Supplementary Information

Enantioselective Decarboxylative Protonation and Deuteration of
β-Ketocarboxylic Acids

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1. General information

**Methods:** All non-aqueous reactions were carried out in dried glassware under an argon atmosphere and stirred using magnetic stir-plates. Thin-layer chromatography analyses were performed using pre-coated silica gel plates with a fluorescent indicator (F254) (Merck Millipore, Darmstadt, Germany). Visualization was accomplished by ultraviolet (UV) light (254 nm), phosphomolybdic acid, or p-anisaldehyde. Flash column chromatography was performed using silica gel 60 (mesh size 40–100) supplied by Kanto Chemical Co., Inc. (Tokyo, Japan). \(^1\)H and \(^{13}\)C nuclear magnetic resonance (NMR) spectra were recorded on a JNM-ECS400 (400 MHz \(^1\)H, 100 MHz \(^{13}\)C) or a JNM-ECX500 (500 MHz \(^1\)H, 126 MHz \(^{13}\)C) instrument (JEOL Ltd., Tokyo, Japan). Chemical shift values (δ) are reported in ppm (tetramethylsilane δ 0.00 ppm or residual benzene δ 7.16 ppm for \(^1\)H; residual chloroform δ 77.0 ppm or residual benzene δ 128.1 ppm for \(^{13}\)C). The high-resolution mass spectra (HRMS) were conducted on a JMS-T100TD time-of-flight mass spectrometer (DART) (JEOL Ltd.) or a microTOF-Q II HRMS/MS instrument with electrospray ionizer (ESI) (Bruker, Billerica, MA, USA). Optical rotations were measured on a P-1030 digital polarimeter (JASCO Co., Ltd., Tokyo, Japan). Analytical high-performance liquid chromatography (HPLC) was performed on a PU1586 instrument with a UV-1575 UV/V is detector (JASCO Co., Ltd.) using a chiral column under the conditions described below. The enantiomeric purity of the compounds was determined by HPLC analyses using chiral stationary phase columns.

**Materials:** Commercial grade reagents and solvents were used without further purification unless otherwise noted. Anhydrous dichloromethane and tetrahydrofuran (THF) were purchased from Kanto Chemical Co., Inc. and used after purification by a Glass Contour solvent dispensing system (Pure Process Technology, Nashua, NH, USA). Anhydrous n-hexane was purchased from Sigma-Aldrich (St. Louis, MO, USA). Deuterium oxide (99.8 atom%) was purchased from Tokyo Chemical Industry Co., Ltd (Tokyo, Japan). 2-(Bromomethyl)thiophen and 1-(bromomethyl)naphthalene were prepared according to literature procedures.\(^1,2\) Catalyst 6 was prepared by following a previously reported procedure.\(^3\) \(^3\) β-Ketocarboxylic acids 2 were synthesized by acidolysis of the corresponding tert-butyl β-ketoesters 4.\(^4\)

2. Synthesis of substrates and catalyst

2.1 Synthesis of tert-butyl β-ketoesters 4

![Synthesis of tert-butyl β-ketoesters](insert_image)

tert-Butyl 1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (289 mg, 0.83 mmol) was added to a stirred suspension of NaH (60% in oil, washed with hexane, 77 mg, 1.98 mmol) in THF (4.1 mL) at 0 °C, and the mixture was stirred for 30 min. Propargyl bromide (193 mg, 1.62 mmol) and tetrabutylammonium iodide (TBAI) (151 mg, 0.41 mmol) were added to the mixture, and the reaction mixture was stirred under reflux for 20 h. The reaction was quenched by adding saturated
NH₄Cl aqueous solution at 0 °C and then extracted with ethyl acetate. The combined organic layer was dried over anhydrous Na₂SO₄ and concentrated. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 15 : 1) to provide the title compound as a pale yellow oil (194 mg, 82% yield).

^1^H NMR (500 MHz, CDCl₃): δ 8.05 (dd, J = 7.6, 1.2 Hz, 1H), 7.47 (dt, J = 7.6, 1.2 Hz, 1H), 7.31 (t, J = 7.6 Hz, 1H), 7.23 (d, J = 7.6 Hz, 1H), 3.19–3.12 (m, 1H), 2.99–2.94 (m, 1H), 2.90 (dd, J = 16.8, 2.7 Hz, 1H), 2.81 (dd, J = 16.8, 2.7 Hz, 1H), 2.59–2.55 (m, 1H), 2.46–2.40 (m, 1H), 2.00 (t, J = 2.7 Hz, 1H), 1.34 (s, 9H); ^13^C NMR (126 MHz, CDCl₃): δ 194.1, 169.8, 142.9, 133.4, 132.1, 128.6, 127.8, 126.7, 82.6, 80.0, 70.9, 57.0, 30.8, 27.7, 25.9, 24.1; IR (NaCl): 2979, 1728, 1690, 1602, 1455, 1369, 1254, 1153, 737, 641 cm⁻¹; HRMS (DART): [M + H]^+ calcd. for C₁₈H₂₁O₃, 285.1491; found, 285.1491.

tert-butyl 1-oxo-2-(thiophen-2-ylmethyl)-1,2,3,4-tetrahydroanaphthalene-2-carboxylate (4e)

\[
\begin{align*}
\text{NaH (2.0 equiv.)} & \quad \text{2-(Bromomethyl)thiophen (2.0 equiv.)} \\
\text{THF, rt} & \\
\text{4e}
\end{align*}
\]

tert-Butyl 1-oxo-1,2,3,4-tetrahydroanaphthalene-2-carboxylate (719 mg, 2.92 mmol) in THF (2.0 mL) was added to a stirred suspension of NaH (60% in oil, washed with hexane, 228 mg, 5.69 mmol) in THF (8.0 mL) at 0 °C, and the mixture was stirred at room temperature for 30 min. 2-(Bromomethyl)thiophen (1.0 g, 5.84 mmol) in THF (4.6 mL) was added to the mixture at 0 °C, and the reaction mixture was stirred at room temperature for 3.5 h. The reaction was quenched by adding saturated NH₄Cl aqueous solution at 0 °C and then extracted with ethyl acetate. The combined organic layer was dried over anhydrous Na₂SO₄ and concentrated. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 15 : 1) to provide the title compound as a yellow oil (820 mg, 82% yield).

^1^H NMR (500 MHz, CDCl₃): δ 8.07 (dd, J = 7.6, 1.2 Hz, 1H), 7.44 (dt, J = 7.6, 1.2 Hz, 1H), 7.30 (t, J = 7.6 Hz, 1H), 7.18 (d, J = 7.6 Hz, 1H), 7.13–7.11 (m, 1H), 6.89–6.88 (m, 2H), 3.65 (d, J = 14.5 Hz, 1H), 3.08 (dd, J = 16.1, 11.1, 4.6 Hz, 1H), 2.92–2.87 (m, 1H), 2.47–2.43 (m, 1H), 2.04 (dd, J = 16.1, 11.1, 5.0 Hz, 1H), 1.32 (s, 9H); ^13^C NMR (126 MHz, CDCl₃): δ 195.1, 170.6, 142.8, 138.5, 133.2, 132.5, 128.6, 128.0, 127.8, 126.6, 126.4, 124.8, 82.4, 59.2, 33.9, 30.5, 27.7, 26.0; IR (NaCl): 2978, 2924, 1727, 1685, 1253, 1224, 1151, 732, 700, 515 cm⁻¹; HRMS (DART): [M + H]^+ calcd. for C₁₈H₂₁O₃S₁, 343.1368; found, 343.1368.

tert-butyl 2-hexyl-1-oxo-1,2,3,4-tetrahydroanaphthalene-2-carboxylate (4g)

\[
\begin{align*}
\text{NaH (2.0 equiv.)} & \quad 1\text{-Bromohexane (2.0 equiv.)} \\
\text{THF, reflux} & \quad \text{TBAI (0.5 equiv.)} \\
\text{4g}
\end{align*}
\]

tert-Butyl 1-oxo-1,2,3,4-tetrahydroanaphthalene-2-carboxylate (766 mg, 3.11 mmol) was added to a stirred suspension of NaH (60% in oil, washed with hexane, 243 mg, 6.06 mmol) in THF (15.2 mL) at 0 °C, and the mixture was stirred at room temperature for 30 min. 1-Bromohexane (1.0 g, 6.06
mmol) and tetrabutylammonium iodide (TBAI) (559 mg, 1.52 mmol) were added to the mixture, and the reaction mixture was stirred under reflux for 18 h. The reaction was quenched by adding saturated NH₄Cl aqueous solution at 0 °C and then extracted with ethyl acetate. The combined organic layer was dried over anhydrous Na₂SO₄ and concentrated. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a yellow oil (944 mg, 94% yield).

