Studies of Diastereoselectivity in Conjugate Addition of Organoaluminum Reagents to (*R*)-[(*p*-Tolylsulfinyl)methyl]quinols and Derivatives

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(*R*)-4-Hydroxy-4-[(*p*-tolylsulfinyl)methyl]-2,5-cyclohexadienones **1**−**3**, and **6** reacted with organoaluminum derivatives from the pro-*R* conjugated position in a highly π-facial diastereoselective manner directed by the C-4 OH. A similar facial diastereoselectivity arose from reactions with 3-alkyl-substituted analogues **4** and **5** and 5-alkyl-4-hydroxy-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexenones **10a,b**. Semiempirical calculations (AM1 model) provide data on transition-state energies for additions in full agreement with the experimental results.

Introduction

Asymmetric 1,4-conjugate additions have been efficiently achieved by using chiral electrophiles, nucleophiles, and to a lesser extent, chiral catalysts.[1] The sulfinyl group situated on either the acceptor[2] or the nucleophile[3] can control the diastereofacial selectivity of the conjugate addition. In connection with our investigations devoted to the use of sulfoxides in asymmetric synthesis,[4] we decided to explore the 1,4-conjugate additions on *p*-quinol derivatives **1**−**6** bearing a sulfoxide and a OH group in a remote position from the α,β-unsaturated moiety. The preliminary results we obtained in the reactions of (*R*)-[(*p*-tolylsulfinyl)methyl]-quinols **1** and **2** revealed that only organoaluminum derivatives[5] were able to afford exclusive 1,4-conjugate addition products in the absence of any other metal catalysts in good yield and under mild conditions. Moreover, we observed an efficient desymmetrization of the prochiral dienone moiety: the 1,4-addition occurred in a highly diastereoselective manner[6] from the pro-*R* double bond syn to the face containing the C-4 OH, giving rise to the formation of two stereogenic centers in a single step. The essential role of the δ hydroxy group in directing the site and face selectivity of 1,4-conjugate additions had been pointed out in reactions of similar *p*-quinol derivatives[7] and acyclic systems[8] with Grignard and organolithium reagents. An analogue-controlling effect by a δ-NBn_2 substituent on a 3-keto acrylate has recently been reported.[9] Nevertheless, the dienone desymmetrization of an optically active *p*-quinol had only been achieved in an intramolecular conjugate addition.[10]

The potential usefulness of the resulting 1,4-adducts as building blocks for chiral targets prompted us to extend the scope of the reaction to differently mono- and disubstituted sulfinylmethyl-*p*-quinols **4**−**6** as well as to cyclohexenone derivatives **10a,b** (Table 2). The effects of varying the double-bond substitution on the reactivity of the systems as well as the π-facial diastereoselectivity of the process were evaluated. In the present paper, we report the results of these studies as well as AM1 calculations showing that transition states arising from the reagent approach to the pro-*R* double bond of *p*-quinols from the face containing the OH group are the lowest in energy.

Results and Discussion

Enantiomerically pure (*R*)-4-hydroxy-4-[(*p*-tolylsulfinyl)methyl]-2,5-cyclohexadienones **1**−**3** (Table 1) were prepared as previously described.[5,6b] The synthesis of

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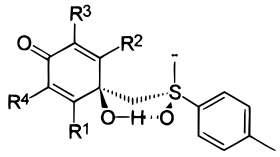
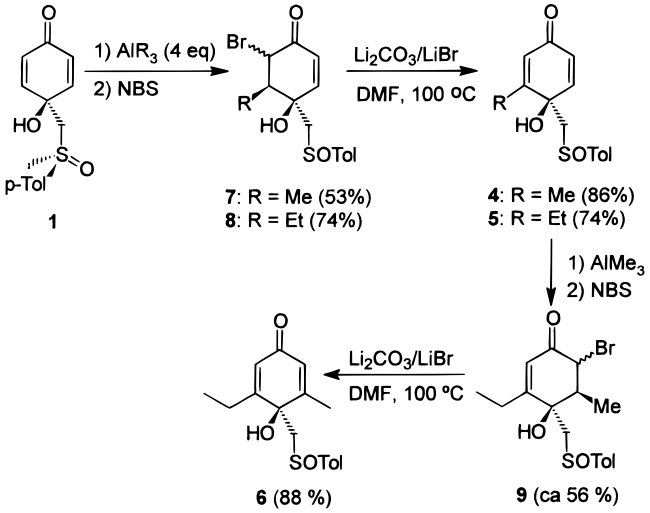
Table 1. ^{1}H NMR Data for Compounds 1−6



1: $R^1 = R^2 = R^3 = R^4 = H$
2: $R^1 = R^2 = Me$, $R^3 = R^4 = H$
3: $R^1 = R^2 = H$, $R^3 = R^4 = Me$
4: $R^1 = Me$, $R^2 = R^3 = R^4 = H$
5: $R^1 = Et$, $R^2 = R^3 = R^4 = H$
6: $R^1 = Et$, $R^2 = Me$, $R^3 = R^4 = H$

	δ in ppm (multiplicity, J in Hz)							
	R^1	R^2	R^3	R^4	OH	AB system	AA′BB′ system	CH_3Ar
1	7.00 (dd, 10.2, 3.2)	7.25 (dd, 12.2, 3.2)	6.29 (dd, 10.2, 1.8)	6.18 (dd, 10.2, 1.9)	4.93	3.16 and 2.85 (13.3)	7.57−7.52 and 7.38−7.34	2.43 (s)
2	2.03 (d, 1.6, 3H)	2.36 (d, 1.6, 3H)	6.16 (q, 1.6)	6.02 (q, 1.6)	4.23	3.29 and 2.79 (13.4)	7.55−7.47 and 7.46−7.36	2.42 (s)
3	6.69 (m)	6.98 (m)	1.94 (d, 1.6, 3H)	1.85 (d, 1.6, 3H)	4.56	3.13 and 2.82 (13.3)	7.57−7.49 and 7.39−7.30	2.42 (s)
4	2.02 (d, 1.5, 3H)	7.49 (d, 10.2)	6.34 (dd, 10.2, 1.5)	6.06 (q, 1.5)		3.32 and 2.63, (13.3)	7.56−7.53 and 7.39−7.32	2.42 (s)
5	2.69−2.59 (m,1H); 2.28−2.15, (m, 1H); 1.11 (t, 7.3, 3H)	7.51 (d, 10.1)	6.33 (dd, 10.1, 1.6)	6.06 (q, 1.6)	5.23	3.33 and 2.62 (13.3)	7.53−7.49 and 7.37−7.34	2.42 (s)
6	2.56−2.47 (m, 1H); 2.20−2.06 (m, 1H); 1.04 (t, 7.3, 3H)	2.24 (s, 3H)	6.09 (s)	5.97 (s)	4.70	3.24 and 2.89 (13.5)	7.42−7.38 and 7.31−7.24	2.40 (s)

