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SYNTHESIS AND ABSOLUTE CONFIGURATION OF NEW CHIRAL EPOXYALCOHOLS BY STEREOSELECTIVE EPOXIDATION OF ALLYLIC AND HOMOALLYLIC ALCOHOLS WITH A (1*R*)-(+)-CAMPHOR SKELETON

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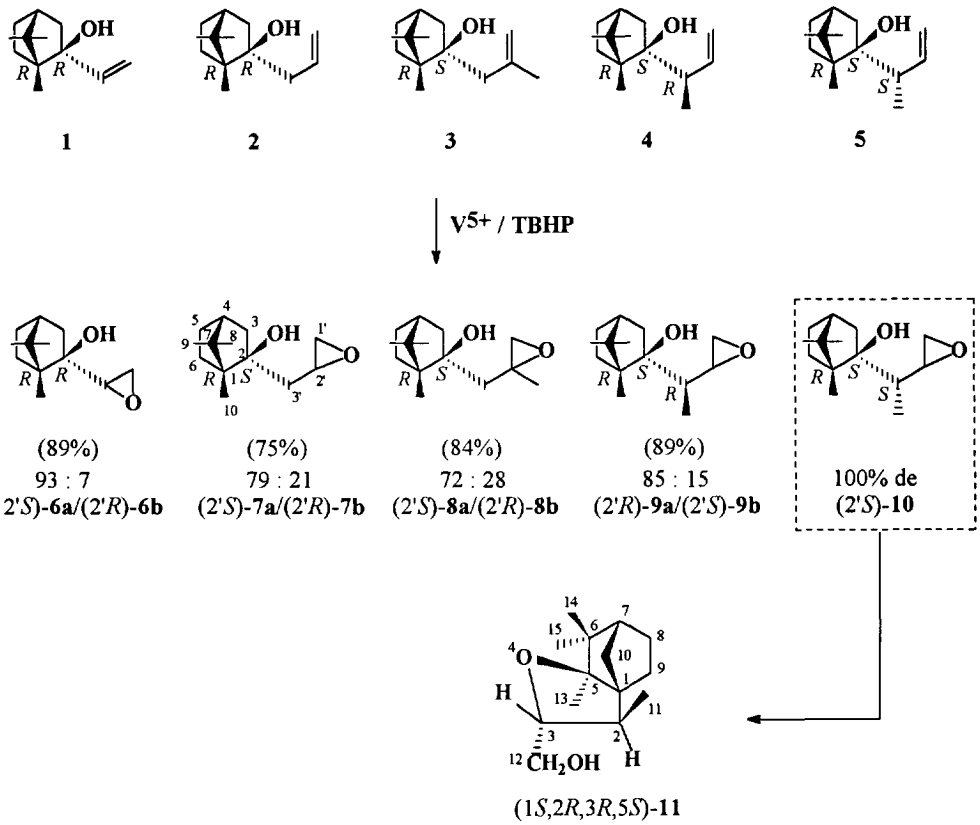
Abstract: The chiral nonracemic alcohols **1-5** were stereoselectively epoxidized with the $VO(acac)_2$/t-butyl hydroperoxide system. The epoxyalcohols **6-9** resulting from alcohols **1-4** were synthesized in high yields and the obtained diastereoisomers were isolated in pure form by chromatography. The homoallylic alcohol **5** epoxidized 100% diastereoselectively to **10**. The epoxyalcohol **10** underwent a stereoselective intramolecular cyclisation during the epoxydation with rearrangement of the camphor skeleton to the oxatricyclo derivative **11**. The absolute configurations of the new chiral compounds were determined by NMR methods.

Chiral nonracemic epoxyalcohols are highly versatile compounds for asymmetric synthesis with large potential for use in ring-opening reactions[2]. The enantioselective epoxidation developed by *Sharpless* and coworkers[2a,3] is one of the most important asymmetric transformations, however the excellent results are limited by the use of allylic alcohols. In contrast, the *Sharpless* $Ti(OR)_4$/tartrate asymmetric epoxidation of homoallylic alcohols is slower and the enantioselectivity is lower[4]. It has been shown that chiral homoallylic alcohols undergo diastereoselectively vanadyl-ion promoted epoxidation with t-butyl hydroperoxide (TBHP)[5].

Recently we reported on the synthesis[6] of the chiral nonracemic alcohols **1-5** (*Scheme 1*), which were used for the preparation of new optically active 1,3-diols[7]. We wish to present now a practical diastereoselective epoxidation of alcohols **1-5**, providing epoxyalcohols in high yields and diastereoselectivities.

