Pergamon

Tetrahedron: *Asymmetry* 13 (2002) 369–375

TETRAHEDRON: *ASYMMETRY*

Sequential asymmetric dihydroxylation and sulfoxidation of homoallylic sulfides. Stereochemical aspects of the preparation of new trifunctional chiral building blocks

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Received 15 January 2002; accepted 7 March 2002

Abstract—Products with three new stereogenic centers were generated via sequential asymmetric dihydroxylation and sulfoxidation of homoallylic sulfides. The non-racemic homoallylic sulfoxides were prepared using chiral, vanadyl-based catalytic system with e.e. of up to 85%. Subsequently, these compounds were dihydroxylated with AD-mix system and gave products of low d.e.s (up to 40%). Recrystallization of *l*-diastereomers furnished both enantiomerically pure 1-phenyl-4-phenylsulfinylbutane-1,2-diols (X-ray), which are new and useful chiral building blocks. Further oxidation at sulfur produced the corresponding enantiomers of 1-phenyl-4-phenylsulfonylbutane-1,2-diol.

1. Introduction

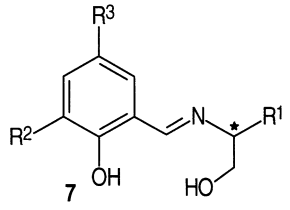
Osmium-catalyzed asymmetric dihydroxylation (AD) using the Sharpless catalytic system is one of the most useful synthetic tools for the preparation of optically active compounds.[1] Catalytic asymmetric oxidation of sulfides allows access to enantiomerically enriched sulfoxides—the most widely used chiral auxiliaries and building blocks.[2] In both cases the stereochemical outcome of the individual oxidative transformation can be predicted. Under these circumstances it seems interesting to examine the mutual interplay of both chiral catalytic oxidations in the preparation of chiral non-racemic dihydroxysulfoxides, which are interesting chiral building blocks.

The OsO_4-catalyzed dihydroxylation of the double bonds separated from chiral sulfinyl group by two or three carbon atoms, additionally with one of them being stereogenic, has already been reported.[3–5] While high degrees of 1,5-stereoinduction was observed for diastereoselective dihydroxylation,[3] for the 1,4-cases the respective stereoselectivities were less pronounced and the influence of the additional stereogenic center was demonstrated.[5] The homoallylic sulfide was chemo- and enantioselectively dihydroxylated by the Sharpless reagent,[6] but the reaction of the analogous sulfone gave the *vic*-diol with modest enantioselectivity only.[7] Moreover, there is no report on the stereoselective sulfoxidation of homoallylic and dihydroxy sulfides.

We describe herein the results of stereoselective sulfoxidations of homoallylic sulfides and enantioenriched 3,4-dihydroxysulfides. We also report the outcomes of the AD reactions of homoallylic sulfides and sulfones, and the dihydroxylation of the double bond of chiral (*E*)-homoallylic sulfoxides (Scheme 1).

2. Results and discussion

With our optimized version **7a**[8c,d] of the Bolm catalytic system (30% H_2O_2/$VO(acac)_2$-chiral ligand **7**, cat.)[8] we oxidized homoallylic sulfides **1** to afford the enantioenriched sulfoxides **2** with the absolute configuration at sulfur corresponding to that of the ligand.[8] It is noteworthy that other chiral oxidizing systems investigated were ineffective in these reactions (Table 1).



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a, R1: *i*-Pr, R2: Ph, R3: NO_2
b, R1, R2, R3: *t*-Bu
c, R1: *t*-Bu, R2: Ph, R3: NO_2

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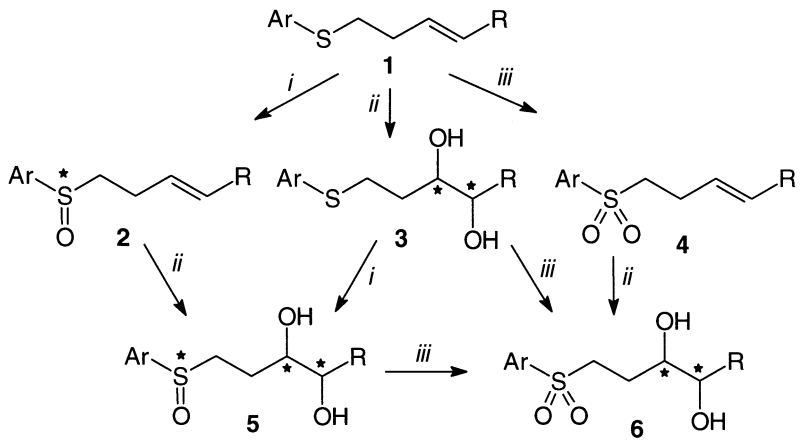
PII: S0957-4166(02)00123-4



1, 2, 3, 4, 5, 6	Ar	R
a	Ph	Ph
b	Ph	H
c	*o*-$CH_3C_6H_4$	H

Scheme 1. (i) $VO(acac)_2$, H_2O_2, ligand **7** or TEMPO, NaOCl; (ii) AD-mix α or AD-mix β or K_2OsO_4/quinuclidine, $K_3[Fe(CN)_6]$; (iii) Oxone®.