**1H NMR** (500 MHz, CDCl₃): δ 8.01 (dd, J = 7.6, 1.2 Hz, 1H), 7.45 (dt, J = 7.6, 1.2 Hz, 1H), 7.30 (t, J = 7.6 Hz, 1H), 7.20 (d, J = 7.6 Hz, 1H), 3.11–3.05 (m, 1H), 2.93–2.87 (m, 1H), 2.51–2.46 (m, 1H), 2.14–2.08 (m, 1H), 1.94–1.81 (m, 2H), 1.48–1.40 (m, 1H), 1.34 (s, 9H), 1.32–1.29 (m, 7H), 0.89–0.86 (m, 3H); **13C NMR** (126 MHz, CDCl₃): δ 196.1, 171.3, 142.8, 133.0, 132.7, 128.6, 127.7, 126.6, 81.7, 58.0, 33.9, 31.6, 30.8, 29.8, 27.8, 26.1, 24.6, 22.6, 14.0; **IR** (NaCl): 2954, 2930, 1727, 1692, 1368, 1296, 1252, 1150, 844, 737 cm⁻¹; **HRMS** (DART): [M + H]⁺ calcd. for C₂₁H₃₁O₃, 331.2273; found, 331.2273.

**tert-butyl 1-(naphthalen-1-ylmethyl)-2-oxocyclohexane-1-carboxylate (4j)**

**tert-butyl 2-oxocyclohexane-1-carboxylate (700 mg, 3.53 mmol) was added to a stirred suspension of NaH (60% in oil, washed with hexane, 148 mg, 3.71 mmol) in THF (11.7 mL) at 0 °C, and the mixture was stirred at room temperature for 1 h. 1-(bromomethyl)naphthalene (1.0 g, 4.24 mmol) were added to the mixture, and the reaction mixture was stirred at room temperature for 18 h. The reaction mixture was quenched by adding saturated NH₄Cl aqueous solution at 0 °C and then extracted with ethyl acetate. The combined organic layer was dried over anhydrous Na₂SO₄ and concentrated. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 10 : 1) to provide the title compound as a colorless oil (797 mg, 67% yield).

**1H NMR** (500 MHz, CDCl₃): δ 8.07 (d, J = 8.4 Hz, 1H), 7.82–7.80 (m, 1H), 7.72 (d, J = 8.4 Hz, 1H), 7.48–7.36 (m, 4H), 3.78 (d, J = 14.5 Hz, 1H), 3.49 (d, J = 14.5 Hz, 1H), 2.54–2.46 (m, 2H), 2.39–2.36 (m, 1H), 2.01–1.98 (m, 1H), 1.65–1.41 (m, 4H), 1.22 (s, 9H); **13C NMR** (126 MHz, CDCl₃): δ 207.6, 170.4, 133.8, 133.5, 133.2, 128.80, 128.6, 127.2, 125.6, 125.2, 125.1, 124.6, 80.1, 62.9, 42.3, 36.7, 34.7, 27.6, 27.5, 22.7.

2.2 Synthesis of β-ketocarboxylic acids 2

General procedure

Trifluoroacetic acid (20 equiv.) was added to a stirred solution of β-ketoesters 4 in dichloromethane at 0 °C, and the reaction mixture was stirred at room temperature. The reaction mixture was concentrated, and then purified by flush column chromatography on silica gel to give β-ketocarboxylic acid 2.

1-oxo-2-(prop-2-yn-1-yl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid (2d)

The title compound was prepared following General procedure, using 4d (500 mg, 1.75 mmol) and trifluoroacetic acid (4.0 g, 35.0 mmol) in dichloromethane (8.8 mL), and the reaction mixture was stirred for 40 min. The crude product was purified by flash column chromatography (hexane : diethyl ether = 10 : 1 to 2 : 1) to provide the title compound as a brown solid (341 mg, 85% yield).

1H NMR (500 MHz, CDCl3): δ 8.73 (br, 1H), 8.06 (dd, J = 7.6, 1.2 Hz, 1H), 7.50 (dt, J = 7.6, 1.2 Hz, 1H), 7.32 (t, J = 7.6 Hz, 1H), 7.25 (d, J = 7.6 Hz, 1H), 3.22–3.15 (m, 1H), 3.02–2.97 (m, 1H), 2.94 (dd, J = 16.8, 2.7 Hz, 1H), 2.87 (dd, J = 16.8, 2.7 Hz, 1H) 2.64–2.59 (m, 1H), 2.53 (ddd, J = 14.7, 10.3, 5.0 Hz, 1H), 2.03 (t, J = 2.7 Hz, 1H); 13C NMR (126 MHz, CDCl3): δ 193.7, 176.1, 143.3, 134.1, 131.2, 128.9, 128.3, 127.0, 79.1, 71.7, 56.3, 30.1, 25.5, 24.1; IR (NaCl): 3293, 2935, 1719, 1685, 1601, 1455, 1238, 793, 742, 650 cm⁻¹; HRMS (DART): [M + NH₄]⁺ calcd. for C₁₄H₁₆O₃N₁, 246.1130; found, 246.1130.

1-oxo-2-(thiophen-2-ylmethyl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid (2e)

The title compound was prepared following General procedure, using 4e (695 mg, 2.03 mmol) and trifluoroacetic acid (4.6 g, 40.6 mmol) in dichloromethane (10.1 mL), and the reaction mixture was stirred for 45 min. The crude product was purified by flash column chromatography (hexane : diethyl ether = 4 : 1 to 1 : 2) to provide the title compound as a white solid (424 mg, 73% yield).

1H NMR (500 MHz, CDCl3): δ 8.10 (dd, J = 7.6, 1.2 Hz, 1H), 7.51 (dt, J = 7.6, 1.2 Hz, 1H), 7.34 (t, J = 7.6 Hz, 1H), 7.23 (d, J = 7.6 Hz, 1H), 7.14 (dd, J = 5.0, 1.2 Hz, 1H), 6.91 (dd, J = 5.4, 3.4 Hz, 1H), 6.88–6.87 (m, 1H), 3.66 (d, J = 14.9 Hz, 1H), 3.47 (d, J = 14.9 Hz, 1H), 3.13 (ddd, J = 14.1, 9.2, 5.0 Hz, 1H), 3.03–2.97 (m, 1H), 2.51–2.46 (m, 1H), 2.22 (ddd, J = 14.1, 9.2, 5.0 Hz, 1H); 13C NMR (126 MHz, CDCl3): δ 195.0, 176.5, 143.3, 137.2, 134.1, 131.4, 128.8, 128.4, 128.2, 127.0, 126.7, 125.1,
58.3, 34.0, 29.5, 25.6; IR (NaCl): 3068, 2931, 1709, 1684, 1599, 1455, 1277, 1229, 742, 701 cm⁻¹; HRMS (ESI): No data. Protonated product 2e was measured.

2-hexyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid (2g)

The title compound was prepared following General procedure, using 4g (480 mg, 1.46 mmol) and trifluoroacetic acid (3.3 g, 29.2 mmol) in dichloromethane (7.3 mL), and the reaction mixture was stirred for 60 min. The crude product was purified by flash column chromatography (hexane : diethyl ether = 5 : 1 to 1 : 1) to provide the title compound as a pale red oil (322 mg, 82% yield), including 4% of 3g.

¹H NMR (500 MHz, CDCl₃): δ 8.09 (dd, J = 7.6, 1.2 Hz, 1H), 7.54 (dt, J = 7.6, 1.2 Hz, 1H), 7.35 (t, J = 7.6 Hz, 1H), 7.26 (d, J = 7.6 Hz, 1H), 3.04 (t, J = 6.1 Hz, 2H) 2.43 (t, J = 6.1 Hz, 2H), 1.95–1.86 (m, 2H), 1.41–1.21 (m, 8H), 0.89–0.84 (m, 3H); ¹³C NMR (126 MHz, CDCl₃): δ 199.7, 174.4, 143.8, 134.6, 130.7, 128.9, 128.5, 127.1, 55.7, 34.5, 31.4, 29.4, 29.3, 25.2, 24.6, 22.5, 14.0; IR (NaCl): 2954, 2929, 2857, 1710, 1688, 1601, 1455, 1297, 1228, 741 cm⁻¹; HRMS (DART): [M + H]⁺ calcd. for C₁₇H₂₃O₃, 275.1647; found, 275.1647.

