Tetrahedron: *Asymmetry* 22 (2011) 381–386

Contents lists available at ScienceDirect

Tetrahedron: *Asymmetry*

journal homepage: www.elsevier.com/locate/tetasy

Synthesis and enantiomeric recognition ability of 22-crown-6 ethers derived from rosin acid and BINOL

Hengshan Wang *, Xiaoyan Tian, Da Yang, Yingming Pan, Qiang Wu, Chunhuan He

Key Laboratory for the Chemistry and Molecular Engineering of Medicinal Resources, School of Chemistry and Chemical Engineering of Guangxi Normal University, Guilin 541004, PR China

ARTICLE INFO

Article history:
Received 19 September 2010
Revised 4 January 2011
Accepted 16 February 2011

ABSTRACT

Four novel chiral 22-crown-6 ethers **6a–b**, **7a–b** bearing hydroxyl side groups derived from rosin acid and BINOL were prepared in optically pure forms, and their enantiodiscriminating abilities towards protonated primary amines and amino acid methyl ester salts were examined by UV–vis titration methods. These receptors exhibited good chiral recognition towards the isomers (up to $K_D/K_L = 6.02$, $\Delta\Delta G_0 = 4.45$ kJ mol^{-1}) and showed different complementarity to various chiral guests.

1. Introduction

The enantiomeric recognition and the separation of amine compounds are amongst the main topics of Host-Guest chemistry because these compounds are the basic building blocks of biological molecules.[1] Since the pioneering work of Cram et al. on the use of chiral macrocyclic ligands in enantiomeric recognition,[2] extensive research has been carried out towards the synthesis of chiral crown ethers and the enantiodiscrimination of protonated primary amines.[3] Accumulated results provide a better understanding in terms of interactions operating in chiral recognition and are helpful in developing new methods for the chromatographic resolution of enantiomers. Accordingly, more and more crown ethers have been demonstrated to be highly effective in enantiomeric separations via chromatographic methods.[4]

Amongst the numerous types of host molecules studied, C_2-symmetric chiral crown ethers, which possess two equivalent faces, are characterized by their relatively simple recognition mechanism. A variety of such homochiral crown ethers using various types of natural and synthetic homochiral compounds as chiral subunits have been synthesized and their chiral recognition behaviour in complexation have been well documented.[5] In contrast, chiral crown ethers without C_2-symmetry, which possess two diastereotopic or non equivalent faces for complexing with a guest, have received less attention.[6] Although some of the latter ones, such as sugar[6] or amino acid[7] derived chiral macrocycles, have been reported to show special chiral discrimininating ability in catalytic asymmetric reactions and enantiomeric separation, there is still a strong requirement for novel types of such host molecules in order to allow a proper evaluation of the chiral microenvironment of changes in each of the two diastereotopic faces during the enantioselective recognition process.

Naturally occurring enantiomeric abietic acid promises to be an excellent starting material for preparing chiral reagents for enantiomeric separations owing to its enantiomeric purity and a very stable stereochemistry structure. Maleopimaric acid, the Diels–Alder adduct of levopimaric acid with maleic anhydride,[8] has been used in material processing, and in the synthesis of chemical products and biologically active compounds.[9] Recently, some of its derivatives have been applied in catalytic asymmetric reactions.[10] In our previous work, we have reported using maleopimaric acid in the separations of D/L-amino acids by capillary electrophoresis.[11] As part of our ongoing programme to develop crown ethers based on multiple cyclic chiral natural products for enantiomeric separation and to investigate the enantiodiscrimination of crown ethers with two significant different diastereotopic faces, we herein report a short-step synthesis of four enantiomerically pure crown ethers containing hydroxyl end groups, using maleopimaric acid, fumaropimaric acid and BINOL as starting materials, and their enantiodiscriminating abilities towards protonated primary amines and amino acid methyl ester salts by using the UV–vis titration method.

2. Results and discussion

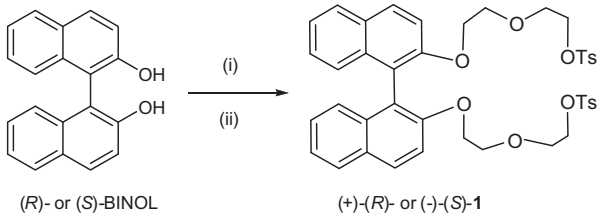
2.1. Synthesis

The Diels–Alder addition products of rosin acid are easily prepared chiral compounds bearing additional functional groups in the fused ring structure. For example, the Diels–Alder products of rosin acid with maleic acid anhydride or fumarate acid **2** or **3** (Scheme 2) contain three functional groups in their cyclic chiral structures,[10] and their reduction products **4** or **5** (Scheme 2)

* Corresponding author. Tel./fax: +86 773 2120958.
E-mail address: wang_hengshan@yahoo.com.cn (H. Wang).

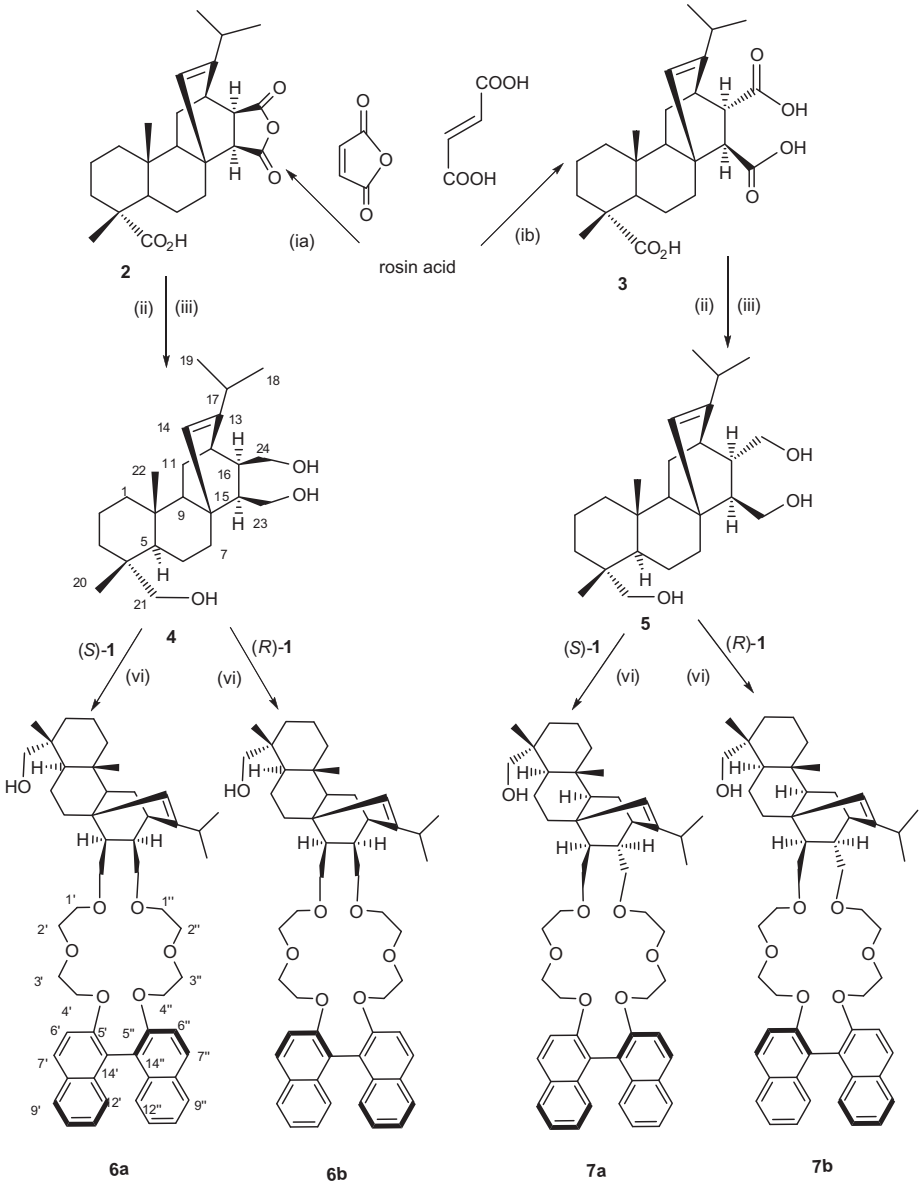
0957-4166/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2011.02.014