The alcohols **1-5** were epoxidized in high yields (*Scheme 1*) in CH_2Cl_2 solution at room temperature using TBHP (3M in octane) and $VO(acac)_2$ as catalyst. The reactions were relatively slow (more than 20 h) for **2-5**, whereas the allylic alcohol **1** epoxidized highly diastereoselectively within 4 h; the completion was monitored by TLC. The allylic alcohol **1** was also epoxidized with the (+)-DET/$Ti(OiPr)_4$/TBHP system - in a course of a very slow reaction (14 days) the epoxyalcohol **6** was isolated in 70 % yield and moderate diastereoselectivity (**6a/6b** = 75:25). The diastereomeric ratio of the epoxyalcohols **6-9** was determined by NMR spectroscopy of the crude mixtures and the observed diastereoselectivities for compounds **7-9** were high (*Scheme 1*). In all cases the corresponding diastereoisomeric epoxyalcohols could be separated and isolated in pure form by column chromatography (see Exp. part). The homoallylic alcohol **5** epoxidized 100 %

diastereoselectively to the epoxyalcohol **10**, which underwent, surprisingly, further transformation under the reaction conditions (V^{5+}/TBHP) to a product identified as the oxatricyclo compound **11** (*Scheme 1*). For the preparation of **10** in maximum yield (56 %) the epoxidation reaction had to be stopped after 21 h. Otherwise the transformation of the epoxyalcohol **10** to **11** proceeded quantitatively. The oxatricyclo derivative **11** was formed as a single diastereoisomer.

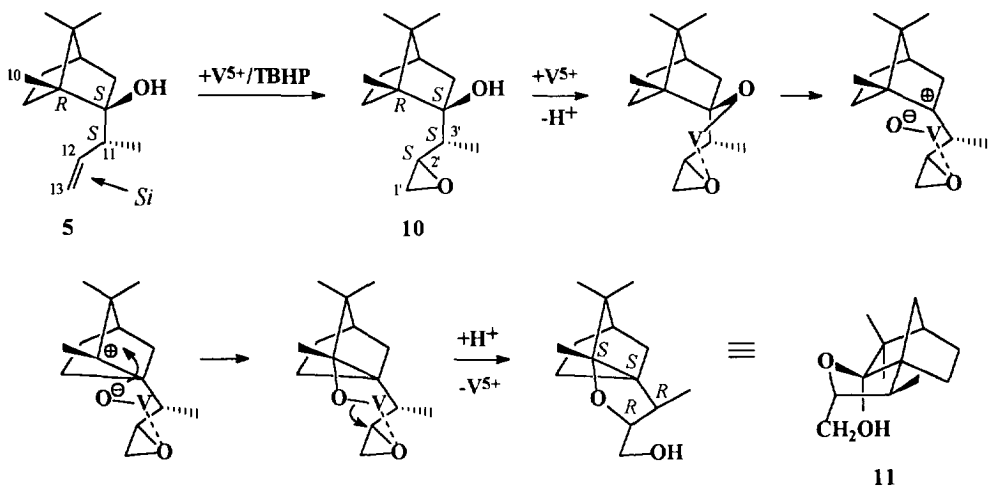


Scheme 1

For the diastereoselectivity of the formation of epoxyalcohol **10**, as well as for the following reaction to **11** we would assume the interpretation presented in *Scheme 2*. The starting alcohol **5** strongly prefers a conformation in which the proton at C-11 is directed towards the camphor ring and the double bond of the allylic moiety is constrained on the side of the C-10 methyl group, as it has been found by NOE studies[6b]. Force field calculations show that there are two conformations concerning the relative position of the C=C double bond upon rotation around the C-11 - C-12 bond, both being suitable for epoxidation. A hydroxyl-directed vanadyl-promoted epoxidation in accordance with the cyclic transition state[5a,8] would rather proceed in the case of the conformation in which the *Si*-face of the double bond is on the side of the hydroxyl group. In the second conformation an epoxidation from the *Re*-side by the approaching V^{5+}/TBHP reagent is significantly

