Available online at www.sciencedirect.com
SCIENCE DIRECT®
Tetrahedron: *Asymmetry* 15 (2004) 881–887
Tetrahedron: *Asymmetry*

Asymmetric synthesis of ternaphthalenes via an ester-mediated nucleophilic aromatic substitution reaction

Tetsutaro Hattori,* Hiroaki Iwato, Koichi Natori and Sotaro Miyano

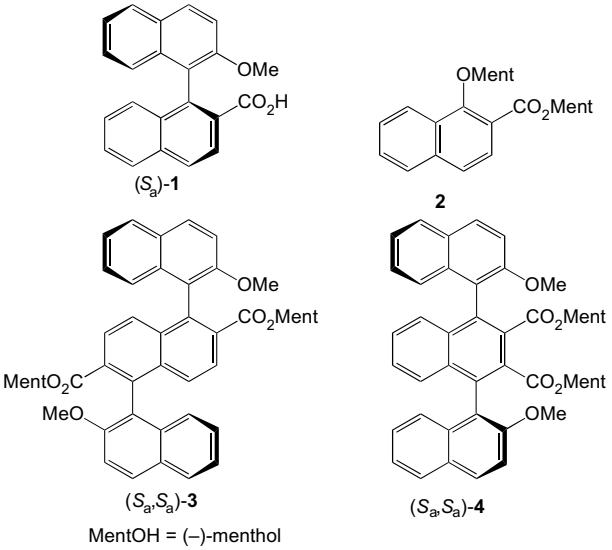
Department of Environmental Studies, Graduate School of Environmental Studies, Tohoku University, Aramaki-Aoba 07, Aoba-ku, Sendai 980-8579, Japan

Received 12 December 2003; accepted 16 January 2004

Abstract—A convenient method is presented for the asymmetric synthesis of axially chiral 1,1′:5′,1″- and 1,1′:4′,1″-ternaphthalenes via the ester-mediated nucleophilic aromatic substitution reaction. Thus, treatment of dimenthyl 1,5-dimenthoxynaphthalene-2,6-dicarboxylate **7** and its regioisomer, dimenthyl 1,4-dimenthoxynaphthalene-2,3-dicarboxylate **10**, with 2-methoxynaphthalen-1-ylmagnesium bromide **12** gave enantiomerically and diastereomerically pure dimenthyl 2,2″-dimethoxy-1,1′:5′,1″-ternaphthalene-2′,6′-dicarboxylate **3** and dimenthyl 2,2″-dimethoxy-1,1′:4′,1″-ternaphthalene-2′,3′-dicarboxylate **4** in 70% and 63% yields, respectively, after chromatographic purification.

1. Introduction

Over the last three decades, axially chiral 2,2′-disubstituted 1,1′-binaphthalenes have enjoyed many successful applications to highly efficient molecular recognitions, as well as asymmetric syntheses, because of their extraordinary chiral recognition abilities.[1] Accordingly, utilization of their higher homologues, oligonaphthalenes, as well as polynaphthalenes, has attracted a growing interest in enhancing the stereodifferentiating abilities or acquiring new functionalities.[2] Although a certain number of methods have been developed for the preparation of these kinds of compounds,[3] those which can achieve high stereoselectivity in the asymmetric synthesis are severely limited.[3a,h] On the other hand, 2′-methoxy-1,1′-binaphthalene-2-carboxylic acid **1** has been utilized not only as an efficient chiral derivatizing agent for the discrimination of chiral alcohols and amines,[4] but also as a convenient starting material for the preparation of axially chiral 2′-methoxy-1,1′-binaphthalenes,[5] because the 2-carboxyl group can be transformed into various functionalities without the loss of axial stereochemical integrity, which even in some cases can involve cleavage of the aryl–carbonyl carbon bond.[5a,b] Therefore, preparation of oligonaphthalenes consisting of this binaphthalene unit should be of much value. Previously,[6] we have reported a versatile synthetic route for biarylcarboxylic acids based on the nucleophilic aromatic substitution (S_NAr) reaction of *o*-alkoxyaromatic esters with aryl Grignard reagents, which provides a convenient substitute for the biaryl coupling based on the oxazoline-mediated S_NAr reaction (the Meyers reaction).[7] Acid (S_a)-**1** could be obtained as a single enantiomer by the S_NAr reaction of menthyl 1-menthoxy-2-naphthoate **2** with 2-methoxynaphthalen-1-ylmagnesium bromide **12**



* Corresponding author. Tel.: +81-22-217-7263; fax: +81-22-217-7293; e-mail: hattori@orgsynth.che.tohoku.ac.jp

0957-4166/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2004.01.021

and subsequent alkaline hydrolysis of the resulting 1,1′-binaphthalene-2-carboxylic ester.[6a,8] Herein, we report an effective extension of this methodology to the asymmetric construction of 1,1′:5′,1″-(**3**) and 1,1′:4′,1″-ternaphthalene-(**4**) skeletons.