possessing three hydroxyl groups served as the linkage part of the host molecular in the present crown ether synthesis. The introduction of a 2,2′-dihydroxy-1,1′-binaphthyl (BINOL) unit on these crown ethers may result in some interesting features: (i) the formation of dual chiral architectures with different rosin structures to control the shape and the cavity of the crown, for observing special selectivity to different guests; (ii) providing supplementary rigid steric and chiral barriers, which may allow different enantioselective interactions with chiral guest enantiomers; and (iii) to facilitate photophysical studies involving intramolecular UV–vis spectroscopy, because of the presence of the photoactive 1,1′-binaphthyl chromophore.[12]



Scheme 1. Synthesis of the ditosylate (+)-(*R*)- or (−)-(*S*)-**1**. Reagents and conditions: (i) K_2CO_3/KI, 2-(2-chloroethoxy)ethanol, DMF, 150 °C, 48 h; (ii) Et_3N, TsCl, dichloromethane, rt, 24 h.

Ditosylate **1** was prepared according to the reported procedure[13] in 20.3% yield, as shown in Scheme 1. Maleopimaric acid **2** and its trimethyl ester were prepared according to the reported procedure.[14] Fumaropimaric acid **3** was prepared according to the reported procedure.[15] The conversion of trimethyl esters to triols **4** and **5** was carried out by the reported procedure[16] and followed by ring closure with (*R*)- or (*S*)-ditosylate **1** in the presence of NaH in THF under high dilution conditions. In the final step, four 1,1′-binaphthyl-appended crown ethers were obtained via a regioselective ring formation reaction (Scheme 2) in over 11% yield. The resulting host compound possesses an hydroxyl group in the side chain which can easily be used as a linkage group covalently bound



Scheme 2. Reagents and conditions: (i) no solvent, **1a** 140 °C, **1b** 200 °C, 3 h; (ii) PCl_3, then MeOH, reflux, 4 h; (iii) $LiAlH_4$, Et_2O, reflux, 8 h; (vi) NaH, **1**, THF, 50 h.

to the silica gel in the preparation of chiral stationary phases or membranes[17] or increasing the polarity of the host compound.

The structures purposed for these new chiral macrocycles are consistent with the data obtained from NMR, MS, and IR spectra. The structural assignment was further confirmed by 2D NMR experiments (including COSY, HSQC, HMBC and ROESY).

2.2. UV–vis spectroscopy

UV–vis spectroscopy is a convenient and a widely used method for the study of recognition phenomena. When the receptor absorbs light at different wavelengths in the free and complexed states, the difference in the UV–vis spectra is sufficient enough for the estimation of molecular recognition thermodynamics. In the UV spectroscopic titration experiments, the addition of varying concentrations of guest molecules resulted in either a gradual increase or decrease of the characteristic absorptions of the host molecules.

Under the conditions employed herein, two primary amines and two amino acid methyl ester hydrochlorides salts were selected as the guest molecules. The absorption increased upon the addition of the selected guests to all the hosts in $CHCl_3$/MeOH (2:1) at 25 °C. Under these conditions, the absorption intensities at 327 nm for NEA-HCl and 281 nm for other guests were collected. The behaviour of the crown ethers **6a**–**b**, **7a**–**b** and the selected guests during the titration indicated a 1:1 complexation, which was confirmed by the strong host-guest 1+1 molecular ion peaks, which appear in the ESI-MS analysis of the Host-Guest system. The association constants (K_a) of all the supramolecular systems formed were determined by titration, and analysed by the Rose–Drago method. The results of the K_a and free-energy changes ($-\Delta G_0$) of these hosts with guest molecules are summarized in Table 1.

Any chiral macrocycles have the potential of being enantioselective as long as they form complexes with guest enantiomers. Eighteen membered chiral macrocycles can easily form stable complexes with ammonium ions in chiral recognition, since the D_{3d}-symmetry of the 18-crown-6 molecule matches the molecular symmetry of NH_3 (C_{3v}), and in the complexes of 18-crown-6 with substituted ammonium ions the macroring portion retains the D_{3d} symmetry.[1b] Taking into account the data in Table 1, it was seen that crown ethers **6–7** formed complexes of appreciable stability constants towards isomers of all the ammonium ion hydrochlorides ($K_a = 6.4 \times 10^2$–2.5×10^4 dm^3 mol^{-1}; $G_0 = 16.0$–25.1 kJ mol^{-1}). The data presented herein are competitive to those obtained with chiral 18-crown-6 receptors, [3] which implies that these 22-crown-6 possess a similar distribution of the oxygen atoms or coordination site and envelop the cation in a fashion similar to that in 18-crown-6 to guests, and based the foundation of chiral recognition. This is further confirmed by comparing the ^{1}H NMR spectrum of **6a**, (*R*)-NEA-HCl and the 1:1 complex determined under the same experimental conditions. In comparison with the proton chemical shift of the (*R*)-NEA-HCl, the signal for H_4, CH and CH_3 protons of the guest moved 0.005, 0.007 and 0.01 ppm upfield, respectively, after forming a complex with **6a**, whereas the chemical shift of the host protons remain unchanged. This implied that the guest combined to the crown near the rosin acid unit and was shielded by its unsaturated ring. Otherwise, if the guest resides near the naphthalene ring of BINOL, it would result in a downfield movement of the guest protons signal, due to the anisotropic properties of the aromatic ring of BINOL.

