Synthesis of Axially Chiral Amino Acid Derivatives via the Selective Monoesterification of 1,1′-Biaryl-2,2′-dicarboxylic Acids

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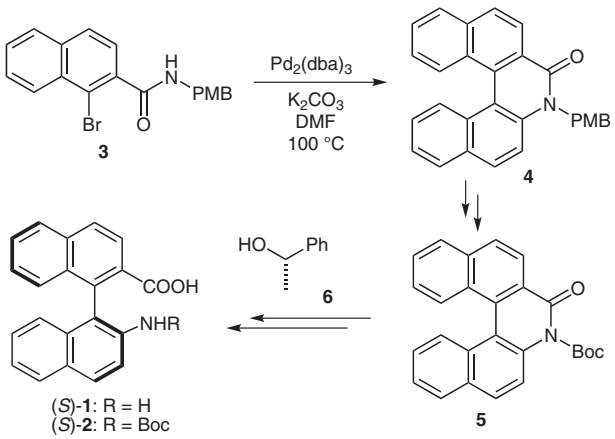
Abstract: Axially chiral amino acid derivatives were synthesized via a selective single-step monoesterification of 1,1′-binaphthyl-2,2′-dicarboxylic acids. In the presence of Ag_2CO_3, the alkylative monoesterification of a 1,1′-binaphthyl-2,2′-dicarboxylic acid with an alkyl halide proceeded selectively in a single operation. Curtius rearrangement of the monomethyl ester and successive alcoholysis of the corresponding isocyanate afforded the N-protected binaphthyl amino acids.

Key words: unnatural amino acid, monoesterification, half-ester, biaryl, axial chirality

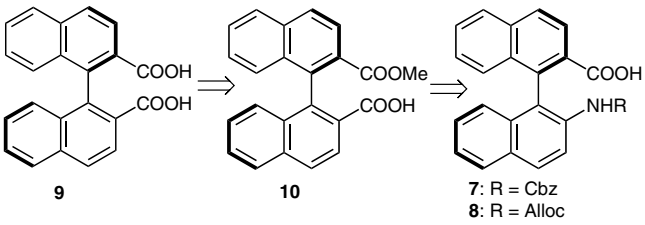
Unnatural amino acids have attracted considerable attentions as chiral organocatalysts,[1] ligands,[2] and as versatile building blocks for peptide mimetics.[3] We developed (*S*)-2-amino-2′-carboxy-1,1′-binaphthalene (**1**) and its *N*-Boc derivative (*S*)-**2** as unique axially chiral amino acid derivatives, prepared via the phosphine ligand-free Pd-catalyzed domino coupling[4] of **3** to **4** and the subsequent lactam ring opening of **5** with sodium alkoxide of (*S*)-phenylethanol (**6**). Diastereomer separation of the corresponding esters was achieved by fractional crystallization and successive removal of the ester moiety yielded the optically active *N*-Boc amino acid (*S*)-**2** (Scheme 1).[5] We also demonstrated that (*S*)-**2** is useful as a chiral building block for artificial dipeptides.[5]



Scheme 1 Previous synthesis of (*S*)-**1** and (*S*)-**2**

Applications of amino acids as chiral building blocks require a variety of N-protected derivatives; however, the synthetic route to (*S*)-**2** (Scheme 1) is hardly applicable to other N-protected amino acids, such as *N*-Cbz and *N*-Alloc derivatives, due to the need for individual optimization and the optical resolution in each case.

An improved synthetic strategy toward achieving access to *N*-Cbz **7** and *N*-Alloc amino acids **8** was envisioned through the synthesis, via Curtius rearrangement, of the optically active monomethyl ester **10**, which enabled the introduction of a variety of N-protecting groups during the latter stages of synthesis (Scheme 2). However, during an investigation of Scheme 2, we noticed that the selective monomethyl esterification of 1,1′-binaphthyl-2,2′-dicarboxylic acid (**9**), yielding **10**, proved to be difficult, even though the transformation initially appeared to be quite simple.



Scheme 2 Synthetic strategy via selective monoesterification and Curtius rearrangement

Compound **9** was derivatized through a selective monoesterification in the context of catalyst preparation in an asymmetric synthesis.[6] For example, monomethyl ester (*R*)-**10** was obtained via selective demethylation of the corresponding dimethyl ester (*R*)-**11**[7] by BBr_3 in 36% yield with 55% recovery of (*R*)-**11** (Figure 1).[6a] As an alternative to the monoesterification of **9**, monoglycidyl ester (*R*)-**12** was obtained by preparing the cyclic anhydride (*R*)-**13**, followed by ring-opening with glycidol in 80% yield (Figure 1).[6b–d] Although the yield of (*R*)-**12** was satisfactory, two manipulation steps were required from dicarboxylic acid **9**.

