

**Cationic Palladium(II)-Catalyzed Highly Enantioselective [3+2] Annulation of
2-Acylarylboronic Acids with Substituted Alkynes**

Miao Yang,[†] Xumu Zhang^{*,‡} and Xiyan Lu^{*,†}

[†]*State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry,
Chinese Academy of Science, 354 Fenglin Road, Shanghai 200032, China*

[‡]*Department of Chemistry, The Pennsylvania State University, University Park, PA, USA.*

xylu@mail.sioc.ac.cn

Supporting Information

Part 1

Table of Contents

I	General	S2
II	Asymmetric annulation of 2-acylarylboronic acids with substituted alkynes	S2
III	References	S9
IV	Copies of ¹ H, ¹³ C NMR spectra of the annulation product	S10
V	Copies of HPLC spectra of the annulation product	S28-S46

I. General

All reactions were carried out under nitrogen atmosphere unless otherwise noted and monitored by thin-layer chromatography to detect the completion of the reaction. NMR spectra were recorded on a Varian Mercury V x300 spectrometer. Infrared spectra were obtained on a Bio-Rad FTS-185 instrument. Mass spectra were provided on HP 5973 or Agilent 1100. The optical rotation was measured on a Perkin-Elmer 341 polarimeter and the enantiomeric excesses were determined after separation of the enantiomers by HPLC on a Perkin-Elmer (785A, 200 IC Pump) or Waters (515 Pump, 2487, Dual Absorbance Detector) instruments. Elemental analyses were carried out on Elementar Vario EL instruments. All solvents were dried and distilled before use according to the standard procedure. All melting points were uncorrected. $[\text{Pd}(\text{dppp})(\text{H}_2\text{O})_2](\text{OTf})_2$ (**4a**),¹ $[\text{Pd}(\text{dppe})(\text{H}_2\text{O})_2](\text{OTf})_2$ (**4b**),² $[\text{Pd}((R)\text{-binap})(\text{H}_2\text{O})_2](\text{OTf})_2$ (**4e**),³ $\text{Pd}(\text{OTf})_2 \cdot 2\text{H}_2\text{O}$ ⁴ and arylboronic acids (**1a-1c**⁵ and **1d**⁶) were synthesized following the literature procedures.

II. Enantioselective annulation of 2-acylarylboronic acids with substituted propynoates

(i) General procedure for Table 1

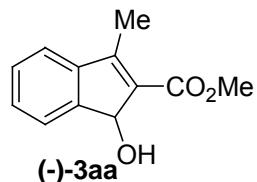


Table 1, entry 1:

To a Schlenk tube were added *o*-formylphenylboronic acid (45 mg, 0.3 mmol, 1.2 equiv.), $[\text{Pd}((R)\text{-binap})(\text{H}_2\text{O})_2](\text{OTf})_2$ (6.8 mg 3 mol%) and methyl 2-butynoate (29 mg, 0.25 mmol, 1 equiv.) and dioxane (2.0 mL) successively under N_2 . The reaction mixture was stirred at 20 °C for 12h until methyl 2-butynoate was disappeared as monitored by TLC. Then, the mixture was concentrated under reduced pressure and purified by flash column chromatography (ethyl acetate: petroleum ether = 1:4 to 1:2) to obtain the product **3aa**.⁷

Yield: 92%. The ee value was determined by chiral HPLC using a Chiralcel OD-H column (250 mm) with hexane : isopropanol = 80 : 20, flow = 0.6 mL/min; ee: 91%; $[\alpha]_D^{20} = -81.9$ (*c* 0.505, CHCl_3). m.p: 123-125 °C;

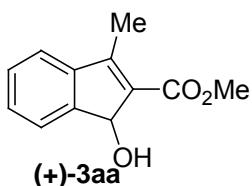
^1H NMR (300 MHz, CDCl_3): δ 7.59-7.61 (m, 1H), 7.39-7.43 (m, 3H), 5.40 (s, 1H), 3.90 (s, 3H), 3.20 (d, *J*=3.3 Hz, 1H), 2.50 (d, *J*=1.8 Hz, 3H); ^{13}C NMR (75 MHz, CDCl_3): δ 166.0, 153.1, 144.5, 142.3, 132.0, 129.0, 128.6, 123.9, 121.3, 75.5, 51.4, 12.4; IR (KBr): ν 3319, 3217, 2943, 2838, 1709, 1618, 1238, 755 cm^{-1} ; MS (70 eV, EI) *m/z* (%): 204 (M^+), 189, 172, 144 (100), 115.

Table 1, entry 4:

When $\text{Pd}(\text{OTf})_2/(R)\text{-binap}$ was used as catalyst, (-)-3aa was obtained similarly.

Yield: 95%. The ee value was determined by chiral HPLC using a Chiralcel OD-H column (250 mm) with hexane : isopropanol = 80 : 20, flow = 0.6 mL/min; ee: 91.3%.

