnBr₂), and this should also be the case for the *exo* approach. Therefore, we have assigned to the major *exo*-adduct (*exo*-6'a) obtained from 3 the same stereochemistry to that of the *exo*-



Fig1: X-ray crystal structure of compound endo-5'a.

adduct, which is not formed from dienophile 2.

The comparison of the results obtained from diester 2 with those from triester 3 (see Table 1 and reference 4b) shows that the reactivity of 3 is only slightly higher than that of 2, which indicates a low influence of the third activating group, perhaps due to the steric resonance inhibition. On the other hand, both π -facial and *endo/exo* selectivities are the opposite from each dienophile, and thus *exo*-6'a (the major diastereoisomer obtained from 3) is not observed starting from 2, whereas *endo*-5a (the major component of the mixture obtained from 2 in the most of the conditions) is not detected in the reactions from 3. Moreover, the proportion of diastereoisomers obtained

from **3** was less dependent on the nature of the catalyst than that derived from **2**. The uncatalyzed reaction of **3** (entry 1) as well as those performed under Eu(fod)₃ (entry 2) and ZnBr₂ (entry 3) catalysis, took place with low *exolendo* selectivity (*exolendo* < 2.5). Only the reaction catalyzed by TiCl₄ (entry 4) is highly *exo* selective (*exolendo* = 15). Additionally, the π -facial selectivity is complete for the *endo* approach on dienophile **3** and very high for the *exo* one.

The observed differences in the behavior of both dienophiles (2 and 3) can be explained on the basis of the conformational preferences around the C-S bond. Thus, in Fig 2 are depicted the presumably favored conformations for 2 and 3. Rotamer A-2, exhibiting the *s*-*cis* arrangement of the sulfinyl oxygen, was suggested as the most reactive conformation for compound 2.^{4b} By the contrary, conformation A-3 must be strongly unstabilized due to the interaction SOTol/CO₂Me, which precludes the ester group and the sulfinyl oxygen became coplanar with the double bond. It suggests that B-3 or C-3 were the most stable rotamers for compound 3.⁶ If we assume that the favored approach of the diene takes place from the less hindered face of the dienophile, the fact that such face was the opposite in conformational preferences could also be related to the different *endo/exo* selectivity exhibited by both dienophiles, although this could be attributed to the *endo* orientating character of the substituents⁷. On the other hand, the fact that the third ester group was not conjugated would explain its moderate influence on the dienophilic reactivity.



Fig 2. Presumably favored conformations for dienophiles 2 and 3.

In a second step, we have studied the reactions of **3** with several acyclic dienes. The reactions were studied under $TiCl_4$ catalysis due to the low conversion obtained under thermal conditions or under $ZnBr_2$ or $Eu(fod)_3$ catalysis. The results are given in Table 2.

Table 2. Diels-Alder reaction of 3 with acyclic dienes catalyzed by TiCl₄ in CH₂Cl₂ at -78°C.



^a In pure product after flash chromatography. ^b Determined by ¹H-NMR in the presence of Pr(hfc)3.

As in the case of the reactions of 2 with acyclic dienes,^{4b} the adducts 9, derived from 3, were not stable (they could not be detected by ¹H-NMR) and rapidly evolved by clean elimination of the sulfinyl group to give 1,3-cyclohexadienes 10, which were isolated after chromatography in 78-89% yield. The reactions took place in

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very mild conditions (-78°C, < 1 h in CH₂Cl₂) with 80-90% yields, and afforded only one regioisomer. From the structure of compounds 10 we can conclude that the regioselectivity of the cycloaddition is controlled by the olefinic carbon supporting the *gem*-diester group, (the *gem*-diester group adopts the "*ortho*" and "*para*" positions with respect to the diene substituents at C-1 (entry 2) and C-2 (entry 1) respectively). For 1,2-disubstituted dienes (entries 3 and 4) the favored orientation is that determined by substituents at C-1. Interestingly the observed regioselectivity for dienophiles 3 and 2^{4b} is the opposite, because in the last one, it was controlled by the olefinic carbon bearing the CO₂Bn and SOTol groups. These results suggest that the orientating effect of a CO₂R group is larger than that of a SOTol one.