From the K_D/K_L values in Table 1, it can be seen that receptors **6**–**7** exhibited good chiral recognition towards all the selected guest isomers, except for **7** to the (*RS*)-PEA-HCl host-guest systems (K_D/K_L less than 1.2; entries 21 and 29). Encouragingly, there were three cases of host-guest chiral recognition in which the binding constants of the favoured enantiomer is 3–6 times greater than the other ($K_D/K_L = 6.02$, 5.99 and 3.31, respectively; entries 3, 7 and 25). The data presented herein are competitively or even better than those obtained from typical examples of homochiral crown ethers. It may be the result of the unique features of the host compounds, including the huge barrier provided by the multiple cyclic chiral structures of rosin and a combination of rigid steric effects and π–π noncovalent interactions provided by the BINOL moiety. Moreover, the extent of enantiomeric recognition varies greatly, depending on the different host-guest systems. The main structural features governing the effective enantiomeric recognition of the four crown ethers are a broadened cavity of the 22-crown-6 and the special configurational characteristics of the ether chain with different diastereotopic faces, which are formed by the combination of the dissimilar chiral units of the rosin and BINOL.

By comparing the K_D/K_L values of NEA-HCl and PEA HCl, (1.80 and 6.02 for **6a**; 2.55 and 1.47 for **6b**; 2.03 and 1.61 for **7a**; 5.99 and 2.01 for **7b**; see in Table 1, entries 1, 3; 9, 11; 17, 19; 25, 27) with that of PhenA-OMe·HCl and PhenG-OMe·HCl (2.57 and 3.31 for **6a**; 1.38 and 2.83 for **6b**; 1.14 and 2.77 for **7a**; 1.19 and 1.83 for **7b**; see in Table 1, entries 5, 7; 13, 15; 21, 23; 29, 31), it can be seen that all of the host compounds had an effective enantiomeric recognition towards all of the primary amines over the amino acid methyl ester guests. This implies that the binding centre formed by oxygen atoms in the four 22-crown-6 through hydrogen bonds with the ammonium cation may be affected by the electronic effect of the methoxycarbonyl group in the guest. As a result, crown ethers **6**–**7** may have the advantage in terms of recognition of primary amine guests.

From the data in Table 1, the different structural features of the chiral crown ethers with different configurations in the side chain to the guests with various structures can be observed, which may play an important role in enantiomeric recognition. Crown ether **6a** with a maleopimaric triol group (possessing a *cis*-15,16-hydroxymethyl group in the rosin moiety) showed better enantiomeric discrimination towards the enantiomers of guests with a relatively large group (PhenA-OMe·HCl and NEA-HCl vs PEA HCl and PhenG-OMe·HCl), while the crown ethers **7a** and **7b** with a fumaropimaric triol group (possessing *trans*-15,16-hydroxymethyl in the rosin moiety) showed better enantiomeric discrimination towards the enantiomers of guests with a relatively small group (PEA HCl and PhenG-OMe·HCl vs PhenA-OMe·HCl and NEA-HCl). The significant enantiomeric discriminations of crown ethers **6a**, **6b** and **7b** to all the guest enantiomers may be a result of their configurational characteristics of the ether chain. Excellent enantioselectivity ($K_D/K_L = 6.02$ and 5.99) was achieved in the cases of **6a** to NEA-HCl and **7b** to NEA-HCl. Since the crown ethers possess two non equivalent faces, it is essential that the complexation for an efficient enantiodiscrimination should occur in such a manner that two guest enantiomers selectively complex to one of the different faces or to the same faces of the crown ether with different steric interactions and stabilities.

In comparison to the recognition process of C_2-symmetric chiral crown ethers with guests (according to the recognition mechanism, the approach of a guest to either face of the crown in a complex will be equivalent), crown ethers without C_2-symmetry can provide one more different diastereotopic faces in complexation for the approach of guests and, therefore ,would seem to offer interesting potential in broadening the range of their complementarity and selectivity to various guests. This characterized feature is advantageous due to its better adaptation to the separation of multi-components chiral compound mixtures in chiral stationary phases. From this point of view, crown ethers **6** and **7** can be chosen as models for the observation of chiral host molecules with two non equivalent faces and the attitude of macrocycles **6a** and **7b** deserves special consideration for application in chiral separation.

Table 1
Binding constants (K_a), free-energy changes ($-\Delta G_0$), enantioselectivities K_L/K_D and $\Delta\Delta G_0$ calculated from $-\Delta G_0$, for complexation for 1:1 complexes between L/D-amine salts and chiral host **6a**, **6b**, **7a** and **7b** in $CHCl_3$/MeOH (2:1) at 25 °C

Entry	Host[a]	Guest[b]	K_a (L mol^{-1})	K_D/K_L	$-\Delta G_0$ (KJ mol^{-1})	$\Delta\Delta G_0$ (KJ mol^{-1})
1	**6a**	(*R*)-PEA-HCl	$(1.10 \pm 0.14) \times 10^4$	1.80[c]	23.07	1.45
2		(*S*)-PEA-HCl	$(6.13 \pm 0.85) \times 10^3$		21.62	
3		(*R*)-NEA-HCl	$(1.41 \pm 0.16) \times 10^4$	6.02[c]	23.68	4.45
4		(*S*)-NEA-HCl	$(2.34 \pm 0.26) \times 10^3$		19.23	
5		D-PhenA-OMe·HCl	$(6.44 \pm 0.51) \times 10^2$	2.57[d]	16.03	−2.34
6		L-PhenA-OMe·HCl	$(1.65 \pm 0.21) \times 10^3$		18.37	
7		D-PhenG-OMe·HCl	$(2.09 \pm 0.20) \times 10^3$	3.31[d]	18.95	−2.97
8		L-PhenG-OMe·HCl	$(6.90 \pm 0.95) \times 10^3$		21.91	
9	**6b**	(*R*)-PEA-HCl	$(7.50 \pm 0.70) \times 10^3$	2.55[c]	22.12	2.32
10		(*S*)-PEA-HCl	$(2.95 \pm 0.48) \times 10^3$		19.80	
11		(*R*)-NEA-HCl	$(2.53 \pm 0.29) \times 10^4$	1.47[c]	25.13	0.96
12		(*S*)-NEA-HCl	$(1.71 \pm 0.33) \times 10^4$		24.17	
13		D-PhenA-OMe·HCl	$(4.80 \pm 0.50) \times 10^3$	1.38[d]	21.01	−0.79
14		L-PhenA-OMe·HCl	$(6.61 \pm 0.29) \times 10^3$		21.80	
15		D-PhenG-OMe·HCl	$(9.26 \pm 0.64) \times 10^2$	2.83[d]	16.93	−2.58
16		L-PhenG-OMe·HCl	$(2.62 \pm 0.66) \times 10^3$		19.51	
17	**7a**	(*R*)-PEA-HCl	$(4.23 \pm 0.45) \times 10^3$	2.03[c]	20.70	1.75
18		(*S*)-PEA-HCl	$(2.08 \pm 0.58) \times 10^3$		18.94	
19		(*R*)-NEA-HCl	$(2.50 \pm 0.28) \times 10^4$	1.61[c]	25.10	1.18
20		(*S*)-NEA-HCl	$(1.55 \pm 0.099) \times 10^4$		23.92	
21		D-PhenA-OMe·HCl	$(3.10 \pm 0.43) \times 10^3$	1.14[d]	19.93	−0.33
22		L-PhenA-OMe·HCl	$(3.55 \pm 0.31) \times 10^3$		20.26	
23		D-PhenG-OMe·HCl	$(3.32 \pm 0.25) \times 10^3$	2.77	20.10	2.53
24		L-PheG-OMe·HCl	$(1.20 \pm 0.06) \times 10^3$		17.57	
25	**7b**	(*R*)-PEA-HCl	$(2.04 \pm 0.54) \times 10^3$	5.99	18.88	−4.44
26		(*S*)-PEA-HCl	$(1.22 \pm 0.13) \times 10^4$		23.32	
27		(*R*)-NEA-HCl	$(1.27 \pm 0.17) \times 10^4$	2.01[c]	23.43	1.73
28		(*S*)-NEA-HCl	$(6.34 \pm 0.63) \times 10^3$		21.70	
29		D-PhenA-OMe·HCl	$(2.04 \pm 0.24) \times 10^3$	1.19	18.89	0.43
30		L-PhenA-OMe·HCl	$(1.71 \pm 0.19) \times 10^3$		18.46	
31		D-PhenG-OMe·HCl	$(1.34 \pm 0.13) \times 10^3$	1.83	17.85	−1.49
32		L-PhenG-OMe·HCl	$(2.45 \pm 0.30) \times 10^3$		19.35	