hindered by the C-10 methyl group. The formation of **11** obviously proceeds with the assistance of the V^{5+} catalyst, which causes the formation of carbonium ion at the C-2 atom, followed by rearrangement of the bicyclic skeleton and oxygen transfer (*Scheme 2*). The decisive participance of V^{5+} ions was proved in experiment - addition of 2 mol % of V^{5+} (prepared separately from $VO(acac)_2$ and TBHP in 1/1-ratio) to pure epoxide **10** in CH_2Cl_2 provided quantitative formation of **11**. The ring opening of the epoxide occurs with inversion of the configuration of the chiral carbon atom at C-2' position. The assistance of the V^{5+} ion makes the reaction faster but the tendency is there, since after prolonged standing (6 months) of pure epoxyalcohol **10** the formation of ca. 30% of **11** is observed. This reaction occurrs only in the case of epoxyalcohol **10** and is probably favoured by the constrained conformation of **10**. Lewis acid mediated ring opening reactions with rearrangements in some cases and participation of hydroxyl group have been previously investigated in other systems[9].

Unlike **5**, in the case of alcohols **2-4** several conformations of the allylic moiety allowing *Si*- and *Re*-attack of the reagent are possible resulting in the lower diastereoselectivity observed.



Scheme 2

The determination of the absolute configuration of the C-2' chiral atom for the individual diastereoisomers formed during the epoxidation reactions could be achieved using NOE distance constrains and force field calculations, taking into account the known configurations[6b] of the starting alcohols **1-5**. Since the C-1' - C-3' side chain has some flexibility, the preferred conformations concerning rotation around the C-2 - C-3' and C-2' - C-3' bonds for both diastereoisomers (2'*S* or 2'*R*) of the corresponding epoxyalcohols **6-10** have been calculated. Comparison of the dissimilarities in the observed NOE's for both diastereoisomers with the calculated structures allowed assignment of the NMR data to the matching structures and consequently determination of the configuration at C-2' position. The differences in the NOE's are summarized as follows:

for 6a/6b: The 1'-H_{trans} proton is situated near the 10-H methyl protons in the case of the 2'*S* isomer **6a** and near 3-H_{endo} in the 2'*R* one (**6b**). This assignment is corroborated by the deshielding effect of the oxygen,

situated close to some of the other protons - 0.21 *ppm* for 3-H_{endo} in **6a** and 0.06 *ppm* for the C-10 methyl protons in **6b**, respectively.

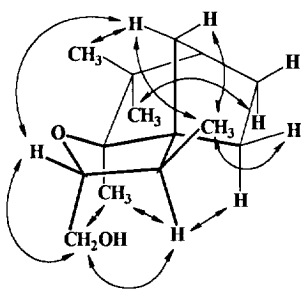
for 7a/7b: The 3'-H_b proton (in *trans*-position to 2'-H) is situated near the 10-H methyl protons in the case of the 2'*S* isomer **7a**. For the 2'*R* isomer **7b** the 3'-H_a (in *gauche*-position to 2'-H) is close to the 10-H protons. These observations are in accordance with the calculated predominant conformers of both diastereoisomers.

for 8a/8b: In the major diastereoisomer the 1'-H proton (*trans* to 4'-H methyl protons) showed NOE's to both 3-H_{exo} (2.3 %) and 3-H_{endo} (1.4 %), a structure that corresponds only to one of the possible conformers of the isomer with 2'*S* configuration, namely the **8a** diastereoisomer.

for 9a/9b: For the major diastereoisomer a 5 % NOE between 1'-H (*trans* to 2'-H) and 3-H_{endo} protons was observed that points to 2'*R* configuration (**9a**). Besides, the deshielding of the 4'-H methyl protons (1.07 *vs.* 0.98 *ppm*) in the major diastereoisomer and of the 3'-H proton in the minor one (1.56 *vs.* 1.50 *ppm*) due to the effect of the proximate epoxide oxygen atom confirmed independently the 2'*R* configuration for the major **9a** isomer [10].

for 10: The 2'-C configuration of the single diastereoisomer obtained could be determined as 2'*S* based on the observed NOE's upon irradiation of the 10-H methyl protons - 7.1 % for 2'-H (2.4 Å) and 2.3 % for 1'-H_{cis} (2.7 Å). This determination was further confirmed by the constitution of the rearrangement product **11**.

The observed NOE's for the oxatricyclo derivative **11** depicted below, together with the proton-proton coupling network and the carbon NMR data confirm unambiguously its structure.



In conclusion, we have demonstrated an effective stereoselective synthesis of optically active epoxyalcohols with defined absolute configurations, which are of practical interest for further transformations.