Scheme 1



asymmetrically substituted compounds **4** and **5** was achieved from *p*-quinol **1** in a two-pot, three-step sequence based on 1,4-addition of $AlMe_3$ or $AlEt_3$ and trapping the intermediate aluminum enolate with NBS followed by HBr elimination upon heating a DMF solution of bromo derivatives **7** and **8** with Li_2CO_3/LiBr (Scheme 1). Inspection of the crude reaction mixture resulting after NBS treatment revealed that compounds **7** and **8** were stereoselectively formed as 5,6-trans diastereomers, but after chromatographic purification, a 1:1 mixture of cis and trans isomers was recovered. The trans diastereomer of **7** could be isolated diastereomerically pure in a 53% yield. For the preparation of (*R*)-3-ethyl-4-hydroxy-5-methyl-4-[(*p*-tolylsulfinyl)methyl]-2,5-cyclohexadienone (**6**), we followed a similar sequence starting from **5** (Scheme 1): chemoselective 1,4-addition of $AlMe_3$ and trapping with NBS to give **9** (ca. 56% overall yield as a cis−trans mixture) and HBr elimination to afford **6** in a 88% isolated yield.

The absolute configuration of the stereogenic hydroxylic carbons in **4**−**6** could be assigned at this stage on the basis of a comparative analysis of their ^{1}H NMR parameters with those of **1**−**3** (Table 1), whose structure had been already assigned.[6b] All **1**−**6** dervatives showed a rigid structure imposed by the internal hydrogen bonding existent between the hydroxylic proton and the sulfinylic oxygen. This association was evidenced by the chemical shift of the hydroxylic hydrogens which appear at δ 5.23−4.23. In such spiro-like structures, the most significant data for the configurational assignment correspond to the different chemical shift observed for the substituents situated at the olefinic β position (R^1 and R^2 in the figure of Table 1). In the prochiral cyclohexadienone moiety of **1** and **3**, protons labeled as R^1 appear at δ 7.00 and 6.69, respectively, more shielded than those labeled as R^2, which are observed at δ 7.25 and 6.98.

If we compare the chemical shift of R^2 for **1** and **3** with those of **4** and **5**, we observe a high δ value for these protons (δ 7.49 and 7.51). A similar trend in the chemical shifts of the methyl substituents is observed for **2**, where R^1 (δ 2.03) appears more shielded than R^2 (δ 2.36) and for **4** where the methyl substituent R^1 (δ 2.02) is slightly shielded. In the case of **6**, the methyl substituent appears at δ 2.24, a chemical shift similar to that of the methyl labeled as R^2 (δ 2.36) in **2**, whereas the CH_2 of the ethyl group R^1 shows a chemical shift (δ 2.56−2.47) very similar to the corresponding group in **5** (δ 2.69−2.59). Thus, every group placed in the pro-*R* double bond appears more shielded than the same group in the pro-*S* double bond. On this basis, and according with the absolute configuration of the starting sulfoxide, we could assign the configuration [4*R*,(S)*R*] for compounds **4**−**6**.

Organoaluminum Additions. With the desired *p*-quinols in hands, we studied the 1,4-conjugate additions, choosing the simplest derivative **1** as a model. The reactions of **1** with organocuprates,[11] which typically gave conjugate additions, yielded complex reaction mixtures. Only organoaluminum reagents[5,12] gave satisfactory results. The reactions of **1** with $AlR^5R^6_2$ were carried out

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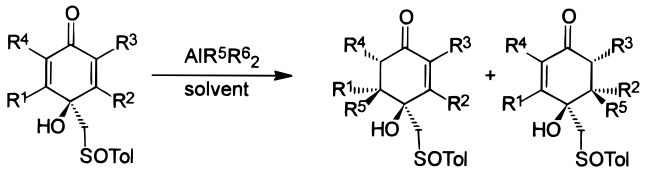
Table 2. Conjugate Additions of $AlR^5R^6_2$ to 1, 2, and 4−6



1, 2, 4-6 **10,12, 17** **11, 15, 16**

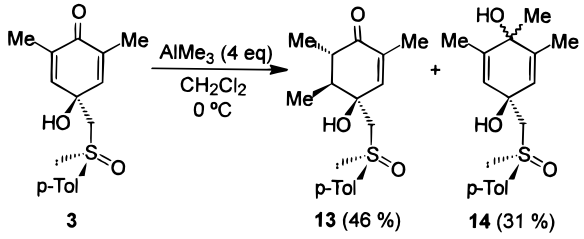
entry	substrate	R^1	R^2	R^3	R^4	R^5	R^6	solvent (equiv)	*T* (°C)	*t*	product	yield (%)
1	**1**	H	H	H	H	Me	Me	CH_2Cl_2 (1)	−78	24 h	**1**	
2	**1**	H	H	H	H	Me	Me	CH_2Cl_2 (2)	−78	24 h	**10a**[a]	
3	**1**	H	H	H	H	Me	Me	CH_2Cl_2 (3)	−78	21 h	**10a**[b]	
4	**1**	H	H	H	H	Me	Me	CH_2Cl_2 (4)	−78	4 h	**10a**	71
5	**1**	H	H	H	H	Me	Me	CH_2Cl_2 (4)	0	30 m	**10a:11a**[c]	70[d]
6	**1**	H	H	H	H	Me	Me	toluene (2)	rt	30 m	**10a: 11a**[c]	79[d]
7	**1**	H	H	H	H	Et	Et	CH_2Cl_2 (4)	−78	3 h	**10b**	89
8	**1**	H	H	H	H	Et	Et	toluene (2)	rt	1 h	**10b:11b**[c]	78[d]
9	**1**	H	H	H	H	TMS-≡-	Me	CH_2Cl_2 (4)	0	2 h	**10c**	69[e]
10	**1**	H	H	H	H	C_4H_9-≡-	Me	CH_2Cl_2 (4)	0	3 h	**10d**	56[e]
11	**1**	H	H	H	H	(*E*)-C_4H_9-=-	Me	CH_2Cl_2 (4)	0	4 h	**10e**	53[e]
12	**2**	Me	Me	H	H	Me	Me	CH_2Cl_2 (4)	0	2 h	**12a**	82
13	**2**	Me	Me	H	H	Me	Me	toluene (2)	rt	24 h	**2**	
14	**2**	Me	Me	H	H	Et	Et	CH_2Cl_2 (4)	0	3 h	**12b**	71
15	**2**	Me	Me	H	H	TMS-≡-	Me	CH_2Cl_2 (4)	0	3 h	**12c**	67
16	**2**	Me	Me	H	H	C_4H_9-≡-	Me	CH_2Cl_2 (4)	0	3 h	**12d**	87
17	**2**	Me	Me	H	H	(*E*)-C_4H_9-=-	Me	CH_2Cl_2 (4)	0	3 h	**12e**	55
18	**4**	Me	H	H	H	Et	Et	CH_2Cl_2 (4)	0	3 h	**15**	48[f]
19	**5**	Et	H	H	H	Me	Me	CH_2Cl_2 (4)	0	3 h	**16**	45[f]
20	**6**	Et	Me	H	H	Me	Me	CH_2Cl_2 (4)	0	4 h	**17**	76