Thus, there is a need for the development of a selective single-step monoesterification method that can yield the corresponding half-ester. To the best of our knowledge, no precedent example has been reported describing the highly selective monoesterification of a symmetric 1,1′-biaryl-2,2′-dicarboxylic acid in a single operation with an

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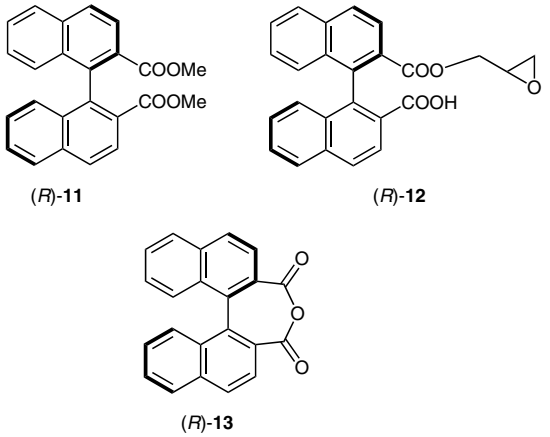


Figure 1 Structures of 1,1′-binaphthyl-2,2′-dicarboxylic acid derivatives

acceptable yield.[8] Herein, we describe the selective single-step monoesterification of **9** and successive transformation of monomethyl ester **10** to various N-protected axially chiral amino acid derivatives.

To achieve the selective monoesterification of **9**, we focused on the differences between the acidities of each carboxy group. A recent X-ray crystallographic analysis of a derivative of **9** indicated the presence of an intramolecular hydrogen bonding interaction between the carboxy groups in the binaphthyl system, which led to differences in the acidity of each carboxy group.[9] The two pK_a values in 1,1′-biphenyl-2,2′-dicarboxylic acid (**14**) were found to be typical (Figure 2). The 1st pK_a and 2nd pK_a values of **14** were reported to be 4.88 and 8.73, respectively, in an 80% aqueous 2-methoxyethanol solution.[10] The 1st pK_a of **14** (4.88) was smaller than the pK_a (7.02) of the corresponding monomethyl ester **15**.[10a]

Given the large differences in their pK_a values, we anticipated that the selective alkylative monoesterification of a

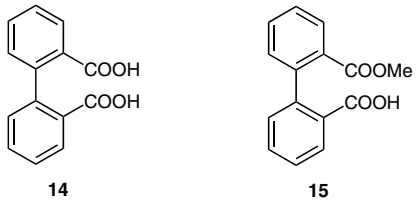


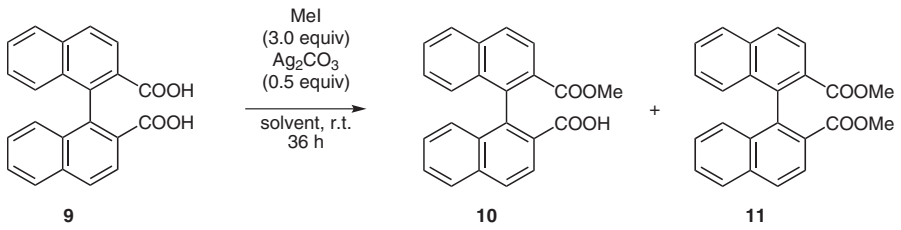
Figure 2 Structures of **14** and its monomethyl ester **15**

1,1′-biaryl-2,2′-dicarboxylic acid would be possible under mild basic conditions in the presence of a weak base, such as a metal carbonate, due to the predominant formation of the monocarboxylate ion of a dicarboxylic acid.

The alkylative monoesterification of **9** was first examined using three equivalents of MeI in the presence of 0.5 equivalent of Ag_2CO_3 in a series of solvents at room temperature (Table 1). Ag_2CO_3 was selected as the base on the expectation that silver cations activate alkyl iodides and can, therefore, increase the chemical yield of **10**. As expected, monomethyl ester **10** was obtained as the major product in a variety of solvents without the substantial formation of the dimethyl ester **11**, except for one reaction conducted in MeCN (Table 1, entry 1). In DMF and $CHCl_3$, the esterifications proceeded to yield **10** in 71% and 77% yield, respectively, with the concomitant formation of a small amount of **11** within 36 hours (Table 1, entries 2 and 5). In acetone, **10** was selectively obtained in 48% yield without overesterification to **11** (Table 1, entry 3). Given the selectivity and low toxicity of acetone, this solvent was used during subsequent optimization studies, the results of which are presented in Table 2.