1-(naphthalen-1-ylmethyl)-2-oxocyclohexane-1-carboxylic acid (2j)

The title compound was prepared following General procedure, using 4j (400 mg, 1.18 mmol) and trifluoroacetic acid (2.7 g, 23.63 mmol) in dichloromethane (5.9 mL), and the reaction mixture was stirred for 60 min. The crude product was purified by flash column chromatography (hexane : diethyl ether = 4 : 1 to 1 : 1) to provide the title compound as a colorless powder (199 mg, 60% yield).

¹H NMR (500 MHz, CDCl₃): δ 8.02 (d, J = 8.0 Hz, 1H), 7.83–7.80 (m, 1H), 7.73 (d, J = 8.0 Hz, 1H), 7.46–7.40 (m, 2H), 7.38–7.35 (m, 1H), 7.32–7.30 (m, 1H), 3.84 (d, J = 14.5 Hz, 1H), 3.54 (d, J = 14.5 Hz, 1H), 2.59–2.55 (m, 1H), 2.52–2.46 (m, 1H), 2.30–2.27 (m, 1H), 2.04–2.00 (m, 1H), 1.72–1.54 (m, 4H); ¹³C NMR (126 MHz, CDCl₃): δ 207.1, 177.3, 133.8, 133.0, 132.5, 128.8, 128.7, 127.7, 125.7, 125.3, 125.1, 124.0, 61.6, 41.6, 35.6, 35.3, 27.3, 22.4; IR (NaCl): 3048, 2941, 2866, 2335, 1705, 1596, 1509, 1396, 1271, 1218, 1126, 801, 781, 737 cm⁻¹ HRMS (ESI): No data. Protonated product 3j was measured.
2.3 Synthesis of catalyst 5

To a suspension of (R)-2,2'-bis(bromomethyl)-1,1'-binaphthalene (1.5 g, 3.41 mmol), tetrabutylammonium hydrogen sulfate (115 mg, 0.34 mmol, 10 mol%) and K₂CO₃ (2.8 g, 20.4 mmol) in CH₃CN (34 mL) was added ethyl isocyanoacetate (449 μL, 4.08 mmol). The solution was refluxed for 18 h under argon atmosphere. The resulting mixture was filtered and the filtrate was concentrated. The residue was dissolved in ethanol (34 mL) was added conc. HCl (2.0 mL) at 0 ºC. The solution was stirred at room temperature for 4.5 h under argon atmosphere. The reaction mixture was quenched by adding saturated NaHCO₃ aqueous solution and then extracted with CH₂Cl₂. The combined organic layer was dried over anhydrous Na₂SO₄ and concentrated. The crude product was purified by flash column chromatography (CH₂Cl₂ : Methanol = 20 : 1) to provide 5 as a pale yellow powder (1077 mg, 83% yield).

¹H NMR (500 MHz, C₆D₆): δ 7.76–7.70 (m, 4H), 7.57–7.54 (m, 3H), 7.32 (d, J = 8.4 Hz, 1H), 7.23–7.18 (m, 2H), 7.00–6.95 (m, 2H) 2.43 (t, J = 6.1 Hz, 2H), 3.93–3.83 (m, 2H), 3.08 (d, J = 13.4 Hz, 1H), 3.05 (d, J = 13.4 Hz, 1H), 2.55 (d, J = 13.4 Hz, 1H), 2.27 (d, J = 1.34 Hz, 1H), 0.87 (t, J = 7.3 Hz, 3H); ¹³C NMR (126 MHz, CDCl₃): δ 175.3, 136.9, 135.3, 134.8, 134.5, 133.6, 133.5, 132.5, 129.3, 129.1, 128.6, 128.3, 129.2, 125.5, 125.4, 69.0, 60.8, 43.7, 43.5, 14.1; IR (NaCl): 3374, 3051, 2979, 2932, 1726, 1508, 1444, 1365, 1224, 1210, 1039, 1026, 817, 750, 705 cm⁻¹; HRMS (ESI): [M + H]⁺ calcd. for C₂₆H₂₄N₂O₂, 382.1802; found, 382.1796.
3. Screening of amine catalysts

Amine catalyst (30 mol%) was added to a stirred solution of 2a in n-hexane (0.1 M), and the reaction mixture was stirred at rt. The mixture was purified by flash column chromatography on silica gel to give 3a.

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</table>

*a* Isolated yield.

*b* Ee value were determined by chiral HPLC analysis.

4. Enantioselective decarboxylative protonation

**General procedure**

Enantioselective decarboxylative protonation of 2 was performed by **General procedure** described below. When the reactions were performed, some starting compounds 2 contained 1–4% of rac-3 because a few starting carboxylic acids 2 slowly decomposed to give 3 while standing at ambient temperature.

Amine catalyst 1 (30 mol%) was added to a stirred solution of α,α-dialkyl-β-ketocarboxylic acids 2 (0.2–0.3 mmol) in n-hexane (2.0–3.0 mL), and the reaction mixture was stirred at 0 °C–room temperature. The mixture was purified by flash column chromatography on silica gel to give 3.
The title compound was prepared following **General procedure**, using 2-methyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2a (61 mg, 0.3 mmol) and amine catalyst 1 (68 mg, 0.09 mmol) in n-hexane (3.0 mL), and the reaction mixture was stirred at 0 °C for 182 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (47 mg, 98% yield, 89% ee).

**1H NMR** (500 MHz, CDCl$_3$): $\delta$ 8.04 (dd, $J = 7.6, 1.2$ Hz, 1H), 7.45 (dt, $J = 7.6, 1.2$ Hz, 1H), 7.29 (t, $J = 7.6$ Hz, 1H), 7.23 (d, $J = 7.6$ Hz, 1H), 3.07–2.94 (m, 2H), 2.20 (ddd, $J = 13.4, 8.8, 4.6$ Hz, 1H), 1.92–1.84 (m, 1H), 1.27 (d, $J = 6.9$ Hz, 3H); **13C NMR** (126 MHz, CDCl$_3$): $\delta$ 200.8, 144.2, 133.0, 132.4, 128.7, 127.4, 126.5, 42.6, 31.3, 28.8, 15.4; **IR** (NaCl): 2963, 2931, 1686, 1602, 1455, 1267, 1228, 968, 907, 739 cm$^{-1}$; **HRMS** (DART): [M + H]$^+$ calcd. for C$_{11}$H$_{13}$O$_1$, 161.0966; found, 161.0969; $[\alpha]_{D}^{26}$ +39.0 (c = 1.32, CHCl$_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OZ-H (0.46 cmφ×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 12.6 min (major) and 13.4 min (minor)).

(S)-2-benzyl-3,4-dihydronaphthalen-1(2H)-one (3b) $^5$

The title compound was prepared following **General procedure**, using 2-benzyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2b (91 mg, 0.3 mmol) and amine catalyst 1 (74 mg, 0.10 mmol) in n-hexane (3.3 mL), and the reaction mixture was stirred at 10 °C for 20 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (70 mg, 91% yield, 62% ee).

**1H NMR** (500 MHz, CDCl$_3$): $\delta$ 8.07 (dd, $J = 7.6, 1.2$ Hz, 1H), 7.45 (dt, $J = 7.6, 1.2$ Hz, 1H), 7.31–7.28 (m, 3H), 7.23–7.20 (m, 4H), 3.49 (dd, $J = 13.8, 3.8$ Hz, 1H), 2.97–2.86 (m, 2H), 2.77–2.71 (m, 1H), 2.64 (dd, $J = 13.8, 9.6$ Hz, 1H), 2.09 (ddd, $J = 13.8, 8.8, 4.6$ Hz, 1H), 1.82–1.73 (m, 1H); **13C NMR** (126 MHz, CDCl$_3$): $\delta$ 199.3, 144.0, 140.0, 133.2, 132.4, 129.2, 128.7, 128.3, 127.5, 126.5, 126.1, 49.4, 35.6, 28.6, 27.6; **IR** (NaCl): 3025, 2927, 1682, 1599, 1454, 1291, 933, 740, 700 cm$^{-1}$; **HRMS** (DART): [M + NH$_4$]$^+$ calcd. for C$_{17}$H$_{20}$O$_1$N, 254.1545; found, 254.1545; $[\alpha]_{D}^{26}$ –8.4 (c = 1.63, CHCl$_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 0.8 mL/min, retention time; 22.0 min (minor) and 24.0 min (major)).
The title compound was prepared following General procedure, using 2-allyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2c (69 mg, 0.3 mmol) and amine catalyst 1 (68 mg, 0.09 mmol) in n-hexane (3.0 mL), and the reaction mixture was stirred at room temperature for 4 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (54 mg, 96% yield, 87% ee).

\[ \text{H NMR (400 MHz, CDCl}_3\]:} \delta 8.04 (d, \( J = 7.6 \) Hz, 1H), 7.46 (t, \( J = 7.6 \) Hz, 1H), 7.30 (t, \( J = 7.6 \) Hz, 1H), 7.24 (d, \( J = 7.6 \) Hz, 1H), 5.89–5.81 (m, 1H), 5.13–5.06 (m, 2H), 2.99 (dd, \( J = 7.6, 4.6 \) Hz, 2H), 2.79–2.74 (m, 1H), 2.58–2.52 (m, 1H), 2.30–2.21 (m, 2H), 1.91–1.83 (m, 1H); HRMS (DART): [M + H]⁺ calcd. for C\(_{13}\)H\(_{15}\)O\(_1\), 187.1123; found, 187.1123; [\( \alpha \)]\(_{D}^{26}\) +20.7 (c = 2.36, CHCl\(_3\)).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cm\(^\phi\)×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 16.0 min (major) and 17.1 min (minor)).