[a] 5% conversion. [b] 66% conversion. [c] An 87:13 mixture of **10**:**11** was formed. [d] Isolated yield of pure **10a**,**b**. [e] In the crude reaction mixture, 5−10% of **10a** and 10−15% of **1** were present. [f] Ca. 20% of a 1:1 mixture of 1,2-addition products.

with an excess of the reagent (4 equiv) at low temperature (−78 or 0 °C) in CH_2Cl_2 to afford only one product **10** (Table 2, entries 4, 7, and 9−11) out of the six possible isomers that could result from 1,2- or 1,4-addition. Compounds **10** resulted from the exclusive 1,4-addition of the organoaluminum reagent to the pro-*R* conjugate position syn to the face containing the hydroxy substituent at C-4.

The use of such a high excess of reagent was necessary to complete the reaction, because with 1 or 2 equiv of $AlMe_3$ the reaction of **1** was not complete at −78 °C (Table 2, entries 1 and 2), and 3 equiv gave only a conversion of 66% (Table 2, entry 3). To overcome the drawback of using such a high excess of reagent, we changed the solvent and the temperature of the reaction. The reaction of **1** with $AlMe_3$ was not complete, working in toluene with 1 or 2 equiv at low temperature (−78 to 0 °C), but with 2 equiv at room temperature (Table 2, entry 6), a 87:13 mixture of **10a** [4*S*,5*S*,(S)*R*] and its [4*R*,5*R*,(S)*R*] isomer **11a**, resulting from 1,4-addition on the pro-*S* double bond from the face bearing the OH, was formed. The major component **10a** could be isolated by chromatography in a 79% yield. In a similar fashion, the reaction between **1** and 2 equiv of $AlEt_3$ in toluene at room temperature (Table 2, entry 8) gave an 87:13 mixture of diastereomers, from which **10b** could be obtained in a 78% yield. These results indicated that the increasing temperature decreased the efficiency of the desymmetrization process but did not affect the π-facial diastereoselectivity. We further confirmed this temperature effect by treating **1** with 4 equiv of $AlMe_3$ in CH_2Cl_2 at 0 °C (Table 2, entry 5), observing the formation of a small amount of diastereomer **11a**. After such experiments, we conclude that the use of an excess of reagent and a low temperature (−78 to 0 °C) should warrant the overall efficiency of the process. Thus, the reactions of

Scheme 2



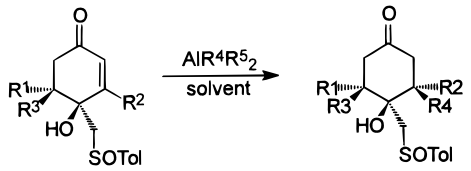
3 **13** (46 %) **14** (31 %)

1 with TMSC≡C$AlMe_2$ (Table 2, entry 9), C_4H_9C≡C$AlMe_2$ (Table 2, entry 10), and (*E*)-C_4H_9C=CH$AlMe_2$ (Table 2, entry 11) yielded **10c**−**e** as a single diastereomer in every case.

p-Quinol derivative **2** (a β,β'-disubstituted enone) behaved similarly toward trialkyl (Table 2, entries 12 and 14), alkynyl (entries 15 and 16), or vinylalanes (Table 2, entry 17) when the reactions were run in CH_2Cl_2, giving rise to compounds **12** in a highly selective manner. Nevertheless, in this case, the addition did not occur in toluene with 2 equiv of $AlMe_3$ at room temperature even after 24 h (Table 2, entry 13), probably as a consequence of the diminished electrophilic character of the alkyl-substituted dienone moiety.

When the substrate was 4-hydroxy-2,6-dimethyl-4-[(*p*-tolylsulfinyl)methyl]-*p*-quinol (**3**), the treatment with $AlMe_3$ (4 equiv) led to different results (Scheme 2). Thus, at 0 °C, the reaction was complete within 4 h, yielding a mixture of the expected derivative **13** (46% isolated yield) and two diastereomeric carbinols **14** (a 1:1 mixture, 31% yield) resulting from 1,2-addition of the reagent to the carbonyl group of the cyclohexadienone. The difficulties in getting the 1,4-addition product, in this case, could be a consequence of their diminished electrophilic character (see above). The formation of two epimeric carbinols in the 1,2-addition was surprising since reactions of meth-

Table 3. Conjugate Additions of $AlR^4R^5_2$ to 10a,b and 12a,b



10,12 **18,19**

entry	substrate	R^1	R^2	R^3	R^4	R^5	solvent (equiv)	*T* (°C)	*t*	product	yield (%)
1	**10a**	H	H	Me	Me	Me	CH_2Cl_2 (4)	−78	4 h	**18a**	53
2	**10a**	H	H	Me	Me	Me	CH_2Cl_2 (2)	0	30 m	**18a**	87
3	**10a**	H	H	Me	Me	Me	toluene (2)	0	30 m	**18a**	82
4	**10a**	H	H	Me	Et	Et	CH_2Cl_2 (4)	−78	4 h	**18b**	65
5	**10a**	H	H	Me	TMS-≡-	Me	CH_2Cl_2 (4)	−78	4 h	**18c**[a]	55
6	**10a**	H	H	Me	TMS-≡-	Et	CH_2Cl_2 (4)	−78	4 h	**18c**[b]	25
7	**10b**	H	H	Et	Me	Me	CH_2Cl_2 (4)	−78	4 h	**19a**	90
8	**10b**	H	H	Et	TMS-≡-	Me	CH_2Cl_2 (4)	−78	4 h	**19c**[c]	57
9	**12a**	Me	Me	Me	Et	Et	CH_2Cl_2 (4)	0	4 h	**12a**	
10	**12b**	Me	Me	Et	Me	Me	CH_2Cl_2 (4)	30	3 h	**12b**	

[a] In the crude reaction mixture, a 10% of **18a** was present. [b] In the crude reaction mixture, a 30% of **18b** was present. [c] In the crude reaction mixture, a 10% of **19a** was present.

ylmagnesium bromide or methyllithium with *p*-quinol derivatives[13] or [1′-(trifluoromethyl)-4,4-propylenedioxy]-2,5-cyclohexadien-1-one,[14] showing a remote differentiation of both diastereotopic faces similar to that found in **3**, evolve diastereoselectively. In our case, the electrophilic nature of the aluminum reagent could be responsible for such a lack of diastereoselectivity.