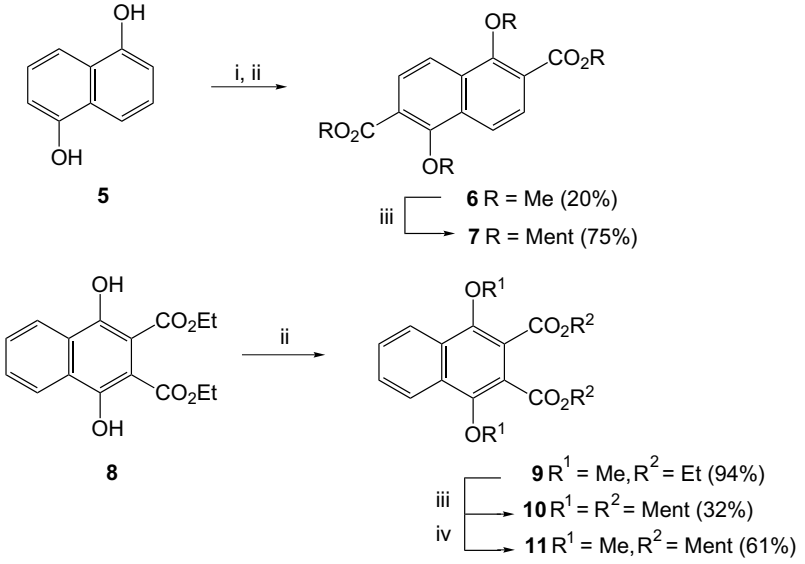
2. Results and discussion

Prerequisite tetramenthylated esters **7** and **10** were readily prepared from diols **5** and **8**, respectively, as described in Scheme 1. Thus, carboxylation of diol **5** with $KHCO_3$,[9] followed by methylation of the resulting diacid with iodomethane in the presence of NaH, gave tetramethylated ester **6**, which, on treatment with 6.0 mol equiv of sodium (−)-menthoxide in DMF, underwent simultaneous transesterification and displacement of the methoxy groups on the naphthalene ring to give tetramenthylated ester **7**.[6a] Similarly, ester **10** was obtained by etherification of diol **8** with iodomethane and subsequent treatment of the resulting diether **9** with sodium menthoxide. By reducing the quantity of the alkoxide to 2.2 mol equiv in the latter reaction, dimenthyl ester **11** was obtained as the main product.

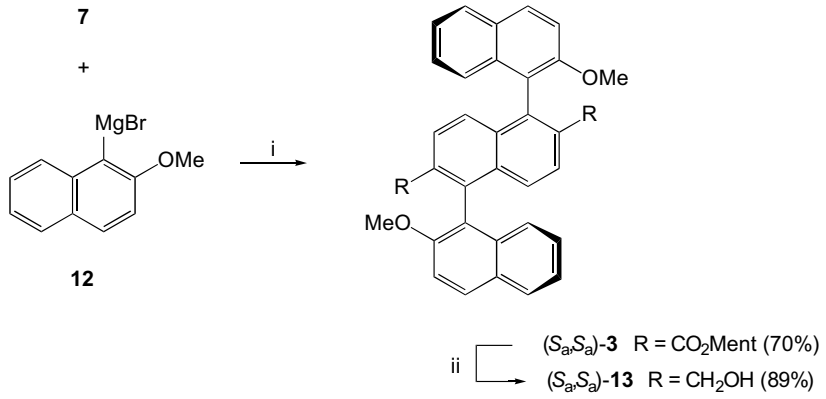
The S_NAr reaction of ester **7** was successfully performed by treatment with the Grignard reagent **12** in diethyl ether–benzene at room temperature for 3 h and then refluxing the mixture for 2 h to give ternaphthalene (S_a,S_a)-**3** in 70% yield with a concomitant formation of another atropisomer (~3%), which should be assigned to be S_a,R_a (vide infra) (Scheme 2). On the other hand, the S_NAr reaction of ester **10** was sluggish under the same conditions, giving binaphthalene **14** as the main product (61%), accompanied by a small amount of the expected ternaphthalene (S_a,S_a)-**4** (8%), together with *cis*-**4** (3%) (Scheme 3). The yield of ternaphthalene (S_a,S_a)-**4** could be improved to 63% by replacing the mixed solvent with benzene in addition to prolonging the heating time, which may indicate that the chelation between the substrate and the Grignard reagent is highly important to further the S_NAr reaction in this case (vide infra).

The absolute configurations of ternaphthalenes **3** and **4** were expected to be S_a,S_a, considering the stereochemistry of the binaphthyl coupling between ester **2** and Grignard reagent **12** (vide supra).[6a] This was confirmed by CD analysis of ternaphthalenes **3** and **4** after conversion into diols **13** and **15**, respectively (Fig. 1): Both CD spectra showed the positive first and negative second Cotton effects at the ^1B_b absorption band, originating from the exciton interaction between the adjacent naphthalene chromophores.[10] This unambiguously shows that they are not meso but chiral compounds and that the two sets of long axis of the adjacent naphthalene moieties twist clockwise, corresponding to S_a,S_a configuration.