The reaction mixture was warmed to 40 °C for 12 hours, which improved the yield of **10** to 92% along with a small amount of **11** (8%) (Table 2, entry 1). A decrease in the quantity of MeI reduced the yield (entry 2). An increase in the quantity of Ag_2CO_3 also diminished the yield of **10** by

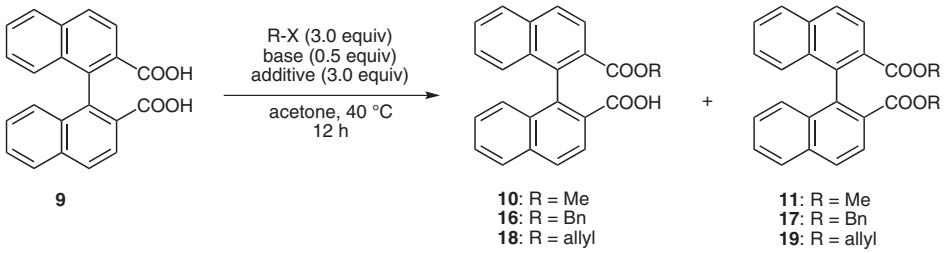
Table 1 Monomethyl Esterification of **9** with MeI in the Presence of Ag_2CO_3



Entry	Solvent	**10** (%)[a]	**11** (%)[a]
1	MeCN	74	26
2	DMF	71	3
3	acetone	48	<1
4	THF	21	<1
5	$CHCl_3$	77	4
6	toluene	55	5

[a] Determined by the integration of ^{1}H NMR signals in the presence of 1,4-dimethoxybenzene as an internal standard.

Table 2 Optimization of Monomethyl, Benzyl, and Allyl Esterification of **9**



9

10: R = Me
16: R = Bn
18: R = allyl

11: R = Me
17: R = Bn
19: R = allyl

Entry	RX	Additive	Base	Monoester	Yield (%)	Diester	Yield (%) (%)
1[a]	MeI	–	Ag_2CO_3	**10**	92	**11**	8
2[a]	MeI[b]	–	Ag_2CO_3	**10**	66	**11**	3
3[a]	MeI	–	Ag_2CO_3[c]	**10**	68	**11**	34
4[a]	MeI	–	Na_2CO_3	**10**	36	**11**	20
5[a]	MeI	–	K_2CO_3	**10**	63	**11**	<1
6[a]	MeI	–	Cs_2CO_3	**10**	45	**11**	<1
7	BnBr	–	Ag_2CO_3	**16**	–	**17**	–
8	BnBr	TBAI	Ag_2CO_3	**16**	75	**17**	18
9	allyl bromide	–	Ag_2CO_3	**18**	54	**19**	<1
10	allyl bromide	TBAI	Ag_2CO_3	**18**	72	**19**	28

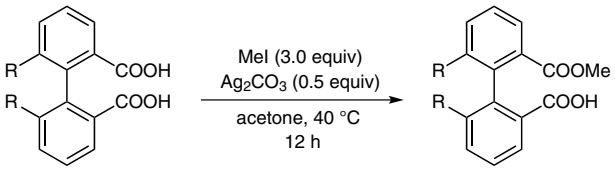
[a] The yields of **10** and **11** were determined by the integration of ^{1}H NMR signals in the presence of 1,4-dimethoxybenzene as an internal standard.
[b] MeI (1.0 equiv) was used.
[c] Ag_2CO_3 (1.0 equiv) was used.

forming significant quantities of **11** (entry 3). Replacing Ag_2CO_3 with other carbonate bases, such as Na_2CO_3, K_2CO_3, and Cs_2CO_3, decreased the yield of **10** in all cases (entries 4–6). The reduced yields of **10** suggested that the silver cation activated MeI under the reaction conditions.

Optically active (*R*)-**10** was also prepared from (*R*)-**9**[11] via the optimized conditions (Table 2, entry 1). Under the conditions, no racemization was observed by HPLC analysis with a chiral stationary phase.

Alkylative monoesterification reactions are applicable to benzyl and allyl esterification. Upon treatment of **9** with benzyl bromide in the presence of three equivalents of the additive TBAI, the esterification proceeded smoothly to afford monobenzyl ester **16**[6c] in 75% yield with the concomitant formation of the dibenzyl ester **17** (Table 2, entry 8). In the absence of TBAI, the benzyl esterification did not proceed at all (entry 7). Monoallyl ester **18** was obtained in the presence of TBAI in 72% yield (entry 10). In contrast to the benzyl esterification reaction, **18** was obtained in 54% yield without the addition of TBAI (entry 9). Although the yield of **18** was unsatisfactory in this case, the overesterified product **19** was not observed, suggesting that this approach may be of practical utility.

The optimized conditions (Table 2, entry 1) were next applied to other biaryls. 1,1′-Biphenyl-2,2′-dicarboxylic acid (**14**) was selectively converted into **15** in 90% yield (Scheme 3).