With asymmetrically substituted *p*-quinol **6**, the 1,4-addition of $AlMe_3$ was also highly chemoselective and π-facial diastereoselective. Thus, compound **17**, resulting from reaction of $AlMe_3$ on the pro-*R* double bond, bearing the ethyl substituent, was formed in 76% yield (Table 2, entry 20). When the reaction was carried out on monoalkyl-substituted compounds **4** and **5**, the system evolved preferentially from the pro-*S* unsubstituted double bond with π-facial diastereoselectivity governed by the OH (Table 2, entries 18 and 19) to give **15** and **16**, respectively. The lower reactivity of the alkyl-substituted pro-*R* double bond should be in the origin of this result.

We further studied the behavior of compounds **10a**, **10b**, **12a**, and **12b**, which contain an α,β-unsaturated cyclohexenone moiety with the hydroxy and *p*-tolylsulfinyl methyl substituent in the δ position, in the presence of organoaluminum reagents. The results are collected in Table 3. Starting from **10a**, compounds **18a**−**c**, which resulted from the exclusive 1,4-conjugate addition, were always formed (Table 3, entries 1−6). Improved yields were achieved with $AlMe_3$ working at 0 °C, both in CH_2Cl_2 (Table 3, entry 2) or toluene (Table 3, entry 3), and 2 equiv of the organoaluminum derivative. When the group to be transferred was TMS−C≡C− (Table 3, entries 5 and 6), a small percentage of the product resulting from the transfer of R^5 (Me or Et) was detected. Derivative **10b** behaved similarly. In all cases, a complete π-facial diastereoselective process occurred syn to the face containing the hydroxy substituent. In contrast, compounds **12a**,**b** did not react with an excess of $AlEt_3$ or $AlMe_3$ (Table 3, entries 9 and 10). The presence of the alkyl substituent at the olefinic β-carbon and/or two alkyl substituents at C-5 of the cyclohexenone in **12a**,**b** precluded both the conjugate and the 1,2-addition. Taking into account that β,β'-alkyl-substituted *p*-quinols **2** and **6** lead to the 1,4-addition products at 0 °C (Table 2, entries 12−17 and 20), the lack of evolution observed in the case of **12a**,**b** could be attributed to the substitution at C-5, which could hinder the approach of any nucleophile either at C-1 or C-3 due to the flexible transition state that emerges from the equatorial attack.[15]

A detailed comparative analysis of the ^{1}H NMR parameters of compounds **10a**−**e**, **12a**−**e**, and **15**−**17** with those of **10b**, whose structure had been unequivocally established by X-ray,[5] enabled the unambiguous configurational assignments shown in Table 2. In the case of compounds **18** and **19**, a simple chemical transformation of **18a** based on the *m*-CPBA oxidation of the sulfoxide to a sulfone led to a meso compound showing a simplified ^{1}H NMR spectrum. The symmetry found in the sulfone could only result from the sulfoxide precursor **18a** bearing both methyl substituents at C-3 and C-5 on the same face. On this basis, we assumed that the stereochemistry of compounds **18** and **19** is that indicated in Table 3.

Several aspects of the results presented are noteworthy. The high reactivity shown by organoalanes with our 4-hydroxy-4-[(*p*-tolylsulfinyl)methyl]-substituted enones is surprising because such an easy 1,4-addition had only been found in a few cases for simple alanes reacting with enones that can adopt an s-cis conformation[16] or cyclopentenones with a hydroxy group at δ-position[17] or in the presence of some transition metals.[18] In the absence of any other metal, the 1,4-transfer was only possible via a free-radical process[19] or by using dialkylaluminum halides.[20] In our case, we could disregard a free-radical process based on a control experiment in the presence of

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(18) For recent references see: (a) Flemming, S.; Kabbara, J.; Nickisch, K.; Neh, H.; Westermann, J. *Synthesis* **1995**, 317−20. (b) Kabbara, J.; Flemming, S.; Nickisch, K.; Neh, H.; Westermann, J. *Tetrahedron* **1995**, *51*, 743−54. (c) Westermann, J.; Nickisch, K. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1368−70. (d) Takemoto, Y.; Kuraoka, S.; Hamaue, N.; Iwata, C. *Tetrahedron: Asymmetry* **1996**, *7*, 993−6.
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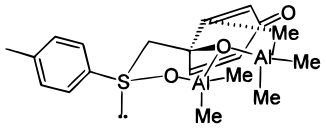

Figure 1. Associated transition state leading to high site and diastereofacial selectivity.

the radical scavenger galvinoxyl with **1** and $AlMe_3$. The high π-facial diastereoselectivity directed by the OH could be expected considering the similar diastereoselective 1,4-addition found in Grignard reactions on lithium alkoxides of *p*-quinols[8a] in racemic series. Moreover, we could assume an essential role of the free OH[21] in directing the reaction to the conjugate position since the reaction of different organometallic species with *p*-quinol derivatives having no free OH proceeded through stereoselective 1,2-addition.[13,14,22] Even more remarkable was the effective diastereotopic C=C bond selection observed when prochiral cyclohexadienones were present, since to our knowledge, the dienone desymmetrization of an optically active *p*-quinol had only been achieved in an intramolecular conjugate addition.[10]

On the basis of a set of experiments previously reported,[5] we could rationalize the role of the OH and the sulfoxide in promoting the 1,4-addition and effecting the desymmetrization of the dienone moiety. A possible transition state for the reaction between **1** and $AlMe_3$, as a model system, is shown in Figure 1.

A stoichiometric addition of $AlMe_3$ to **1** produced the formation of an unreactive aluminum alkoxide where the metal is associated with the sulfinylic oxygen. This species has a frozen chairlike conformation by the equatorial *p*-tolyl group. In such an arrangement, the axial methyl group linked to the aluminum atom is hindering the pro-*S* double bond to any nucleophile approach from the face containing the alkoxide group and renders only the pro-*R* conjugate position available. This could be the origin of the diastereotopic group selection. A second alane equivalent should begin the addition assisted by the alkoxide oxygen. The use of an excess of aluminum reagent warrants the completion due to the association between the reagent and the sulfinylic oxygen, which could retard the intramolecular transfer assisted by the alkoxide and the association to the carbonyl oxygen, which activates the enone moiety. When pro-*R* positions have an alkyl substituent, the more electrophilic pro-*S* double bond reacts preferentially as was the case in *p*-quinols **4** and **5** to yield **15** and **16**.