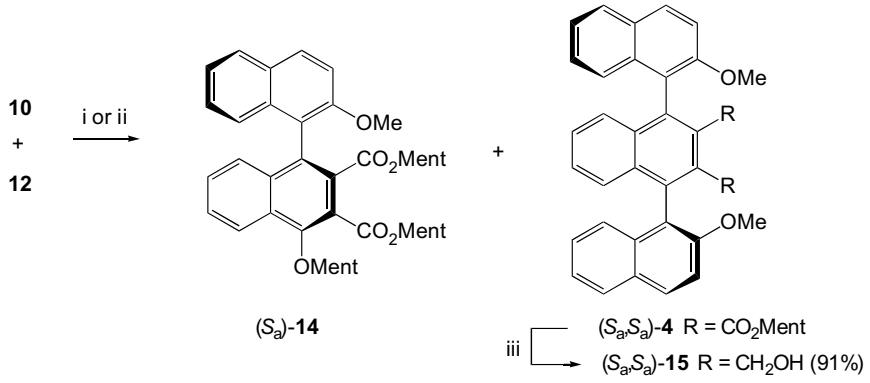
In order to gain insight into the low reactivity of ester **10** towards the S_NAr reaction as compared to that of ester **7**, giving binaphthalene **14** as the major product in diethyl ether–benzene, a controlled reaction was carried out by using dimenthyl ester **11** as the substrate (Scheme 4). The reaction proceeded smoothly to give three possible diastereomers of ternaphthalene **4**; that is, *cis*-, (R_a,R_a)- and (S_a,S_a)-**4** in 67%, 12% and 2% yields, respectively. In previous papers,[6a,f] we have shown that the almost perfect asymmetric induction of an *S*-axial twist in a coupling reaction between ester **2** and Grignard reagent **12** originated from the *C*-centrochirality of the menthoxy leaving group, while the chirality of the ester alkoxy group subtly affected the stereoselectivity. Therefore, the preferential formation of *cis*-**4** in the reaction of ester **11** is attributed to the axial chirality of the binaphthyl intermediate, although the reason is not clear at present. This implies that the axial chirality of



Scheme 1. Reagents and conditions: (i) $KHCO_3$, 1,2,4-trichlorobenzene; (ii) NaH, MeI, DMF; (iii) MentONa (6.0 mol equiv), DMF; (iv) MentONa (2.2 mol equiv), DMF.



Scheme 2. Reagents and conditions: (i) Et_2O–PhH, rt (3 h) then reflux (2 h); (ii) $LiAlH_4$, THF.



Scheme 3. Reagents and conditions: (i) Et_2O–PhH, rt (3 h) then reflux (2 h), (S_a)-**14** (61%, 90% de), (S_a,S_a)-**4** (8%), *cis*-**4** (3%); (ii) PhH, reflux (20 h), (S_a,S_a)-**4** (63%); (iii) $LiAlH_4$, THF.

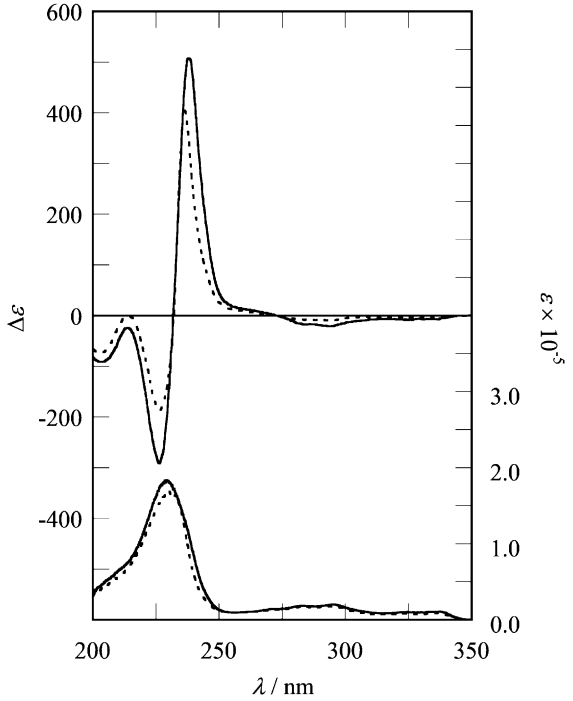
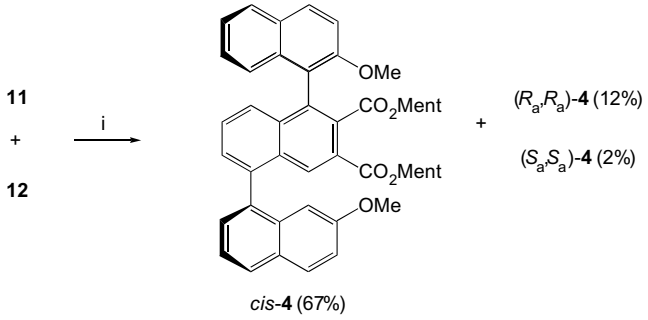


Figure 1. CD and UV spectra of diols (S_a,S_a)-**13** (solid curves) and (S_a,S_a)-**15** (dotted curves) in 10% v/v 1,4-dioxane/ethanol.

(S_a)-**14**, which should mediate the S_NAr reaction of ester **10** to ternaphthalene **4**, prefers to induce an *R*-axial twist in the second coupling, leading to the formation of *cis*-**4**. Therefore, it can be concluded that the stereochemical preference of the axial chirality of binaphthalene (S_a)-**14** conflicted with that of the menthoxy leaving group to retard the S_NAr reaction and that the replacement of the mixed solvent with benzene facilitated the chelation between **14** and **12** to promote the reaction,[6a] giving (S_a,S_a)-**4** under the major influence of the *C*-centrochirality of the menthoxy leaving group.



Scheme 4. Reagents and conditions: (i) Et_2O–PhH, rt (3 h) then reflux (2 h).