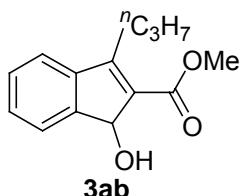
(ii) General procedure for Table 2



Entry 1

To a Schlenk tube were added *o*-formylphenylboronic acid (45 mg, 0.3 mmol, 1.2 equiv.), a solution of Pd(OTf)₂·2H₂O (3.6 mg, 3 mol%) and (S)-S1 (5.4 mg, 3.3 mol%) in dioxane (0.5 mL), methyl 2-butynoate (29 mg, 0.25 mmol, 1 equiv.) and dioxane (1.5 mL) successively under N₂. The reaction mixture was stirred at 20 °C for 12 h until methyl 2-butynoate was disappeared as monitored by TLC. Then, the mixture was concentrated under reduced pressure and purified by flash column chromatography (ethyl acetate: petroleum ether = 1:4 to 1:2) to obtain the product: **3aa**.⁷

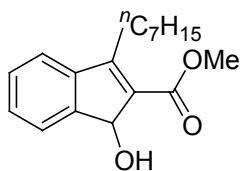
Yield: quantitative; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 80 : 20, flow = 0.6 mL/min; ee: 97.8%; [α]_D²⁰ = +96.6 (c 1.015, CHCl₃).



Entry 2

Yield: 84%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 90 : 10, flow = 0.6 mL/min; ee: 86.1%; [α]_D²⁰ = +76.3 (c 1.02, CHCl₃). m.p: 97-98.5 °C;

¹H NMR (300 MHz, CDCl₃): δ 7.59-7.62 (m, 1H), 7.38-7.46 (m, 3H), 5.40 (d, *J*=3 Hz, 1H), 3.89 (s, 3H), 3.21 (d, *J*=3.3 Hz, 1H), 2.91-2.99 (m, 2H), 1.64-1.71 (m, 2H), 1.03 (t, *J*=7.2 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.8, 157.5, 144.8, 141.7, 131.8, 128.9, 128.6, 124.0, 121.6, 75.7, 51.4, 28.4, 22.2, 14.3; IR (KBr): ν 3346, 2951, 2868, 1707, 1614, 1245 cm⁻¹; MS (70 eV, EI) *m/z* (%): 232 (M⁺), 215, 200, 189, 172, 157, 144 (100), 129, 115, 77; Anal. Calcd for C₁₄H₁₆O₃: C, 72.39; H, 6.94. Found: C, 72.30; H, 7.04.

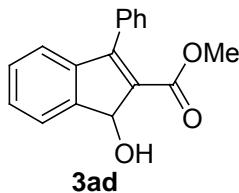


Entry 3

Yield: 88%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 97 : 3, flow = 0.7 mL/min; ee: 89.3%; [α]_D²⁰ = +61.8 (c 1.04, CHCl₃). m.p: 89-90.5 °C;

¹H NMR (300 MHz, CDCl₃): δ 7.59-7.61 (m, 1H), 7.38-7.44 (m, 3H), 5.40 (d, *J*=3.6 Hz, 1H), 3.89 (s, 3H), 3.20 (d, *J*=3.0 Hz, 1H), 2.91-2.99 (m, 2H), 1.59-1.64 (m, 2H), 1.29-1.45 (m, 8H), 0.88 (t, *J*=6.9 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.8, 157.8, 144.9, 141.7, 131.5, 128.9, 128.6, 124.0,

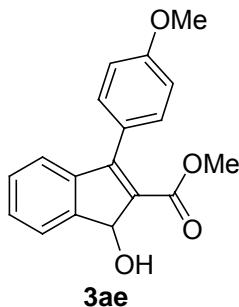
121.6, 75.7, 51.4, 31.7, 29.8, 29.0, 28.8, 26.6, 22.6, 14.1; IR (KBr): ν 3359, 3283, 2927, 2856, 1701, 1699, 1614, 1244 cm^{-1} ; MS (70 eV, EI) m/z (%): 288 (M^+), 256, 229, 199, 157, 144(100), 131, 115, 43; Anal. Calcd for $C_{18}\text{H}_{24}\text{O}_3$: C, 74.97; H, 8.39. Found: C, 75.19; H, 8.37.



Entry 4

Yield: 58%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 80 : 20, flow = 0.7 mL/min; ee: 90.4%; $[\alpha]_D^{20} = +68.1$ (c 0.69, CHCl_3). m.p: 122-124 $^\circ\text{C}$;

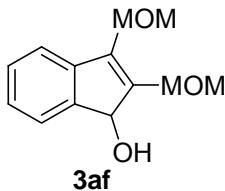
^1H NMR (300 MHz, CDCl_3): δ 7.66 (d, $J=7.2$ Hz, 1H), 7.38-7.50 (m, 6H), 7.32 (t, $J=7.8$ Hz, 1H), 7.19 (d, $J=7.5$ Hz, 1H), 5.57 (d, $J=3.3$ Hz, 1H), 3.72 (s, 3H), 3.39-3.42 (m, 1H); ^{13}C NMR (75 MHz, CDCl_3): δ 165.4, 154.0, 144.6, 142.0, 133.0, 132.5, 129.1, 128.8, 128.7, 128.6, 127.9, 124.2, 123.3, 76.2, 51.5; IR (KBr): ν 3362, 2943, 1714, 1601, 1577, 1226, 1130 cm^{-1} ; MS (70 eV, EI) m/z (%): 266 (M^+), 234, 206 (100), 178; HRMS Calcd for $C_{17}\text{H}_{14}\text{O}_3$: 266.0943. Found: 266.0943.