Table 1. Asymmetric sulfoxidation of sulfides **1** to sulfoxides **2**

Sulfide	Oxidant	Yield of **2** (%)	$[\alpha]_D$[a]	E.e.(%)[b]
1a	$VO(acac)_2/H_2O_2$, (*S*)-**7a**	60	−48	(−)-(*S*) 67
	$VO(acac)_2/H_2O_2$, (*R*)-**7a**	77	+47	(+)-(*R*) 66
	$VO(acac)_2/H_2O_2$, (*S*)-**7b**	60	−43	(−)-(*S*) 60
	Ti(O-*i*Pr)$_4$, CHP, (+)-DET[c]	52		*rac*
1b	$VO(acac)_2/H_2O_2$, (*S*)-**7a**	65	−131	(−)-(*S*) 70
	$VO(acac)_2/H_2O_2$, (*S*)-**7c**	92	−90	(−)-(*S*) 48
	Ti(O-*i*Pr)$_4$, TBHP, (*R*)-Binol[d]	10	+47	(+)-(*R*) 25
1c	$VO(acac)_2/H_2O_2$, (*S*)-**7a**	90	−118	(−)-(*S*) 85

[a] In CH_2Cl_2, $c=1.0$, 25°C.
[b] Enantiomeric excess was determined by ^1H NMR measurement with $Eu(hfc)_3$ in CCl_4.
[c] See Ref. 9.
[d] See Ref. 10.

The configurational stability of these chiral sulfoxides was limited and for neat **2a** at 20°C the e.e. value was half that of the original value after 20 days. All data given in Table 1 refer to the values obtained 3–4 days after the oxidation was performed. The highest enantioselectivity for **2a** (84% e.e. using **7a**) was recorded when the sample was analyzed immediately after the oxidation.

The thus obtained optically active sulfoxides **2a** and **2b** were dihydroxylated with potassium ferricyanide using OsO_4/quinuclidine as a catalyst.[11] The resulting product **5a** was obtained as a mixture of two diastereomers in ca. 6:4 d.r. The major diastereomer showed the high field ^1H NMR signals for the aliphatic part being shifted downfield versus the signals for the minor one ($\Delta\delta$ ca. 0.08 ppm). In the case of **5b** an opposite diastereomer slightly dominated. After further sulfur oxidation **5a** and **5b** gave enantioenriched sulfones **6a** and **6b** in over 90% yield. Their enantiomeric excesses were markedly reduced as compared to that for the starting sulfoxides **2** (Table 2). Nevertheless, since the dihydroxylating agent is not an asymmetric one, this outcome proved undoubtedly the remote stereoinduction from the stereogenic sulfur atom to the prochiral double bond. Moreover, the sign of specific rotation for the enantioenriched **6a** suggested that the major diastereomer of **5a** was that of like (*l*) configurations and the corresponding sign of **6b** indicated that for **5b** an unlike (*u*) diastereomer was in excess (vide infra).

Table 2. Dihydroxylation of enantioenriched sulfoxide **2** to **5**, and its oxidation to sulfone **6**

Sulfoxide (E.e., %)	Yield of **5** (%)	D.e. (%)	Sulfone **6**
(*S*)-(−)-**2a** (35)	75	24 (*l*)	(−)-(3*S*,4*S*)[a]
(*R*)-(+)-**2a** (59)	35	16 (*l*)	(+)-(3*R*,4*R*)[b]
(*S*)-(−)-**2b** (70)	40	10 (*u*)	(+)-(3*R*)[c]

[a] After several recrystallizations pure *l*-diastereomer of **5a** was obtained. Its oxidation gave sulfone (−)-**6a** in 58% e.e.
[b] (+)-**6a**, 21% e.e.
[c] (+)-**6b**, 10% e.e.

Table 3. AD of enantioenriched sulfoxide **2a** to **5a**, and its oxidation to sulfone **6a**

Sulfoxide **2a** (E.e., %)	Oxidant	**5a**		**6a**	
		Yield (%)	D.e. (%)	Yield (%)	E.e. (%)
(*S*)-(−) (35)	AD-mix α	99	24 (*S*s,3*S*,4*S*)	92	58 (3*S*,4*S*)[a]
(*S*)-(−) (35)	AD-mix β	82	36 (*S*s,3*R*,4*R*)	70	49 (3*R*,4*R*)
(*R*)-(+) (59)	AD-mix α	60	40 (*R*s,3*S*,4*S*)	81	43 (3*S*,4*S*)
(*R*)-(+) (66)	AD-mix β	98	26 (*R*s,3*R*,4*R*)	99	87 (3*R*,4*R*)[b]

[a] In the second step, recrystallized **5a** was used ($[\alpha]_D = -118$, 100% d.e.).
[b] In the second step, recrystallized **5a** was used ($[\alpha]_D = +117$, 100% d.e.)

Moreover, we observed that pure *l*-**5a** can be obtained by recrystallization and this process leads also to its enantioenrichment (Table 2, footnote a).