$\Delta\Delta G_0 = \Delta G_0$ (D/*R*) − ΔG_0 (L/*S*).
[a] Concentration of the receptor (**6a**, **6b**, **7b**: 2.1 mg/50 ml; **7a**: 2.0 mg/50 ml).
[b] PEA-HCl: 1-phenylethylamine hydrochloride salts; NEA-HCl: 1-(1-naphthyl)ethylamine hydrochloride salts; PhenA-OMe·HCl: phenylalanine methyl ester hydrochloride salts; PhenG-OMe·HCl phenylglycine methyl ester hydrochloride salts.
[c] K_R/K_S.
[d] K_L/K_D.

3. Conclusion

We have synthesized a series of 22-crown-6 ethers bearing hydroxyl side group derivatives comprising of 1,1′-binaphthyl and rosin acid moieties in the crown ring. These receptors showed strong affinity and different complementarity for various amine salts, and exhibit excellent enantiodiscriminating abilities towards protonated primary amines and amino acid methyl ester salt isomers in chiral recognition. Practically, via a short-step synthesis, the free OH side groups in the resulting host molecule facilitate the crown ether to be covalently bound to silica gel in the preparation of chiral stationary phases.

4. Experimental

4.1. General information

Enantiomerically pure primary amines and amino acid methyl ester salts and 2,2′-dihydroxy-1,1′-binaphthyl were purchased from Sigma-Aldrich Chemicals (St. Louis, MO, USA). Gum rosin was purchased from Wuzhou Pine Chemicals (Wuzhou, China). All the other chemicals and organic solvents used in this work were of analytical grade unless otherwise specified. Optical rotations were measured using a Perkin Elmer Model 341polarimeter at ambient temperature and $[\alpha]_D$ values are given in units of 10^{-1} deg cm^2 g^{-1}. The NMR spectra were measured in $CDCl_3$ on a BRUKER AVANCE AV500 spectrometer using TMS as the internal standard. IR spectra were recorded on a Nicolet ESP 360 FT-IR instrument. The mass spectra were obtained on a BRUKER ESQUIRE HCT spectrometer. HR-ESI-MS was recorded in Agilent 6210LC/MSD TOF. UV–vis absorption spectra were recorded with a CARY 100 spectrophotometer.

4.2. UV spectroscopic measurements

The ability of crown ethers to coordinate to amines and amino acid methyl ester hydrochloride salts was investigated using UV spectroscopic titration. The UV–vis spectra were measured at 25 ± 0.1 °C with a thermostated cell compartment by a CARY 100 spectrophotometer. The same concentration of guest solution was added to the sample cell and reference cell. The maximum wavelengths are 327 nm for **6–7** to NEA-HCl and 281 nm for other host-guest systems. $CHCl_3$/MeOH (2:1) was used as the solvent. The concentration of the hosts is 5.0×10^{-5} mol dm^{-3} with the increasing concentration of the added guest.

4.3. General experimental procedure for the preparation of triols

To a suspension of 1 g (27 mmol) of $LiAlH_4$ in 200 ml of ether, a solution of 3.1 g (5.6 mmol) of maleopimaric acid trimethyl ester or fumaropimaric acid trimethyl ester in 50 ml of ether was added

dropwise at 0 °C. The reaction mixture was stirred and heated at reflux for 8 h, after which 50 ml of ethyl acetate were added, followed by 50 ml of 1 M HCl. The organic layer was separated, washed with water, and dried over Na_2SO_4. After evaporation, the residue was recrystallised from either ethyl acetate or acetone and the reduction product triol **4** or **5** was obtained as colourless needles.

4.4. 15β-Hydroxymethyl-13-(1-methylethyl)-16α*H*-atis-13-ene-17,19-diol 4

Yield: 92.2%; mp 172.9–173.6 °C (ref: mp 170 °C[15]); $[\alpha]_D^{25} = +5.2$ (*c* 1.50, CH_3OH); ^1H NMR (CD_3OD, 500 MHz) δ: 0.59 (s, 3H, C*H*$_3$-22), 0.73 (s, 3H, C*H*$_3$-20), 0.783–0.86 (m, 1H, H$_\alpha$-1), 0.99, 1.00 (2d, *J* = 6.8 Hz, 6H, CH_3-18, CH_3-19), 1.07–1.17 (m, 1H, H$_\alpha$-11), 1.16–1.24 (m, 2H, H$_\alpha$-3, H-5), 1.31–1.34 (m, 1H, H-9), 1.37–1.52 (m, 7H, H$_\beta$-1, H-2, H$_\beta$-3, H-6, H$_\alpha$-7), 1.65 (ddd, *J* = 13.1, 11.4, 2.6 Hz, 1H, H$_\beta$-11), 1.83 (dt, *J* = 9.9, 2.3 Hz, 1H, H-15), 2.02–2.03 (m, 1H, H$_\beta$-7), 2.18–2.22 (m, 2H, H-16, H-17), 2.35 (br s, 1H, H-12), 3.07 (d, *J* = 10.9 Hz, 1H, H$_\alpha$-21), 3.41 (d, *J* = 10.6 Hz, 1H, H$_\beta$-21), 3.45 (d, *J* = 10.9 Hz, 1H, H$_\alpha$-23), 3.51 (dd, *J* = 11.4, 3.7 Hz, 1H, H$_\alpha$-24) 3.58 (t, *J* = 10.1 Hz, 1H, H$_\beta$-24), 3.76 (dd, *J* = 11.3, 1.9 Hz, 1H, H$_\beta$-23), 5.35 (s, 1H, H-14).