3. Conclusion

We have shown here that our previously reported methodology for the synthesis of biarylcarboxylic esters based on the ester-mediated S_NAr reaction can be advantageously extended to the asymmetric construction of 1,1′:5′,1″- and 1,1′:4′,1″-ternaphthalene skeletons.

4. Experimental

4.1. General

Melting points were taken using a Mitamura Riken MP-P apparatus and are uncorrected. Optical rotations were measured on a JASCO DIP-1000 polarimeter and $[\alpha]_D$ values are given in units of 10^{-1} deg cm^2 g^{-1}. Microanalyses were carried out in the Microanalytical Laboratory of the Institute of Multidisciplinary Research for Advanced Materials, Tohoku University. IR spectra were recorded on a Shimadzu FTIR-8300 spectrometer. ^{1}H NMR spectra were recorded on a Bruker DPX-400 or DRX-500 spectrometer using tetramethylsilane as the internal standard and $CDCl_3$ as the solvent. *J*-Values are given in hertz. UV and CD spectra were measured on a Shimadzu UV-2500 and a JASCO J-805 spectrometer, respectively. Silica gel columns were prepared by the use of Merck silica gel 60 (63–200 μm). Water- and air-sensitive reactions were routinely carried out under nitrogen. Diethyl ether, THF and benzene were distilled from sodium diphenyl ketyl just before use. Other solvents for experiments requiring anhydrous conditions were purified by the usual methods. Grignard reactions were carried out by a similar procedure to that described in the previous papers.[6a,e] Diethyl 1,4-dihydroxynaphthalene-2,3-dicarboxylate **8** was prepared by the reaction of diethyl phthalate with diethyl succinate in the presence of sodium ethoxide, according to the literature procedure.[11]

4.2. Dimethyl 1,5-dimethoxynaphthalene-2,6-dicarboxylate 6

A mixture of naphthalene-1,5-diol **5** (319 mg, 1.99 mmol), $KHCO_3$ (727 mg, 7.26 mmol) and 1,2,4-trichlorobenzene (10 cm^3) was heated at 230 °C for 3 h. The cooled mixture was filtered and the filter cake suspended in water. After the insoluble part was filtered, the filtrate was acidified by the addition of concd HCl to liberate the free acid, which was extracted with diethyl ether. The extract was washed with brine, dried over Na_2SO_4 and evaporated to give crude 1,5-dihydroxynaphthalene-2,6-dicarboxylic acid,[9] which was used in the following step without further purification. To a solution of the diacid in dry DMF (9.0 cm^3) was added NaH (156 mg, 6.50 mmol) portionwise and the mixture stirred at room temperature for 1 h. To the mixture was added iodomethane (1.07 g, 7.55 mmol) and the mixture heated at 80 °C for 4 h. The cooled mixture was poured into 2 M HCl and extracted with diethyl ether. The extract was washed successively with 2 M HCl, 2 M Na_2CO_3 and water, dried over Na_2SO_4 and evaporated. The residue was chromatographed on silica gel with dichloromethane as the eluent to give the tetramethylated ester **6** (121 mg, 20%) as crystals, mp 138.0–138.5 °C (Found: C, 63.20; H, 5.38. Calcd for $C_{16}H_{16}O_6$: C, 63.15; H, 5.30); ν_{max} (KBr)/cm^{-1} 1730; δ_H (400 MHz) 3.99 (6H, s, 2×OMe), 4.05 (6H, s, 2×OMe), 7.90 (2H, d, *J* 8.8, ArH) and 8.04 (2H, d, *J* 8.8, ArH).

4.3. Di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl] 1,5-di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyloxy]naphthalene-2,6-dicarboxylate 7

Compound **7** was prepared by a similar procedure to that described in a previous paper.[6a] Sodium menthoxide was prepared from (−)-menthol (7.20 g, 46.1 mmol) and NaH (954 mg, 39.8 mmol) and dissolved in dry DMF (30 cm^3). To the solution was added ester **6** (2.00 g, 6.57 mmol) and the mixture stirred at 50 °C for 3 h. After the usual work-up, the crude product was chromatographed on silica gel with hexane–ethyl acetate (100:1) as the eluent to give tetramenthylated ester **7** (3.97 g, 75%) as crystals, mp 221–223 °C; $[\alpha]_D^{21} = -90.7$ (*c* 1.05, $CHCl_3$) (Found: C, 77.90; H, 9.79. Calcd for $C_{52}H_{80}O_6$: C, 77.95; H, 10.06); ν_{max} (KBr)/cm^{-1} 1716; δ_H (400 MHz) 0.74–1.76 (66H, m, menthyl), 2.02–2.08 (2H, m, menthyl), 2.16–2.18 (2H, m, menthyl), 2.56–2.63 (2H, m, menthyl), 4.29 (2H, td, *J* 10.5 and 3.7, 2×OCH), 5.03 (2H, td, *J* 10.8 and 4.4, 2×OCH), 7.65 (2H, d, *J* 8.8, ArH) and 7.99 (2H, d, *J* 8.8, ArH).