We also examined asymmetric dihydroxylation using AD-mix α and β.[1] These reagents, when applied to **1a** gave **3a** in 71% e.e. (*S*,*S*) and 76% e.e. (*R*,*R*), respectively. Both products were oxidized with Oxone® to the corresponding sulfones **6a** and recrystallization gave these compounds in over 95% e.e. This reaction sequence is more selective than the direct AD of sulfone **4a** (40% e.e., this work) or **4b** (53% e.e., Ref. 7). When enantioenriched sulfoxides **2a** were dihydroxylated with both AD-mixes, AD-mix α led to the (S_C,S_C)-isomer and AD-mix β to the (R_C,R_C)-isomer, regardless of the configuration at sulfur. We observed a better match (higher diastereoselectivity) for the formation of an *unlike* diastereomer (*u*) (Table 3). However, in the mismatched cases (lower d.e.), (*l*)-isomers formed as the main products and could be recrystallized to give pure (S_S,*S*,*S*)-**5a** and (R_S,*R*,*R*)-**5a**. We confirmed these assignments by a single-crystal X-ray analysis for (S_S,*S*,*S*)-**5a** (Fig. 1). Their further oxidation[12] with Oxone® again furnished the enantiomeric sulfones **6a**.

Additionally, (*S*)-(−)-**2a** (84% e.e.) was dihydroxylated shortly with 0.7 equiv. of AD-mix-β and gave 21% of (S_s,3*R*,4*R*)-**5a** (88% d.e.) along with 70% of the highly enantioenriched substrate (92% e.e.). Consequently, the kinetic resolution of the chiral substrate took place during the AD reaction.

Finally, we examined the sulfoxidation of chiral diols **3** using $VO(acac)_2$-chiral ligand **7a**/30% H_2O_2 and TEMPO/NaOCl systems. The last achiral oxidant has already proved its high chemo- and diastereoselectivity in sulfoxidation.[13] The obtained results (Table 4) suggest that the stereoselectivity of the first reaction is steered by the configuration of diol substrate, leading to (*u*)-**5** in ca. 20% d.e. Thus, in spite of the fact that usually the (R_S)-configuration of the sulfoxide is induced by (*R*)-**7a**, in the case of (*R*,*R*)-**3a** the formation of (S_S,*R*,*R*)-**5a** was favored. It seems that the chiral diol moiety builds into the coordination sphere of the vanadyl oxidant, thus changing its regular stereochemical preferences. However, it is interesting to note that at the some time, kinetic resolution of the enantioenriched substrate/product took place, so the sulfone **6a** obtained after second oxidation step was of higher e.e. than the starting dihydroxysulfide **3a** (Table 4, entry 4). The TEMPO-catalyzed sulfoxidation led to higher yields of *l*-diastereomers, but the products obtained at ca. 50% conversion were less enantioenriched than the starting diols.

3. Conclusions

In conclusion, we have demonstrated direct remote stereoinduction in the osmium-catalyzed dihydroxylation of nonracemic homoallylic sulfoxides. The asymmetric dihydroxylation of these compounds led to the products of low d.e.s, but for *l*-diastereomers simple recrystallization furnished both enantiomeric 1-phenyl-4-phenylsulfinylbutane-1,2-diols, which are interesting new chiral building blocks. The chiral and achiral catalytic sulfoxidations of enantioenriched diols resulted in the additional kinetic resolution of substrate and/or product.

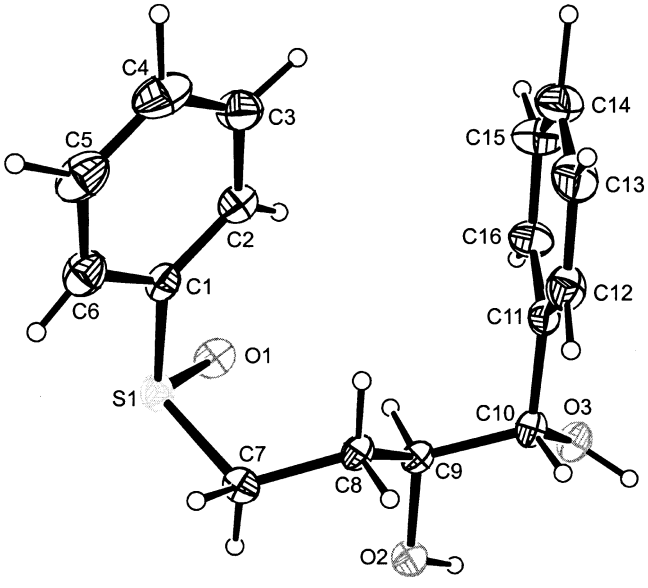


Figure 1. An Ortep view of the molecule **5a**.[14] Thermal ellipsoids were drawn on the 25% probability level. Hydrogen atoms were diminished for clarity.

Table 4. Sulfoxidation of enantioenriched diol **3a** to sulfoxide **5a**, and then to **6a**

Entry	Diol **3a** (E.e., %)	Oxidant	**5a**		**6a**	
			Yield (%)	D.e. (%)	Yield (%)	E.e. (%)
1	(*S*,*S*)-(−) (71)	$VO(acac)_2$, (*S*)-**7a**, H_2O_2	90	26 (*R*s,3*S*,4*S*)	[a]	
2	(*R*,*R*)-(+) (60)	$VO(acac)_2$, (*S*)-**7a**, H_2O_2	73	20 (*S*s,3*R*,4*R*)	85	54 (3*R*,4*R*)
3	(*S*,*S*)-(−) (71)	$VO(acac)_2$, (*R*)-**7a**, H_2O_2	76	18 (*R*s,3*S*,4*S*)	76	37 (3*S*,4*S*)
4	(*R*,*R*)-(+) (60)	$VO(acac)_2$, (*R*)-**7a**, H_2O_2	84	24 (*S*s,3*R*,4*R*)	81	82 (3*R*,4*R*)
5	(*S*,*S*)-(−) (53)	TEMPO (cat.)/NaOCl	40	62 (*S*s,3*S*,4*S*)	84	47 (3*S*,4*S*)
6	(*R*,*R*)-(+) (78)	TEMPO (cat.)/NaOCl	46	62 (*R*s,3*R*,4*R*)	ca. 100[b]	43 (3*R*,4*R*)

[a] Oxidation to sulfone not performed.
[b] In the second step recrystallized pure *l*-**5a** was used.