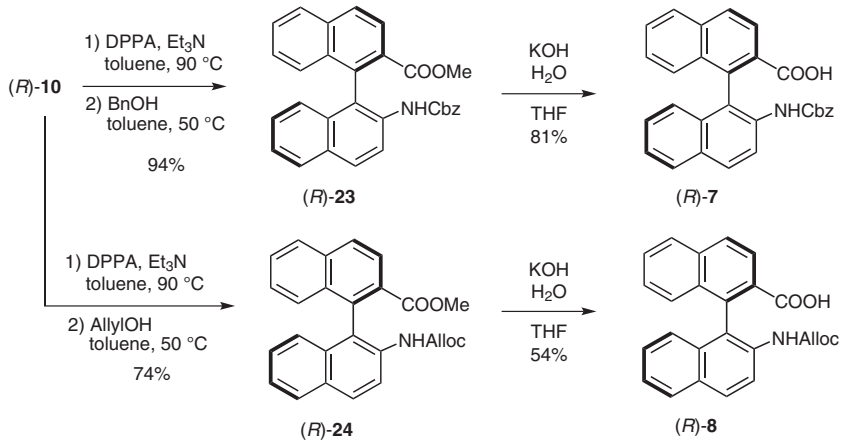


14: R = H
20: R = Me

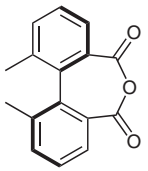
15: R = H (90%)
21: R = Me (89%)

Scheme 3 Monomethyl esterification of 1,1′-biphenyl-2,2′-dicarboxylic acid derivatives

The axially chiral 6,6′-dimethyl-1,1′-biphenyl-2,2′-dicarboxylic acid (**20**) was transformed to **21**[6a] in 89% yield. Cyclic anhydride (*R*)-**22** (Figure 3) derived from configurationally stable (*R*)-**20** was found to be racemized by heating at 85 °C in DME.[12] This suggested that some care should be taken with racemization, at which point the optically active biphenyl monoester was prepared by opening a cyclic anhydride with an alcohol under heating conditions. The selective monoesterification described here is suitable for preparing axially chiral 1,1′-biphenyl-2,2′-dicarboxylic acid derivatives due to the mild reaction conditions, which do not require a racemizable cyclic anhydride as an intermediate.



Scheme 4 Transformation to the N-protected axially chiral amino acids



(*R*)-**22**

Figure 3 Structure of cyclic anhydride (*R*)-**22**

With the selective monoesterification conditions in hand, we investigated the transformation of (*R*)-**10** to the corresponding N-protected axially chiral amino acids (Scheme 4). Curtius rearrangement of (*R*)-**10** in the presence of diphenylphosphoryl azide (DPPA) proceeded to give the isocyanate intermediate, and the subsequent addition of benzyl alcohol or allyl alcohol to the intermediate afforded (*R*)-**23** and (*R*)-**24** in 94% and 74% yield, respectively. During these transformations, no racemization was observed by HPLC analysis with chiral stationary phase. Successive hydrolysis of (*R*)-**23** and (*R*)-**24** afforded the corresponding *N*-Cbz and *N*-Alloc amino acids (*R*)-**7** and (*R*)-**8**, respectively.

In conclusion, we have developed a readily accessible route to axially chiral N-protected amino acids via a selective single-step monoesterification of the 1,1′-biaryl-2,2′-dicarboxylic acids. The variety of the binaphthyl N-protected amino acid was expanded by synthesizing the *N*-Cbz and *N*-Alloc derivatives. The selective monoesterification was characterized by mild conditions and a simple procedure. This protocol would be valuable as a pivotal transformation of the axially chiral 1,1′-biaryl-2,2′-dicarboxylic acids.[13]

NMR spectra were recorded on a JEOL JMN 400 spectrometer, chemical shifts being given in ppm units. IR spectra were recorded on a JASCO FT/IR-300 spectrometer. Specific rotation was measured with a Horiba SEPA-200 automatic digital polarimeter. MS spectra were recorded on a JEOL JMS-700 mass spectrometer. Melting points were measured with a Yanako melting points apparatus. TLC analysis and preparative TLC were performed on commercial glass plates bearing a 0.25 mm layer and 0.5 mm layer of Merck Kieselgel 60 F254, respectively. Silica gel chromatography was carried out Wakogel C-200, Fuji Silysia BW-1277H, or Nacalai Tesque Silica gel 60 (150–325 mesh). Anhyd MeCN, $CHCl_3$, and toluene were purchased from Kanto Chemical Co., Inc. Anhyd acetone, THF, and DMF were purchased from Wako Pure Chemical Industries, Ltd.

Monomethyl Esterification of 9 (Table 2, Entry 1)

To a solution of 1,1′-binaphthyl-2,2′-dicarboxylic acid (**9**; 50 mg, 0.15 mmol, 1.0 equiv), and Ag_2CO_3 (20 mg, 73 μmol, 0.5 equiv) in acetone (2.0 mL) was added MeI (27 μL, 0.44 μmol, 3.0 equiv) at r.t. After stirring at 40 °C for 12 h, the reaction was quenched with 2 M aq HCl (5.0 mL), and extracted with EtOAc (2 × 20 mL). The combined organic layers were washed with H_2O (20 mL), dried (Na_2SO_4), filtered, and concentrated in vacuo. The yields of the monomethyl ester **10**[6a] (92%) and the dimethyl ester **11**[7] (8%) were determined by the integration of ^{1}H NMR signals in the presence of 1,4-dimethoxybenzene as an internal standard.