To find further support to our mechanistic proposal, we undertook a theoretical study of the energy content of the two possible transition states giving rise to the attack of the alkylalane syn to the face containing the OH by using the semiempiric method AM1.[23] We assumed that at least 2 equiv of $AlMe_3$ was necessary for the reaction. We first calculated the geometry of minimum energy content for the transition state of the syn addition on the pro-*R* double bond [[(S)*R*]-**TS1** in Figure 2]. The transition state for syn addition on the pro-*S* double bond [[(S)*S*]-**TS2** in Figure 2] was modeled by changing sulfur configuration in (S)*R*-**TS1**. Figure 2 presents the geometries[24] and energies of these transition states, which give rise to the [4*S*,5*S*,(S)*R*] isomer **10a** [[(S)*R*]-**TS1**] and to the [4*S*,5*S*,(S)*S*] isomer, corresponding to the enantiomer of compound **11a** [[(S)*S*]-**TS2**]. Both structures were fully optimized followed by vibrational frequency calculations, which confirmed that transition structures have one imaginary frequency.

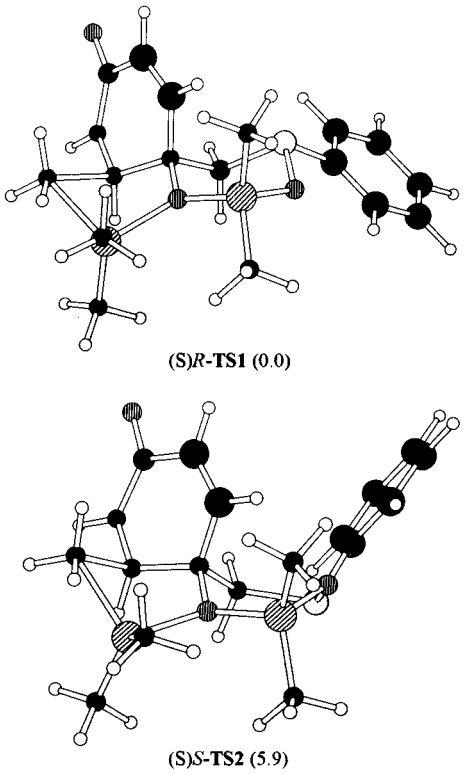

Figure 2. AM1 transition states for conjugate addition of $AlMe_3$ (relative energies in kJ·mol^{-1}).

Data indicated in Figure 2 show that transition state [(S)*S*]-**TS2** has higher energy than [(S)*R*]-**TS1** ($\Delta E = 5.9$ kJ mol^{-1}). This is consistent with complete pro-*R* double bond evolution experimentally observed at −78 °C (de > 95%) and matches well with the formation of a 13% of the product resulting from the pro-*S* double bond approach (74% de of **10a**) observed at 0 °C (theoretically, a 85% de would be observed). A detailed analysis of the geometry represented in Figure 2 for the most stable [(S)*R*]-**TS1** revealed that the moiety with the aluminum alkoxide associated to the sulfinyl oxygen is adopting a chairlike conformation with the *p*-tolyl substituent in a pseudoequatorial position, and a second $AlMe_3$ equivalent is transferring a methyl group to the pro-*R* double bond, through a favorable five-membered ring formed by association to the alkoxide oxygen. From this analysis, no evidence of a blocked pro-*S* double bond in [(S)*R*]-**TS1** arose. Thus, the efficient desymmetrization observed can only be a consequence of the different stability [(S)*R*]-**TS1** and [(S)*S*]-**TS2**. The geometry shown in Figure 2 for the latter revealed a boatlike unstable conformation

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(21) The reaction of methyl-protected *p*-quinol **1** with $AlMe_3$ (4 equiv) led to a mixture of 1,2-syn (8%) and 1,2-anti (2%) addition products and 90% of starting material. See ref 5.

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(24) Optimized geometries of both structures are available from the authors.

for the six-membered ring species resulting from the association of the aluminum alkoxide and the sulfinylic oxygen, which can be in the origin of its lower stability.

Conclusion

The 1,4-conjugate addition to *p*-quinols **1**−**6** and 4-hydroxy-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexenones **10a** and **10b** was achieved with organoaluminum derivatives in a highly diastereoselective manner directed by the OH substituent, which acts as an anchimeric assistant in the transfer of the reagent. The sulfoxide is introducing optical activity to the enone. Moreover, in the case of *p*-quinols **1**−**3**, the sulfinyl group is playing an essential role in the desymmetrization of the prochiral cyclohexadienone moiety or, in the case of substrate **6**, effecting a chemoselective addition. A mechanistic proposal supported by semiempirical AM1 calculations, based on the assisted intramolecular transfer of the organoaluminum reagent, could justify the easy and controlled formation of a stereogenic tertiary or quaternary center. At present, we are applying the good results obtained to the asymmetric synthesis of complex molecules.

Experimental Section

All moisture-sensitive reactions were performed in oven- or flame-dried glassware equipped with rubber septa under a positive pressure of argon. Solvents were dried according to literature procedures,[25] and commercial reagents were used without further purification. Melting points were determined in open capillaries. Proton spectra were recorded at 200.1 or 300.1 MHz, and ^{1}H NMR data of compounds **4**−**6** are collected in Table 2. Carbon spectra were recorded at 50.3 or 75.4 MHz. Combustion analyses were performed at the Servicio de Investigación de la Universidad Autónoma de Madrid (SIdI).

Method A: $AlMe_3$ and $AlEt_3$ Additions. A solution of 1 equiv of *p*-quinol **1**−**6** (0.2 M in dried CH_2Cl_2) was added to a solution of 4 equiv of trialkylaluminun in hexane (2 M for $AlMe_3$ and 1 M for $AlEt_3$) diluted in the same volume of CH_2Cl_2. The temperature for each reaction is indicated in Tables 2 and 3. The reaction was monitored by TLC (AcOEt/hexane 3:1). The excess organoaluminum reagent was destroyed with methanol, and the mixture was poured into an Erlenmeyer containing ethyl acetate and a saturated solution of sodium potasium tartrate and stirred vigorously for 30 min. The organic layer was washed with brine, dried over Na_2SO_4, filtered, and concentrated in vacuo.

Method B: Synthesis of α-Bromo Derivatives. A solution of 1 equiv of *p*-quinols **1**, **4**, and **5** was added to a solution of 4 equiv of trialkylaluminum in hexane (2 M for $AlMe_3$ and 1 M for $AlEt_3$) diluted in the same volume of CH_2Cl_2. The temperature for each reaction is indicated in Tables 2 and 3. Once the reaction was completed, the mixture was diluted with the same volume of THF, and a solution (0.5 M) of NBS (3 equiv) in THF was added at −78 °C. After 30 min, the reaction mixture was treated as in method A.