4. Experimental

4.1. General

Melting points were determined using a Boetius hot-stage apparatus and are uncorrected. IR spectra were recorded on a Perkin–Elmer 1600 FT-IR spectrophotometer. ^1H and ^{13}C NMR spectra were measured on a Bruker CPX (^1H, 300 MHz) spectrometer using TMS as an internal standard. Enantioselectivities of the reaction were determined by the NMR discrimination of appropriate signals using $Eu(hfc)_3$ as a chiral shift reagent. Observed rotations at 578 nm were measured using an Optical Activity Ltd. Model AA-5 automatic polarimeter. GC–MS analyses were determined on a Hewlett–Packard 5890 II gas chromatograph (25 m capillary column) with a Hewlett–Packard mass spectrometer 5971 A operating in electron impact mode (70 eV). Separations of products by chromatography were performed on silica gel 60 (230–400 mesh) purchased from Merck. Thin-layer chromatography analyses were performed using silica gel 60 precoated plates (Merck).

4.2. X-Ray crystallographic data

Colorless crystals of **5a** suitable for X-ray diffraction studies were grown by dissolving the compound in an *n*-hexane–methylene chloride mixture, and then by the slow evaporation at room temperature. The crystal was examined on a Kuma KM4CCD diffractometer equipped with a CCD camera ($\lambda=0.71073$ Å, $\theta_{max}=26°$) at 293(2) K. Precise cell constants were determined by the least-squares method on the ground of the most of the data collection reflections. The data were corrected for the Lorentz-polarization effect.[18] The structure was solved by direct methods from SHELXS-97[19] and refined by SHELXL-97.[20] All non-hydrogen atoms were treated anisotropically. Hydrogen atoms were found from a ΔF map and refined without constraints.

Orthorhombic, $P2_12_12_1$, $a=5.9906(7)$, $b=5.9906(7)$, $c=30.152(4)$ Å, $D_x=1.331$ Mg m^{-3}, $V=1449.6(3)$ Å^3, $Z=4$, $\mu=0.228$ mm^{-1}, $F(000)=616$, CCD camera, 7704 reflections collected, 2805 unique reflections, 2515 observed unique reflections, $R_{int}=0.072$, $R_1=0.070$ and $wR_2=0.110$ for $I>2\sigma(I)$, $R_1=0.084$ and $wR_2=0.115$ for all data, $S=1.16$, $\rho_{max}=0.28$, $\rho_{min}=-0.28$ e Å^{-3}, Flack absolute structure parameter $x=-0.02(13)$.

Crystallographic data (excluding structure factors) for the structure in this paper has been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 176272. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK [fax: +44(0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

4.3. Homoallylic sulfides 1

1-Phenyl-4-phenylsulfanylbut-1-ene **1a** was prepared according to the standard procedure[15] using thiophenol and 4-bromo-1-phenylbut-1-ene obtained from cyclopropyl phenyl ketone.[16] 4-Arylsulfanylbut-1-enes **1b–c** were obtained in a similar manner from commercially available homoallylic bromide (Aldrich) and the appropriate thiophenols.

4.3.1. 1-Phenyl-4-phenylsulfanylbut-1-ene 1a. Yield 94%. ^1H NMR ($CDCl_3$): $\delta=2.51$–2.58 (m, 2H, CH_2), 3.02–3.07 (m, 2H, CH_2), 6.18–6.28 (m, 1H, -CH=CH-), 6.40–6.46 (d, 1H, -CH=CH-, $J=15.9$ Hz), 7.15–7.37 ppm (m, 10 H, ArH). ^{13}C NMR ($CDCl_3$): $\delta=32.8$, 33.5, 125.8, 126.0, 127.2, 128.0, 128.5, 129.0, 129.4, 131.5, 136.4, 137.3 ppm. IR (KBr): 692, 740, 967, 1091, 1386, 1583, 1679, 2925, 3058 cm^{-1}. $R_f=0.83$ (*t*-BuOMe/$CHCl_3$, 3:2). MS (EI, 70 eV): m/z (%) = 240 (57) [M^+], 123 (100) [$M^+-C_6H_5CH{=}CHCH_2$], 91 (33) [$C_6H_5CH_2^+$], 77 (22) [$C_6H_5^+$].

4.3.2. 4-(Phenylsulfanyl)but-1-ene 1b. Yield 91%. Characteristics in agreement with the literature data.[17]

4.3.3. 4-(2-Tolylsulfanyl)but-1-ene 1c. Yield 91%. ^1H NMR ($CDCl_3$): $\delta=2.34$–2.42 (m, 5H, CH_3, CH_2), 2.91–2.96 (m, 2H, CH_2), 5.03–5.12 (m, 2H, $=CH_2$), 5.81–5.90 (m, 1H, =CH-), 7.05–7.25 ppm (m, 5H, ArH). ^{13}C NMR ($CDCl_3$): $\delta=20.8$, 32.7, 33.7, 116.1, 125.5, 126.3, 127.9, 130.0, 135.7, 136.4, 137.5 ppm. IR (film): 743, 916, 1066, 1469, 1589, 1640, 2923, 3062 cm^{-1}. $R_f=0.72$ (*t*-BuOMe/$CHCl_3$, 3:2). MS (EI, 70 eV): m/z (%) = 178 (77) [M^+], 137 (100) [$M^+-CH_2{=}CHCH_2$], 91 (27) [$M^+-SCH_2CH_2CH{=}CH_2$].