Unfortunately, the optical purity of dienes 10, determined by ¹H-NMR in the presence of Pr(hfc)₃, is very low (8-18 % *ee*). This suggests that the use of acyclic dienes determines a strong decrease of either the π facial selectivity or the *endo/exo* selectivity (or both). Taking into account the behavior of compound 2 (the π facial selectivity increased with the use of acyclic dienes and only one *endo* and one *exo* adducts were isolated) we propose that the low optical purity of compounds obtained from 3 must be attributed to the strong decrease of the *endo/exo* selectivity, determining the initial formation of nearly 1:1 mixtures of *endo*-9 and *exo*-9 adducts, which respectively evolve into a different enantiomer of compound 10. As the reactions of 2 with acyclic dienes catalyzed by TiCl₄ were more *endo* selective than those with cyclopentadiene, ^{4b} and the reaction of 3 with cyclopentadiene takes place with high *exo*-selectivity (see Table 1), the increase of the *endo* adduct proportion in reaction of 3 with acyclic dienes, and therefore the decrease of the *endo/exo* selectivity, is not unexpected.⁸

Finally, we have studied the effect of the high pressures on some of these reactions, with the aim of improving the stereochemical results (Table 3).

Entry	Diene	Catalyst	Pressure	Reaction Time	Product	Yield (%)
1	Cyclopentadiene		10 Kbar	22 h	<i>exo-</i> 6'a (60%)+ <i>endo-</i> 5'a (40%) ^a	89
2			l bar	3 days	<i>exo-</i> 6'a (62%)+ <i>exo-</i> 6a (8%)	83
					+endo- 5'a (30%) ^a	
3	Piperylene		8 Kbar	48 h	10b (26% <i>ee</i>)	72 ^b
4			l bar	7 days	c	C
5	Piperylene	$ZnBr_2$	12 Kbar	36 h	10b (17% <i>ee</i>)	60
6			l bar	7 days	10b (24% <i>ee</i>)	19d
7	Piperylene	Eu(fod) ₃	11 Kbar	48 h	10b (4% <i>ee</i>)	85
8			l bar	7 days	e	e

Table 3. Effect of the presence in the Diels-Alder reactions of 3 with cyclopentadiene and piperylene.

^a Determined by ¹H-NMR on the crude mixtures. ^b 38% of starting dienophile was recovered. ^c No reaction was observed ^d 81% of starting dienophile was recovered. ^e Complex mixture was obtained.

We have studied only those reactions which at room temperature require long reaction times or do not work. As a consequence of the high pressure, the reactivity is substantially increased. Thus, piperylene reacted under high pressure without catalyst (entry 3) or under Eu(fod)₃ or ZnBr₂ catalysis (entries 5 and 7), whereas all these transformations were not satisfactory at normal pressure (entries 4, 6 and 8). The influence of the pressure on the stereoselectivity can be deduced from the results obtained in the reaction with cyclopentadiene. At normal

pressure, the π -facial selectivity is high but not complete for the *exo* approach (two *exo* adducts are obtained, entry 2), whereas at 10 Kbar, only one *exo* adduct was detected (entry 1). The *endo* approach is completely stereoselective in both conditions. This behavior suggests that the high pressure increases the π -facial selectivity. Nevertheless, the *exo/endo* selectivity is scarcely modified by the pressure and it varies from *exo /endo*= 1.5 at high pressure (entry 1) to *exo /endo*= 2.3 at normal pressure (entry 2). This is also the case in reactions with piperylene. The *ee* of the isolated cyclohexadienes are low and similar to that observed at normal pressure. These results support the assumption that the decrease of the *endo/exo* selectivity must be the main responsible of the low optical purity of the compounds **10** obtained by reaction of triester **3** with acyclic dienes (see above).

From these studies we can conclude that the incorporation of a third ester group into the maleates 2 has scarce influence on its reactivity, but it inverts both the regioselectivity and the π -facial selectivity of their cycloadditions. The *exo* selectivity is also increased which determines that almost equimolecular mixtures of *endo* and *exo* adducts were obtained from acyclic dienes.