4.4. Diethyl 1,4-dimethoxynaphthalene-2,3-dicarboxylate 9

To a solution of diol **8** (3.75 g, 12.3 mmol) in dry DMF (40 cm^3) was added NaH (1.20 g, 50.0 mmol) portionwise and the mixture stirred at room temperature for 1 h. To the mixture was added dropwise iodomethane (8.89 g, 62.6 mmol) over 30 min and the resulting mixture stirred for 2 h. The mixture was quenched with 2 M HCl and extracted with diethyl ether. The extract was washed successively with 2 M $NaHCO_3$ and water, dried over Na_2SO_4 and evaporated. The residue was chromatographed on silica gel with hexane–ethyl acetate (6:1) as the eluent to give diether **9**[11] (3.85 g, 94%) as an oil, ν_{max} (neat)/cm^{-1} 1736; δ_H (400 MHz) 1.41 (6H, t, *J* 7.0, 2×CH_2*Me*), 4.03 (6H, s, 2×OMe), 4.42 (4H, q, *J* 7.0, 2×CH_2Me), 7.61–7.65 (2H, m, ArH) and 8.16–8.19 (2H, m, ArH).

4.5. Di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl] 1,4-di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyloxy]naphthalene-2,3-dicarboxylate 10

This compound was prepared by a similar procedure to that described in a previous paper.[6a] Sodium menthoxide was prepared from (−)-menthol (29.6 g, 189 mmol) and NaH (3.42 g, 143 mmol) and dissolved in dry DMF (21 cm^3). To the solution was added diether **9** (7.87 g, 23.7 mmol) and the mixture stirred at 50 °C for 3 h. After the usual work-up, excess menthol was distilled off under reduced pressure (120 °C/400 Pa) and the residue

chromatographed on silica gel with hexane–ethyl acetate (25:1) as the eluent to give tetramenthylated ester **10** (5.98 g, 32%) as crystals, mp 129–130 °C; $[\alpha]_D^{20} = -45.2$ (*c* 1.06, $CHCl_3$) (Found: C, 77.91; H, 10.09. Calcd for $C_{52}H_{80}O_6$: C, 77.95; H, 10.06); ν_{max} (KBr)/cm^{-1} 1730; δ_H (400 MHz) 0.74–1.74 (66H, m, menthyl), 2.21–2.35 (4H, m, menthyl), 2.68–2.75 (2H, m, menthyl), 4.16 (2H, td, *J* 10.5 and 4.2, 2×OCH), 4.85 (2H, td, *J* 10.9 and 4.3, 2×OCH), 7.50–7.54 (2H, m, ArH) and 8.13–8.17 (2H, m, ArH).

4.6. Di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl] 1,4-dimethoxynaphthalene-2,3-dicarboxylate 11

This compound was prepared by a similar procedure to that used for the preparation of ester **10**. Sodium menthoxide prepared from (−)-menthol (2.08 g, 13.3 mmol) and NaH (319 mg, 13.3 mmol) was dissolved in dry DMF (20 cm^3) and cooled to 0 °C. To the mixture was added diether **9** (1.99 g, 5.99 mmol) and the resulting mixture stirred at this temperature for 1 h. After the usual work-up, the crude product was chromatographed on silica gel with hexane–ethyl acetate (30:1) as the eluent to give dimenthyl ester **11** (2.02 g, 61%) as crystals, mp 146–147 °C; $[\alpha]_D^{20} = -74.1$ (*c* 1.20, $CHCl_3$) (Found: C, 73.90; H, 8.81. Calcd for $C_{34}H_{48}O_6$: C, 73.88; H, 8.75); ν_{max} (KBr)/cm^{-1} 1730; δ_H (400 MHz) 0.84–1.62 (28H, m, menthyl), 1.71–1.77 (4H, m, menthyl), 2.16–2.23 (2H, m, menthyl), 2.26–2.31 (2H, m, menthyl), 3.99 (6H, s, 2×OMe), 5.01 (2H, td, *J* 10.9 and 4.4, 2×OCH), 7.57–7.63 (2H, m, ArH) and 8.10–8.17 (2H, m, ArH).

4.7. Di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl] (S_a,S_a)-2,2″-dimethoxy-1,1′:5′,1″-ternaphthalene-2′,6′-dicarboxylate (S_a,S_a)-3

Treatment of 1-bromo-2-methoxynaphthalene (751 mg, 3.17 mmol) with magnesium turnings (123 mg, 5.06 mmol) in diethyl ether (10 cm^3) gave Grignard reagent **12** as a slurry, which was dissolved by the addition of benzene (15 cm^3). The Grignard solution was added to a solution of ester **7** (605 mg, 755 μmol) in benzene (5.0 cm^3). The mixture was stirred at room temperature for 3 h and then heated at reflux for 2 h. After the usual work-up, the crude product was chromatographed on silica gel with hexane–dichloromethane (2:1 to 2:3) as the eluent to give ternaphthalene (S_a,S_a)-**3** (428 mg, 70%) as crystals, mp 280–281.5 °C; $[\alpha]_D^{25} = -154$ (*c* 1.02, $CHCl_3$) (Found: C, 80.63; H, 7.68. Calcd for $C_{54}H_{60}O_6$: C, 80.56; H, 7.51); ν_{max} (KBr)/cm^{-1} 1710; δ_H (400 MHz) 0.42–1.57 (36H, m, menthyl), 3.80 (6H, s, 2×OMe), 4.44 (2H, td, *J* 10.8 and 4.4, 2×OCH), 7.03 (2H, d, *J* 8.5, ArH), 7.22–7.34 (4H, m, ArH), 7.45 (2H, d, *J* 9.1, ArH), 7.51 (2H, d, *J* 8.7, ArH), 7.86–7.90 (4H, m, ArH) and 8.02 (2H, d, *J* 9.0, ArH).