4.4. Oxidation of sulfides

4.4.1. Oxidation with $VO(acac)_2$ and chiral Schiff bases.[8] Vanadyl acetylacetonate (5.2 mg, 0.02 mmol) and the ligand **7** (0.03 mmol) were dissolved in a test tube in dichloromethane (4 mL), and the solution was stirred for 5 min at 25°C. After the addition of the sulfide (2 mmol) the solution was cooled to 0°C and 30% H_2O_2 (0.26 mL, 2.3 mmol) was added dropwise during 10 min. The mixture was stirred for 20 h at 0°C and extracted with CH_2Cl_2 (2×5 mL). The combined organic extracts were washed with H_2O, brine and dried over Na_2SO_4. The solvent was removed in vacuo and the crude product was submitted to the chromatography on silica gel (*t*-BuOMe/$CHCl_3$/hexane).

4.4.2. Other oxidation methods. Hydroperoxide asymmetric oxidation was performed according to two literature procedures A[9] and B.[10]

Method A.[9] (+)-(*R*,*R*)-DET (4 mmol, 0.7 mL) was dissolved in dichloromethane (20 mL) under an argon atmosphere. Ti(O-*i*-Pr)$_4$ (2 mmol, 0.6 mL) and H_2O (2 mmol, 0.04 mL) were introduced to the solution by means of syringe. The mixture was stirred for 20 min, and then sulfide (2 mmol) was added. After 0.5 h of mixing at 0°C, cumyl hydroperoxide (2 mmol, 0.42 mL of 70% solution in cumene) was introduced, and the mixture was stirred for 24 h at 0°C. Water (0.8 mL) was added, and the stirring was maintained for 1 h at room temperature. After filtration over Celite the solution was stirred with aqueous NaOH (5%) and brine for another hour. The organic phase was separated, dried (Na_2SO_4), and concentrated to give the crude product which was purified on a silica gel column.

Method B.[10] To a solution of (+)-(*R*)-1,1′-binaphthol (0.2 mmol, 57 mg) in CCl_4 (3 mL) were introduced Ti(O-*i*-Pr)$_4$ (0.1 mmol, 0.03 mL) and H_2O (2 mmol, 0.04 mL) by means of syringe under an argon atmosphere. The resulting solution was stirred for 1 h at room temperature, and the sulfide (1 mmol) dissolved in a small amount of CCl_4 was added with a syringe. After stirring for 0.5 h at 0°C, *tert*-butyl hydroperoxide (2 mmol, 0.25 mL of 80% solution in di-*tert*-butyl peroxide) was introduced, and the mixture was stirred for 24 h at 0°C. The reaction mixture was directly chromatographed on a silica gel column. The sulfoxide was eluted with *tert*-BuOMe/$CHCl_3$ (3:2).

4.5. TEMPO catalyzed oxidation

TEMPO oxidation was performed according to the described procedure.[13] A 50 mL flask was charged with a solution of sulfide **3a** (3 mmol) in 20 mL of CH_2Cl_2, TEMPO (0.09 mmol, 14 mg), and a saturated aqueous $NaHCO_3$ (16 mL) containing KBr (36 mg, 0.3 mmol). To this cooled (0°C, ice-water bath) and well-stirred mixture, a solution of NaOCl (0.90 M, 3.6 mL) together with saturated aqueous $NaHCO_3$ (4 mL) was added dropwise. The mixture was stirred for 2–5 h at 0°C (monitored by TLC) and the layers were separated. The aqueous phase was extracted with CH_2Cl_2 (3×10 mL) and the combined organic phases were washed with water, brine and dried (Na_2SO_4). The products were chromatographed on a silica gel column with *tert*-BuOMe/$CHCl_3$ (3:2) and finally purified by recrystallization from CH_2Cl_2/hexane.

4.5.1. 1-Phenyl-4-phenylsulfinylbut-1-ene (*R*)-2a. $[\alpha]_D^{20}=+47$ (0.50, CH_2Cl_2, 66% e.e.), (*S*)-**2a**: $[\alpha]_D^{20}=-48$ (0.58, CH_2Cl_2, 67% e.e.), $[\alpha]_D^{20}=-60$ (0.91, CH_2Cl_2, 84% e.e.), $[\alpha]_D^{20}=-66$ (0.64, CH_2Cl_2, 92% e.e.). ^{1}H NMR ($CDCl_3$): $\delta=2.45$–2.55 (m, 1H, CH_2), 2.64–2.76 (m, 1H, CH_2), 2.88–2.96 (m, 2H, CH_2), 6.09–6.19 (m, 1H, -CH=CH-), 6.42–6.47 (d, 1H, -CH=CH-, $J=15.6$ Hz), 7.19–7.29 (m, 5H, ArH), 7.50–7.65 ppm (m, 5H, ArH). $\Delta\delta=0.100$ ppm in the presence of equimolar amount of Eu(hfc)$_3$ in CCl_4 (α-CH_2). ^{13}C NMR ($CDCl_3$): $\delta=25.5$, 56.5, 124.0, 126.0, 126.3, 127.4, 128.5, 129.2, 130.9, 132.3, 136.9, 143.7 ppm. IR (film): 535, 693, 748, 968, 1043, 1087, 1443, 1598, 3026, 3056 cm^{-1}. $R_f=0.67$ (*t*-BuOMe/$CHCl_3$, 3:2).