4.5. 13-(1-Methylethyl)-15β-hydroxymathyl-atis-13-ene-17,18-diol 5

Yield: 43.5%; mp 203–204 °C (ref.: mp 205 °C[15]); $[\alpha]_D^{25} = -15.2$ (*c* 1.40, CH_3OH); ^1H NMR ($CDCl_3$, 500 MHz) δ: 0.62 (s, 3H, C*H*$_3$-22), 0.74 (s, 3H, C*H*$_3$-20), 0.76–0.83 (m, 1H, H$_\alpha$-1), 0.94–0.98 (m, 1H, H$_\alpha$-11), 1.02 (d, *J* = 6.75 Hz, 6H, CH_3-18 and CH_3-19), 1.14 (d, *J* = 9.75 Hz, 1H, H$_\alpha$-15), 1.23–1.61 (m, 14H, H$_\beta$-1, H-2, H-3, H-5, H-6, H$_\alpha$-7, H-9, H$_\beta$-11, H$_\alpha$-12 and H-16), 1.89–1.94 (m, 1H, H$_\beta$-7), 2.30–2.35 (m, 1H, H-17), 2.42 (s, 1H, H$_\beta$-12), 2.69 (br s, 2H, OH), 2.96 (t, *J* = 9.95 Hz, 1H, H$_\alpha$-23), 3.11 (d, *J* = 10.85 Hz, 1H, H$_\alpha$-21), 3.39 (d, *J* = 10.7 Hz, 1H, H$_\beta$-21), 3.53 (t, *J* = 9.7 Hz, 1H, H$_\alpha$-24), 3.66 (dd, *J* = 4.25, 9.45 Hz, 1H, H$_\beta$-24), 3.75 (dd, *J* = 3.75, 9.3 Hz, 1H, H$_\beta$-23), 5.32 (s, 1H, H-14); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 16.0 (C-22), 17.3 (C-20), 17.7 (C-2), 19.2 (C-6), 20.6, 20.7 (C-18 and C-19), 23.4 (C-11), 32.7 (C-17), 35.3 (C-12), 35.5 (C-3), 35.6 (C-7), 37.3 (C-4), 37.9 (C-10), 38.7 (C-1), 39.9 (C-8), 44.7 (C-16), 48.2 (C-5), 55.5 (C-15), 55.8 (C-9), 64.5 (C-23), 67.2 (C-24), 72.2 (C-21), 124.3 (C-14), 150.2 (C-13).

4.6. General experimental procedure for the preparation of chiral 22-crown-6 derivatives 6 and 7

To a suspension of NaH (0.96 g, 24 mmol 60% in paraffin oil) in dry THF (80 mL) was slowly added dropwise within 2 h at 45 °C a mixture of triol **4** or **5** (1.18 g, 3 mmol) and (*S*)- or (*R*)-**1** (2.4 g, 3 mmol) in dry THF (90 mL). The suspension was stirred for another 72 h at reflux. After cooling to room temperature, 10 mL of water was added to the mixture in order to deactivate the excess NaH and the mixture was filtered and concentrated in vacuo. Water (30 mL) was added to the residue, and then extracted with dichloromethane (30 mL × 3). The combined organic layer was dried over $MgSO_4$ and the dichloromethane was evaporated off. The residue was purified by chromatography over silica (petroleum ether/acetone = 9:1) to give **6a**, **6b**, **7a** or **7b** as colourless powder.

Compound **6a**: Yield 11.8%; $[\alpha]_D^{20} = -93.3$ (*c* 0.1, acetone); ^1H NMR ($CDCl_3$, 500 MHz) δ: 0.61 (s, 3H, C*H*$_3$-22), 0.75 (s, 3H, C*H*$_3$-20), 0.79–0.89 (m, 1H, H$_\alpha$-1), 1.02, 1.04 (2d, *J* = 7.0 Hz, 6H, C*H*$_3$-18 and C*H*$_3$-19), 1.09–1.14 (m, 2H, H-5 and H$_\alpha$-11), 1.24–1.61 (m, 10H, H$_\beta$-1, H-2, H-3, H-6, H$_\alpha$-7, H-9 and H$_\beta$-11), 1.75 (t, *J* = 8.5 Hz, 1H, H-15), 1.97 (d, 1H, *J* = 11 Hz, H$_\beta$-7), 2.11–2.23 (m, 2H, H-16 and H-17), 2.65 (s, 1H, H-12), 2.88 (t, *J* = 9.5 Hz, 1H, H$_\alpha$-21), 2.98 (t, *J* = 9.5 Hz, 1H, H$_\beta$-21, 3.10–3.16 (m, 2H, H-24), 3.21–3.41 (m, 10H, H-23, OC*H*$_2$C*H*$_2$O), 3.45–3.73 (m, 4H, OC*H*$_2$C*H*$_2$O), 4.00–4.22 (m, 4H, OC*H*$_2$C*H*$_2$O), 5.36 (s, 1H, H-14), 7.14 (d, *J* = 8.5 Hz, 2H), 7.21 (t, *J* = 6.5 Hz, 2H), 7.32 (dd, *J* = 9.0 Hz, 2H), 7.43 (d, *J* = 9.0 Hz, 1H), 7.47 (d, *J* = 10.0 Hz, 1H), 7.85 (t, *J* = 8.0 Hz, 2H), 7.90 (d, *J* = 9.0 Hz, 1H), 7.94 (d, *J* = 9.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ: 16.1 (C-22), 17.4 (C-2), 17.8 (C-20), 19.5 (C-6), 20.4, 21.1 (C-18, C-19), 29.5 (C-11), 33.5 (C-17), 35.4 (C-3), 36.0 (C-12), 36.2 (C-7), 37.4 (C-4), 38.1 (C-10), 38.9 (C-1), 40.0 (C-8), 42.4 (C-16), 48.4 (C-5), 50.6 (C-15), 56.0 (C-9), 69.7, 69.7, 69.8, 70.0, 70.3, 70.4, 70.6, 70.8, 71.0, 71.6 (C-23 and C-24), 72.4 (C-21), 115.3, 117.8 (C-6′ and C-6″), 120.3, 121.5, 123.7, 123.9, 125.2 (C-11), 125.5, 125.6, 126.2, 126.4, 127.9, 128.0, 129.2, 129.4, 129.5, 129.8, 134.1, 134.2, 147.6 (C-14), 154.4, 155.0 (C-5′ and C-5″); IR (KBr, *v*, cm^{-1}): 3446, 2925, 2868, 1622, 1090; MS (APCI) *m*/*z*: 405 (M+H$^+$); MS (APCI) *m*/*z*: 804 [M]$^+$. HRMS (ESI) 825.4684 [M−2H+Na]$^+$, calcd for $C_{53}H_{66}O_8Na$: 825.4701.