Entry 5

Yield: 83%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 90 : 10, flow = 0.7 mL/min; ee: 89.5%; $[\alpha]_D^{20} = +64.2$ (c 0.775, CHCl_3). m.p: 143-145;

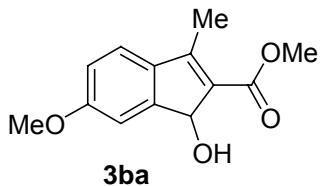
^1H NMR (300 MHz, CDCl_3): δ 7.66 (d, $J=6.9$ Hz, 1H), 7.28-7.43 (m, 5H), 7.0 (d, $J=8.7$ Hz, 2H), 5.57 (d, $J=3.3$ Hz, 1H), 3.89 (s, 3H), 3.74 (s, 3H), 3.32 (d, $J=3.3$ Hz, 1H); ^{13}C NMR (75 MHz, CDCl_3): δ 165.8, 160.0, 153.9, 144.7, 142.1, 131.7, 130.4, 129.1, 128.7, 125.0, 124.2, 123.4, 113.4, 76.1, 55.2, 51.5; IR (KBr): ν 3352, 2940, 1712, 1613, 1512, 1179, 1130 cm^{-1} ; MS (70 eV, EI) m/z (%): 296 (M^+), 280, 264, 237, 236 (100), 165; Anal. Calcd for $C_{18}\text{H}_{14}\text{O}_4$: C, 72.96; H, 5.44. Found: C, 72.70; H, 5.46.



Entry 6

Yield: 95%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 95 : 5, flow = 0.6 mL/min; ee: 57.3%; $[\alpha]_D^{20} = -42.8$ (c 2.555, CHCl_3).

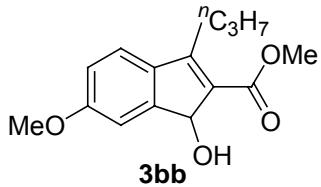
¹H NMR (300 MHz, CDCl₃): δ 7.52 (d, *J*=6.9 Hz, 1H), 7.21-7.38 (m, 3H), 5.23 (d, *J*=5.4 Hz, 1H), 4.42-4.47 (m, 4H), 3.43 (s, 3H), 3.40 (s, 3H), 2.71 (d, *J*=3.0 Hz, 1H); ¹³C NMR (75 MHz, CDCl₃): δ 144.5, 143.1, 141.9, 137.0, 128.4, 126.3, 123.3, 120.3, 77.4, 66.9, 65.9, 58.5, 58.2; IR (KBr): ν 3383, 3070, 3048, 2986, 2928, 2893, 2823, 1712, 1607, 1460, 1108 cm⁻¹; MS (70 eV, EI) *m/z* (%): 220 (M⁺), 188, 173, 158, 144, 128, 115 (100), 75, 45; HRMS Calcd for C₁₃H₁₆O₃: 220.1099. Found: 220.1107.



Entry 7

Yield: 83%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 97 : 3, flow = 0.7 mL/min; ee: 98.6%; [α]_D²⁰ = +108.1 (*c* 0.94, CHCl₃). m.p: 138-140 °C;

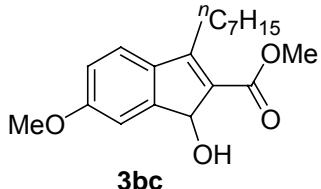
¹H NMR (300 MHz, CDCl₃): δ 7.33 (d, *J*=8.1 Hz, 1H), 7.18 (d, *J*=2.4 Hz, 1H), 6.91 (dd, *J*=2.4 Hz, 8.4 Hz, 1H), 5.36 (s, 1H), 3.88 (s, 3H), 3.87 (s, 3H), 3.26 (d, *J*=3.3 Hz, 1H), 2.47 (d, *J*=1.8 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 166.1, 161.3, 153.6, 146.9, 135.0, 127.0, 122.4, 114.5, 109.8, 75.4, 55.5, 51.3, 12.6; IR (KBr): ν 3275, 3003, 2949, 2841, 1695, 1614, 1585, 1454, 1440, 1226 cm⁻¹; MS (70 eV, EI) *m/z* (%): 234 (M⁺), 218, 203, 187, 175, 174 (100); Anal. Calcd for C₁₃H₁₄O₄: C, 66.66; H, 6.02. Found: C, 66.90; H, 5.98



Entry 8

Yield: 92%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 90 : 10, flow = 0.7 mL/min; ee: 84.3%; [α]_D²⁰ = +88.2 (*c* 0.88, CHCl₃). m.p: 113-114 °C;

¹H NMR (300 MHz, CDCl₃): δ 7.33 (d, *J*=8.4 Hz, 1H), 7.18 (d, *J*=2.1 Hz, 1H), 6.90 (dd, *J*= 2.4 Hz, 8.1 Hz, 1H), 5.35 (d, *J*=2.1 Hz, 1H), 3.87 (s, 3H), 3.85 (s, 3H), 3.26 (d, *J*=3 Hz, 1H), 2.86-2.95 (m, 2H), 1.58-1.70 (m, 2H), 1.01 (t, *J*=7.2 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.9, 161.2, 158.0, 147.2, 134.4, 130.0, 122.7, 114.5, 109.9, 75.5, 55.2, 51.2, 28.5, 22.2, 14.3; IR (KBr): ν 3351, 3003, 2950, 1706, 1609, 1457, 1440, 1233, 1217 cm⁻¹; MS (70 eV, EI) *m/z* (%): 262 (M⁺), 231, 219, 203, 202, 187, 174 (100), 160, 131, 115, 77; Anal. Calcd for C₁₅H₁₈O₄: C, 68.68; H, 6.92. Found: C, 68.89; H, 7.07.