4.5.2. 4-(Phenylsulfinyl)but-1-ene (*S*)-2b. $[\alpha]_D^{20}=-131$ (1.0, CH_2Cl_2, 70% e.e.). ^{1}H NMR (CCl_4): $\delta=2.45$–2.50 (m, 1H, CH_2), 2.68–2.73 (m, 1H, CH_2), 2.83–2.98 (m, 2H, CH_2), 5.20–5.31 (m, 2H, =CH_2), 5.90–6.04 (m, 1H, =CH-), 7.55–7.75 ppm (m, 5H, ArH). $\Delta\delta=0.118$ ppm in the presence of equimolar amount of Eu(hfc)$_3$ in CCl_4 (α-CH_2). ^{13}C NMR ($CDCl_3$): $\delta=26.3$, 56.2, 117.0, 124.1, 129.0, 130.4, 135.4 ppm. IR (film): 535, 693, 748, 1043, 1087, 1444, 1478, 1641, 2916, 3059 cm^{-1}. $R_f=0.6$ (*t*-BuOMe/$CHCl_3$/hexane, 3:2:0,8).

4.5.3. 4-(2-Tolylsulfinyl)but-1-ene (*S*)-2c. $[\alpha]_D^{20}=-118$ (1.0, CH_2Cl_2, 85% e.e.). ^{1}H NMR (CCl_4): $\delta=1.58$ (m, 4H, CH_2, CH_3), 1.80–1.86 (m, 2H, CH_2), 1.98–2.02 (m, 1H, CH_2), 4.25–4.37 (m, 2H, CH_2), 4.96–5.06 (m, 1H, CH_2), 6.33–6.35 (d, 1H, ArH, $J=7.3$ Hz), 6.50–6.64 (m, 2H, ArH), 7.04–7.06 ppm (d, 1H, ArH, $J=7.4$ Hz). $\Delta\delta=0.201$ ppm in the presence of equimolar amount of Eu(hfc)$_3$ in CCl_4 (α-CH_2).^{13}C NMR ($CDCl_3$):18.1, 26.3, 54.1, 116.9, 123.8, 127.1, 130.6, 130.6, 134.2, 134.8, 141.8 ppm. IR (film): 757, 1035, 1065, 1446, 1472, 1594, 1641, 2918, 2979, 3065 cm^{-1}. $R_f=0.55$ (*t*-BuOMe/$CHCl_3$, 3:2).

4.6. Dihydroxylation

4.6.1. General procedure for OsO_4 dihydroxylation.[11] A round-bottomed flask was charged with potassium ferricyanide (3.0 mmol, 0.98 g), potassium carbonate (3.0 mmol, 0.41 g), quinuclidine (0.04 mmol, 4.4 mg), potassium osmate dihydrate (0.01 mmol, 3.7 mg) and methanesulfonamide (1.0 mmol, 95.1 mg, added only in the case of **2a**) in a two-phase system (5 mL of water and 5 mL of *t*-butanol). The mixture was stirred until all solids had dissolved. The substrate **2** (1 mmol) was added and the suspension was stirred vigorously for 72 h at 0°C. Anhydrous sodium sulfite (0.01 mol, 1.26 g) was added and stirring continued for 1 h before the addition of ethyl acetate (15 mL). The layers were separated and the aqueous phase was extracted with ethyl acetate (3×10 mL). The combined organic extracts were washed with 2 M KOH (3 mL, in the case of **2a**

substrate), dried ($MgSO_4$) and evaporated under reduced pressure. The residue was purified by column chromatography, eluted with *tert*-BuOMe:CH_2Cl_2 3:2, and recrystallized (CH_2Cl_2–hexane).

4.6.2. Typical procedure for AD-reactions.[6] These reactions were run as follows: The substrate **1**, **2** or **4** (1 mmol) was dissolved in 1:1 water/*t*-BuOH mixture (10 mL) and cooled to 0°C. Then, the commercial (Aldrich) AD-mix α or AD-mix β (1.4 g) and methanesulfonamide (1.0 mmol, 95.1 mg, except for substrates with a terminal double bond) were added and the mixture was stirred for 48 h at 0°C. Anhydrous sodium sulfite (0.01 mol, 1.26 g) was introduced and after 1 h stirring dichloromethane (15 mL) was added. The layers were separated and the aqueous phase was extracted with dichloromethane (3×10 mL). The combined organic extracts were washed with 2 M KOH (3 mL, in the case of non-terminal substrates), dried ($MgSO_4$) and evaporated under reduced pressure. The residue was purified by column chromatography, eluted with *tert*-BuOMe:CH_2Cl_2 3:2, and recrystallized (CH_2Cl_2–hexane).