Compound **6b**: Yield 12.3%; $[\alpha]_D^{20} = +65.7$ (*c* 0.1, acetone); ^1H NMR ($CDCl_3$, 500 MHz) δ: 0.60 (s, 3H, C*H*$_3$-22), 0.76 (s, 3H, C*H*$_3$-20), 0.85–0.90 (m, 1H, H$_\alpha$-1), 1.01 (t, *J* = 6.2 Hz, 6H, C*H*$_3$-18 and C*H*$_3$-19), 1.10–1.13 (m, 2H, H-5 and H$_\alpha$-11), 1.22–1.55 (m, 10H, H$_\beta$-1, H-2, H$_\alpha$-3, H-6, H-7, H-9 and H$_\beta$-11), 1.81 (t, *J* = 10.6 Hz, 1H, H-15), 1.95 (d, *J* = 6.8 Hz, 1H, H$_\beta$-3), 2.07–2.12 (m, 1H, H-16), 2.20–2.26 (m, 1H, H-17), 2.60 (s, 1H, H-12), 2.91 (t, *J* = 10.0 Hz, 1H, H$_\alpha$-21), 3.05 (t, *J* = 9.5 Hz, 1H, H$_\beta$-21), 3.12–3.66 (m, 16H, H-24, H-23, OC*H*$_2$C*H*$_2$O), 3.97–4.16 (m, 4H, OC*H*$_2$C*H*$_2$O), 5.34 (s, 1H, H-14), 7.10, 7.12 (d, *J* = 8.9 Hz, 2H), 7.19–7.22 (d, *J* = 8.1 Hz, 2H), 7.29–7.32 (m, 2H), 7.41 (d, *J* = 9.0 Hz, 1H), 7.46 (d, *J* = 9.0 Hz, 1H), 7.84, 7.85 (d, *J* = 8.0 Hz, 2H), 7.91, 7.93 (d, *J* = 8.9 Hz, 2H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ: 16.2 (C-22), 17.5 (C-2), 17.9 (C-20), 19.7 (C-6), 20.4, 21.2 (C-18 and C-19), 29.8 (C-11), 33.6 (C-17), 35.6 (C-3), 36.2 (C-12), 36.3 (C-7), 37.5 (C-4), 38.2 (C-10), 39.0 (C-1), 40.1 (C-8), 42.4 (C-16), 48.6 (C-5), 51.0 (C-15), 56.1 (C-9), 69.7, 69.89, 69.95, 69.98, 70.1, 70.2, 70.3, 70.7, 71.1, 71.8 (C-23 and C-24), 72.6 (C-21), 116.1, 117.0 (C-6′ and C-6″), 120.9, 121.1, 123.8, 123.84, 125.0 (C-11), 125.6, 125.7, 126.3, 126.4, 127.96, 128.0, 129.4, 129.5, 129.6, 129.8, 134.3, 134.4, 148.0 (C-14), 154.6, 154.9 (C-5′ and C-5″); IR (KBr, *v*, cm^{-1}): 3445, 2924, 1621, 1086; MS (APCI) *m*/*z*: 803 [M−H]$^+$.

Compound **7a**: Yield 11.7%; $[\alpha]_D^{20} = -39.0$ (*c* 0.1, acetone); ^1H NMR ($CDCl_3$, 500 MHz) δ: 0.64 (s, 3H, C*H*$_3$-22), 0.75 (s, 3H, C*H*$_3$-20), 0.78–0.84 (m, 1H, H$_\alpha$-1),0.89–1.04 (m, 2H, H$_\alpha$-11, H-15), 1.10 (d, *J* = 6.5 Hz, 6H, C*H*$_3$-18 and C*H*$_3$-19), 1.12–1.17 (m, 2H, H-5 and H-9), 1.22–1.55 (m, 9H, H$_\beta$-1, H-2, H-3, H-6, H$_\alpha$-7 and H-16), 1.77 (sept. d, *J* = 6.5, 1.2 Hz, 1H, H$_\beta$-11), 1.85 (d, *J* = 12.5 Hz, 1H, H$_\beta$-7), 2.34–2.40 (m, 1H, H-17), 2.48 (s, 1H, H-12), 2.86 (t, *J* = 9.5 Hz, 1H, H$_\alpha$-23), 3.11–3.13 (d, *J* = 10.5 Hz, 2H, H$_\alpha$-21 and OC*H*$_2$C*H*$_2$O), 3.21–4.22 (m, 19H, H$_\beta$-20, H-16, H$_\beta$-21, H$_\beta$-23, OC*H*$_2$-C*H*$_2$O), 5.31 (s, 1H, H-14), 7.12 (dd, *J* = 8.5, 4.0 Hz, 2H), 7.20 (m, 2H), 7.32 (dd, *J* = 7.0 Hz, 2H), 7.45 (t, *J* = 9.5 Hz, 2H), 7.85 (t, *J* = 8.5 Hz, 2H), 7.88 (d, *J* = 9.0 Hz, 1H), 7.95 (d, *J* = 9.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ: 16.2 (C-22), 17.5 (C-2), 17.9 (C-20), 19.4 (C-6), 20.9 (C-18), 21.0 (C-19), 22.7 (C-11), 33.0 (C-17), 33.8 (C-12), 35.6 (C-3), 35.8 (C-7), 37.4 (C-4), 38.1 (C-10), 38.9 (C-1), 39.9 (C-8), 41.6 (C-16), 48.5 (C-5), 51.0 (C-15), 56.0 (C-9), 69.7, 69.8, 70.0, 70.5, 70.9, 71.0, 71.1, 71.2, 72.5 (C-21), 74.2 (C-24), 74.7 (C-23), 115.4, 117.8 (C-6′ and C-6″), 120.4, 121.5, 123.7, 123.9, 124.4 (C-14), 125.6, 125.7, 126.3, 126.4, 127. 9, 128.0, 129.3, 129.4, 129.5, 129.7, 134.2, 134.3, 150.2 (C-13), 154.5, 155.2 (C-5′ and C-5″); IR (KBr, *v*, cm^{-1}): 3446, 2927, 2862, 1622, 1090; MS (APCI) *m*/*z*: 804 [M]$^+$; HRMS (ESI) *m*/*z* 825.4686 [M−2H+Na]$^+$, calcd for $C_{53}H_{66}O_8Na$: 825.4701.