1-(prop-2-yn-1-yl)-3,4-dihyronaphthalen-1(2H)-one (3d)

The title compound was prepared following General procedure, using 1-oxo-2-(prop-2-yn-1-yl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2d (69 mg, 0.3 mmol) and amine catalyst 1 (68 mg, 0.09 mmol) in n-hexane (3.0 mL), and the reaction mixture was stirred at 10 °C for 21 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a white solid (48 mg, 86% yield, 67% ee).

\[ \text{H NMR (500 MHz, CDCl}_3\]:} \delta 8.04 (dd, \( J = 7.6, 1.2 \) Hz, 1H), 7.48 (dt, \( J = 7.6, 1.2 \) Hz, 1H), 7.31 (t, \( J = 7.6 \) Hz, 1H), 7.26–7.25 (m, 1H), 3.13–3.01 (m, 2H), 2.91 (ddd, \( J = 6.9, 4.2, 2.7 \) Hz, 1H), 2.68 (ddd, \( J = 13.0, 8.4, 4.2 \) Hz, 1H), 2.52–2.44 (m, 2H), 2.00 (t, \( J = 2.7 \) Hz, 1H); \[ \text{C NMR (126 MHz, CDCl}_3\]:} \delta 197.8, 144.1, 133.4, 132.1, 128.7, 127.4, 126.6, 82.2, 69.7, 46.6, 28.9, 19.3; IR (NaCl): 3292, 2931, 2862, 1684, 1455, 1284, 1221, 946, 636 cm\(^{-1}\); HRMS (DART): [M + NH\(_4\)]⁺ calcd. for C\(_{13}\)H\(_{16}\)O\(_1\)N\(_1\), 202.1232; found, 202.1232; [\( \alpha \)]\(_{D}^{26}\) −6.6 (c = 1.36, CHCl\(_3\)).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cm\(^\phi\)×25 cm), hexane : i-PrOH = 99 : 1, flow rate = 0.7 mL/min, retention time; 21.9 min (major) and 23.5 min (minor)).
The title compound was prepared following General procedure, using 1-oxo-2-(thiophen-2-ylmethyl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2e (87 mg, 0.3 mmol) and amine catalyst 1 (68 mg, 0.09 mmol) in n-hexane (3.0 mL), and the reaction mixture was stirred at room temperature for 3 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (72 mg, 98% yield, 67% ee).

\[ \text{H NMR (500 MHz, CDCl}_3\text{): } \delta 8.07 \text{ (dd, } J = 7.6, 1.2 \text{ Hz, 1H)}, 7.47 \text{ (dt, } J = 7.6, 1.2 \text{ Hz, 1H)}, 7.31 \text{ (t, } J = 7.6 \text{ Hz, 1H)}, 7.23 \text{ (d, } J = 7.6 \text{ Hz, 1H)}, 7.14 \text{ (d, } J = 5.0 \text{ Hz, 1H)}, 6.93 \text{ (dd, } J = 5.0, 3.4 \text{ Hz, 1H}), 6.86 \text{ (d, } J = 3.4 \text{ Hz, 1H}), 3.59 \text{ (dd, } J = 14.9, 4.2 \text{ Hz, 1H}), 3.04 \text{ (dd, } J = 14.9, 4.2 \text{ Hz, 1H}), 2.23 \text{ (dd, } J = 13.0, 8.8, 4.2 \text{ Hz, 1H}), 1.89 \text{–}1.80 \text{ (m, 1H); 13C NMR (126 MHz, CDCl}_3\text{): } \delta 198.7, 144.0, 142.2, 133.3, 132.3, 128.7, 127.5, 126.7, 126.6, 125.8, 123.6, 49.6, 29.8, 28.7, 27.8; \text{ IR (NaCl): } 3067, 2928, 2862, 1677, 1599, 1455, 1287, 1225, 753, 698 \text{ cm}^{-1}; \text{ HRMS (ESI): } [M + Na]^+ \text{ calcd. for } C_{15}H_{14}O_1SNa, 265.0658; \text{ found, 265.0654; } \text{[α]D}_{27} -31.3 \text{ (c = 2.28, CHCl}_3\text{).}

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IE-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 98 : 2, flow rate = 0.7 mL/min, retention time; 23.5 min (major) and 26.0 min (minor)).

The title compound was prepared following General procedure, using 2-(3-chloropropyl)-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2f (80 mg, 0.3 mmol) and amine catalyst 1 (68 mg, 0.09 mmol) in n-hexane (3.0 mL), and the reaction mixture was stirred at 0 °C for 23 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (63 mg, 95% yield, 76% ee).

\[ \text{H NMR (500 MHz, CDCl}_3\text{): } \delta 8.02 \text{ (dd, } J = 7.6, 1.2 \text{ Hz, 1H)}, 7.46 \text{ (dt, } J = 7.6, 1.2 \text{ Hz, 1H)}, 7.30 \text{ (t, } J = 7.6 \text{ Hz, 1H)}, 7.24 \text{ (d, } J = 7.6 \text{ Hz, 1H)}, 3.63 \text{–}3.55 \text{ (m, 2H)}, 3.02 \text{ (dd, } J = 7.6, 5.0 \text{ Hz, 2H}), 2.54 \text{–}2.48 \text{ (m, 1H)}, 2.24 \text{ (dd, } J = 13.4, 9.6, 5.0 \text{ Hz, 1H}), 2.09 \text{–}2.02 \text{ (m, 1H)}, 1.95 \text{–}1.89 \text{ (m, 3H)}, 1.71 \text{–}1.65 \text{ (m, 1H); 13C NMR (126 MHz, CDCl}_3\text{): } \delta 199.8, 143.8, 133.2, 132.4, 128.7, 127.4, 126.7, 126.6, 46.9, 45.1, 30.2, 28.6, 28.5, 27.2; \text{ IR (NaCl): } 2931, 2858, 1682, 1601, 1455, 1293, 1228, 914, 741, 649 \text{ cm}^{-1}; \text{ HRMS (DART): } [M + NH}_4^+] \text{ calcd. for } C_{13}H_{14}O_1NCl, 260.0658; \text{ found, 260.0654; } \text{[α]D}_{27} +17.8 \text{ (c = 1.01, CHCl}_3\text{).}

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 38.0 min (major) and 40.2 min (minor)).
The title compound was prepared following General procedure, using 2-hexyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2g (83 mg, 0.3 mmol) and amine catalyst 1 (69 mg, 0.09 mmol) in n-hexane (3.0 mL), and the reaction mixture was stirred at 0 °C for 28 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (56 mg, 80% yield, 82% ee).

\[ \text{H NMR (500 MHz, CDCl}_3\text{): } \delta 8.02 (d, J = 7.6 Hz, 1H), 7.44 (t, J = 7.6 Hz, 1H), 7.29 (t, J = 7.6 Hz, 1H), 7.22 (t, J = 7.6 Hz, 1H), 3.04–2.93 (m, 2H), 2.49–2.44 (m, 1H), 2.23 (ddd, J = 14.1, 9.6, 4.6 Hz, 1H), 1.97–1.86 (m, 2H), 1.53–1.21 (m, 9H), 0.90–0.87 (m, 3H); \text{C NMR (126 MHz, CDCl}_3\text{): } \delta 200.5, 143.9, 133.0, 132.5, 128.6, 127.4, 126.5, 47.5, 31.7, 29.4, 28.3, 28.1, 27.0, 22.6, 14.1; \text{IR (NaCl): } 2951, 2926, 2854, 1685, 1600, 1545, 1286, 1224, 910, 742 \text{ cm}^{-1}; \text{HRMS (DART): } [M + H]^+ \text{ calcd. for C}_{16}H_{23}O_1, 231.1749; \text{found, 231.1749; } [\alpha]_D^{27} +17.2 \text{ (c = 1.28, CHCl}_3\text{).} \]

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 1.0 mL/min, retention time; 10.3 min (minor) and 10.8 min (major)).