Experimental section

General Methods. All reactions were carried out under argon atmosphere to avoid the moisture from the air. The solvents were dried and distilled. Thin layer chromatography (TLC): aluminium sheets precoated with silica gel 60 F_{254} (Merck). Column chromatography: at normal pressure, silicagel 60 (0.040-0.063 mm, Merck). $[\alpha]_D^{20}$: Perkin-Elmer 241 polarimeter. Masspektra (MS): Jeol-JMS-D-300 spectrometer; fragmentation in *m/z* with relative intensities (%) in parentheses. NMR spektra: Bruker Avance DRX-250 (^1H at 250.1 MHz; ^{13}C at 62.9 MHz; TMS as internal standart); standard Bruker library programs (cosy45, hxdepttp and noemul) were used; the samples for the NOE difference experiments were prepared by blowing argon through the $CDCl_3$ solution; the individual lines in the multiplet were irradiated for 0.05 s maintaining the whole irradiation time to

be 3 s; the irradiation power was adjusted to suppress approximately 80% of the multiplet intensity. Elemental analyses were performed by the Microanalytical Service Laboratory of the Institute of Organic Chemistry.

Starting Materials. The following starting materials (commercially available or prepared according to the literature) were used: alcohols **1-5** (lit.[6]), vanadium(IV)-oxide-bis(2,4-pentadionate) ($VO(acac_2)$) (Fluka AG), t-butyl hydroperoxide (TBHP) 3M solution in octane (Fluka AG).

Table 1. ^{13}C NMR data for the epoxyalcohols **6-10** and compound **11** (Bruker Avance DRX-250 spectrometer, solvent $CDCl_3$, chemical shifts in *ppm* relative to TMS); assignments are based on heteronuclear CH-correlation experiments; for the numbering of the C-atoms see Scheme 1.

C-atom No.	6a	6b	7a	7b	8a	8b	9a	9b	10	11[a]
1	51.79	52.44	52.25	52.02	53.03	53.16	53.34	52.65	52.48	63.10 (1)
2	77.53	77.37	81.18	81.08	80.00	80.76	82.70	81.77	83.38	34.54 (2)
3	44.09	42.93	45.86	46.39	47.58	46.91	46.49	45.65	46.88	86.19 (3)
4	45.28	44.76	45.01	44.78	45.24	45.37	45.16	44.52	44.18	91.25 (5)
5	26.79	27.11	26.94	26.83	26.87	27.01	28.22	27.25	27.55	46.17 (6)
6	29.73	30.27	30.47	30.54	30.00	29.84	30.29	29.63	29.91	48.57 (7)
7	49.62	49.54	49.00	49.17	48.45	48.24	50.52	49.78	50.34	23.27 (8)
8	20.92	21.08	21.36	21.21	21.38	21.34	21.98	21.32	21.44	24.20 (9)
9	19.98	20.45	20.95	20.85	20.90	20.94	21.61	20.86	21.11	34.80 (10)
10	10.46	10.80	10.24	10.79	10.19	9.95	12.81	12.08	12.03	11.65 (11)
1'	55.59	55.19	46.35	47.78	54.69	53.67	49.33	45.08	47.53	64.07 (12)
2'	43.53	41.87	50.05	50.37	57.48	56.72	55.70	54.42	54.30	20.40 (13)
3'	-	-	41.83	42.00	42.21	44.43	45.60	45.00	41.46	24.76 (14)
4'	-	-	-	-	24.08	22.16	13.09	12.17	11.26	22.63 (15)

[a]The numbering of the C-atoms for **11** is given in parentheses.

General procedure (*GP*) for V^{5+}-catalyzed epoxidation of alcohols (1-5):

To a ca. 0.1 M solution of the corresponding alcohol (**1-5**) in anhydrous CH_2Cl_2 was added 1-2% of $VO(acac)_2$ and 1.5-2.5 equiv. of TBHP (anhydrous 3M solution in octane) at ice-bath temperature. The mixture was then stirred at room temperature. The reaction was monitored by TLC. After completion of the reaction the mixture was washed with sat. NaCl soln., dried (Na_2SO_4) and concentrated under reduced pressure. The crude product (containing TBHP) was purified by column chromatography.