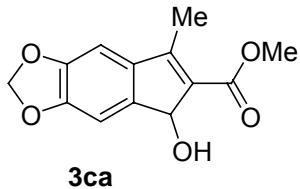


Entry 9

Yield: 94%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm)

with hexane : isopropanol = 90 : 10, flow = 0.7 mL/min; ee: 87.3%; $[\alpha]_D^{20} = +72.5$ (*c* 1.065, CHCl₃). m.p: 92-93 °C;

¹H NMR (300 MHz, CDCl₃): δ 7.32 (d, *J*=8.4 Hz, 1H), 7.17 (d, *J*=2.4 Hz, 1H), 6.89 (dd, *J*=2.4 Hz, 8.4 Hz, 1H), 5.34 (d, *J*=3.0 Hz, 1H), 3.863 (s, 3H), 3.86 (s, 3H), 3.26 (d, *J*=3.0 Hz, 1H), 2.90-2.93 (m, 2H), 1.60 (m, 2H), 1.26-1.41 (m, 8H), 0.88 (t, *J*=6.6 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.9, 161.2, 158.3, 147.2, 134.4, 129.4, 122.3, 114.5, 109.9, 75.5, 55.6, 51.2, 31.7, 29.9, 29.0, 28.9, 26.7, 22.6, 14.1; IR (KBr): ν 3358, 3274, 3002, 2950, 2924, 2854, 1704, 1609, 1225, 1087, 809 cm⁻¹; MS (70 eV, EI) *m/z* (%): 318 (M⁺), 287, 258, 220, 201, 187, 174 (100), 43; Anal. Calcd for C₁₉H₂₆O₅: C, 71.67; H, 8.23. Found: C, 71.76; H, 8.07.

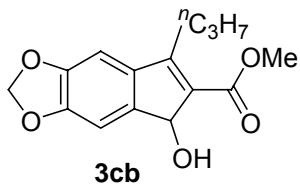


Entry 10

Yield: quantitative; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 95 : 5, flow = 0.7 mL/min; ee: 76.1%; $[\alpha]_D^{20} = -71.6$ (*c* 1.005, CHCl₃).

m.p: 170-172 °C;

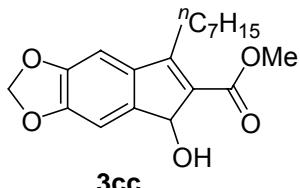
¹H NMR (300 MHz, CDCl₃): δ 7.09 (s, 1H), 6.88 (s, 1H), 6.02 (s, 2H), 5.27 (s, br, 1H), 3.87 (s, 3H), 3.21 (d, *J*=2.7 Hz, 1H), 2.44 (d, *J*=1.8 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.8, 153.2, 149.2, 148.4, 139.8, 136.5, 131.0, 105.5, 102.2, 101.6, 75.2, 51.3, 12.7; IR (KBr): ν 3341, 2951, 2914, 1696, 1595, 1214 cm⁻¹; MS (70 eV, EI) *m/z* (%): 248 (M⁺), 231, 216, 201, 188 (100); Anal. Calcd for C₁₃H₁₂O₅: C, 62.90; H, 4.87. Found: C, 62.91; H, 4.80.



Entry 11

Yield: 99%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 90 : 10, flow = 0.7 mL/min; ee: 83.1%; $[\alpha]_D^{20} = -62.3$ (*c* 0.68, CHCl₃). m.p: 117-118 °C;

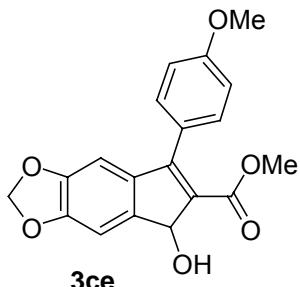
¹H NMR (300 MHz, CDCl₃): δ 7.09 (s, 1H), 6.88 (s, 1H), 6.02 (s, 2H), 5.27 (d, *J*=2.4 Hz, 1H), 3.86 (s, 3H), 3.22 (d, *J*=3.0 Hz, 1H), 2.84-2.89 (m, 2H), 1.60-1.89 (m, 2H), 1.02 (t, *J*=7.5 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.5, 157.6, 149.0, 148.3, 140.1, 135.7, 130.7, 105.6, 102.3, 101.6, 75.1, 51.2, 28.5, 22.1, 14.3; IR (KBr): ν 3340, 2875, 1701, 1592, 1249, 1211, 1033 cm⁻¹; MS (70 eV, EI) *m/z* (%): 276 (M⁺), 259, 244, 234, 227, 216, 201, 188 (100), 174, 159, 115; Anal. Calcd for C₁₅H₁₆O₅: C, 65.21; H, 5.84. Found: C, 65.23; H, 5.85.