\((R)-2\text{-methyl-2,3-dihydro-1H-indene-1-one (3h) }^5\)

The title compound was prepared following General procedure, using 2-methyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylic acid 2h (44 mg, 0.23 mmol) and amine catalyst 1 (52 mg, 0.07 mmol) in n-hexane (2.3 mL), and the reaction mixture was stirred at 0 °C for 6 h. The crude product was purified by flash column chromatography (hexane : diethyl ether = 8 : 1) to provide the title compound as a colorless oil (24 mg, 70% yield, 57% ee).

\[ \text{H NMR (500 MHz, CDCl}_3\text{): } \delta 7.76 (d, J = 7.6 Hz, 1H), 7.59 (t, J = 7.6 Hz, 1H), 7.45 (d, J = 7.6 Hz, 1H), 7.37 (t, J = 7.6 Hz, 1H), 3.43–3.38 (m, 1H), 2.76–2.68 (m, 2H), 1.32 (d, J = 7.6 Hz, 3H); \text{C NMR (126 MHz, CDCl}_3\text{): } \delta 209.5, 153.5, 136.3, 134.7, 127.3, 126.5, 124.0, 42.0, 34.9, 16.3; \text{IR (NaCl): } 2963, 2929, 1713, 1608, 1464, 1293, 1204, 965, 787, 742 \text{ cm}^{-1}; \text{HRMS (DART): } [M + NH}_4^+ \text{ calcd. for C}_{16}H_{21}O_1N_1, 164.1075; \text{found, 164.1076; } [\alpha]_D^{26} –24.6 \text{ (c = 0.53, CHCl}_3\text{).} \]

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : i-PrOH = 9 : 1, flow rate = 0.5 mL/min, retention time; 11.0 min (minor) and 11.6 min (major)).
(S)-2-benzylcyclohexan-1-one (3i)  

![Chemical Structure](image)

The title compound was prepared following General procedure, using 1-benzyl-2-oxocyclohexane-1-carboxylic acid 2i (68 mg, 0.29 mmol) and amine catalyst 1 (66 mg, 0.09 mmol) in n-hexane (2.9 mL), and the reaction mixture was stirred at room temperature for 1 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 15 : 1) to provide the title compound as a colorless oil (38 mg, 69% yield, 24% ee).

\[ ^1H\text{NMR} \ (500 \text{ MHz, CDCl}_3): \delta 7.29–7.26 \ (m, 2H), 7.20–7.15 \ (m, 3H), 3.24 \ (dd, J = 13.8, 4.6 \text{ Hz, 1H}), 2.58–2.52 \ (m, 1H), 2.46–2.39 \ (m, 2H), 2.36–2.30 \ (m, 1H), 2.09–1.99 \ (m, 2H), 1.85–1.81 \ (m, 1H), 1.73–1.53 \ (m, 2H), 1.40–1.31 \ (m, 1H); ^13C\text{NMR} \ (126 \text{ MHz, CDCl}_3): \delta 212.6, 140.3, 129.1, 128.3, 52.5, 42.2, 35.4, 33.4, 28.0, 25.0; IR \ (\text{NaCl}): 2936, 2862, 1710, 1452, 1131, 769, 732, 700, 516 \text{ cm}^{-1}; \text{HRMS (ESI): [M + Na]^+ calcd. for C}_{13}H_{16}O_1Na, 211.1093; found, 211.1093; [\alpha]_D^{24} – 10.1 \ (c = 0.45, CHCl}_3).\]

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : i-PrOH = 98 : 2, flow rate = 1.0 mL/min, retention time; 10.5 min (minor) and 11.7 min (major)).

2-(naphthalen-1-ylmethyl)cyclohexan-1-one (3j)

![Chemical Structure](image)

The title compound was prepared following General procedure, using 2-methyl-3-oxo-2,3-diphenylpropanoic acid 2j (56 mg, 0.20 mmol) and amine catalyst 1 (46 mg, 0.06 mmol) in n-hexane (2.0 mL), and the reaction mixture was stirred at room temperature for 11 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 10 : 1 to 4 : 1) to provide the title compound as a colorless oil (30 mg, 64% yield, 30% ee).

\[ ^1H\text{NMR} \ (500 \text{ MHz, CDCl}_3): \delta 7.94–7.92 \ (m, 1H), 7.87–7.85 \ (m, 1H), 7.72 \ (d, J = 8.0 \text{ Hz, 1H}), 7.51–7.46 \ (m, 2H), 7.38 \ (dd, J = 8.0, 7.1 \text{ Hz, 1H}), 7.31 \ (d, J = 6.9 \text{ Hz, 1H}), 3.85 \ (dd, J = 13.8, 3.6 \text{ Hz, 1H}), 2.75 \ (dd, J = 13.8, 9.2 \text{ Hz, 1H}), 2.72–2.66 \ (m, 1H), 2.48 \ (dddd, J = 13.8, 4.6, 3.1, 1.5 \text{ Hz, 1H}), 2.34 \ (ddd, J = 13.4, 13.4, 6.1, 1.2 \text{ Hz, 1H}), 2.09–2.03 \ (m, 1H), 2.01–1.96 \ (m, 1H), 1.83–1.79 \ (m, 1H), 1.75–1.62 \ (m, 1H), 1.55–1.40 \ (m, 1H); ^13C\text{NMR} \ (126 \text{ MHz, CDCl}_3): \delta 212.5, 136.3, 133.9, 131.9, 128.9, 127.4, 126.8, 125.8, 125.4, 125.3, 123.7, 51.4, 42.2, 33.8, 32.4, 28.0, 25.1; IR \ (\text{NaCl}): 2935, 2860, 1708, 1596, 1509, 1447, 1396, 1127, 801, 780, 506 \text{ cm}^{-1}; \text{HRMS (ESI): [M + Na]^+ calcd. for C}_{17}H_{18}O_1Na, 261.1250; found,261.1252; [\alpha]_D^{26} – 10.5 \ (c = 1.42, CHCl}_3).\]

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL IC-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 50 : 1, flow rate = 1.0 mL/min, retention time; 13.6 min (major) and 15.7 min (minor)).
(R)-1,2-diphenylpropan-1-one (3k)\(^7\)

The title compound was prepared following General procedure, using 2-methyl-3-oxo-2,3-diphenylpropanoic acid 3k (64 mg, 0.25 mmol) and amine catalyst 1 (57 mg, 0.08 mmol) in n-hexane (2.5 mL), and the reaction mixture was stirred at room temperature for 2 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (32 mg, 61% yield, 23% ee).

\(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta 7.96–7.94\) (m, 2H), \(7.49–7.46\) (m, 1H), \(7.40–7.36\) (m, 2H), \(7.30–7.28\) (m, 4H), \(7.23–7.18\) (m, 1H), 4.69 (q, \(J = 6.9\) Hz, 1H), 1.54 (d, \(J = 6.9\) Hz, 3H); \(^13\)C NMR (126 MHz, CDCl\(_3\)): \(\delta 200.3, 141.4, 136.4, 132.7, 128.9, 128.7, 128.4, 127.7, 126.8, 47.8, 19.5\); IR (NaCl): 2975, 2930, 1683, 1597, 1448, 1222, 952, 698, 564 cm\(^{-1}\); HRMS (ESI): [M + Na]\(^+\) calcd. for C\(_{15}\)H\(_{14}\)O\(_1\)Na\(_1\), 233.0937; found, 233.0937; \([\alpha]_D^{24} = -40.1\) (c = 1.49, CHCl\(_3\)).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmϕ×25 cm), hexane : i-PrOH = 99 : 1, flow rate = 1.0 mL/min, retention time; 18.6 min (minor) and 21.6 min (major)).