(1*R*,2*R*)-2-*endo*-(1',2'-epoxyethyl)-1,7,7-trimethylbicyclo[2.2.1]heptan-2-ol (6). Following *GP*, 0.50 g (2.80 mmol) of **1** in 30 ml CH_2Cl_2, 0.01 g (0.04 mmol) $VO(acac)_2$ and 2.3 ml (7.00 mmol) 3M TBHP were combined and stirred for 4 h. After workup 0.57 g of crude **6** (1*R*,2*S*,2'*S*-**6a**/1*R*,2*S*,2'*R*-**6b** = 93:7 by NMR) were chromatographied (Ø 17 mm, h = 490 mm, 42 g silica gel, hexane/Et_2O = 10:1) to give 0.03 g (6%) **6b** (colourless solid) and 0.45 g (83%) **6a** (colourless solid). The total yield of **6** was 0.48 g (89%).

MS (CI: NH_3) *m/z* (%): = 214 ($[M+18]^+$, 100), 196 ($[(M-H_2O)+18]^+$, 40), 179 ($[(M-H_2O)+1]^+$, 41). Anal. calc. for $C_{12}H_{20}O_2$: C, 73.43; H, 10.27; O, 16.30; found: C, 73.33; H, 10.18

Data for (1*R*,2*R*,2'*S*)-6a: mp 50°C. $[\alpha]_D^{20}$ = -39.30 (c 3.68, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.83 (s, 6H, 9-H, 10-H), 1.11 (s, 3H, 8-H), 1.11 (m, 1H, 5-H_{endo}), 1.40-1.65 (m, 2H, 6-H), 1.55 (d, 1H, 3-H_{endo}, J = 13.0 Hz), 1.74 (m, 1H, 5-H_{exo}), 1.76 (t, 1H, 4-H, J = 4.3 Hz), 1.88 (dt, 1H, 3-H_{exo}, J = 13.0, 4.1 Hz), 2.06 (s, 1H, OH), 2,71 (dd, 1H, 1'-H_{cis}, J = 5.0, 4.0 Hz), 2.73 (dd, 1H, 1'-H_{trans}, J = 5.0, 3.1 Hz), 3.00 (dd, 1H, 2'-H, J = 4.0, 3.1 Hz)

Data for (1*R*,2*R*,2'*R*)-6b: mp 90°C. $[\alpha]_D^{20}$ = -8.00 (c 3.68, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.87 (s, 3H, 10-H), 0.91 (s, 3H, 9-H), 1.05 (m, 1H, 5-H_{endo}), 1.11 (s, 3H, 8-H), 1.34 (d, 1H, 3-H_{endo}, J = 13.7 Hz), 1.46-1.72 (m, 2H, 6-H), 1.75 (m, 1H, 5-H_{exo}), 1.76 (t, 1H, 4-H, J = 3.5 Hz), 1.89 (s, 1H, OH), 1.93 (dt, 1H, 3-H_{exo}, J = 13.7, 3.7 Hz), 2.63 (dd, 1H, 1'-H_{cis}, J = 5.2, 4.1 Hz), 2.78 (dd, 1H, 1'-H_{trans}, J = 5.2, 2.8 Hz), 3.18 (dd, 1H, 2'-H, J = 4.1, 2.8 Hz).

(1*R*,2*S*)-2-*endo*-(1',2'-epoxypropyl)-1,7,7-trimethylbicyclo[2.2.1]heptan-2-ol (7). Following ***GP***, 1.00 g (5.20 mmol) of **2** in 52 ml CH_2Cl_2, 0.02 g (0.08 mmol) $VO(acac)_2$ and 2.60 ml (7.80 mmol) 3M TBHP were combined and stirred for 26 h. After workup 1.02 g of crude **7** (1*R*,2*S*,2'*S*-**7a**/1*R*,2*S*,2'*R*-**7b** = 79:21 by NMR) were chromatographied (Ø 23 mm, h = 580 mm; 90 g silica gel, hexane/Et_2O = 8:1) to give 0.65 g (60%) **7a** (oil), 0.15 g (14%) **7b** (colourless solid) and 0.01 g mixed fractions. The total yield of **7** was 0.81 g (75%).