4.8. (S_a,S_a)-2′,6′-Dihydroxymethyl-2,2″-dimethoxy-1,1′:5′,1″-ternaphthalene (S_a,S_a)-13

To an ice-cold solution of ternaphthalene (S_a,S_a)-**3** (253 mg, 314 μmol) in dry THF (10 cm^3) was added portionwise $LiAlH_4$ (47.8 mg, 1.26 mmol) and the mixture stirred at room temperature for 6 h. The mixture was cooled in an ice bath and quenched by the successive addition of water and 2 M HCl. The mixture was extracted with diethyl ether and the extract washed with brine, dried over Na_2SO_4 and evaporated. The residue was chromatographed on silica gel with hexane–ethyl acetate as the eluent to give diol (S_a,S_a)-**13** (140 mg, 89%) as crystals, mp 152–153 °C; $[\alpha]_D^{26} = -23.2$ (*c* 0.10, $CHCl_3$) (Found: C, 81.46; H, 5.61. Calcd for $C_{34}H_{28}O_4$: C, 81.58; H, 5.64); ν_{max} (KBr)/cm^{-1} 3410; δ_H (400 MHz) 3.80 (6H, s, 2×OMe), 4.32 (4H, s, 2×CH_2), 7.06 (2H, d, *J* 8.5, ArH), 7.25–7.40 (6H, m, ArH), 7.50 (2H, d, *J* 9.1, ArH), 7.51 (2H, d, *J* 8.6, ArH), 7.92 (2H, d, *J* 8.1, ArH) and 8.05 (2H, d, *J* 9.1, ArH).

4.9. Reaction of tetramenthylated ester 10 with Grignard reagent 12

Grignard reagent **12** was prepared from 1-bromo-2-methoxynaphthalene (479 mg, 2.02 mmol) and magnesium turnings (102 mg, 4.20 mmol) in THF (10 cm^3). The solvent was removed under reduced pressure and the residue dissolved by the addition of benzene (6.0 cm^3). In the case of the reaction conducted in diethyl ether–benzene, the Grignard reagent was prepared from the bromide (443 mg, 1.87 mmol) and magnesium turnings (118 mg, 4.85 mmol) in diethyl ether (6.0 cm^3) with induction of dissolution by addition of benzene (6.0 cm^3). The Grignard solution was added to a solution of ester **10** (400 mg, 499 μmol) in benzene (4.0 cm^3) and the mixture then stirred at an appropriate temperature for 5–20 h. After the usual work-up, the crude products were purified by column chromatography on silica gel with hexane–ethyl acetate as the eluent. See Scheme 3 for the reaction conditions and product yields. The physical and spectral characteristics of the products are given below.

4.9.1. Di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl] (S_a)-4-[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyloxy]-2′-methoxy-1,1′-binaphthalene-2,3-dicarboxylate (S_a)-14. As crystals (Found: C, 78.97; H, 8.80. Calcd for $C_{53}H_{70}O_6$: C, 79.26; H, 8.79); δ_H (400 MHz) 0.52–2.72 (54H, m, menthyl), 3.71, 3.77 [3H: s, OMe (R_a); s, OMe (S_a)], 4.28–4.70 (1H, m, OCH), 4.37–4.40 (1H, m, OCH), 4.90–4.95 (1H, m, OCH) and 7.04–8.30 (10H, m, ArH). ^{1}H NMR analysis of the sample differentiated well the methoxy signals of the (S_a)- and (R_a)-diastereomers; integration of which determined the diastereomeric composition to be 90% de.

4.9.2. Di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl] (S_a,S_a)-2,2″-dimethoxy-1,1′:4′,1″-ternaphthalene-2′,3′-dicarboxylate (S_a,S_a)-4. As crystals, mp 304–307 °C; $[\alpha]_D^{25} = -188$ (*c* 1.08, $CHCl_3$) (Found: C, 80.69; H, 7.49. Calcd for $C_{54}H_{60}O_6$: C, 80.56; H, 7.51); ν_{max} (KBr)/cm^{-1} 1701; δ_H (400 MHz) 0.36 (6H, d, *J* 6.9, CH*Me*$_2$), 0.50–1.48 (30H, m, menthyl), 3.91 (6H, s, 2×OMe), 4.36 (2H, td, *J* 10.7 and 4.1, 2×OCH), 7.11–7.33 (10H, m, ArH), 7.47 (2H, d, *J* 9.0, ArH), 7.82–7.85 (2H, m, ArH) and 8.00 (2H, d, *J* 8.8, ArH).

4.9.3. Di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl] (S_a,R_a)-2,2″-dimethoxy-1,1′:4′,1″-ternaphthalene-2′,3′-dicarboxylate *cis*-4. As crystals, mp 233–235 °C; $[\alpha]_D^{21} = -65.6$ (*c* 1.02, $CHCl_3$) (Found: C, 80.54; H, 7.53. Calcd for $C_{54}H_{60}O_6$: C, 80.56; H, 7.51); ν_{max} (KBr)/cm^{-1} 1710; δ_H (400 MHz) 0.25–1.57 (36H, m, menthyl), 3.78 (3H, s, OMe), 3.88 (3H, s, OMe), 4.30 (1H, td, *J* 10.8 and 4.3, OCH), 4.39 (1H, td, *J* 10.7 and 4.2, OCH), 7.12–7.39 (10H, m, ArH), 7.40 (1H, d, *J* 9.0, ArH), 7.46 (1H, d, *J* 9.0, ArH), 7.83–7.89 (2H, m, ArH) and 7.99 (2H, d, *J* 9.0, ArH).