5. Enantioselective decarboxylative deuteration

**General procedure**

\(\text{R}^1\text{R}^2\text{R}^3\text{COOH} \xrightarrow{\text{D}_2\text{O/n-hexane temp., 30 min}} \text{1 (30 mol%)} \xrightarrow{\text{temp., time}} \text{R}^1\text{R}^2\text{R}^3\text{CO}_2\text{D}\)

\(\alpha,\alpha\)-Dialkyl-\(\beta\)-ketocarboxylic acid 2 (0.3 mmol) was added to a stirred solution of deuterium oxide and \(n\)-hexane (1 : 1, 1.5 mL), and the mixture was stirred for 30 min. Then, amine catalyst 1 (30 mol%) was added to the mixture and stirred for a further 1–66 h. The reaction mixture was directly purified by flash column chromatography on silica gel to give corresponding \(\alpha\)-deuterated ketone 3-\(d\).

2-methyl-3,4-dihydronaphthalen-1(2H)-one-2-\(d\) (3a-\(d\))\(^8\)

The title compound was prepared following General procedure, using 2-methyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2a (61 mg, 0.3 mmol) in \(n\)-hexane : D\(_2\)O (1 : 1, 1.5 mL), and the reaction mixture was stirred at room temperature for 30 min. Then, the reaction mixture was added amine catalyst 1 (68 mg, 0.09 mmol), and stirred at room temperature for 15 h. The crude product was
purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (43 mg, 90% yield, 84% ee, 90% D).

$^1$H NMR (500 MHz, CDCl$_3$): δ 8.03 (d, $J = 7.6$ Hz, 1H), 7.44 (t, $J = 7.6$ Hz, 1H), 7.29 (t, $J = 7.6$ Hz, 1H), 7.23 (d, $J = 7.6$ Hz, 1H), 3.07–2.94 (m, 2H), 2.19 (dt, $J = 13.4$, 4.6 Hz, 1H), 1.90–1.84 (m, 1H), 1.26 (s, 3H);

$^{13}$C NMR (126 MHz, CDCl$_3$): δ 200.8, 144.1, 133.0, 132.3, 128.7, 127.3, 126.5, 42.1 ($J = 19.2$ Hz), 31.2, 28.7, 15.3;

IR (NaCl): 2963, 2931, 1686, 1601, 1455, 1303, 1227, 968, 765, 729 cm$^{-1}$;

HRMS (DART): [M + NH$_4$]$^+$ calcd. for C$_{11}$H$_{15}$O$_1$N$_1$D$_1$, 179.1282; found, 179.1295; $[\alpha]_{D}^{27}$ $+$35.3 (c = 1.33, CHCl$_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OZ-H (0.46 cmφ×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 13.0 min (major) and 13.9 min (minor)).

2-benzyl-3,4-dihydronaphthalen-1(2H)-one-2-d (3b-d)

The title compound was prepared following General procedure, using 2-benzyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2b (92 mg, 0.33 mmol) in n-hexane : D$_2$O (1 : 1, 1.6 mL), and the reaction mixture was stirred at 10 °C for 30 min. Then, the reaction mixture was added amine catalyst 1 (75 mg, 0.10 mmol), and stirred at 10 °C for 19 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (68 mg, 87% yield, 62% ee, 87% D).

$^1$H NMR (500 MHz, CDCl$_3$): δ 8.06 (d, $J = 7.6$ Hz, 1H), 7.46 (dt, $J = 7.6$, 1.2 Hz, 1H), 7.32–7.29 (m, 3H), 7.23–7.21 (m, 4H), 3.47 (d, $J = 13.8$ Hz, 1H), 2.98–2.87 (m, 2H), 2.64 (d, $J = 13.8$ Hz, 1H), 2.10 (ddd, $J = 13.4$, 9.2, 4.6 Hz, 1H), 1.83–1.76 (m, 1H);

$^{13}$C NMR (126 MHz, CDCl$_3$): δ 199.3, 143.9, 139.9, 133.2, 132.4, 129.2, 128.6, 128.3, 127.4, 126.5, 126.0, 48.8 (t, $J = 19.2$ Hz), 35.5, 28.4, 27.4;

IR (NaCl): 3026, 2927, 1677, 1600, 1496, 1454, 1291, 1231, 745, 700 cm$^{-1}$;

HRMS (DART): [M + NH$_4$]$^+$ calcd. for C$_{17}$H$_{18}$O$_1$N$_1$D$_1$, 254.1529; found, 254.1530; $[\alpha]_{D}^{26}$ $-$6.2 (c = 2.49, CHCl$_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 0.8 mL/min, retention time; 21.9 min (minor) and 23.5 min (major)).

2-allyl-3,4-dihydronaphthalen-1(2H)-one-2-d (3c-d)

The title compound was prepared following General procedure, using 2-allyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2c (73 mg, 0.32 mmol) in n-hexane : D$_2$O (1 : 1, 1.6 mL), and the reaction mixture was stirred at room temperature for 30 min. Then, the reaction mixture was added amine catalyst 1 (72 mg, 0.09 mmol), and stirred at room temperature for 6 h. The crude product
was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (59 mg, 98% yield, 87% ee, 87% D).

\[ ^1H \text{ NMR (500 MHz, CDCl}_3\]: \( \delta \) 8.04 (dd, \( J = 7.6, 1.2 \text{ Hz, 1H} \), 7.46 (dt, \( J = 7.6, 1.2 \text{ Hz, 1H} \), 7.30 (t, \( J = 7.6 \text{ Hz, 1H} \), 7.24 (d, \( J = 7.6 \text{ Hz, 1H} \), 5.89–5.81 (m, \( 1H \), 5.15–5.06 (m, \( 2H \), 3.00 (dd, \( J = 7.6, 4.6 \text{ Hz, 2H} \)), 2.77–2.73 (m, \( 1H \), 2.30–2.21 (m, \( 2H \), 1.91–1.83 (m, \( 1H \)); \[ ^13C \text{ NMR (126 MHz, CDCl}_3\]: \( \delta \) 199.5, 144.0, 136.1, 133.1, 132.4, 128.7, 127.4, 126.5, 116.8, 46.6 (t, \( J = 19.2 \text{ Hz, 2H} \), 33.9, 28.5, 27.8; \[ \text{IR (NaCl): 3073, 2931, 1684, 1601, 1455, 1237, 1156, 995, 915, 740 cm}^{-1}; \[ \text{HRMS (DART): [M + H]+ calcd. for C}_{13}H_{14}O_1D_1, 188.1186; found, 188.1186; [\alpha]_D^{26} +25.8 (c = 1.99, CHCl}_3\]).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 0.7 mL/min, retention time; 16.3 min (major) and 17.3 min (minor)).

2-(prop-2-yn-1-yl)-3,4-dihyronaphthalen-1(2H)-one-2-d (3d-d)

The title compound was prepared following General procedure, using 1-oxo-2-(prop-2-yn-1-yl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid \( 2d \) (69 mg, 0.3 mmol) in \( n \)-hexane : D\(_2\)O (1 : 1, 1.5 mL), and the reaction mixture was stirred at 10 °C for 30 min. Then, the reaction mixture was added amine catalyst \( 1 \) (68 mg, 0.09 mmol), and stirred at 10 °C for 22 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a white solid (53 mg, 95% yield, 69% ee, 90% D).

\[ ^1H \text{ NMR (500 MHz, CDCl}_3\]: \( \delta \) 8.04 (d, \( J = 7.6 \text{ Hz, 1H} \), 7.48 (t, \( J = 7.6 \text{ Hz, 1H} \), 7.31 (t, \( J = 7.6 \text{ Hz, 1H} \), 7.26–7.25 (m, \( 1H \), 3.13–3.01 (m, \( 2H \), 2.90 (dd, \( J = 17.2, 2.7 \text{ Hz, 1H} \), 2.51–2.45 (m, \( 2H \), 2.00 (t, \( J = 2.7 \text{ Hz, 1H} \); \[ ^13C \text{ NMR (126 MHz, CDCl}_3\]: \( \delta \) 198.0, 144.1, 133.4, 132.2, 128.7, 127.5, 126.6, 82.3, 69.7, 46.2 (t, \( J = 19.2 \text{ Hz, 2H} \), 28.9, 28.1, 19.2; \[ \text{IR (NaCl): 3295, 2933, 1681, 1600, 1455, 1217, 766, 740 cm}^{-1}; \[ \text{HRMS (DART): [M + H]+ calcd. for C}_{13}H_{12}O_1, 186.1030; found, 186.1030; [\alpha]_D^{27} –11.7 (c = 1.93, CHCl}_3\]).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 99 : 1, flow rate = 0.7 mL/min, retention time; 22.2 min (major) and 23.8 min (minor)).