(*R*)-2′-(Methoxycarbonyl)-1,1′-binaphthalene-2-carboxylic Acid [(*R*)-10][6a]

Optically active (*R*)-**9**[11] (>99% ee) was also converted to (*R*)-**10**[6a] (>99% ee) without racemization under the optimized conditions. Optical purity of (*R*)-**10**[6a] was confirmed by the optical rotation and HPLC analysis with a chiral stationary phase; $[\alpha]_D^{20}$ +45.3 (*c* 1.02, $CHCl_3$) (>99% ee) {Lit.[6a] $[\alpha]_D^{22}$ +43.7 (*c* 1.07, $CHCl_3$)}.

HPLC: Chiralpak AD-H (0.46 × 25 cm), hexane–*i*-PrOH (60:40), 0.5 mL/min, 254 nm, t_R = 19.8 min (*R*), 23.0 min (*S*).

Monobenzyl Esterification of 9 (Table 2, Entry 8)

To a solution of **9** (50 mg, 0.15 mmol), Ag_2CO_3 (20 mg, 73 μmol), and TBAI (162 mg, 0.44 mmol) in acetone (2.0 mL) was added benzyl bromide (52 μL, 0.44 mmol) at r.t. After stirring at 40 °C for 12 h, the mixture was directly evaporated in vacuo. The residue was purified by preparative TLC (SiO_2, hexane–EtOAc, 1:1) to give the monobenzyl ester **16**[6c] and dibenzyl ester **17**, respectively.

1,1′-Binaphthyl-2,2′-dicarboxylic Acid Monobenzyl Ester (16)[6c]

Yield: 47 mg (75%); colorless solid; mp 154–155 °C.

IR (KBr): 1239, 1279, 1691, 1722, 3062 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 4.76–4.92 (m, 2 H), 6.82 (d, *J* = 8.2 Hz, 2 H), 6.90–7.40 (m, 2 H), 7.06–7.22 (m, 5 H), 7.48 (t, *J* = 7.8 Hz, 2 H), 7.84 (t, *J* = 6.0 Hz, 2 H), 7.93 (d, *J* = 8.2 Hz, 1 H), 7.94–8.20 (m, 2 H), 8.18 (d, *J* = 8.7 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 66.8, 126.0, 126.3, 126.7, 127.1, 127.3, 127.7, 127.86, 127.90, 127.93, 127.99, 128.03, 128.2, 132.8, 134.9, 135.05, 135.14, 139.6, 140.8, 167.1, 171.1.

MS (FAB): *m*/*z* = 432 $(M)^+$, 433 $(M + H)^+$, 455 $(M + Na)^+$.

HRMS (FAB): *m*/*z* calcd for $C_{29}H_{20}O_4$ $(M)^+$: 432.1362; found: 432.1357.

1,1′-Binaphthyl-2,2′-dicarboxylic Acid Dibenzyl Ester (17)
Yield: 14 mg (18%); pale yellow oil.

IR (KBr): 1132, 1237, 1276, 1723, 2952, 3033, 3062, 3427 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 4.84 (ABq, J_{AB} = 12.4 Hz, $\Delta\nu_{AB}$ = 12.9 Hz, 2 H), 6.84 (d, *J* = 7.3 Hz, 4 H), 7.03 (d, *J* = 8.7 Hz, 2 H), 7.10–7.26 (m, 8 H), 7.49 (d, *J* = 8.2 Hz, 2 H), 7.87 (d, *J* = 8.7 Hz, 4 H), 8.09 (d, *J* = 8.7 Hz, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 66.6, 126.1, 126.7, 127.2, 127.3, 127.6, 127.8, 127.9, 128.1, 128.2, 132.9, 134.8, 135.3, 140.0, 166.7.

MS (FAB): *m*/*z* = 522 $(M)^+$, 523 $(M + H)^+$, 545 $(M + Na)^+$.

HRMS (FAB): *m*/*z* calcd for $C_{36}H_{26}O_4$ $(M)^+$: 522.1831; found: 522.1845.

Monoallyl Esterification of 9 (Table 2, Entry 10)
To a solution of **9** (50 mg, 0.15 mmol), Ag_2CO_3 (20 mg, 73 μmol), and TBAI (162 mg, 0.44 mmol) in acetone (2.0 mL) was added allyl bromide (38 μL, 0.44 mmol) at r.t. After stirring at 40 °C for 12 h, the mixture was directly evaporated in vacuo. The residue was purified by preparative TLC (SiO_2, hexane–EtOAc, 1:1) to give the monoallyl ester **18** and the diallyl ester **19**.