MS (EI) *m/z* (%): = 210 (M^+, 7), 192 (5), 179 (11), 169 (5), 123 (12), 111 (29), 97 (36), 95 (100), 93 (18), 69 (36), 57 (55). Anal. calc. for $C_{13}H_{22}O_2$: C, 74.24; H, 10.54; O, 15.21; found: C, 74.38; H, 10.29

Data for (1*R*,2*S*,2'*S*)-7a: $[\alpha]_D^{20}$ = +17.88 (c 1.04, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.87 (s, 6H, 9-H, 10-H), 0.98 (m, 1H, 5-H_{endo}), 1.13 (s, 3H, 8-H), 1.35-1.50 (m, 2H, 6-H), 1.48 (d, 1H, 3-H_{endo}, J = 13.1 Hz), 1.52 (dd, 1H, 3'-H_{trans}, J = 14.2, 7.8 Hz), 1.70 (m, 1H, 5-H_{exo}), 1.76 (t, 1H, 4-H, J = 4.3 Hz), 1.91 (dd, 1H, 3'-H_{gauche}, J = 14.2, 3.4 Hz), 2.09 (s, 1H, OH), 2.13 (dt, 1H, 3-H_{exo}, J = 13.1, 3.7 Hz), 2.50 (dd, 1H, 1'-H_{trans}, J = 4.9, 2.8 Hz), 2.81 (dd, 1H, 1'-H_{cis}, J = 4.9, 4.1 Hz), 3.18 (m, 1H, 2'-H).

Data for (1*R*,2*S*,2'*R*)-7b: 51-51°C. $[\alpha]_D^{20}$ = -10.48 (c 1.03, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.87 (s, 3H, 9-H), 0.94 (s, 3H, 10-H), 1.05 (m, 1H, 5-H_{endo}), 1.10 (s, 3H, 8-H), 1.25-1.60 (m, 2H, 6-H), 1.49 (d, 1H, 3-H_{endo}, J = 13.2 Hz), 1.62 (dd, 1H, 3'-H_{trans}, J = 14.4, 7.3 Hz), 1.73 (m. 1H, 5-H_{exo}), 1.73 (t, 1H, 4-H, J = 3.8 Hz), 1.94 (dd, 1H, 3'-H_{gauche}, J = 14.4, 4.5 Hz), 2.05 (dt, 1H, 3-H_{exo}, J = 13.2, 3.8 Hz), 2.24 (s, 1H, OH), 2.51 (dd, 1H, 1'-H_{trans}, J = 4.9, 2.8 Hz), 2.82 (dd, 1H, 1'-H_{cis}, J = 4.9, 4.1 Hz), 3.20 (m, 1H, 2'-H).

(1*R*,2*S*)-2-*endo*-(2'-methyl-1',2'-epoxypropyl)-1,7,7-trimethylbicyclo[2.2.1]heptan-2-ol (8). Following ***GP***, 0.200 g (0.960 mmol) of **2** in 10 ml CH_2Cl_2, 0.004 g (0.015 mmol) $VO(acac)_2$ and 0.800 ml (2.400 mmol) 3M TBHP were combined and stirred for 22 h. After workup 0.208 g of crude **8** (1*R*,2*S*,2'*S*-**8a**/1*R*,2*S*,2'*R*-**8b** = 72:28 by NMR) were chromatographied (Ø 13 mm, h = 430 mm, 20 g silica gel, hexane/Et_2O = 6:1) to give 0.132 g (62%) **8a** (oil) and 0.048 g (22%) **8b** (oil). The total yield of **8** was 0.180 g (84%)

MS (EI) *m/z* (%): = 224 (M^+, 1), 193 (8), 191 (3), 153 (13), 151 (6), 135 (6), 123 (11), 109 (43), 108 (40), 95 (100), 81 (32), 69 (27), 55 (25), 41 (30). Anal. calc. for $C_{14}H_{24}O_2$: C, 79.95; H, 10.78; O, 14.26; found: C, 74.80; H, 10.66.

Data for (1*R*,2*S*,2'*S*)-8a: $[\alpha]_D^{20}$ = +19.27 (c 0.83, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.85 (s, 6H, 9-H, 10-H), 0.97 (m, 1H, 5-H_{endo}), 1.09 (s, 3H, 8-H), 1.36-1.41 (m, 2H, 6-H), 1.41 (s, 3H, 4'-H), 1.48 (d, 1H, 3-H_{endo}, J = 12.9 Hz), 1.67 (m, 1H, 5-H_{exo}), 1.72 (t, 1H, 4-H, J = 3.8 Hz), 1.84; 1.92 (AB-system, 2H, 3'-H, J =

14.5 Hz), 2.04 (dt, 1H, 3-H_{exo}, J = 12.9, 3.8 Hz), 2.67 (d, 1H, 1'-H_{cis}, J = 4.3 Hz), 2.94 (d, 1H, 1'-H_{trans}, J = 4.3 Hz), 3.04 (s, 1H, OH).