2-(thiophen-2-ylmethyl)-3,4-dihyronaphthalen-1(2H)-one-2-d (3e-d)

The title compound was prepared following General procedure, using 1-oxo-2-(thiophen-2-ylmethyl)-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid \( 2e \) (86 mg, 0.3 mmol) in \( n \)-hexane : D\(_2\)O (1 : 1, 1.5 mL), and the reaction mixture was stirred at room temperature for 30 min. Then, the reaction mixture was added amine catalyst \( 1 \) (68 mg, 0.09 mmol), and stirred at room temperature for 6.5 h.
The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (72 mg, 98% yield, 64% ee, 90% D).

$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 8.06 (dd, $J = 7.6$, 1.2 Hz, 1H), 7.46 (dt, $J = 7.6$, 1.2 Hz, 1H), 7.31 (t, $J = 7.6$ Hz, 1H), 7.22 (d, $J = 7.6$ Hz, 1H), 7.14 (dd, $J = 5.0$, 1.2 Hz, 1H), 6.93 (dd, $J = 5.0$, 3.4 Hz, 1H), 6.85 (d, $J = 3.4$ Hz, 1H), 3.57 (d, $J = 14.9$ Hz, 1H), 3.03 (d, $J = 14.9$ Hz, 1H), 2.99–2.95 (m, 2H), 2.24–2.19 (m, 1H), 1.88–1.80 (m, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$): $\delta$ 198.9, 144.0, 142.2, 133.3, 132.4, 128.7, 127.5, 126.8, 126.6, 125.9, 123.7, 49.1 (t, $J = 19.2$ Hz), 29.7, 28.7, 27.8; IR (NaCl): 3067, 2928, 2854, 1681, 1599, 1455, 1292, 1227, 751, 698 cm$^{-1}$; HRMS (ESI): [M + Na]$^+$ calcd. for C$_{15}$H$_{13}$O$_1$D$_1$S$_1$Na$_1$, 266.0720; found, 266.0721; $[^{[\alpha]}]D_{26}$ – 24.9 (c = 3.03, CHCl$_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IE-3 (0.46 cmφ×25 cm), exane : i-PrOH = 98 : 2, flow rate = 0.7 mL/min, retention time; 23.5 min (major) and 26.1 min (minor)).

2-(3-chloropropyl)-3,4-dihydronaphthalen-1(2H)-one-2-d (3f-d)

The title compound was prepared following General procedure, using 2-(3-chloropropyl)-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2f (80 mg, 0.3 mmol) in n-hexane : D$_2$O (1 : 1, 1.5 mL) and sodium chloride (100 mg), and the reaction mixture was stirred at 0 °C for 30 min. Then, the reaction mixture was added amine catalyst 1 (68 mg, 0.09 mmol), and stirred at 0 °C for 40 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (66 mg, 98% yield, 81% ee, 82% D).

$^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 8.02 (dd, $J = 7.6$, 1.2 Hz, 1H), 7.46 (dt, $J = 7.6$, 1.2 Hz, 1H), 7.31 (t, $J = 7.6$ Hz, 1H), 7.24 (d, $J = 7.6$ Hz, 1H), 3.63–3.54 (m, 2H), 3.04–3.00 (m, 2H), 2.26–2.21 (m, 1H), 2.07–2.01 (m, 1H), 1.96–1.88 (m, 3H), 1.72–1.65 (m, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$): $\delta$ 199.8, 143.8, 133.2, 132.4, 128.7, 127.4, 126.6, 46.4 (t, $J = 19.2$ Hz), 45.1, 30.1, 28.5, 28.4, 27.0; IR (NaCl): 2931, 2862, 1683, 1601, 1455, 1293, 1228, 935, 764, 738 cm$^{-1}$; HRMS (DART): [M + Nh$_4$]$^+$ calcd. for C$_{13}$H$_{18}$O$_1$N$_1$D$_1$Cl$_1$, 241.1218; found, 241.1218; $[^{[\alpha]}]D_{26}$ +14.0 (c = 1.77, CHCl$_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF-3 (0.46 cmφ×25 cm), hexane : i-PrOH = 98 : 2, flow rate = 0.7 mL/min, retention time; 37.6 min (major) and 40.0 min (minor)).

2-hexyl-3,4-dihydronaphthalen-1(2H)-one-2-d (3g-d)

The title compound was prepared following General procedure, using 2-hexyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylic acid 2g (94 mg, 0.34 mmol) in n-hexane : D$_2$O (1 : 1, 3.6 mL) and sodium chloride (516 mg), and the reaction mixture was stirred at 0 °C for 30 min. Then, the reaction
mixture was added amine catalyst 1 (78 mg, 0.10 mmol), and stirred at 0 °C for 66 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (63 mg, 79% yield, 88% ee, 87% D).

**1H NMR** (500 MHz, CDCl3): δ 8.03 (dd, \( J = 7.6, 1.2 \text{ Hz}, 1H \)), 7.45 (dt, \( J = 7.6, 1.2 \text{ Hz}, 1H \)), 7.30 (t, \( J = 7.6 \text{ Hz}, 1H \)), 7.23 (d, \( J = 7.6 \text{ Hz}, 1H \)), 3.04–2.93 (m, 2H), 2.27–2.21 (m, 1H), 1.95–1.86 (m, 2H), 1.52–1.21 (m, 9H), 0.90–0.87 (m, 3H);

**13C NMR** (126 MHz, CDCl3): δ 200.5, 143.9, 133.0, 132.5, 128.6, 127.4, 126.5, 46.9 (t, \( J = 19.2 \text{ Hz} \)), 31.7, 29.4, 29.2, 28.1, 28.0, 26.9, 22.6, 14.1;

**IR** (NaCl): 2953, 2926, 2857, 1685, 1602, 1455, 1296, 1227, 764, 739 cm⁻¹;

**HRMS** (DART): \([M + H]^+\) calcd. for C₁₆H₂₂O_D₁, 232.1812; found, 232.1812; \([\alpha]_{D}^{24} +12.4 (c = 2.13, \text{CHCl}_3)\).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALPAC IF (0.46 cmφ×25 cm), hexane : i-PrOH = 150 : 1, flow rate = 1.0 mL/min, retention time; 10.3 min (minor) and 11.0 min (major)).

2-methyl-2,3-dihydro-1H-inden-1-one-2-d (3h-d)

![Chemical Structure](image)

The title compound was prepared following **General procedure**, using 2-methyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylic acid 2h (57 mg, 0.3 mmol) in n-hexane : D₂O (1 : 1, 1.5 mL), and the reaction mixture was stirred at 15 °C for 30 min. Then, the reaction mixture was added amine catalyst 1 (68 mg, 0.09 mmol), and stirred at 15 °C for 2.5 h. The crude product was purified by flash column chromatography (hexane : diethyl ether = 8 : 1) to provide the title compound as a colorless oil (33 mg, 74% yield, 60% ee, 87% D).

**1H NMR** (500 MHz, CDCl3): δ 7.76 (d, \( J = 7.6 \text{ Hz}, 1H \)), 7.58 (t, \( J = 7.6 \text{ Hz}, 1H \)), 7.45 (t, \( J = 7.6 \text{ Hz} \)), 7.37 (t, \( J = 7.6 \text{ Hz}, 1H \)), 3.39 (d, \( J =17.2 \text{ Hz}, 1H \)), 2.73 (d, \( J =17.2 \text{ Hz}, 1H \)), 1.31 (s, 3H);

**13C NMR** (126 MHz, CDCl3): δ 209.5, 153.5, 136.3, 134.7, 127.3, 126.5, 123.9, 41.5 (t, \( J = 19.2 \text{ Hz} \)), 34.8, 16.2;

**IR** (NaCl): 2927, 1713, 1609, 1465, 1327, 1283, 993, 766, 738, 715 cm⁻¹;

**HRMS** (ESI): \([M + Na]^+\) calcd. for C₁₀H₉O_D₁Na, 170.0687; found, 170.0687; \([\alpha]_{D}^{26} +30.2 (c = 0.55, \text{CHCl}_3)\).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : i-PrOH = 9 : 1, flow rate = 0.5 mL/min, retention time; 11.8 min (minor) and 12.5 min (major)).

2-benzylcyclohexan-1-one-2-d (3i-d)

![Chemical Structure](image)

The title compound was prepared following **General procedure**, using 1-benzyl-2-oxocyclohexane-1-carboxylic acid 2i (61 mg, 0.26 mmol) and amine catalyst 1 (60 mg, 0.08 mmol) in n-hexane : D₂O (1 : 1, 1.3 mL), and the reaction mixture was stirred at room temperature for 1.5 h. The crude product
was purified by flash column chromatography (hexane : diethyl ether = 15 : 1) to provide the title compound as a yellow oil (21mg, 43% yield, 22% ee, 73% D).