1,1′-Binaphthyl-2,2′-dicarboxylic Acid Monoallyl Ester (18)
Yield: 40 mg (72%); colorless solid; mp 129–131 °C.

IR (KBr): 1241, 1280, 1692, 3062, 3426 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 4.26–4.42 (m, 2 H), 4.88–5.00 (m, 2 H), 5.32–5.48 (m, 1 H), 6.94–7.04 (m, 2 H), 7.14–7.24 (m, 2 H), 7.44–7.54 (m, 2 H), 7.84–8.00 (m, 4 H), 8.04–8.18 (m, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 65.5, 118.0, 125.8, 126.1, 126.6, 126.8, 127.1, 127.25, 127.29, 127.3 127.7, 127.9, 128.0, 131.5, 132.8, 134.9, 135.1, 139.6, 140.7, 166.8, 171.0.

MS (FAB): *m*/*z* = 382 $(M)^+$, 383 $(M + H)^+$, 405 $(M + Na)^+$.

HRMS (FAB): *m*/*z* calcd for $C_{25}H_{18}O_4$ $(M)^+$: 382.1205; found: 382.1207.

1,1′-Binaphthyl-2,2′-dicarboxylic Acid Diallyl Ester (19)
Yield: 17 mg (28%); colorless oil.

IR (KBr): 1133, 1725 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 4.30–4.39 (m, 4 H), 4.90–5.00 (m, 4 H), 5.34–5.50 (m, 2 H), 7.09 (d, *J* = 8.7 Hz, 2 H), 7.20–7.28 (m, 2 H), 7.46–7.54 (m, 2 H), 7.93 (d, *J* = 8.2 Hz, 2 H), 8.00 (d, *J* = 8.7 Hz, 2 H), 8.20 (d, *J* = 8.7 Hz, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 65.4, 117.9, 126.0, 126.7, 127.3, 127.7, 127.87, 127.90, 131.7, 134.9, 140.2, 166.5.

MS (FAB): *m*/*z* = 422 $(M)^+$, 423 $(M + H)^+$, 445 $(M + Na)^+$.

HRMS (FAB): *m*/*z* calcd for $C_{28}H_{22}O_4$ $(M)^+$: 422.1518; found: 442.1517.

Monomethyl Esterification of 1,1′-Biphenyl-2,2′-dicarboxylic Acid (15)
To a solution of **14** (71 mg, 0.29 mmol) and Ag_2CO_3 (40 mg, 0.15 mmol, 0.5 equiv) in acetone (4.0 mL) was added MeI (55 μL, 0.88 mmol, 3.0 equiv) at r.t. After stirring at 40 °C for 12 h, the reaction was quenched with 2 M aq HCl (5.0 mL), and extracted with EtOAc (2 × 20 mL). The combined organic layers were washed with H_2O (20 mL), dried (Na_2SO_4), filtered, and concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane–EtOAc, 1:1) to afford the monomethyl ester **15**; yield: 67 mg (90%); colorless prisms (MeOH–H_2O); mp 102–103 °C (Lit.[10b] mp 107–108.5 °C)

Monomethyl Esterification of 6,6′-Dimethyl-1,1′-biphenyl-2,2′-dicarboxylic Acid (21)
To a solution of **20** (101 mg, 0.38 mmol), and Ag_2CO_3 (52 mg, 0.19 mmol, 0.5 equiv) in acetone (4.0 mL) was added MeI (70 μL, 1.13 mmol, 3.0 equiv) at r.t. After stirring at 40 °C for 12 h, the reaction was quenched with 2 M aq HCl (5.0 mL), and extracted with EtOAc (2 × 20 mL). The combined organic layers were washed with H_2O (20 mL), dried (Na_2SO_4), filtered, and concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane–EtOAc, 1:1) to afford the monomethyl ester **21**;[6a] yield: 95 mg (89%); colorless prisms (hexane–EtOAc); mp 136–137 °C.

Transformation of (*R*)-10 to (*R*)-Methyl 2′-(Benzyloxycarbonylamino)-1,1′-binaphthalene-2-carboxylate [(*R*)-23]
To a solution of (*R*)-**10** (>99% ee) (320 mg, 0.90 mmol) in toluene (10 mL) were added DPPA (0.21 mL, 0.99 mmol) and Et_3N (0.38 mL, 2.7 mmol) at 0 °C under an argon atmosphere. After stirring for 1.5 h at 90 °C, the reaction mixture was cooled to r.t. and treated with BnOH (0.10 mL, 0.99 mmol). The mixture was stirred for 3 h at 50 °C. The reaction was quenched with 2 M aq HCl (20 mL), and extracted with EtOAc (2 × 40 mL). The combined organic layers were washed with 2 M aq NaOH (20 mL), brine (20 mL), dried (Na_2SO_4), filtered, and concentrated in vacuo to give a residue. The residue was purified by column chromatography (SiO_2, hexane–EtOAc, 6:1) to afford (*R*)-**23**; yield: 390 mg (94%); colorless needles (hexane–toluene); mp 152 °C; $[\alpha]_D^{20}$ +36 (*c* 1.3, $CHCl_3$) (>99% ee). Optical purity of (*R*)-**23** (>99% ee) was confirmed by HPLC analysis with a chiral stationary phase.