4.6.2.1. 1-Phenyl-4-phenylsulfanylobutane-1,2-diol 3a. Mp = 56–58°C (petroleum ether/CH_2Cl_2). (*R*,*R*)-(**3a**): $[\alpha]_D^{20}$ = +49 (0.60, CH_2Cl_2, 76% e.e.), (*S*,*S*)-(**3a**): $[\alpha]_D^{20}$ = −46 (0.48, CH_2Cl_2, 71% e.e.). ^{1}H NMR ($CDCl_3$): δ = 1.52–1.77 (m, 2H), 2.63 (s, 2H, 2×OH), 2.88–2.98 (m, 1H), 3.03–3.16 (m, 1H), 3.87–3.94 (m, 1H), 4.42–4.44 (d, 1H, J = 6.8 Hz), 7.14–7.36 ppm (m, 10H, ArH). $\Delta\delta$ = 0.122 ppm in the presence of Eu(hfc)$_3$ in CCl_4 (CH_2C**H**OH). ^{13}C NMR ($CDCl_3$): 30.3, 31.9, 74.6, 77.8, 126.0, 126.8, 128.2, 128.6, 128.8, 129.4, 135.9, 140.7 ppm. IR (KBr): 702, 739, 910, 1052, 1078, 1199, 1439, 1454, 1584, 2971, 3387 cm^{-1}. R_f = 0.50 (*t*-BuOMe/$CHCl_3$, 3:2). Anal. calcd for: $C_{16}H_{18}O_2S$ (M = 274.38): C, 70.05; H, 6.62; S, 11.66; found C, 70.28; H, 6.90; S, 11.46%.

4.6.2.2. 1-Phenyl-4-phenylsulfinylbutane-1,2-diol 5a. Isomer *l*: mp = 134–135°C (hexane/CH_2Cl_2). (*R*,*R*,*R*)-**5a**: $[\alpha]_D^{20}$ = +126 (0.40, CH_2Cl_2, >98% e.e.), (*S*,*S*,*S*)-**5a**: $[\alpha]_D^{20}$ = −125 (0.34, CH_2Cl_2, >98% e.e.). ^{1}H NMR ($CDCl_3$): δ = 1.77–1.87 (m, 2H, CH_2), 2.84–3.05 (m, 2H, CH_2), 3.13 (s, 2H, 2×OH), 3.78–3.84 (m, 1H, -CH), 4.44–4.46 (d, 1H, -CH, J = 6.8 Hz), 7.33–7.37 (m, 5H, ArH), 7.49–7.57 (m, 5H, ArH); ^{13}C NMR ($CDCl_3$): δ = 26.5, 53.6, 74.3, 77.6, 124.0, 126.9, 128.2, 128.6, 129.3, 131.1 ppm. Mixture of *l* and *u*: ^{1}H NMR ($CDCl_3$): δ = 1.70–1.75 and 1.77–1.87 (two m, 2H, CH_2), 2.84–3.05 (m, 2H, CH_2), 3.13 (br. s, 2H, 2×OH), 3.69–3.74 and 3.78–3.84 (two m, 1H, -CH), 4.39–4.42 and 4.44–4.46 (two d, 1H, -CH, J = 7.2 Hz and J = 6.8 Hz, respectively), 7.32–7.48 (m, 5H, ArH), 7.48–7.57 ppm (m, 5H, ArH). ^{13}C NMR ($CDCl_3$): δ = 26.5, 26.9, 53.5, 53.6, 74.3, 74.5, 77.6, 77.9, 124.0, 124.2, 125.9, 126.9, 127.0, 128.2, 128.6, 128.6, 129.3, 131.1 ppm. IR (KBr): 698, 745, 1015, 1044, 1181, 1442, 2911, 3361 cm^{-1}. R_f = 0.23 (*t*-BuOMe/$CHCl_3$, 3:2). Anal. calcd for: $C_{16}H_{18}O_3S$ (M = 290.38): C, 66.18; H, 6.25; S, 11.04; found C, 65.90; H, 6.20; S, 11.30%.

4.6.2.3. 4-Phenylsulfinylbutane-1,2-diol 5b. D.m. ^{1}H NMR ($CDCl_3$): δ = 1.72–1.95 (m, 2H, CH_2), 2.86–3.18 (m, 2H, CH_2), 3.27 (s, 2H, 2×OH), 3.44–3.49 (m, 2H), 3.70–3.74 (m, 1H, CH), 7.50–7.91 ppm (m, 5H, ArH). ^{13}C NMR ($CDCl_3$): 21.0, 21.1, 48.2, 48.3, 61.4, 65.5, 65.8, 119.3, 124.5, 126.4, 138.0 ppm. IR (film): 692, 996, 1086, 1405, 1668, 2927, 3364 cm^{-1}. R_f = 0.15 (*t*-BuOMe/$CHCl_3$, 3:2).

4.6.2.4. 4-(2-Tolylsulfinyl)butane-1,2-diol 5c. D.m. ^{1}H NMR ($CDCl_3$): δ = 1.81–1.90 (m, 2H, CH_2), 2.37 (s, 3H, CH_3), 2.82–2.89 (m, 1H, CH_2), 3.03–3.10 (m, 1H, CH_2), 3.44–3.50 (m, 1H), 3.59–3.74 (m, 3H, 2×OH, CH_2), 3.60–3.86 (m, 1H, *CH), 7.19–7.21 (d, 1H, ArH, J = 6.8 Hz), 7.36–7.45 (m, 2H, ArH), 7.84–7.86 ppm (d, 1H, ArH, J = 6.9 Hz). ^{13}C NMR ($CDCl_3$): 18.2, 18.2, 26.3, 26.3, 51.0, 51.4, 66.4, 66.4, 70.4, 70.7, 123.9, 124.1, 127.2, 127.2, 130.8, 130.8, 130.9, 130.9, 134.4, 134.5, 140.7, 140.9 ppm. IR (film): 758, 1020, 1455, 1472, 1656, 2925, 3369 cm^{-1}. R_f = 0.29 (*t*-BuOMe/$CHCl_3$/MeOH, 2:1:1).