Data for (1*R*,2*S*,2'*R*)-8b: $[\alpha]_D^{20}$ = +17.57 (c 0.83, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.80 (s, 3H, 10-H), 0.85 (s, 3H, 9-H), 0.98 (m, 1H, 5-H_{endo}), 1.11 (s, 3H, 8-H), 1.26-1.32 (m, 2H, 6-H), 1.46 (s, 3H, 4'-H), 1.49 (d, 1H, 3'-H_b, J = 14.3 Hz), 1.59 (d, 1H, 3-H_{endo}, J = 13.1 Hz), 1.70 (m, 1H, 5-H_{exo}), 1.74 (t, 1H, 4-H, J = 4.4 Hz), 2.02 (d, 1H, 3'-H_a, J = 14.3 Hz), 2.16 (dt, 1H, 3-H_{exo}, J = 13.1, 3.8 Hz), 2.54 (s, 1H, OH), 2.56 (s, 2H, 1'-$H_{a,b}$).

(1*R*,2*S*,3'*R*)-2-*endo*-(3'-methyl-1',2'-epoxypropyl)-1,7,7-trimethylbicyclo[2.2.1]heptan-2-ol (9). Following ***GP***, 0.50 g (2.40 mmol) of **4** in 25 ml CH_2Cl_2, 0.01 g (0.04 mmol) $VO(acac)_2$ and 2.00 ml (6.00 mmol) 3M TBHP were combined and stirred for 48 h. After workup 0.54 g of crude **9** (1*R*,2*S*,2'*R*,3'*R*-**9a**/1*R*,2*S*,2'*S*,3'*R*-**9b** = 85:15 by ^1H NMR) was chromatographied (Ø 17 mm, h = 490 mm, 46 g silica gel, hexane/Et_2O = 8:1) and 0.41 g (76%) **9a** (oil) and 0.07 g (13%) **9b** (colourless amorphous solid) were obtained. The total yield of **9** was 0.48 g (89%).

MS (EI) *m/z* (%): = 224 (M^+, 2), 192 (3), 153 (23), 108 (27), 107 (46), 95 (100), 69 (36), 55 (30), 41 (43).

Anal. calc. for $C_{14}H_{24}O_2$: C, 74.95, H, 10.78, O, 14.26; found: C, 74.74; H, 10.61.

Data for (1*R*,2*S*,2'*R*,3'*R*)-9a: $[\alpha]_D^{20}$ = -6.88 (c 1.80, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.84 (s, 3H, 9-H), 0.96 (s, 3H, 10-H), 1.00 (m, 1H, 5-H_{endo}), 1.07 (d, 3H, 4'-H, J = 7.0 Hz), 1.09 (s, 3H, 8-H), 1.30-1.50 (m, 2H, 6-H), 1.50 (qt, 1H, 3'-H, J = 7.0 Hz), 1.60 (d, 1H, 3-H_{endo}, J = 13.2 Hz), 1.71 (t, 1H, 4-H, J = 4.1 Hz), 1.72 (m, 1H, 5-H_{exo}), 1.87 (s, 1H, OH), 2.06 (dt, 1H, 3-H_{exo}, J = 13.2, 3.8 Hz), 2.70 (dd, 1H, 1'-H_{trans}, J = 4.8, 2.8 Hz), 2.85 (dd, 1H, 1'-H_{cis}, J = 4.8, 4.0 Hz), 3.14 (ddd, 1H, 2'-H, J = 6.8, 4.0, 2.8 Hz).

Data for (1*R*,2*S*,2'*S*,3'*R*)-9b: $[\alpha]_D^{20}$ = +7.03 (c 1.81, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.84 (s, 3H, 9-H), 0.98 (s, 3H, 10-H), 0.98 (d, 3H, 4'-H, J = 7.0 Hz), 1.00 (m, 1H, 5-H_{endo}), 1.09 (s, 3H; 8-H), 1.39-1.46 (m, 2H, 6-H), 1.56 (qt, 1H, 3'-H, J = 7.0 Hz), 1.72 (m, 1H, 5-H_{exo}), 1.72 (s, 1H, OH), 1.74 (t, 1H, 4-H, J = 3.3 Hz), 1.90 (d, 1H, 3-H_{endo}, J = 13.4 Hz), 2.03 (dt, 1H, 3-H_{exo}, J = 13.4, 3.3 Hz), 2.50 (dd, 1H, 1'-H_{trans}, J = 4.9, 2.9 Hz), 2.73 (dd, 1H, 1'-H_{cis}, J = 4.9, 4.2 Hz), 3.19 (ddd, 1H, 2'-H, J = 7.0, 4.2, 2.9 Hz).