EXPERIMENTAL

Melting points were determined with a Gallenkamp apparatus in open capillaries and are uncorrected. ¹H-NMR spectra and ¹³C-NMR spectra were recorded in the FT mode on a Bruker WP-200-SY instrument coupled to an ASPECT 2000 computer, transforming 16K data points. Both chemical shifts (ppm downfield from internal tetramethylsilane) and coupling constants (Hz) were obtained by first order analysis of spin patterns. Mass spectra (MS) were recorded on a Hewlett-Packard 5985 spectrometer with electron impact (EI, 70eV). Mass data are reported in mass units (m/z) and the values in brackets regard the relative intensity from base peak (as 100%). High-resolution mass spectra were determined at an ionizing voltage of 70 eV. Infrared (IR) spectra were recorded on a Philips PU-9716 spectrometer. Optical rotations were measured with a Perkin-Elmer 241 polarimeter. High pressure data were obtained from a High Pressure Apparatus (Unipressequipment Division), maximun pressure 1.3GPa.

Analytical thin-layer chromatography was performed on DC-Alufolien 0.2 mm silica gel 60-F plates (MERCK). Visualization was accomplished with UV light, iodine and ethanolic fosfomolybdic acid solution followed by heating. Flash chromatography was performed by use of silica gel (MN-Kieselgel 60, 230-400 mesh).

All solvents were dried before use. Tetrahydrofuran and ether were distilled from sodium-benzophenone under argon. Dichloromethane and chloroform were distilled from P_2O_5 . Diisopropylamine was distilled from sodium hydroxide. Cyclopentadiene was freshly distilled. Zinc bromide was dried at 160°C for 12h with P_2O_5 under vacuo. Eu(fod)₃, TiCl₄, isoprene, *trans*-1,3-pentadiene, were purchased from Aldrich and used without further purification. Vinylcyclohexene and Dane's diene were prepared according to described procedures.⁹ (+)-(R)-Benzyl p-tolylsulfinylacetate was described according to reference 4b.

(+)-(S)-Benzyl 3,3-diethoxycarbonyl-2-*p*-Tolylsulfinylpropenoate (3).

A solution of (+)-(*R*)-benzyl *p*-tolylsulfinylacetate (1.0 g, 3.5 mmol, 1.0 equiv) in THF (17 ml) was added, under argon atmosphere, to a solution of Li-HMDS 1M in THF (4.2ml, 4.2 mmol, 1.2 equiv), cooled to -78°C. After being stirred for 30 min, a solution of diethyl oxomalonate (587 μ l, 3.8 mmol, 1.1 equiv) was slowly added. Stirring was continued for 4 h. Then, a solution of saturated NH₄Cl (10 ml) was added, and the mixture was extracted with CH₂Cl₂ (2x20 ml). The combined organic layers were dried (MgSO₄), and concentrated to give crude 4 (¹H NMR δ : 1.15 (t, 3H, J = 7.3Hz), 1.16 (t, 3H, J = 7.3 Hz), 1.36 (t, 3H, J =

7.3 Hz), 1.37 (t, 3H, J = 7.3 Hz), 2.38 (s, 3H), 4.16 (m, 4H), 4.37 (m, 4H), 4.70 (s, 1H), 4.85 (s, 1H), 4.90 (AB system, 2H, J = 11.9 Hz), 5.16 (AB system , 2H, J = 12.1 Hz), 7.14-7.36 (m, 14H), 7.55-7.59 (half on an AA'BB' system, 2H), 7.57-7.61 (half on an AA'BB' system, 2H). Crude **4** was dissolved in dry CH₂Cl₂ (14 ml), and Et₃N (1.9 ml, 14 mmol, 4.0 equiv) and MsCl (1.1 ml, 14 mmol, 4.0 equiv) were added at 0°C. The mixture was allowed to stand at rt for 1 h. The mixture was treated with 10% HCl (10 ml) and extracted with CH₂Cl₂ (2x20 ml). The combined organic layers were washed with water (15 ml), dried (MgSO₄), and concentrated. The residue was purified by chromatography (hexane-ethyl acetate 4:1) to give 1.08g (69%) of 3. $[\alpha]^{20}$ D= +71.69 (c = 1.06, CHCl₃), ee \geq 97% . IR (CHCl₃): 2990, 1725, 1495, 1455, 1370, 1260, 1090, and 1020 cm⁻¹.¹H NMR δ : 1.21 (t, 2H, J = 7.1 and 7.3 Hz), 1.38 (t, 2H, J = 7.1 and 7.3 Hz), 2.38 (s, 3H), 4.15 (q, 3H, J = 7.1 Hz), 4.40 (q, 3H, J = 7.1 Hz), 5.11 (s, 2H), 7.18-7.34 (m, 7H), and 7.59-7.63 (half on an AA'BB' system , 2H).¹³C NMR δ : 13.6, 13.8, 21.3, 62.7, 68.0, 125.8, 128.3, 128.4, 128.5, 129.9, 134.1, 137.3, 142.7, 151.3, 160.5, 160.7, and 162.0. MS (EI):444 (5.6, M⁺), 399 (7.8), 337 (14.2), 289 (7.2), 215 (14.5), 171 (14.4), 139 (32.8), 123 (11.9), and 91 (100). HRMS: exact mass calcd for C₂₃H₂₄O₇S-(M⁺) 444.124275, found 444.124050.