Entry 12

Yield: 90%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 97 : 3, flow = 1.0 mL/min; ee: 83.7%; $[\alpha]_D^{20} = -50.5$ (*c* 1.005, CHCl₃). m.p: 92-93 °C;

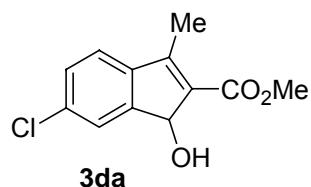
¹H NMR (300 MHz, CDCl₃): δ 7.08 (s, 1H), 6.88 (s, 1H), 6.02 (s, 2H), 5.26 (d, *J*=2.7 Hz, 1H), 3.86 (s, 3H), 3.22 (d, *J*=3.0 Hz, 1H), 2.84-2.89 (m, 2H), 1.56-1.60 (m, 2H), 1.28-1.40 (m, 8H), 0.88 (t, *J*=6.9 Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.6, 157.9, 149.0, 148.3, 140.1, 135.7, 130.4, 105.6, 102.3, 101.6, 75.2, 51.3, 31.7, 29.8, 29.0, 28.8, 26.8, 22.6, 14.1; IR (KBr): ν 3358, 2955, 2926, 2854, 1699, 1593, 1214, 1033 cm⁻¹; MS (70 eV, EI) *m/z* (%): 332 (M⁺), 314, 300, 272, 215, 201, 188 (100), 174, 159, 43; Anal. Calcd for C₁₉H₂₄O₅: C, 68.66; H, 7.28. Found: C, 68.62; H, 7.43.



Entry 13

Yield: 71%; The ee value was determined by chiral HPLC using a Chiralcel OJ-H column (150 mm) with hexane : isopropanol = 60 : 40, flow = 0.7 mL/min; ee: 89.2%; $[\alpha]_D^{20} = -51.9$ (*c* 0.355, CHCl₃). m.p: 166-167 °C.

¹H NMR (300 MHz, CDCl₃): δ 7.38 (d, *J*=8.4 Hz, 2H), 7.14 (s, 1H), 6.99 (d, *J*=8.4 Hz, 2H), 6.70 (s, 1H), 6.43 (d, *J*=3.0 Hz, 1H), 6.00 (s, 2H), 3.88 (s, 3H), 3.71 (s, 3H), 3.45 (d, *J*=3.0 Hz, 1H); ¹³C NMR (75 MHz, CDCl₃): δ 165.2, 159.9, 154.1, 149.1, 148.3, 139.9, 138.1, 130.5, 130.2, 125.0, 113.4, 105.6, 103.9, 101.6, 75.6, 55.2, 51.3; IR (KBr): ν 3400, 2900, 1716, 1208, 1178, 1305 cm⁻¹; MS (70 eV, EI) *m/z* (%): 340 (M⁺), 324, 308, 281, 280 (100); Anal. Calcd for C₁₉H₁₆O₆: C, 67.05; H, 4.74. Found: C, 66.93; H, 4.94.

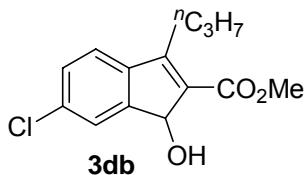


Entry 14

Yield: quantitative; The ee value was determined by chiral HPLC using a Chiralcel OD-H (250 mm) column with hexane : isopropanol = 90 : 10, flow = 0.7 mL/min; ee: 96.4%; $[\alpha]_D^{20} = +95.4$ (*c* 1.015, CHCl₃).

m.p: 131-133 °C;

¹H NMR (300 MHz, CDCl₃): δ 7.58 (s, 1H), 7.31-7.36 (m, 2H), 5.38 (s, 1H), 3.89 (s, 3H), 3.21 (d, *J*= 3.3Hz, 1H), 2.47 (d, *J*=1.2Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.8, 152.2, 146.1, 140.8, 135.3, 132.4, 128.9, 124.7, 122.4, 75.3, 51.5, 12.5; IR (KBr): ν 3315, 2949, 1704, 1619, 1576, 1436, 1237, 829 cm⁻¹; MS (70 eV, EI) *m/z* (%): 240 [M+2], 238 (M⁺), 223, 207, 191, 189, 180, 179, 178 (100), 171, 115; Anal. Calcd for C₁₂H₁₁ClO₃: C, 60.39; H, 4.65. Found: C, 60.46; H, 4.72.