4.7. Preparation of sulfones[12]

A solution of sulfoxide **3** (1 mmol) in methanol (20 mL) was treated with Oxone® (675 mg, 1.1 mmol—in the case of sulfide **1** oxidation the amount of oxidant was doubled) in water (10 mL). The reaction mixture was stirred at room temperature for 2 h. The solution was extracted with dichloromethane (30 mL), the organic phase was separated, dried (Na_2SO_4), and evaporated under reduced pressure. The products were recrystallized or chromatographed on silica gel.

4.7.1. 1-Phenyl-4-phenylsulfonylbut-1-ene 4a. Yield 91%. Mp = 68–69.5°C (MeOH). ^{1}H NMR ($CDCl_3$): δ = 2.63–2.70 (m, 2H, CH_2), 3.24–3.29 (m, 2H, CH_2), 6.02–6.12 (m, 1H, -CH=CH-), 6.39–6.45 (d, 1H, -CH=CH-, J = 15.8 Hz), 7.25–7.29 ppm (m, 5H, ArH), 7.57–7.68 ppm (m, 3H, ArH), 7.95–7.98 ppm (d, 2H, ArH, J = 7.7 Hz). ^{13}C NMR ($CDCl_3$): δ = 26.3, 55.7, 125.1, 126.1, 127.5, 128.1, 128.5, 129.3, 132.4, 133.7, 136.6, 139.0 ppm. IR (KBr): 536, 566, 682, 741, 795, 976, 1086, 1139, 1230, 1282, 1294, 1449, 1480, 1585, 1597, 2919, 3031, 3081 cm^{-1}. Anal. calcd for: $C_{16}H_{16}O_2S$ (M = 272.36): C, 70.56; H, 5.92; S, 11.75; found C, 70.40; H, 5.74; S, 11.47%.

4.7.2. (*R*,*R*)-1-Phenyl-4-phenylsulfonylbutane-1,2-diol 6a. Mp = 90–92°C (CH_2Cl_2/hexane). $[\alpha]_D^{20}$ = +17 (0.30, CH_2Cl_2, 89% e.e.). ^{1}H NMR ($CDCl_3$): δ = 1.78–1.80 (m, 2H), 2.68 (s, 2H, 2×OH), 3.04–3.20 (m, 1H), 3.24–3.34 (m, 1H), 3.82 (s, 1H), 4.42 (s, 1H), 7.27–7.36 (m, 5H, ArH), 7.49–7.57 (m, 2H, ArH), 7.61–7.66 (m, 1H, ArH), 7.79–7.82 ppm (m, 2H, ArH). ^{13}C NMR ($CDCl_3$): 25.9, 52.9, 73.8, 77.6, 126.7, 127.9, 128.5, 128.8, 129.2, 133.7, 138.9, 142.0 ppm. IR (KBr): 527, 736, 913, 1020, 1072, 1087, 1288, 1405, 1445, 1494, 1471, 2892, 3063, 3510 cm^{-1}. R_f = 0.41 (*t*-BuOMe/$CHCl_3$, 3:2). Anal. calcd for: $C_{16}H_{18}O_4S$ (M = 306.38): C, 62.72; H, 5.92; S, 10.46; found C, 63.04; H, 6.10, S, 10.73%.

4.7.3. 4-Phenylsulfonylbutane-1,2-diol 6b. Mp = 76–78°C. $[\alpha]_D^{20} = +2.5$ (0.42, CH_2Cl_2, 10% e.e.), $[\alpha]_D^{20} = +2.7$ (1.48, EtOH, ca. 10% e.e.), lit.[7] $[\alpha]_D^{20} = +23.2$ (1.4, EtOH, 94% e.e.). ^{1}H NMR ($CDCl_3$): $\delta = 1.79$–1.91 (m, 2H, CH_2), 2.27 (br s, 2H, 2×OH), 3.24–3.35 (m, 2H, CH_2), 3.42–3.48 (m, 1H, CH_2), 3.61–3.68 (dd, 1H, $J_1 = 3.3$ Hz, $J_2 = 11.2$ Hz, CH), 3.79–3.85 (m, 1H, CH), 7.56–7.70 (m, 3H, ArH), 7.90–7.93 ppm (m, 2H, ArH). IR (KBr): 539, 689, 737, 1040, 1086, 1143, 1305, 1447, 2931, 3388 cm^{-1}. $R_f = 0.38$ (*t*-BuOMe/$CHCl_3$/MeOH, 2:1:1). Anal. calcd for: $C_{10}H_{14}O_4S$ (M = 230.212): C, 52.16; H, 6.13; S, 13.90; found C, 52.35; H, 5.96; S, 14.01%.

Acknowledgements

The authors thank the Polish Committee for Scientific Research for financial support (KBN Grant 7 T09A 109 21). The support of the Foundation for Polish Science for the purchase of the CCD camera is gratefully acknowledged.

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