Method C: Hydrogen Bromide Elimination. Lithium bromide (3 equiv) and lithium carbonate (3.1 equiv) were added to a solution of **7**−**9** (ca. 0.15 M) in DMF. After 1 h at 100 °C, the mixture was cooled at room temperature and poured into a separatory funnel containing water. The mixture was extracted three times with ethyl acetate, and the solvent extracts were washed with brine, dried with Na_2SO_4, and evaporated to dryness.

[4*R*,5*R*,6*S*,(S)*R*]-6-Bromo-4-hydroxy-5-methyl-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexen-1-one (7). Compound **7** was obtained from 1 g of **1** following method B and purified by flash chromatography (AcOEt/hexane 1:1) in 53% yield as a white solid: mp 151 °C dec; $[\alpha]^{20}_D = +127$ (*c* 0.99, $CHCl_3$); ^{1}H NMR δ 7.59−7.53 (AA′, 2H), 7.45 (d, J = 10.2 Hz, 1H), 7.44−7.37 (BB′, 2H), 6.25 (d, J = 10.2 Hz, 1H), 5.06 (s, OH), 4.77 (d, J = 9.8 Hz, 1H), 3.30 (d, J = 13.3 Hz, 1H), 3.01 (d, J = 13.3 Hz, 1H), 2.45 (s, 3H), 2.38 (dq, J = 9.8, 7.2 Hz, 1H), 1.32 (d, J = 7.2 Hz, 3H); ^{13}C NMR δ 190.8, 149.3, 142.5, 139.0, 130.3 (2C), 127.0, 123.8 (2C), 71.2, 64.8, 56.5, 46.2, 21.3, 14.8.

[4*R*,5*R*,6*S*,(S)*R*]- and [4*R*,5*R*,6*R*,(S)*R*]-6-Bromo-5-ethyl-4-hydroxy-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexen-1-one (8). Compound **8** was obtained from 500 mg of **1** following method B and purified by flash chromatography (CH_2Cl_2/acetone from 15:1 to 10:1) in 74% yield as a colorless oil mixture of epimers in C_6. Spectroscopic data for compound **8** as a single epimer were obtained from the crude reaction: ^{1}H NMR δ 7.56−7.52 (AA′, 2H), 7.38−7.34 (BB′, 2H), 7.30 (dd, J = 10.5, 1.2 Hz, 1H), 6.16 (d, J = 10.5 Hz, 1H), 5.36 (s, OH), 4.70 (d, J = 6.1 Hz, 1H), 3.53 (d, J = 13.4 Hz, 1H), 3.29 (d, J = 13.4 Hz, 1H), 2.42 (s, 3H), 2.32−2.26 (m, 1H), 2.20−2.01 (m, 1H), 1.39 (dq, J = 14.7, 7.5 Hz, 1H), 0.99 (t, J = 7.5 Hz, 3H); ^{13}C NMR δ 190.8, 150.4, 142.7, 139.4, 130.4 (2C), 126.7, 123.9 (2C), 72.2, 65.5, 53.4, 50.8, 22.2, 21.4, 12.7.

[4*R*,5*R*,6*S*,(S)*R*]- and [4*R*,5*R*,6*R*,(S)*R*]-6-Bromo-3-ethyl-4-hydroxy-5-methyl-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexen-1-one (9). Compound **9** was obtained as a 69:31 mixture of epimers from 230 mg of **5** following method B and was flash purified by flash chromatography (AcOEt/hexane 1:3): ^{1}H NMR δ 7.61−7.52 (AA′, 2H), 7.40−7.27 (BB′, 2H), 5.93 (s, 1/3H), 5.87 (s, 2/3H), 5.32 (s, 2/3OH), 5.02 (d, J = 4.3 Hz, 1/3H), 4.99 (s, 1/3OH), 4.53 (d, J = 2.1 Hz, 2/3H), 3.75 (d, J = 13.4 Hz, 2/3H), 3.62−3.44 (m, 1H), 3.25 (d, J = 14.0 Hz, 1/3H), 3.16 (d, J = 13.4 Hz, 2/3H), 2.93 (d, J = 14.0 Hz, 1/3H), 2.63−2.47 (m, 1H), 2.44 (s, 1/3 3H), 2.43 (s, 2/3 3H), 2.38−2.16 (m, 1H), 1.33 (d, J = 7.0 Hz, 2/3 3H), 1.29 (d, J = 7.0 Hz, 1/3 3H), 1.07 (t, J = 7.0 Hz, 3H).

[4*R*,(S)*R*]-4-Hydroxy-3-methyl-4-[(*p*-tolylsulfinyl)methyl]-2,5-cyclohexadien-1-one (4). Compound **4** was obtained from 389 mg of **7** following method C and purified by flash chromatography (AcOEt/hexane 3:1) in 86% yield as a pale yellow solid: mp 114.5−116 °C; $[\alpha]^{20}_D = +69$ (*c* 1.00, $CHCl_3$); ^{13}C NMR δ 184.8, 159.0, 149.3, 142.9, 139.7, 130.4 (2C), 128.3, 126.7, 123.8 (2C), 71.5, 65.0, 21.4, 18.2.

[4*R*,(S)*R*]-3-Ethyl-4-hydroxy-4-[(*p*-tolylsulfinyl)methyl]-2,5-cyclohexadien-1-one (5). Compound **5** was obtained from 389 mg of **8** following method C and purified by flash chromatography (CH_2Cl_2/acetone 10:1) in 74% yield as a pale yellow solid: mp 122−123 °C; $[\alpha]^{20}_D = +49$ (*c* 1.00, $CHCl_3$); ^{13}C NMR δ 185.1, 164.4, 149.8, 142.7, 139.8, 130.3 (2C), 128.0, 124.4, 123.8 (2C), 71.5, 65.9, 22.9, 21.4, 11.0. Anal. Calcd for $C_{16}H_{18}O_3S$: C, 66.18; H, 6.25; S, 11.04. Found C, 66.22; H, 6.33; S, 11.30.

[4*R*,(S)*R*]-3-Ethyl-4-hydroxy-5-methyl-4-[(*p*-tolylsulfinyl)methyl]-2,5-cyclohexadien-1-one (6). Compound **6** was obtained from 230 mg of **9** following method C and purified by flash chromatography (AcOEt/hexane 3:2) in 88% yield as a pale yellow solid: mp 125−126 °C; $[\alpha]^{20}_D = +53$ (*c* 1.11, $CHCl_3$); ^{13}C NMR δ 185.2, 165.2, 161.3, 142.5, 140.1, 130.3 (2C), 127.3, 125.1, 123.9 (2C), 73.6, 65.6, 23.0, 21.4, 19.5, 11.4. Anal. Calcd for $C_{17}H_{20}O_3S$: C, 67.08; H, 6.62; S, 10.53. Found: C, 67.16; H, 6.72; S, 10.95.