HPLC: Chiralpak AD-H (0.46 × 25 cm), hexane–*i*-PrOH (80:20), 1.0 mL/min, 254 nm, t_R = 23.0 min (*S*), 52.6 min (*R*).

IR (KBr): 1595, 1722, 2949, 3060, 3327, 3418 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 3.46 (s, 3 H), 5.04 (ABq, J_{AB} = 12.4 Hz, $\Delta\nu_{AB}$ = 15.3 Hz, 2 H), 6.30 (br s, 1 H), 6.80 (d, *J* = 8.2 Hz, 1 H), 7.12–7.38 (m, 9 H), 7.55 (t, *J* = 7.3 Hz, 1 H), 7.87 (d, *J* = 8.2 Hz, 1 H), 7.92–8.12 (m, 4 H), 8.34 (br s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 52.2, 66.8, 124.6, 125.0, 125.9, 126.5, 126.9, 127.6, 127.9, 128.1, 128.15, 128.22, 128.4, 128.8, 129.2, 129.9, 130.4, 132.4, 132.8, 133.7, 134.9, 135.2, 135.8, 153.6, 167.5.

MS (FAB): *m*/*z* = 461 $(M)^+$, 462 $(M + H)^+$, 484 $(M + Na)^+$.

HRMS (FAB): *m*/*z* calcd for $C_{30}H_{23}NO_4$ $(M)^+$: 461.1627; found: 461.1627.

Hydrolysis of (*R*)-23 to 2′-(Benzyloxycarbonylamino)-1,1′-binaphthalene-2-carboxylic Acid [(*R*)-7]
To a solution of (*R*)-**23** (34 mg, 74 μmol) in THF–MeOH–H_2O (2:1:1, 8.0 mL) was added KOH (30 mg, 0.53 mmol) at r.t. After stirring for 12 h at r.t., the reaction was quenched with 2 M aq HCl (10 mL), and extracted with EtOAc (2 × 20 mL). The combined organic layers were washed with brine (20 mL), dried (Na_2SO_4), filtered, and concentrated in vacuo to give (*R*)-**7**. Recrystallization from hexane–toluene afforded (*R*)-**7** as colorless needles; yield: 27 mg (81%); mp 235 °C; $[\alpha]_D^{20}$ +38 (*c* 0.4, THF) (>99% ee). Optical purity of (*R*)-**7** (>99% ee) was confirmed by HPLC analysis with a chiral stationary phase.

HPLC: Chiralpak ID (0.46 × 25 cm), hexane–*i*-PrOH (60:40), 1.0 mL/min, 254 nm, t_R = 10.9 min (*S*), 15.0 min (*R*).

IR (KBr): 1503, 1603, 1722, 3057, 3414 cm^{-1}.

^1H NMR (400 MHz, DMSO-d_6): δ = 4.95 (s, 2 H), 6.73 (d, *J* = 8.7 Hz, 1 H), 6.99 (d, *J* = 8.7 Hz, 1 H), 7.06–7.12 (m, 2 H), 7.14–7.32 (m, 5 H), 7.33–7.40 (m, 1 H), 7.54–7.62 (m, 5 H), 7.86–7.97 (m, 2 H), 8.00 (d, *J* = 8.7 Hz, 1 H), 8.04–8.11 (m, 2 H), 8.14 (d, *J* = 8.7 Hz, 1 H), 8.28 (br s, 1 H).

^{13}C NMR (100 MHz, THF-d_8): δ = 66.8, 122.4, 125.1, 126.1, 126.8, 127.2, 127.8, 128.46, 128.53, 128.67, 128.70, 128.9, 129.0, 129.3, 131.7, 132.1, 133.7, 134.2, 135.6, 136.1, 136.3, 137.9, 154.7, 168.5.

MS (FAB): m/z = 447 $(M)^+$, 448 $(M + H)^+$, 470 $(M + Na)^+$.

HRMS (FAB): m/z calcd for $C_{29}H_{21}NO_4$ $(M)^+$: 447.1471; found: 447.1469.