4.10. (S_a,S_a)-2′,3′-Dihydroxymethyl-2,2″-dimethoxy-1,1′:4′,1″-ternaphthalene (S_a,S_a)-15

To a solution of ternaphthalene (S_a,S_a)-**4** (45.1 mg, 56.0 μmol) in dry THF (3.0 cm^3) was added $LiAlH_4$ (22.5 mg, 593 μmol) and the mixture stirred at room temperature for 3 h. The mixture was cooled in an ice bath and quenched by the successive addition of water and 2 M HCl. The mixture was extracted with diethyl ether and the extract washed with brine, dried over Na_2SO_4 and evaporated. The residue was chromatographed on silica gel with hexane–ethyl acetate (1:2) as the eluent to give diol (S_a,S_a)-**15** (25.4 mg, 91%) as crystals, mp 308–310 °C; $[\alpha]_D^{25} = +16.9$ (*c* 0.40, $CHCl_3$) (Found: C, 81.54; H, 5.70. Calcd for $C_{34}H_{28}O_4$: C, 81.58; H, 5.64); ν_{max} (KBr)/cm^{-1} 3370; δ_H (400 MHz) 3.85 (6H, s, 2×OMe), 4.57 (2H, d, *J* 12.0, 2×CH), 4.73 (2H, d, *J* 12.0, 2×CH), 7.15–7.21 (6H, m, ArH), 7.27–7.31 (2H, m, ArH), 7.36–7.40 (2H, m, ArH), 7.53 (2H, d, *J* 8.0, ArH), 7.92 (2H, d, *J* 9.1, ArH) and 8.06 (2H, d, *J* 8.9, ArH).

4.11. Reaction of dimenthyl ester 11 with Grignard reagent 12

This reaction was performed in diethyl ether–benzene by the same procedure used for the reaction between ester **10** and Grignard reagent **12**. Column chromatography isolated the following compound besides isomers *cis*-**4** and (S_a,S_a)-**4**.

4.11.1. Di[(1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl] (R_a,R_a)-2,2″-dimethoxy-1,1′:4′,1″-ternaphthalene-2′,3′-dicarboxylate (R_a,R_a)-4. As an amorphous solid (Found: C, 80.33; H, 7.80. Calcd for $C_{54}H_{60}O_6$: C, 80.56; H, 7.51); δ_H (400 MHz) 0.46–1.68 (36H, m, menthyl), 3.81 (6H, s, 2×OMe), 4.33–4.40 (2H, m, 2×OCH) and 7.24–8.00 (16H, m, ArH).

Acknowledgements

We are grateful to Dr. Osamu Yamabe for experimental support. This study was supported in part by a grant from the General Sekiyu Research Promotion Foundation.