Method D: Alkynyldimethylaluminum Additions. To a solution of (trimethylsilyl)acetylene (5 equiv, 1 M) in hexane at 0 °C was added *n*-BuLi (5 equiv, 2.5 M) in hexane, and the heterogeneous mixture was stirred for 30 min. A commercial solution of $AlMe_2Cl$ (5 equiv, 1 M in hexane) was added at the same temperature and then stirred for 30 min at room temperature. The mixture was concentrated in vacuo to obtain a solution ca. 1 M. After cooling at 0 °C, a solution of 1 equiv of the indicated compound (1 equiv, 0.2 M in dried CH_2Cl_2) was added. From here we followed method A.

[4*R*,5*S*,6*R*,(S)*R*]-4-Hydroxy-2,5,6-trimethyl-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexen-1-one (13). Compound **13** was obtained from 166 mg of **3** following method A ($AlMe_3$) and purified by flash chromatography (AcOEt/hexane 1:2) in 46% yield as a white solid: mp 188 °C dec; $[\alpha]^{20}_D = +217$ (*c* 1.02, $CHCl_3$); ^{1}H NMR δ 7.59−7.53 (AA′, 2H), 7.38−7.32 (BB′,

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2H), 6.72 (dq, J = 2.2, 1.4 Hz, 1H), 4.94 (s, OH), 3.24 (A, J = 13.1 Hz, 1H), 3.13 (B, J = 13.1 Hz, 1H), 2.57 (qd, J = 6.7, 4.0 Hz, 1H), 2.42 (s, 3H), 2.28 (qdd, J = 6.7, 4.0, 2.3 Hz, 1H), 1.84 (d, J = 1.4 Hz, 3H), 1.07 (d, J = 6.7 Hz, 3H), 0.93 (d, J = 6.9 Hz, 3H); ^{13}C NMR δ 200.4, 143.8, 142.4, 140.3, 135.8, 130.3 (2C), 123.9 (2C), 74.3, 64.9, 46.8, 43.6, 21.4, 15.7, 12.8, 8.1. Anal. Calcd for $C_{17}H_{22}O_3S$: C, 66.64; H, 7.24; S, 10.46. Found: C, 66.40; H, 7.33; S, 10.40.

[4*R*,5*R*,(S)*R*]-5-Ethyl-4-hydroxy-3-methyl-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexen-1-one (15). Compound **15** was obtained from 95 mg of **4** following method A ($AlEt_3$) and purified by flash chromatography (AcOEt/hexane 1:3) in 48% yield as a colorless oil: $[\alpha]^{20}_D = -75$ (*c* 1.40, $CHCl_3$); ^{1}H NMR δ 7.55−7.52 (AA′, 2H), 7.36−7.33 (BB′, 2H), 5.75 (quint, J = 1.2 Hz, 1H), 4.76 (s, OH), 3.19 (d, J = 13.7 Hz, 1H), 2.90 (d, J = 13.7 Hz, 1H), 2.78−2.69 (m, 2H), 2.58−2.50 (m, 1H), 2.41 (s, 3H), 2.12−2.04 (m, 1H), 1.95 (s, 3H), 1.28−1.17 (m, 1H), 0.97 (t, J = 7.5 Hz, 3H); ^{13}C NMR δ 196.5, 163.3, 124.7, 139.4, 130.4 (2C), 126.6, 123.9 (2C), 76.2, 62.3, 44.9, 38.9, 21.4, 20.3, 19.0, 12.1.

[4*S*,5*R*,(S)*R*]-3-Ethyl-4-hydroxy-5-methyl-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexen-1-one (16). Compound **16** was obtained from 60 mg of **5** following method A ($AlMe_3$) and purified by flash chromatography (AcOEt/hexane 1:3) in 45% yield as a colorless oil: $[\alpha]^{20}_D = -67$ (*c* 1.10, $CHCl_3$); ^{1}H NMR δ 7.56−7.51 (AA′, 2H), 7.38−7.34 (BB′, 2H), 5.76 (d, J = 1.3 Hz, 1H), 4.74 (s, OH), 3.19 (d, J = 13.7 Hz, 1H), 3.16−2.90 (m, 1H), 2.87 (d, J = 13.7 Hz, 1H), 2.67 (dd, J = 18.0, 5.0 Hz, 1H), 2.56−2.45 (m, 2H), 2.42 (s, 3H), 2.22 (dqd, J = 17.8, 7.3, 1.6 Hz, 1H), 1.19 (d, J = 6.9 Hz, 3H), 1.04 (t, J = 7.2 Hz, 3H); ^{13}C NMR (C_6D_6) δ 195.4, 166.5, 142.0, 140.9, 130.3 (2C), 124.4, 124.1, 76.9, 62.7, 43.0, 38.3, 24.3, 21.1, 15.0, 11.6.

[4*S*,5*R*,(S)*R*]-5-Ethyl-4-hydroxy-3,5-dimethyl-4-[(*p*-tolylsulfinyl)methyl]-2-cyclohexen-1-one (17). Compound **17** was obtained from 90 mg of **6** following method A ($AlMe_3$) and purified by flash chromatography (AcOEt/hexane 1:3) in 97% yield as a colorless oil: $[\alpha]^{20}_D = +176$ (*c* 1.15, $CHCl_3$); ^{1}H NMR δ 7.52−7.48 (AA′, 2H), 7.34−7.30 (BB′, 2H), 6.00 (t, J = 1.3 Hz, 1H), 4.93 (s, OH), 3.22 (d, J = 12.9 Hz, 1H), 2.68 (d, J = 12.9 Hz, 1H), 2.39 (s, 3H), 2.36 (d, J = 1.6 Hz, 3H), 2.33 (d, J = 18.2 Hz, 1H), 2.04 (d, J = 18.2 Hz, 1H), 1.77 (dq, J = 13.3, 7.5 Hz, 1H), 1.26 (dq, J = 13.3, 7.2 Hz, 1H), 0.99 (s, 3H), 0.82 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 196.9, 167.3, 142.6, 139.8, 130.3 (2C), 126.6, 123.8 (2C), 76.6, 63.8, 46.3, 44.7, 28.4, 22.2, 21.3, 17.7, 7.9.