Diels-Alder reaction of 3 with cyclopentadiene catalyzed by Eu(fod)3.

A solution of **3** (50.0 mg, 0.11 mmol, 1.0 equiv) in 0.3 ml CH₂Cl₂ was added, under an argon atmosphere, to a solution of Eu(fod)₃ (136.9 mg, 0.13 mmol, 1.2 equiv) in 0.3 ml of CH₂Cl₂ at 0°C. The mixture was stirred for 10 min, and then 55 μ l (0.66 mmol, 6 equiv) of cyclopentadiene was added. Stirring was continued for 2h. Then, 5% HCl (3 ml) was added. The organic layer was separated, and the aqueous layer was extracted with CH₂Cl₂ (2x10 ml). The combined organic layer were washed with water (2 ml), dried (MgSO₄), and concentrated. The mixture was analyzed by ¹H NMR (isomer ratio: 30% *endo-5'a*, 8% *exo-6a*, and 62% *exo-6'a*), and purified by flash cromatgraphy (CH₂Cl₂-Et₂O 40:1) to give 43.2 mg (77% yield) of adducts.

Diels-Alder reaction of 3 with cyclopentadiene catalyzed by ZnBr₂.

A solution of **3** (91.0 mg, 0.20 mmol, 1.0 equiv) in 0.5 ml CH₂Cl₂ was added, under an argon atmosphere, to a suspension of ZnBr₂ (81.1 mg, 0.36 mmol, 1.8 equiv) in 0.5 ml of CH₂Cl₂ at -10°C. The mixture was stirred for 10 min, and then 102 μ l (1.2 mmol, 6 equiv) of cyclopentadiene was added. Stirring was continued for 2h at -10°C. Then, 10% NaHCO₃ (5 ml) was added. The organic layer was separated, and the aqueous layer was extracted with CH₂Cl₂ (2x15 ml). The combined organic layer were washed with water (5 ml), dried (MgSO₄), and concentrated. The mixture was analyzed by ¹H NMR (isomer ratio: 45% *endo-5'a*, 8% *exo-6a*, and 55% *exo-6'a*), and purified by flash cromatography (CH₂Cl₂-Et₂O 40:1) to give 90.8 mg (89% yield) of adducts.

General procedure for the Diels-Alder reaction of 3 catalyzed by TiCl₄.

TiCl₄ (0.30 mmol, 1.2 equiv from a solution 1.0 M in CH₂Cl₂) was added dropwise, under argon atmosphere, to a solution of dienophile **3** (110 mg, 0.25 mmol, 1.0 equiv) in 1.2 ml of CH₂Cl₂ at -78°C. The mixture was stirred for 10 min, and then 6 equiv (1.5 mmol) of the corresponding diene was added. Stirring was continued until dienophile disappered by TLC (the reaction times are indicated in tables 1-2). Then, 10% NaHCO₃ (4 ml) was added. The organic layer was separated and the aqueous layer was extracted with CH₂Cl₂ (2x10 ml). The combined organic layers were washed with water (5 ml), dried (MgSO₄), and concentrated. The residue was purified by flash chromatography (eluents are indicated below for each case and yields are indicated in tables 1 and 2).

General procedure for the Diels-Alder Reactions of 3 under high pressure.

In a high pressure reaction tube was placed a solution of **3** (35 mg, 0.08 mmol, 1.0 equiv) and cyclopentadiene or piperylene (10 equiv) and the catalyst (1.5 equiv of $ZnBr_2$ or $Eu(fod)_3$) in 1.7 ml CH₂Cl₂. After standing at rt for the reaction times and pressures indicated in table 3, the reactions were allowed to reach atmospheric pressure and were treated and isolated as in the case of the reactions conducted under normal pressure (yields are indicated in table 3)

(S_1, S_2, R_4, S_s) -Benzyl 3,3-diethoxycarbonyl-2-(p-tolylsulfinyl)-bicyclo[2.2.1]hept-5-ene-2-carboxylate (endo-5'a).