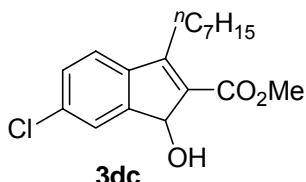


Entry 15

Yield: quantitative; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 90 : 10, flow = 0.7 mL/min; ee: 98.7%; $[\alpha]_D^{20} = +88.4$ (*c* 1.015, CHCl₃).

m.p: 136-138 °C;

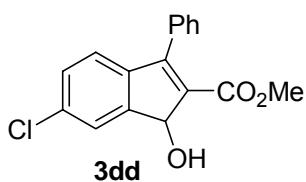
¹H NMR (300 MHz, CDCl₃): δ 7.58 (s, 1H), 7.35 (s, 2H), 5.37 (d, *J*= 3.3Hz, 1H), 3.89 (s, 3H), 3.21 (d, *J*= 3.3Hz, 1H), 2.09-2.95 (m, 2H), 1.61-1.69 (m, 2H), 1.02 (t, *J*= 7.5Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.6, 156.6, 146.5, 140.3, 135.2, 132.1, 128.9, 124.8, 122.6, 75.4, 51.5, 28.4, 22.1, 14.3; IR (KBr): ν 3353, 3269, 3025, 2996, 2875, 1704, 1613, 1434, 1244, 823 cm⁻¹; MS (70 eV, EI) *m/z* (%): 268 [M+2], 266 (M⁺), 251, 235, 223, 206, 191, 178 (100), 165, 149, 128, 115; HRMS Calcd for C₁₄H₁₅ClO₃: 266.0710. Found: 266.0703.



Entry 16

Yield: 65%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane: isopropanol = 90 : 10, flow = 0.7 mL/min; ee: 91%; $[\alpha]_D^{20} = +61.5$ (*c* 0.765, CHCl₃). m.p: 82-83 °C;

¹H NMR (300 MHz, CDCl₃): δ 7.58 (s, 1H), 7.35 (s, 2H), 5.37 (d, *J*= 3.3Hz, 1H), 3.88 (s, 3H), 3.21 (d, *J*= 3.6Hz, 1H), 2.91 (m, 2H), 1.57-1.62 (m, 2H), 1.28-1.44 (m, 8H), 0.88 (t, *J*= 6.9Hz, 3H); ¹³C NMR (75 MHz, CDCl₃): δ 165.6, 156.9, 146.5, 140.3, 135.3, 131.8, 128.9, 124.8, 122.6, 75.4, 51.5, 31.7, 29.8, 29.0, 28.8, 26.6, 22.6, 14.1; IR (KBr): ν 3367, 2854, 1708, 1612, 1432, 1234, 1197, 813 cm⁻¹; MS (70 eV, EI) *m/z* (%): 324 [M+2], 322 (M⁺), 305, 291, 255, 224, 205, 193, 191, 180, 178 (100); HRMS Calcd for C₁₈H₂₃ClO₃: 322.1336. Found: 322.1347.



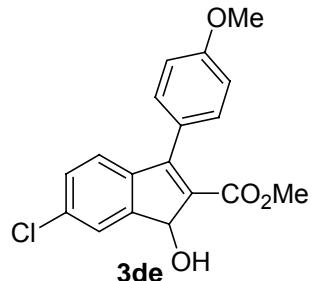
Entry 17

Yield: 75%; The ee value was determined by chiral HPLC using a Chiralcel OJ-H column with hexane : isopropanol = 85 : 15, flow = 0.7 mL/min; ee: 89.8%; $[\alpha]_D^{20} = +75.1$ (*c* 0.86, CHCl₃).

m.p: 120-122 °C;

¹H NMR (300 MHz, CDCl₃): δ 7.65 (s, 1H), 7.42-7.49 (m, 3H), 7.39-7.41 (m, 2H), 7.31 (dd, *J*=1.8Hz, 8.1Hz, 1H), 7.12 (d, *J*= 7.2Hz, 1H), 5.56 (d, *J*= 3.6Hz, 1H), 3.71 (s, 3H), 3.37 (d, *J*= 3.3 Hz, 1H); ¹³C NMR (75 MHz, CDCl₃): δ 165.1, 153.1, 146.2, 140.5, 135.5, 132.6, 132.5, 129.0,

128.9, 128.5, 128.0, 124.9, 124.2, 75.8, 51.6; IR (KBr): ν 3318, 2946, 1711, 1574, 1432, 1228, 1072 cm⁻¹; MS (70 eV, EI) m/z (%): 302 [M+2], 300 (M⁺), 285, 267, 253, 243, 242, 242, 240 (100), 205, 178, 176, 88; HRMS Calcd for C₁₇H₁₃ClO₃: 300.0553. Found: 300.0546.