Compound **7b**: Yield 11.5%; $[\alpha]_D^{20} = -35.6$ (*c* 0.1, acetone); ^1H NMR ($CDCl_3$, 500 MHz) δ: 0.64 (s, 3H, C*H*$_3$-22), 0.76 (s, 3H, C*H*$_3$-20), 0.79–0.98 (m, 3H, H$_\alpha$-1, H-11 and H-15), 1.04, 1.05 (2d, *J* = 7.0 Hz, 6H, C*H*$_3$-18 and C*H*$_3$-19), 1.09–1.18 (m, 2H, H$_\alpha$-5 and

H_α-9), 1.24–1.60 (m, 9H, H_β-1, H-2, H-3, H-6, H_α-7 and H-16), 1.67–1.74 (m, 1H, H_β-11), 1.84–1.86 (m, 1H, H_β-7), 2.31–2.38 (m, 1H, H-17), 2.53 (s, 1H, H-12), 2.76 (t, J = 9.5 Hz, 1H, H_α-23), 3.12–3.68 (m, 17H, H-21, H_β-23, H-24, CH_2O), 4.02–4.22 (m, 4H, CH_2O), 5.30 (s, 1H, H-14), 7.14 (d, J = 9.0 Hz, 2H), 7.21 (t, J = 8.5 Hz, 2H), 7.33 (dd, J = 7.5 Hz, 2H), 7.43 (d, J = 9.0 Hz, 1H), 7.49 (d, J = 10.0 Hz, 1H), 7.86 (d, J = 8.0 Hz, 1H), 7.88 (d, J = 8.0 Hz, 1H), 7.95 (d, J = 9.5 Hz, 1H), 7.96 (d, J = 9.5 Hz, 1H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 16.2 (C-22), 17.5 (C-2), 17.9 (C-20), 19.4 (C-6), 20.8, 20.9 (C-18 and C-19), 22.7 (C-11), 32.8 (C-17), 34.0 (C-12), 35.5 (C-3), 35.7 (C-7), 37.4 (C-4), 38.1 (C-10), 38.9 (C-1), 39.9 (C-8), 42.4 (C-16), 48.5 (C-5), 51.3 (C-15), 56.0 (C-9), 69.7, 69.8, 70.21, 70.23, 70.3, 70.4, 70.7, 71.0, 72.5 (C-21), 74.0 (C-24), 74.7 (C-23), 115.6, 117.1 (C-6′ and C-6″), 120.5, 121.2, 123.7, 123.9, 124.3 (C-14), 125.7 (C-2), 126.3, 126.4, 127.9, 128.0, 129.3, 129.4 (C-7′ and C-7″), 129.5, 129.8, 134.2, 134.3, 150.3 (C-13), 154.5, 154.9 (C-5′ and C-5″). IR (KBr, ν, cm^{-1}): 3446, 2928, 2862, 1623, 1092; MS (APCI) m/z: 804 $[M]^+$; HRMS (ESI) m/z 825.4683 $[M-2H+Na]^+$, calcd for $C_{53}H_{66}O_8Na$: 825.4701.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (No. 20762001), the Project of Ten, Hundred, Thousand Distinguished Talents in New Century of Guangxi (No. 2007228), the open fund of Key Laboratory of Development & Application of Forest Chemicals of Guangxi (GXFC08-05) and Guangxi National Science Foundation of China (2010GXNSFF013001).