Diene: Cyclopentadiene. Eluent: CH₂Cl₂-Et₂O 40:1. MP: 117-123°C. $[\alpha]^{20}D = +20.6$ (c = 2.0, CHCl₃). IR (CHCl₃): 2990, 1730, 1460, 1255, 1080, and 1060 cm⁻¹. ¹H NMR δ : 1.19 (t, 3H, J = 7.1 Hz), 1.37 (t, 3H, J = 7.1 Hz), 1.41 (dt, 1H, J = 1.63 and 3.29 Hz), 2.39 (s, 3H), 2.68 (dt, 1H, J = 1.63 and 3.29 Hz), 3.08 (m, 1H), 3.57 (m, 1H), 4.07 (m, 2H), 4.41 (m, 2H), 5.01 and 5.08 (AB system, 2H, J = 3.2 and 5.4 Hz), 7.21-7.23 (half of an AA'BB' system, 2H), and 7.32-7.39 (m, 7H). ¹³C NMR δ : 13.9, 21.5, 45.4, 47.31, 51.6, 61.9, 62.4, 66.9, 67.6, 82.4, 126.2, 126.4, 127.8, 128.1, 128.4, 129.6, 135.2, 136.4, 137.5, 141.9, 142.5, 167.6, 167.9, and 168.7. MS (EI): 510 (0.1, M⁺), 494 (3.6), 403 (8.2), 371 (14.7), 139 (12.5), 91 (100), and 65 (16.1).

(R_1, S_2, S_4, S_s) -Benzyl 3,3-diethoxycarbonyl-2-(p-tolylsulfinyl)-bicyclo[2.2.1]hept-5ene-2-carboxylate (exo-6'a).

Diene: Cyclopentadiene. Eluent: CH₂Cl₂-Et₂O 40:1. $[\alpha]^{20}D = +7.98$ (c = 2.77, CHCl₃). IR (CHCl₃): 2290, 1730, 1460, 1255, 1080, and 1060 cm⁻¹. ¹H NMR δ : 1.16 (t, 2H, J = 7.1 Hz), 1.35 (t, 2H, J = 7.1 Hz), 1.57 (dt, 1H, J = 1.7 and 9.7 Hz), 2.15 (bd, 1H, J = 6.3 Hz), 2.37 (s, 3H), 3.36 (bs, 1H), 3.47 (bs, 1H), 3.91 (m, 3H), 4.18 (m, 3H), 4.81 (AB system, 2H, J = 13.6 Hz), 6.44 (dd, 1H, J = 3.0 and 5.5 Hz), 6.70 (dd, 1H, J = 3.0 and 5.5 Hz), 7.20-7.37 (m, 7H) and 7.58-7.63 (half on an AA'BB' system, 2H). ¹³C-NMR: 13.7, 13.9, 21.3, 46.7, 53.4, 61.9, 62.1, 67.1, 85.9, 126.3, 127.7, 128.0, 128.4, 129.2, 129.6, 136.8, 137.6, 138.9, 141.5, 141.8, 167.2, 168.1, and 169.9. MS (EI): 510 (0.2, M⁺), 494 (3.1), 403 (7.0), 371 (14.2), 139 (15.9), 91 (100), and 65 (15.7).

Benzyl 6,6-diethoxycarbonyl-3-methyl-1,3-cyclohexadien-1-carboxylate (10a).

Diene: isoprene. Eluent: CH₂Cl₂. IR (CHCl₃): 2980, 1720, 1450, 1370, 1255, 1200, 1040, 1020, and 860 cm⁻¹. ¹H NMR δ : 1.18 (t, 6H, J = 7.1 Hz), 1.82 (q, 3H, J = 1.9 Hz), 3.01 (m, 2H), 4.13 (dq, 4H, J = 2.3 and 7.2 Hz), 5.22 (s, 2H), 5.83 (m, 1H), 7.14 (d, 1H, J = 1.3 Hz), and 7.29-7.39 (m, 5H). MS (EI): 313 (16.0), 281 (2.5), 271 (25.0), 252 (16.9), 237 (3.9), 224 (21.5), 208 (13.4), 167 (4.8), 135 (19.4), 119 (35.6), 91 (100), and 65 (5.8).