Entry 18

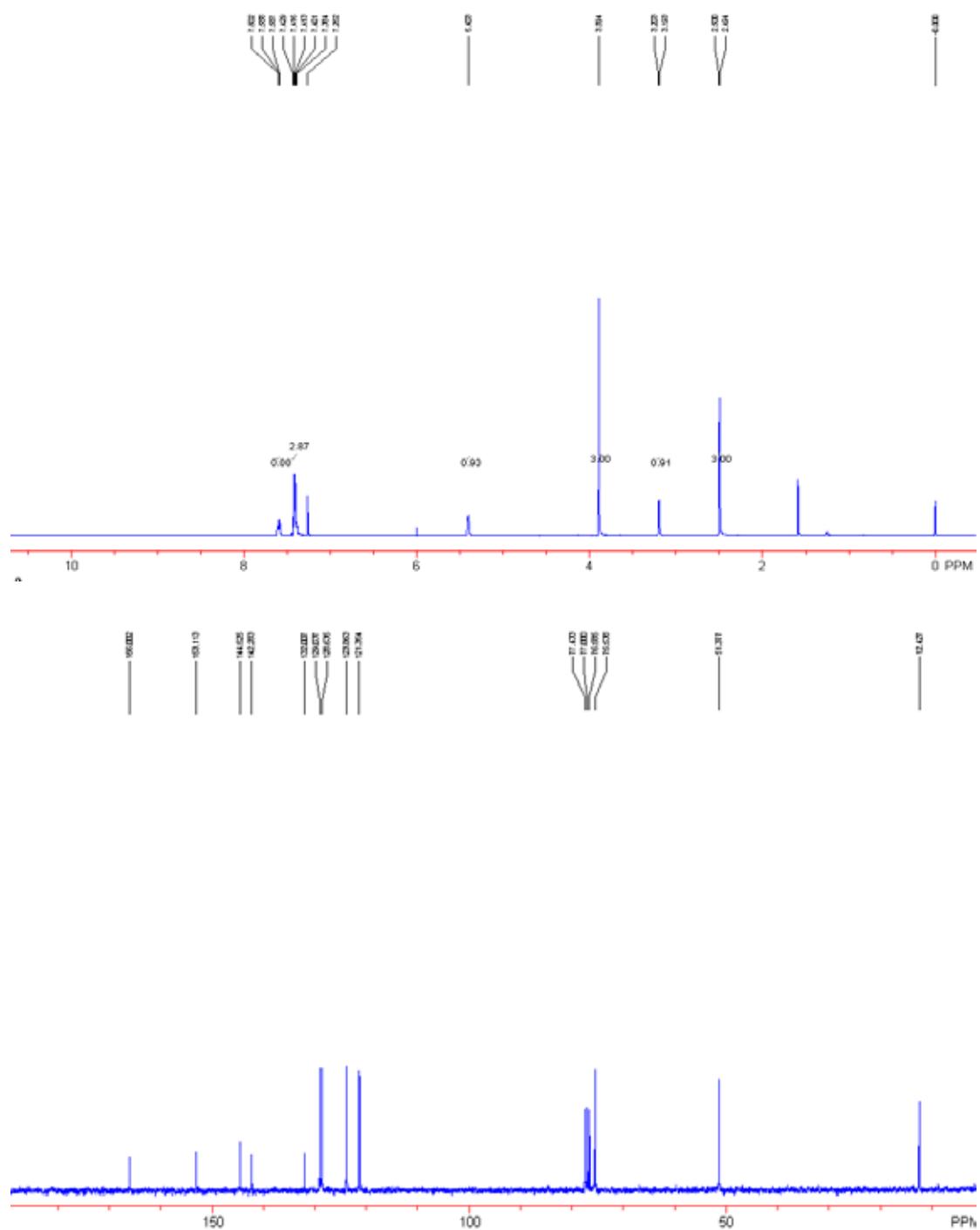
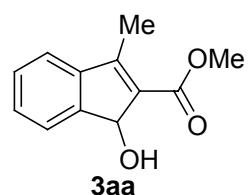
Yield: 55%; The ee value was determined by chiral HPLC using a Chiralcel OD-H column (150 mm) with hexane : isopropanol = 90 : 10, flow = 0.7 mL/min; ee: 87.3%; $[\alpha]_D^{20} = +58$ (*c* 0.21, CHCl₃). m.p: 137-139 °C;