References

1. (a) Berthod, A. In *Chiral Recognition in Separation Methods, Mechanism and Applications*; Springer: New York, 2010.; (b) Hembury, G. A.; Borovkov, V. V.; Inoue, Y. *Chem. Rev.* **2008**, *108*, 1–73; (c) Zhang, X. X.; Bradshaw, J. S.; Izatt, R. M. *Chem. Rev.* **1997**, *97*, 3313–3362.
2. Kyba, E. B.; Koga, K.; Sousa, L. R.; Siegel, M. G.; Cram, D. J. *J. Am. Chem. Soc.* **1973**, *95*, 2692–2693.
3. (a) Chelvi, T.; Sennappan, K.; Yong, E. L.; Gong, Y. *J. Sep. Sci.* **2010**, *33*, 74–78; (b) Turgut, Y.; Aral, T.; Hosgoren, H. *Tetrahedron: Asymmetry* **2009**, *20*, 2293–2298; (c) Nakatsuji, Y.; Nakahara, Y.; Muramatsu, A.; Kida, T.; Akashi, M. *Tetrahedron Lett.* **2005**, *46*, 4331–4335; (d) Lovely, A. E.; Wenzel, T. *J. Org. Lett.* **2006**, *8*, 2823–2826; (e) Karakaplan, M.; Turgut, Y. i.; Aral, T.; Hoşgören, H. *J. Incl. Phenom. Macrocycl. Chem.* **2006**, *54*, 315–319; (f) Chen, X.; Du, D.-M.; Hua, W.-T. *Tetrahedron: Asymmetry* **2003**, *14*, 999–1007; (g) BarIs, D.; Seker, S.; Hosgören, H.; Togrul, M. *Tetrahedron: Asymmetry* **2010**, *21*, 1893–1899; (h) Demirtas, H. N.; Bozkurt, S.; Durmaz, M.; Yilmaz, M.; Sirit, A. *Tetrahedron* **2009**, *65*, 3014–3018.
4. (a) Farkas, V.; Tóth, T.; Orosz, G.; Huszthy, P.; Hollósi, M. *Tetrahedron: Asymmetry* **2006**, *17*, 1883–1889; (b) Lakatos, S.; Fetter, J.; Bertha, F.; Huszthy, P.; Tóth, T.; Farkas, V.; Orosz, G.; Hollósi, M. *Tetrahedron* **2008**, *64*, 1012–1022; (c) Kim, E.; Koo, Y.-M.; Chung, D. S. *J. Chromatogr., A* **2004**, *1045*, 119–124; (d) Steffeck, R. J.; Zelechonok, Y.; Gahm, K. H. *J. Chromatogr., A* **2002**, *947*, 301–305; (e) Choi, H. J.; Park, Y. J.; Hyun, M. H. *J. Chromatogr., A* **2007**, *1164*, 235–239; (f) Yongzhu, J.; Hirose, K.; Nakamura, T.; Nishioka, R.; Ueshige, T.; Tobe, Y. *J. Chromatogr., A* **2006**, *1129*, 201–207; (g) Machida, Y.; Nishi, H.; Nakamura, K.; Nakai, H.; Sato, T. *J. Chromatogr., A* **1998**, *805*, 85–92; (h) Lämmerhofer, M. *J. Chromatogr., A* **2010**, *1217*, 814–856; (i) Seyhan, S.; Turgut, Y.; Merdivan, M.; Hosgören, H. *Tetrahedron: Asymmetry* **2006**, *17*, 1700–1704; (j) Cho, H. S.; Choi, H. J.; Hyun, M. H. *J. Chromatogr., A* **2009**, *1216*, 7446–7449; (k) Hyun, M. H.; Jin, J. S.; Lee, W. *J. Chromatogr., A* **1998**, *822*, 155–161; (l) Hyun, M. H.; Jin, J. S.; Koo, H. J.; Lee, W. *J. Chromatogr., A* **1999**, *837*, 75–82; (m) Hirose, K.; Nakamura, T.; Nishioka, R.; Ueshige, T.; Tobe, Y. *Tetrahedron Lett.* **2003**, *44*, 1549–1551; (n) Hirose, K.; Jin, Y. Z.; Nakamura, T.; Nishioka, R.; Ueshige, T.; Tobe, Y. *Chirality* **2005**, *17*, 142–148.
5. (a) Li, Z.-B.; Lin, J.; Sabat, M.; Hyacinth, M.; Pu, L. *J. Org. Chem.* **2007**, *72*, 4905–4916; (b) Hirose, K.; Ogasahara, K.; Nishioka, K.; Tobe, Y.; Naemura, K. *J. Chem. Soc., Perkin Trans. 2* **2000**, 1984–1993; (c) Naemura, K.; Matsunaga, K.; Fuji, J.; Ogasahara, K.; Nishikawa, Y.; Hirose, K.; Tobe, Y. *Anal. Sci.* **1998**, *14*, 175–182; (d) Naemura, K.; Nishioka, K.; Ogasahara, K.; Nishikawa, Y.; Hirose, K.; Tobe, Y. *Tetrahedron: Asymmetry* **1998**, *9*, 563–574.
6. (a) Chen, J.; Du, Y.; Zhu, F.; Chen, B. *J. Chromatogr., A* **2010**, *1217*, 7158–7163; (b) Zaher, M.; Baussanne, I.; Ravelet, C.; Halder, S.; Haroun, M.; Fize, J.; Décout, J.-L.; Peyrin, E. *J. Chromatogr., A* **2008**, *1185*, 291–295; (c) Nishi, H.; Kuwahara, Y. *J. Biochem. Biophys. Methods* **2001**, *48*, 89–102; (d) Nishi, H.; Kuwahara, Y. *J. Pharm. Biomed.* **2002**, *27*, 577–585.
7. (a) Ghosh, S.; Badruddoza, A. Z. M.; Uddin, M. S.; Hidajat, K. J. *Colloid Interface Sci.* **2011**, *354*, 483–492; (b) Nicolas, I.; Chevance, S.; Maux, P. L.; Simonneaux, G. *Tetrahedron: Asymmetry* **2010**, *21*, 1788–1792; (c) Werner, A.; Nassauer, T.; Kiechle, P.; Erni, F. *J. Chromatogr., A* **1994**, *666*, 375–379; (d) Escuder, B.; Rowan, A. E.; Feiters, M. C.; Nolte, R. J. M. *Tetrahedron* **2004**, *60*, 291–300; (e) Shizuma, M.; Ohta, M.; Yamada, H.; Takai, Y.; Nakaoki, T.; Takeda, T.; Sawada, M. *Tetrahedron* **2002**, *58*, 4319–4330; (f) Tran, D. N.; Blazkiewicz, C.; Menuel, S.; Roucoux, A.; Philippot, K.; Hapiot, F.; Monflier, E. *Carbohyd. Res.* **2011**, *346*, 210–218; (g) Gavin, J. A.; Garcia, M. E.; Benesi, A. J.; Mallouk, T. E. *J. Org. Chem.* **1998**, *63*, 7663–7669.
8. Pan, Y.-M.; Yang, L.; Wang, H.-S.; Zhao, Z.-C.; Zhang, Y. *Acta Crystallogr., Sect. E* **2006**, *62*, o5701–o5703.
9. (a) Lee, J. S.; Hong, S. I. *Eur. Polym. J.* **2002**, *38*, 387–392; (b) Wang, H.; Liu, B.; Liu, X.; Zhang, J.; Xian, M. *Green Chem.* **2008**, *10*, 1190–1196.
10. Tolstikov, A. H.; Tolstikova, O. V.; Khlebnikova, T. B.; Karpyshev, N. N. *Chemistry and Computational Simulation, Butlerov Communications* **2002**, *2*, 1–8.
11. (a) Ye, F. G.; Wang, H. S.; Huang, B. J.; Zhao, S. L. *Electrophoresis* **2010**, *31*, 1488–1492; (b) Wang, H.; Zhao, S.; He, M.; Zhao, Z.; Pan, Y.; Liang, Q. *J. Sep. Sci.* **2007**, *30*, 2748–2753; (c) Zhao, S.; Zhang, R.; Wang, H.; Tang, L.; Pan, Y. *J. Chromatogr., B* **2006**, *83*, 186–190; (d) Zhao, S. L.; Wang, H. S.; Zhang, R. C.; Tang, L. D.; Liu, Y. M. *Electrophoresis* **2006**, *27*, 3428–3433.
12. Ayer, W. A.; McDonald, C. E. *Can. J. Chem.* **1963**, *41*, 1113–1126.
13. (a) Mazaleyrat, J.-P.; Wright, K.; Azzini, M.-V.; Gaucher, A.; Wakselman, M. *Tetrahedron Lett.* **2003**, *44*, 1741–1745; (b) Wright, K.; Lohier, J.-F.; Wakselman, M.; Mazaleyrat, J.-P.; Formaggio, F.; Peggion, C.; Zotti, M. D.; Toniolo, C. *Tetrahedron* **2008**, *64*, 2307–2320.
14. Benniston, A. C.; Gunning, P.; Peacock, R. D. *J. Org. Chem.* **2005**, *70*, 115–123.
15. Halbrook, N. J.; Lawrence, R. V. *J. Am. Chem. Soc.* **1958**, *80*, 368–370.
16. (a) Seebacher, W.; Hüfner, A.; Haslinger, E.; Weis, R. *Monatsh. Chem.* **1998**, *129*, 697–703; (b) Khlebnikova, T. B.; Karpyshev, N. N.; Tolstikova, O. V.; Tolstikov, A. G. *Chirality* **2004**, *16*, S40–S50.
17. Hyun, M. H.; Han, S. C.; Lipshutz, B. H.; Shin, Y.-J.; Welch, C. J. *J. Chromatogr., A* **2001**, *910*, 359–365.

Further reading

18. Hirose, K. *J. Incl. Phenom. Macrocycl. Chem.* **2001**, *39*, 193–209.
19. Naemura, K.; Wakebe, T.; Hirose, K.; Tobe, Y. *Tetrahedron: Asymmetry* **1997**, *8*, 2585–2595.