Benzyl 6,6-diethoxycarbonyl-5-methyl-1,3-cyclohexadien-1-carboxylate (10b).

Dienc: piperylene. Eluent: hexane- ethyl acetate 4:1. ee=24% (ZnBr₂). $[\alpha]^{20}_{D} = -21.0$ (c = 1.42, CHCl₃). IR (CHCl₃): 2980, 2940, 1720, 1450, 1375, 1260, 1210, 1100, and 1030 cm⁻¹. ¹H NMR δ : 1.16 (t, 2H, J = 7.0 Hz), 1.18 (t, 3H, J = 7.0 Hz), 1.24 (d, 2H, J = 7.4 Hz), 3.37 (m, 1H), 4.13 (m, 6H), 5.21 (s, 2H), 6.07 (m, 2H), 7.21 (dd, 1H, J = 1.3 and 5.2), and 7.31-7.38 (m, 5H).¹³C NMR δ : 13.9, 14.0, 15.3, 37.4, 61.3, 61.9, 66.5, 122.0, 128.2, 128.4, 128.5, 129.9, 134.5, 135.9, 139.7, 166.7, 168.6, and 168.9. MS (EI): 327 (0.2), 253 (6.7), 191 (10.0), 163 (18.5), 119 (6.8), 91 (100), and 65 (6.1).

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Benzyl 1,1-diethoxycarbonyl-1,5,6,7,8,8a-hexahydronaphtalene-2-carboxylate (10c).

Diene: Vinylcyclohexene. Eluent: hexane-ethyl acetate 4:1. ee=18%. $[\alpha]^{20} D = + 60.06 (c = 1.7, CHCl_3)$. IR (CHCl_3): 2920, 1710, 1580, 1440, 1360, 1240, 1200, 1130, 1060, and 1020 cm⁻¹. ¹H NMR δ : 1.15 (t, 3H, J = 7.1 Hz), 1.16 (t, 3H, J = 7.1 Hz), 1.29-2.45 (m, 8H), 3.31 (m, 1H), 4.11 (m, 4H), 5.20 (s, 2H), 5.76 (1H, bd, J = 6.1 Hz), and 7.16 (1H, d, J = 6.1 Hz). ¹³C NMR δ : 13.8, 26.4, 29.2, 30.8, 35.8, 46.1, 59.0, 61.2, 61.8, 66.2, 114.6, 122.8, 128.0, 128.1, 128.4, 135.1, 136.3, 152.4, and 168.7. MS (EI): 412 (0.2), 3.39 (1.6), 293 (7.0), 231 (10.1), 203 (21.3), and 91 (100). HRMS: exact mass calcd for C₂₄H₂₈O₆-(M⁺) 412.188589, found 412.187350.

Benzyl 1,1-diethoxycarbonyl-7-methoxy-1,9,10,10a-tetrahydrophenanthrene-2-carboxylate (10d).

Diene: Dane's Diene. Eluent: hexane-ehtyl acetate 10:1. ee = 8%. $[\alpha]^{20}D = +2.1$ (c = 2.5, CHCl₃). IR (CHCl₃): 2980, 2920, 2820, 1710, 1600, 1530, 1490, 1445, 1365, 1260, 1200, 1120, and 1050 cm⁻¹. ¹H NMR δ : 1.09 (t, 2H, J = 7.2 Hz), 1.89 (t, 2H, J = 7.2 Hz), 1.86 (m, 1H), 2.51-3.29 (m, 4H), 3.42 (m, 1H), 3.83 (3H, s), 4.18 (m, 6H), 5.28 (AB system, 2H, J = 12.5 Hz), 6.49 (dd, 1H, J = 2.84 and 6.23 Hz), 6.78 (dd, 1H, J = 2.7 and 8.78 Hz), 7.38-7.41 (m, 5H), 7.39 (d, 1H, J= 7.4 Hz), and 7.60 (d, 1H, J = 8.7 Hz). ¹³C NMR δ : 13.8, 13.9, 24.1, 31.2, 45.2, 55.3, 59.3, 61.1, 61.8, 66.3, 112.9, 113.3, 113.4, 125.5, 125.8, 126.2, 127.9, 128.1, 128.4, 136.3, 141.1, 143.9, 160.2, 165.1, 168.3, and 171.4. MS (EI): 490 (3.0, M⁺), 445 (0.3), 371 (8.2), 3094 (16.1), 281 (20.8), 237 (7.7), 165 (5.3) and 91 (100). HRMS: exact mass calcd for C₂₉H₃₀O₇-(M⁺) 490.199154, found 490.198850.