Transformation of (*R*)-10 to (*R*)-Methyl 2′-(Allyloxycarbonylamino)-1,1′-binaphthalene-2-carboxylate [(*R*)-24]

To a solution of (*R*)-**10**[6a] (>99% ee) (100 mg, 0.28 mmol) in toluene (10 mL) were added DPPA (85 μL, 0.39 mmol) and Et_3N (68 μL, 0.84 mmol) at r.t. under an argon atmosphere. After stirring for 2 h at 90 °C, the reaction mixture was cooled to r.t. and treated with allyl alcohol (25 μL, 0.37 mmol). The mixture was stirred for 10 h at 50 °C. The reaction was quenched with H_2O (20 mL) and extracted with EtOAc (2 × 20 mL). The combined organic layers were washed with brine (20 mL), dried (Na_2SO_4), filtered, and concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane–EtOAc, 3:1) to afford (*R*)-**24**; yield: 86 mg (74%); colorless oil; $[\alpha]_D^{20}$ +21 (*c* 1.1, $CHCl_3$). Optical purity of (*R*)-**24** (>99% ee) was confirmed by HPLC analysis with a chiral stationary phase.

HPLC: Chiralpak AD-H (0.46 × 25 cm), hexane–*i*-PrOH (80:20), 1.0 mL/min, 254 nm, t_R = 9.9 min (*S*), 23.8 min (*R*).

IR (KBr): 1502, 1725, 3030, 3417 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 3.49 (s, 3 H), 4.42–4.59 (m, 2 H), 5.10–5.20 (m, 2 H), 5.74–5.88 (m, 1 H), 6.27 (br s, 1 H), 6.80 (d, *J* = 8.7 Hz, 1 H), 7.13–7.19 (m, 1 H), 7.22 (d, *J* = 8.2 Hz, 1 H), 7.28–7.40 (m, 2 H), 7.54–7.60 (m, 1 H), 7.84 (d, *J* = 7.8 Hz, 1 H), 7.94–8.03 (m, 2 H), 8.04–8.14 (m, 2 H), 8.33 (br s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 52.2, 65.8, 118.1, 120.1, 124.6, 125.0, 125.9, 126.5, 127.0, 127.6, 127.9, 128.2, 128.3, 128.8, 129.2, 129.9, 130.4, 132.3, 132.4, 132.8, 133.7, 134.9, 135.2, 153.4, 167.6.

MS (FAB): m/z = 411 $(M)^+$, 412 $(M + H)^+$, 434 $(M + Na)^+$.

HRMS (FAB): m/z calcd for $C_{26}H_{21}NO_4$ $(M)^+$: 411.1471; found: 411.1472.

Hydrolysis of (*R*)-24 to 2′-(Allyloxycarbonylamino)-1,1′-binaphthalene-2-carboxylic Acid [(*R*)-8]

To a solution of (*R*)-**24** (189 mg, 0.46 mmol) in THF–MeOH–H_2O (2:1:1, 12 mL) was added KOH (104 mg, 1.8 mmol) at r.t. After stirring at r.t. for 6 h, the reaction was quenched with 2 M aq HCl (20 mL), and extracted with EtOAc (2 × 40 mL). The combined organic layers were washed with brine (20 mL), dried (Na_2SO_4), filtered, and concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane–EtOAc, 1:2) to afford (*R*)-**8**; yield: 98 mg (54%); colorless oil; $[\alpha]_D^{20}$ +75 (*c* 0.4, $CHCl_3$). Optical purity of (*R*)-**8** (>99% ee) was confirmed by HPLC analysis with a chiral stationary phase.

HPLC: Chiralpak ID (0.46 × 25 cm), hexane–*i*-PrOH (60:40), 0.5 mL/min, 254 nm, t_R = 14.5 min (*S*), 20.1 min (*R*).

IR ($CHCl_3$): 1502, 1599, 1697, 2851, 2920, 3062, 3418 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 4.45 (d, *J* = 5.5 Hz, 2 H), 5.00–5.15 (m, 2 H), 5.65–5.80 (m, 1 H), 6.02–6.06 (br s, 1 H), 6.10–6.50 (br s, 1 H), 6.76 (d, *J* = 8.2 Hz, 1 H), 7.06–7.20 (m, 2 H), 7.20–7.38 (m, 2 H), 7.52–7.59 (m, 1 H), 7.85 (d, *J* = 8.2 Hz, 1 H), 7.95 (d, *J* = 8.7 Hz, 2 H), 8.04 (d, *J* = 8.7 Hz, 1 H) 8.09 (d, *J* = 8.7 Hz, 1 H), 8.10–8.40 (br s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 65.8, 118.0, 120.4, 124.8, 125.0, 126.2, 126.5, 127.1, 127.5, 127.9, 128.1, 128.4, 128.80, 128.84, 129.1, 130.6, 132.1, 132.4, 132.8, 133.4, 135.5, 135.9, 153.7, 171.4.

MS (FAB): m/z = 397 $(M)^+$, 398 $(M + H)^+$, 420 $(M + Na)^+$.

HRMS (FAB): m/z calcd for $C_{25}H_{19}NO_4$ $(M)^+$: 397.1314; found: 397.1314.

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