References and notes

1. Review: (a) Rosini, C.; Franzini, L.; Raffaelli, A.; Salvadori, P. *Synthesis* **1992**, 503; (b) Pu, L. *Chem. Rev.* **1998**, *98*, 2405.
2. (a) Yamamoto, K.; Yumioka, H.; Okamoto, Y.; Chikamatsu, H. *J. Chem. Soc., Chem. Commun.* **1987**, 168; (b) Müller, U.; Baumgarten, M. *J. Am. Chem. Soc.* **1995**, *117*, 5840; (c) Pu, L. *Chem. Eur. J.* **1999**, *5*, 2227; (d) Fuji, K.; Furuta, T.; Otsubo, T.; Tanaka, K. *Tetrahedron Lett.* **1999**, *40*, 3001; (e) Ma, L.; White, P. S.; Lin, W. *J. Org. Chem.* **2002**, *67*, 7577; (f) Tsubaki, K.; Tanaka, H.; Furuta, T.; Tanaka, K.; Kinoshita, T.; Fuji, K. *Tetrahedron* **2002**, *58*, 5611.
3. (a) Hayashi, T.; Hayashizaki, K.; Ito, Y. *Tetrahedron Lett.* **1989**, *30*, 215; (b) Marin, G. H.; Horak, V. *J. Org. Chem.* **1994**, *59*, 4267; (c) Bělohradský, M.; Buděšínský, M.; Günterová, J.; Hodačová, J.; Holý, P.; Závada, J.; Císařová, I.; Podlaha, J. *J. Org. Chem.* **1996**, *61*, 1205; (d) Hagen, S.; Scott, L. T. *J. Org. Chem.* **1996**, *61*, 7198; (e) Zoltewicz, J. A.; Maier, N. M.; Lavieri, S.; Ghiviriga, I.; Abboud, K. A.; Fabian, W. M. F. *Tetrahedron* **1997**, *53*, 5379; (f) Harada, N.; Hiyoshi, N.; Vassilev, V. P.; Hayashi, T. *Chirality* **1997**, *9*, 623; (g) Bringmann, G.; Wuzik, A.; Kraus, J.; Peters, K.; Peters, E.-M. *Tetrahedron Lett.* **1998**, *39*, 1545; (h) Sugimura, T.; Inoue, S.; Tai, A. *Tetrahedron Lett.* **1998**, *39*, 6487; (i) Fuji, K.; Furuta, T.; Tanaka, K. *Org. Lett.* **2001**, *3*, 169; (j) Chow, H.-F.; Wan, C.-W. *J. Org. Chem.* **2001**, *66*, 5042; (k) Habaue, S.; Seko, T.; Okamoto, Y. *Macromolecules* **2002**, *35*, 2437.
4. (a) Miyano, S.; Okada, S.; Hotta, H.; Takeda, M.; Kabuto, C.; Hashimoto, H. *Bull. Chem. Soc. Jpn.* **1989**, *62*, 1528; (b) Miyano, S.; Okada, S.; Hotta, H.; Takeda, M.; Suzuki, T.; Kabuto, C.; Yasuhara, F. *Bull. Chem. Soc. Jpn.* **1989**, *62*, 3886; (c) Goto, J.; Shao, G.; Fukasawa, M.; Nambara, T.; Miyano, S. *Anal. Sci.* **1991**, *7*, 645; (d) Fukushi, Y.; Yajima, C.; Mizutani, J. *Tetrahedron Lett.* **1994**, *35*, 599; (e) Latypov, S. K.; Aganov, A. V.; Tahara, S.; Fukushi, Y. *Tetrahedron* **1999**, *55*, 7305; (f) Oi, S.; Terada, E.; Ohuchi, K.; Kato, T.; Tachibana, Y.; Inoue, Y. *J. Org. Chem.* **1999**, *64*, 8660; (g) Hattori, T.; Minato, Y.; Yao, S.; Finn, M. G.; Miyano, S. *Tetrahedron Lett.* **2001**, *42*, 8015; (h) Koshiishi, E.; Hattori, T.; Ichihara, N.; Miyano, S. *J. Chem. Soc., Perkin Trans. 1* **2002**, 377.
5. (a) Hattori, T.; Shijo, M.; Sakamoto, J.; Kumagai, S.; Nakajima, A.; Miyano, S. *J. Chem. Res. (M)* **1995**, 124; (b) Ito, Y.; Miyake, T.; Hatano, S.; Shima, R.; Ohara, T.; Suginome, M. *J. Am. Chem. Soc.* **1998**, *120*, 11880; (c) Fukui, H.; Fukushi, Y.; Tahara, S. *Tetrahedron Lett.* **1999**, *40*, 325; (d) Murase, N.; Hoshino, Y.; Oishi, M.; Yamamoto, H. *J. Org. Chem.* **1999**, *64*, 338; (e) Einhorn, C.; Einhorn, J.; Marcadal-Abbadi, C.; Pierre, J.-L. *J. Org. Chem.* **1999**, *64*, 4542; (f) Hungerhoff, B.; Metz, P. *Tetrahedron* **1999**, *55*, 14941; (g) Knölker, H.-J. *Chem. Rev.* **2000**, *100*, 2941; (h) Brunner, H.; Henning, F.; Weber, M. *Tetrahedron: Asymmetry* **2002**, *13*, 37; (i) Van Veldhuizen, J. J.; Garber, S. B.; Kingsbury, J. S.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2002**, *124*, 4954.
6. (a) Hattori, T.; Hotta, H.; Suzuki, T.; Miyano, S. *Bull. Chem. Soc. Jpn.* **1993**, *66*, 613; (b) Hattori, T.; Suzuki, T.; Hayashizaka, N.; Koike, N.; Miyano, S. *Bull. Chem. Soc. Jpn.* **1993**, *66*, 3034; (c) Hattori, T.; Koike, N.; Miyano, S. *J. Chem. Soc., Perkin Trans. 1* **1994**, 2273; (d) Hattori, T.; Tanaka, H.; Okaishi, Y.; Miyano, S. *J. Chem. Soc., Perkin Trans. 1* **1995**, 235; (e) Hattori, T.; Hayashizaka, N.; Miyano, S. *Synthesis* **1995**, 41; (f) Hattori, T.; Koike, N.; Okaishi, Y.; Miyano, S. *Tetrahedron Lett.* **1996**, *37*, 2057; (g) Hattori, T.; Koshiishi, E.; Wada, S.; Koike, N.; Yamabe, O.; Miyano, S. *Chirality* **1998**, *10*, 619; (h)

Koshiishi, E.; Hattori, T.; Ichihara, N.; Miyano, S. *J. Chem. Soc., Perkin Trans. 1* **2002**, 377; (i) Hattori, T.; Shimazumi, Y.; Goto, H.; Yamabe, O.; Morohashi, N.; Kawai, W.; Miyano, S. *J. Org. Chem.* **2003**, *68*, 2099.
7. Review: (a) Reuman, M.; Meyers, A. I. *Tetrahedron* **1985**, *41*, 837; (b) Gant, T. G.; Meyers, A. I. *Tetrahedron* **1994**, *50*, 2297.
8. See also: Wilson, J. M.; Cram, D. J. *J. Org. Chem.* **1984**, *49*, 4930.
9. (a) Hemmelmayr, V. *Monatsh. Chem.* **1917**, *38*, 84; (b) Cate, L. A. *Synthesis* **1983**, 385.
10. Harada, N.; Nakanishi, K. *Circular Dichroic Spectroscopy: Exciton Coupling in Organic Stereochemistry*; University Science Books and Oxford University Press: Mill Valley, CA and Oxford, 1983.
11. Homeyer, A. H.; Wallingford, V. H. *J. Am. Chem. Soc.* **1942**, *64*, 798.