General procedure for the oxidation of sulfoxides endo-5'a and exo-6'a.

A solution of sulfoxide (*endo-5'a* or *exo-6'a*) (93mg, 0.182 mmol, 1.0 equiv) in 0.7 ml CH₂Cl₂ was added to a solution of MCPBA (50-60%) (126mg, 0.728 mmol, 2.0 equiv) in 1.5 ml of CH₂Cl₂ at 0°C. The mixture was stirred at 0°C for 1h, and then 10% Na₂S₂O₃ (5 ml) was added. The organic layer was separated, and the aqueous layer was extracted with CH₂Cl₂ (2 x 15 ml). The organic layer was separated, and the aqueous layer was extracted with CH₂Cl₂ (2 x 10 ml). The combined organic layers were washed with water (2 ml), dried (MgSO₄), and concentrated. The mixture was analyzed by ¹H NMR and purified by flash cromatography (CH₂Cl₂-hexane 3:1) to give 77.5 mg (81% yield) of sulfone **7** or **8**.

(S_1, S_2, R_4) -Benzyl 3,3-diethoxycarbonyl-2-(p-tolylsulfonyl)-bicyclo[2.2.1]hept-5-ene-2-carboxylate (7).

Eluent: CH₂Cl₂-bexane 3:1. IR (CHCl₃): 2980, 1720, 1330, 1260, 1220, 1140, and 1080 cm⁻¹. ¹H NMR δ : 1.15 (t, 3H, J= 7.2 Hz), 1.35 (t, 3H, J = 7.2 Hz), 1.08 (dt, 1H, J = 1.6 and 9.7 Hz), 2.75 (bd, 1H, J = 9.9 Hz), 2.36 (s, 3H), 3.09 (bs, 1H), 3.89 (bs, 1H), 3.99 (m, 2H), 4.30 (m, 2H), 4.83 (AB system, 2H), 6.43 (dd, 1H, J = 2.8 and 5.4 Hz), 6.69 (dd, 1H, J = 3.1 and 5.4 Hz), 7.19-7.40 (m, 7H), and 7.58-7.62 (half on an AA'BB' system, 2H).

(R_1, S_2, R_4) -Benzyl 3,3-diethoxycarbonyl-2-(p-tolylsulfonyl)-bicyclo[2.2.1]hept-5-ene-2-carboxylate (8).

Eluent: CH₂Cl₂-hexane 3:1. MP: 128-130°C. $[\alpha]^{20}_D = -2.1$ (c =2.86, CHCl₃).IR (CHCl₃): 2980, 1720, 1330, 1260, 1220, 1140, and 1080 cm⁻¹. ¹H NMR δ : 1.05 (t, 3H, J = 7.2 Hz), 1.35 (t, 3H, J = 7.2 Hz), 1.47 (dt, 1H, J = 1.6 and 9.7 Hz), 2.26 (bd, 1H, J = 9.9 Hz), 2.31 (s, 3H), 3.21 (bs, 1H), 3.88 (m, 2H), 4.39 (m, 2H), 4.95 (AB system, 2H, J = 12.9 Hz), 6.43 (dd, 1H, J = 2.8 and 5.4 Hz), 6.67 (dd, 1H, J = 3.1 and 5.4

Hz), 7.15-7.40 (m, 7H) and 7.58-7.62 (half on an AA'BB' system, 2H).¹³C NMR δ : 13.6, 21.5, 45.4, 51.5, 53.8, 61.8, 62.3, 67.6, 69.9, 88.5, 127.5, 127.8, 128.1, 129.1, 129.4, 134.7, 135.7, 137.5, 138.8, 144.7, 167.3, 167.6, and 170.2. MS (EI): 526 (15.8), 415 (20.8), 371 (44.2), 326 (7.8), 279 (18.3), 139 (14.6), 91 (100), and 65 (13.9).

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