(1*R*,2*S*,2'*S*,3'*S*)-2-*endo*-(3'-methyl-1',2'-epoxypropyl)-1,7,7-trimethylbicyclo[2.2.1]heptanol (10).

Following ***GP***, 0.200 g (0.960 mmol) of **5** in 10 ml CH_2Cl_2, 0.004 g (0.015 mmol) $VO(acac)_2$ and 0.800 ml (2.400 mmol) 3M TBHP were combined and stirred for 21 h. After workup the crude product (0.204 g) was chromatographied (Ø 13 mm, **h** = 430 mm, 20 g silica gel, hexane/Et_2O = 5:1) to give 0.110 g unconverted **5** and 0.054 g (56 %) of **10** (colourless solid).

MS (EI) *m/z* (%): = 224 (M^+, 6), 193 (25), 153 (22), 108 (48), 95 (100), 81 (25), 69 (36), 55 (35), 41 (63).

Anal. calc. for $C_{14}H_{24}O_2$: C,.74.95; H, 10.78; O, 14.26; found: C, 74.95; H, 10.70. mp 32-36°C. $[\alpha]_D^{20}$ = +5.73 (c 1.15, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.85 (s, 3H, 9-H), 0.99 (d, 1H, 4'-H, J = 6.5 Hz), 1.00 (m, 1H, 5-H_{endo}), 1.01 (s, 3H, 10-H), 1.09 (s, 3H, 8-H), 1.41 (d, 1H, 3-H_{endo}, J = 13.3 Hz), 1.47-1.58 (m, 2H, 6-H), 1.74 (m, 1H, 5-H_{exo}), 1.78 (qt, 1H, 3'-H, J = 6.5 Hz), 1.78 (t, 1H, 4-H, J = 3.8 Hz), 1.94 (dt, 1H, 3-H_{exo}, J = 13.3, 3.8 Hz), 2.03 (s, 1H, OH), 2.72 (dd, 1H, 1'-H_{trans}, J = 3.9, 2.9 Hz), 2.75 (t, 1H, 1'-H_{cis}, J = 3.9 Hz), 3.14 (ddd, 1H, 2'-H, J = 6.9, 3.9, 2.9 Hz).

(1*S*,2*R*,3*R*,5*S*)-2,5,6,6-tetramethyl-4-oxatricyclo[5.2.1.$0^{1,5}$]-deca-3-methanol (11). Following ***GP***, 0.100 g (0.480 mmol) of **5** in 5 ml CH_2Cl_2, 0.002 g (0.007 mmol) $VO(acac)_2$ and 0.400 ml (1.200 mmol) 3M TBHP were combined and stirred for 72 h. After workup the crude product was chromatographied (Ø 11 mm, h = 530 mm, 10 g silica gel, hexane/Et_2O = 8:1) to give 0.065 g (60%) of **11** (oil).
MS (EI) *m/z* (%): = 224 (M^+, 1), 193 (3), 181 (1), 167 (1), 165 (1), 155 (1), 141 (3), 135 (3), 91 (20), 79 (20), 67 (20), 55 (23), 53 (21), 43 (100), 41 (84). Anal. calc. for $C_{14}H_{24}O_2$: C, 74.95; H, 10.78; O, 14.26; found: C, 74.84; H,10.65. $[\alpha]_D^{20}$ = -9.78 (c 0.92, $CHCl_3$). ^1H NMR ($CDCl_3$, 300K): δ = 0.93 (d, 3H, 11-H, J = 6.6 Hz), 0.96 (s, 3H, 15-H), 1.01 (s, 3H, 14-H), 1.02 (s, 3H, 13-H), 1.01 (dd, 1H, 10-H_{anti}, J = 9.7, 1.7 Hz), 1.11-1.24 (m, 1H, 9-H_{endo}), 1.32-1.49 (m, 2H, 9-H_{exo}, 8-H_{exo}), 1.57-1.71 (m, 1H, 8-H_{endo}), 1.76-1.94 (m, 1H, 10-H_{syn}), 2.00 (dq, 1H, 2-H, J = 9.5, 6.6 Hz), 3.43-3.53 (m, 1H, 12-H_b), 3.66-3.75 (m, 2H, 3-H, 12-H_a).

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References and Notes

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