$^1$H NMR (500 MHz, CDCl$_3$): δ 7.29–7.26 (m, 2H), 7.20–7.15 (m, 3H), 3.22 (d, $J = 14.1$ Hz, 1H), 2.46–2.39 (m, 2H), 2.36–2.29 (m, 1H), 2.09–2.00 (m, 2H), 1.73–1.53 (m, 2H), 1.39–1.31 (m, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$): δ 212.6, 140.3, 129.1, 128.2, 52.0 (t, $J = 19.2$ Hz), 42.1, 35.3, 33.3, 28.0, 25.0; IR (NaCl): 2936, 2859, 1709, 1605, 1451, 1128, 730, 700, 512 cm$^{-1}$; HRMS (ESI): [M + Na]$^+$ calcd. for C$_{13}$H$_{15}$O$_1$Na$^+$D$_1$, 212.1156; found, 212.1150; $[\alpha]_D^{24} = -6.8$ (c = 0.85, CHCl$_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : $i$-PrOH = 98 : 2, flow rate = 1.0 mL/min, retention time; 10.2 min (minor) and 11.4 min (major)).

1,2-diphenylpropan-1-one-2-$d$ (3k-$d$)

The title compound was prepared following General procedure, using 2-methyl-3-oxo-2,3-diphenylpropanoic acid 2k (64 mg, 0.25 mmol) and amine catalyst 1 (57 mg, 0.08 mmol) in n-hexane : D$_2$O (1 : 1, 1.3 mL), and the reaction mixture was stirred at room temperature for 6 h. The crude product was purified by flash column chromatography (hexane : ethyl acetate = 20 : 1) to provide the title compound as a colorless oil (33mg, 62% yield, 23% ee, 93% D).

$^1$H NMR (500 MHz, CDCl$_3$): δ 7.96–7.94 (m, 2H), 7.49–7.46 (m, 1H), 7.40–7.37 (m, 2H), 7.30–7.29 (m, 4H), 7.23–7.18 (m, 1H), 1.53 (s, 3H); $^{13}$C NMR (126 MHz, CDCl$_3$): δ 200.3, 141.4, 136.4, 132.7, 128.9, 128.7, 128.4, 127.7, 126.8, 47.4 (t, $J = 19.2$ Hz), 19.4; IR (NaCl): 2975, 2859, 1682, 1597, 1447, 1263, 976, 739, 696, 559 cm$^{-1}$; HRMS (ESI): [M + Na]$^+$ calcd. for C$_{15}$H$_{13}$O$_1$Na$^+$D$_1$, 234.1000; found, 234.0995; $[\alpha]_D^{24} = -39.1$ (c = 0.45, CHCl$_3$).

The enantiomeric purity of the title compound was determined by HPLC analyses (DAICEL CHIRALCEL OJ-H (0.46 cmφ×25 cm), hexane : $i$-PrOH = 99 : 1, flow rate = 1.0 mL/min, retention time; 18.5 min (minor) and 21.2 min (major)).

6. References
7. NMR spectra

Supplementary figure 1. $^1$H NMR spectrum for β-ketoester 4d

Supplementary figure 2. $^{13}$C NMR spectrum for β-ketoester 4d
Supplementary figure 3. $^1$H NMR spectrum for β-ketoester 4e

Supplementary figure 4. $^{13}$C NMR spectrum for β-ketoester 4e
Supplementary figure 5. $^1$H NMR spectrum for β-ketoester 4g

Supplementary figure 6. $^{13}$C NMR spectrum for β-ketoester 4g
Supplementary figure 7. $^1$H NMR spectrum for β-ketocarboxylic acid 2d

Supplementary figure 8. $^{13}$C NMR spectrum for β-ketocarboxylic acid 2d
Supplementary figure 9. $^1$H NMR spectrum for β-ketocarboxylic acid 2e

Supplementary figure 10. $^{13}$C NMR spectrum for β-ketocarboxylic acid 2e
Supplementary figure 11. $^1$H NMR spectrum for β-ketocarboxylic acid 2g

Supplementary figure 12. $^{13}$C NMR spectrum for β-ketocarboxylic acid 2g
Supplementary figure 13. $^1$H NMR spectrum for β-ketocarboxylic acid 2j

Supplementary figure 14. $^{13}$C NMR spectrum for β-ketocarboxylic acid 2j
Supplementary figure 15. $^1$H NMR spectrum for 3a

Supplementary figure 16. $^{13}$C NMR spectrum for 3a
Supplementary figure 17. HPLC spectra for 3a
Supplementary figure 18. $^1$H NMR spectrum for 3b

Supplementary figure 19. $^{13}$C NMR spectrum for 3b
Supplementary figure 20. HPLC spectra for 3b

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Supplementary figure 21. $^1$H NMR spectrum for $3c$

Supplementary figure 22. $^{13}$C NMR spectrum for $3c$
Supplementary figure 23. HPLC spectra for 3c
**Supplementary figure 24.** $^1$H NMR spectrum for 3d

**Supplementary figure 25.** $^{13}$C NMR spectrum for 3d
Supplementary figure 26. HPLC spectra for 3d

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Supplementary figure 27. $^1$H NMR spectrum for 3e

Supplementary figure 28. $^{13}$C NMR spectrum for 3e
Supplementary figure 29. HPLC spectra for 3e

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Supplementary figure 30. $^1$H NMR spectrum for 3f

Supplementary figure 31. $^{13}$C NMR spectrum for 3f
Supplementary figure 32. HPLC spectra for 3f

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Supplementary figure 33. $^1$H NMR spectrum for 3g

Supplementary figure 34. $^{13}$C NMR spectrum for 3g
Supplementary figure 35. HPLC spectra for 3g

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Supplementary figure 36. $^1$H NMR spectrum for 3h

Supplementary figure 37. $^{13}$C NMR spectrum for 3h
Supplementary figure 38. HPLC spectra for 3h

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Supplementary figure 39. $^1$H NMR spectrum for 3i

Supplementary figure 40. $^{13}$C NMR spectrum for 3i
Supplementary figure 41. HPLC spectra for 3i
Supplementary figure 42. $^1$H NMR spectrum for 3j

Supplementary figure 43. $^{13}$C NMR spectrum for 3j
Supplementary figure 44. HPLC spectra for 3j
Supplementary figure 45. $^1$H NMR spectrum for 3k

Supplementary figure 46. $^{13}$C NMR spectrum for 3k
Supplementary figure 47. HPLC spectra for 3k

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Supplementary figure 48. $^1$H NMR spectrum for 3a-d

Supplementary figure 49. $^{13}$C NMR spectrum for 3a-d
Supplementary figure 50. HPLC spectra for 3a-d

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Supplementary figure 51. $^1$H NMR spectrum for 3b-d

Supplementary figure 52. $^{13}$C NMR spectrum for 3b-d
Supplementary figure 53. HPLC spectra for 3b-d
Supplementary figure 54. $^1$H NMR spectrum for 3c-d

Supplementary figure 55. $^{13}$C NMR spectrum for 3c-d
Supplementary figure 56. HPLC spectra for 3c-d

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Supplementary figure 57. $^1$H NMR spectrum for 3d-d

Supplementary figure 58. $^{13}$C NMR spectrum for 3d-d
Supplementary figure 59. HPLC spectra for 3d-d
Supplementary figure 60. $^1$H NMR spectrum for 3e-d

Supplementary figure 61. $^{13}$C NMR spectrum for 3e-d
Supplementary figure 62. HPLC spectra for 3e-d

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Supplementary figure 63. $^1$H NMR spectrum for 3f-d

Supplementary figure 64. $^{13}$C NMR spectrum for 3f-d
Supplementary figure 65. HPLC spectra for 3f-d

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Supplementary figure 66. $^1$H NMR spectrum for 3g-d

Supplementary figure 67. $^{13}$C NMR spectrum for 3g-d
Supplementary figure 68. HPLC spectra for 3g-d

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Supplementary figure 69. $^1$H NMR spectrum for 3h-d

Supplementary figure 70. $^{13}$C NMR spectrum for 3h-d
Supplementary figure 71. HPLC spectra for 3h-d

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Supplementary figure 71. $^1$H NMR spectrum for 3i-d

Supplementary figure 72. $^{13}$C NMR spectrum for 3i-d
Supplementary figure 73. HPLC spectra for 3i-\(^d\)

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Supplementary figure 74. $^1$H NMR spectrum for 3k-d

Supplementary figure 75. $^{13}$C NMR spectrum for 3k-d
Supplementary figure 76. HPLC spectra for 3k-d