[3*R*,4*S*,5*S*,(S)*R*]-4-Hydroxy-3,5-dimethyl-4-[(*p*-tolylsulfinyl)methyl]cyclohexan-1-one (18a). Compound **18a** was obtained from 61 mg of **10a** following method A ($AlMe_3$) and purified by flash chromatography (AcOEt/hexane 1:1) in 87% yield as a white solid: mp 162−163 °C; $[\alpha]^{20}_D = +223$ (*c* 1.00, $CHCl_3$); ^{1}H NMR δ 7.55−7.50 (AA′, 2H), 7.35−7.31 (BB′, 2H), 3.25 (d, J = 13.9 Hz, 1H), 3.03 (s, OH), 2.73 (d, J = 13.9 Hz, 1H), 2.60−2.50 (m, 2H), 2.42 (s, 3H), 2.34−2.14 (m, 4H), 1.20 (d, J = 6.4 Hz, 3H), 1.05 (d, J = 6.4 Hz, 3H); ^{13}C NMR δ 210.0, 142.1, 141.1, 130.2 (2C), 123.8 (2C), 73.6, 63.3, 45.2, 44.9, 40.8, 39.8, 21.4, 16.1, 15.5. Anal. Calcd for $C_{16}H_{22}O_3S$: C, 65.28; H,7.53; S, 10.89. Found: C, 65.11; H, 7.67; S, 11.20.

[3*R*,4*S*,5*S*,(S)*R*]-3-Ethyl-4-hydroxy-5-methyl-4-[(*p*-tolylsulfinyl)methyl]cyclohexan-1-one (18b). Compound **18b** was obtained from 300 mg of **10a** following method A ($AlEt_3$) and purified by flash chromatography (AcOEt/hexane 1:2) in 65% yield as a white solid: mp 151.4−152.0 °C; $[\alpha]^{20}_D = +200$ (*c* 1.04, $CHCl_3$); ^{1}H NMR δ 7.57−7.52 (AA′, 2H), 7.37−7.32 (BB′, 2H), 3.31 (d, J = 14.0 Hz, 1H), 2.81 (s, OH), 2.78 (d, J = 14.0 Hz, 1H), 2.65−2.41 (m, 3H), 2.43 (s, 3H), 2.34−2.16 (m, 2H), 2.13−1.94 (m, 2H), 1.65−1.39 (m, 1H), 1.06 (d, J = 6.3 Hz, 3H), 0.97 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 210.5, 142.0, 141.0, 130.2 (2C), 123.8 (2C), 74.0, 63.1, 47.1, 44.8, 41.1, 39.9, 22.6, 21.4, 15.5, 11.4. Anal. Calcd for $C_{17}H_{24}O_3S$: C, 66.20; H, 7.84; S, 10.39. Found: C, 65.88; H, 7.70; S, 10.72.

[3*S*,4*S*,5*S*,(S)*R*]-4-Hydroxy-3-methyl-4-[(*p*-tolylsulfinyl)methyl]-5-[(trimethylsilyl)ethynyl]cyclohexan-1-one (18c). Compound **18c** was obtained from 300 mg of **10a** following method D and purified by flash chromatography (AcOEt/hexane 1:1) in 55% yield as a white solid: mp 139−140; $[\alpha]^{20}_D = +144$ (*c* 1.03, $CHCl_3$); ^{1}H NMR δ 7.60−7.54 (AA′, 2H), 7.37−7.32 (BB′, 2H), 3.53 (d, J = 13.5 Hz, 1H), 3.46 (dd, J = 12.8, 5.3 Hz, 1H), 2.84−2.17 (m, 6H), 2.78 (d, J = 13.5 Hz, 1H), 2.43 (s, 3H), 1.18 (d, J = 6.3 Hz, 3H), 0.18 (s, 9H); ^{13}C NMR δ 207.3, 141.9, 141.3, 130.0 (2C), 123.8 (2C), 104.4, 91.0, 72.3, 63.2, 44.2, 42.4, 41.1, 37.2, 21.3, 15.8, −0.2 (3C). Anal. Calcd for $C_{20}H_{28}O_3SSi$: C, 63.79; H, 7.49; S, 8.51. Found: C, 63.83; H, 7.19; S, 8.83.

[3*S*,4*R*,5*R*,(S)*R*]-3-Ethyl-4-hydroxy-5-methyl-4-[(*p*-tolylsulfinyl)methyl]cyclohexan-1-one (19a). Compound **19a** was obtained from 266 mg of **10b** following method A ($AlMe_3$) and purified by flash chromatography (AcOEt/hexane 1:2) in 90% yield as a white solid: mp 125−126 °C; $[\alpha]^{20}_D = +200$ (*c* 1.00, $CHCl_3$); ^{1}H NMR δ 7.51−7.47 (AA′, 2H), 7.32−7.29 (BB′, 2H), 3.26 (d, J = 14.1 Hz, 1H), 3.20 (s, OH), 2.29 (d, J = 14.1 Hz, 1H), 2.54 (dd, J = 13.7, 13.4 Hz, 1H), 2.46−2.35 (m, 2H), 2.40 (s, 3H), 2.33−2.18 (m, 1H), 2.13 (ddd, J = 14.1, 4.2, 1.7 Hz, 1H), 2.07−1.88 (m, 1H), 1.73−1.63 (m, 1H), 1.40−1.29 (m, 1H), 1.13 (d, J = 6.5 Hz, 3H), 0.88 (t, J = 7.4 Hz, 3H); ^{13}C NMR δ 210.6, 142.0, 141.0, 130.2 (2C), 123.8 (2C), 73.80, 63.1, 46.1, 45.1, 41.1, 40.8, 22.4, 21.4, 16.0, 11.5.

[3*S*,4*S*,5*S*,(S)*R*]-3-Ethyl-4-hydroxy-4-[(*p*-tolylsulfinyl)-methyl]-5-[(trimethylsilyl)ethynyl]cyclohexan-1-one (19c). Compound **19c** was obtained from 335 mg of **10b** following method D and purified by flash chromatography (AcOEt/hexane 1:3) in 57% yield as a white solid: mp 153.5−154.5 °C; $[\alpha]^{20}_D = +130$ (*c* 0.99, $CHCl_3$); ^{1}H NMR δ 7.58−7.55 (AA′, 2H), 7.35−7.32 (BB′, 2H), 3.59 (d, J = 13.8 Hz, 1H), 3.46 (dd, J = 12.9, 5.3 Hz, 1H), 2.83 (d, J = 13.8 Hz, 1H), 2.80−2.71 (m, 2H), 2.80−2.41 (m, 3H), 2.42 (s, 3H), 2.16−2.08 (m, 1H), 1.87−1.77 (m, 1H), 1.58−1.47 (m, 1H), 0.93 (t, J = 7.5 Hz, 3H), 0.16 (s, 9H); ^{13}C NMR δ 207.6, 142.0, 141.5, 130.1 (2C), 123.9 (2C), 104.4, 91.3, 72.8, 63.4, 43.4, 42.4, 41.6, 40.5, 22.8, 21.4, 11.3, −0.1 (3C). Anal. Calcd for $C_{21}H_{30}O_3SSi$: C, 64.57; H, 7.74; S, 8.21. Found: C, 64.48; H, 7.64; S, 7.94.

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Supporting Information Available: Copies of ^{1}H NMR and ^{13}C NMR spectra for compounds **4**, **15**−**17**, and **19a** (10 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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