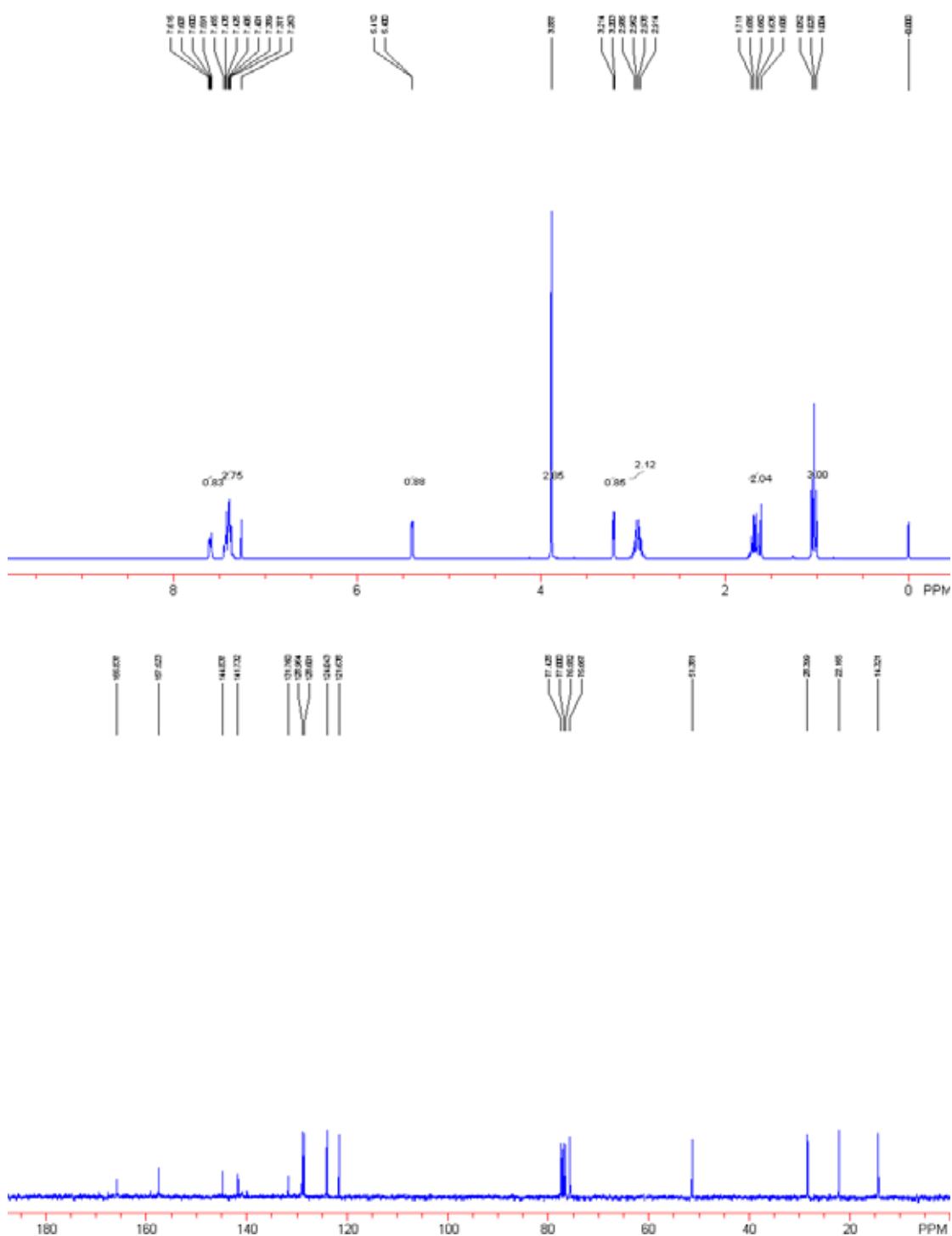
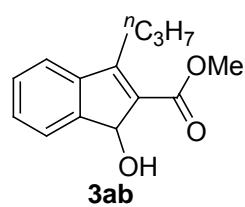
¹H NMR (300 MHz, CDCl₃): δ 7.64 (s, 1H), 7.40 (d, *J*= 8.7Hz, 2H), 7.32 (d, *J*= 8.1Hz, 1H), 7.18 (d, *J*= 8.7Hz, 1H), 7.00 (d, *J*= 9.0Hz, 2H), 5.44 (d, *J*= 3.0Hz, 1H), 3.88 (s, 3H), 3.74 (s, 3H), 3.35 (d, *J*= 3.3Hz, 1H); ¹³C NMR (75 MHz, D⁶-DMSO and D⁶-Acetone): δ 164.5, 159.7, 148.9, 148.7, 140.0, 135.1, 133.4, 130.1, 128.3, 124.4, 123.6, 113.6, 74.9, 55.0, 51.0; IR (KBr): ν 2950, 2838, 1718, 1610, 1569, 1511, 1256, 1228, 1176 cm⁻¹; MS (70 eV, EI) m/z (%): 332 [M+2], 330 (M⁺), 314, 273, 272, 271, 270 (100), 255, 235, 199, 165; HRMS Calcd for C₁₈H₁₅ClO₄: 330.0659. Found: 330.0656.

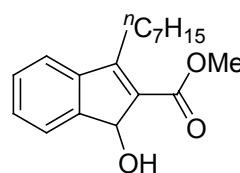
References:

- 1). Stang, P. J.; Cao, D. H.; Poulter, G. T.; Arif, A. M. *Orgaometallics* **1995**, *14*, 1110.
- 2). Fallis, S.; Anderson, G. K.; Rath, N. P. *Organometallics* **1991**, *10*, 3180.
- 3). Fujii, A.; Hagiwara, E.; Sodeoka, M. *J. Am. Chem. Soc.* **1999**, *121*, 5450.
- 4). Murata, S.; Ido, Y. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 1746.
- 5). (a) Lautens, M.; Marquardt, T. *J. Org. Chem.* **2004**, *69*, 4607. (b) Koepf, M.; Melin, F.; Jaillard J.; Weiss, J. *Tetrahedron Lett.* **2005**, *46*, 139.
- 6). a) Geen, G. R.; Mann, I. S.; Mullane, M. V. *Tetrahedron* **1998**, *54*, 9875. (b) Monovich, L. G. ; Le Huérou, Y. ; Rönn, M. ; Molander, G. A. *J. Am. Chem. Soc.* **2000**, *122*, 52.
- 7) (a) Shintani, R.; Okamoto, K.; Hayashi, T. *Chem. Lett.* **2005**, *34*, 1294. (b) Fisnerova, L.; Kakac, B.; Nemecek, O.; Simek, A. *Vejdelek, Z. J. Coll. Czech. Chem. Comm.* **1967**, *32*, 4082.

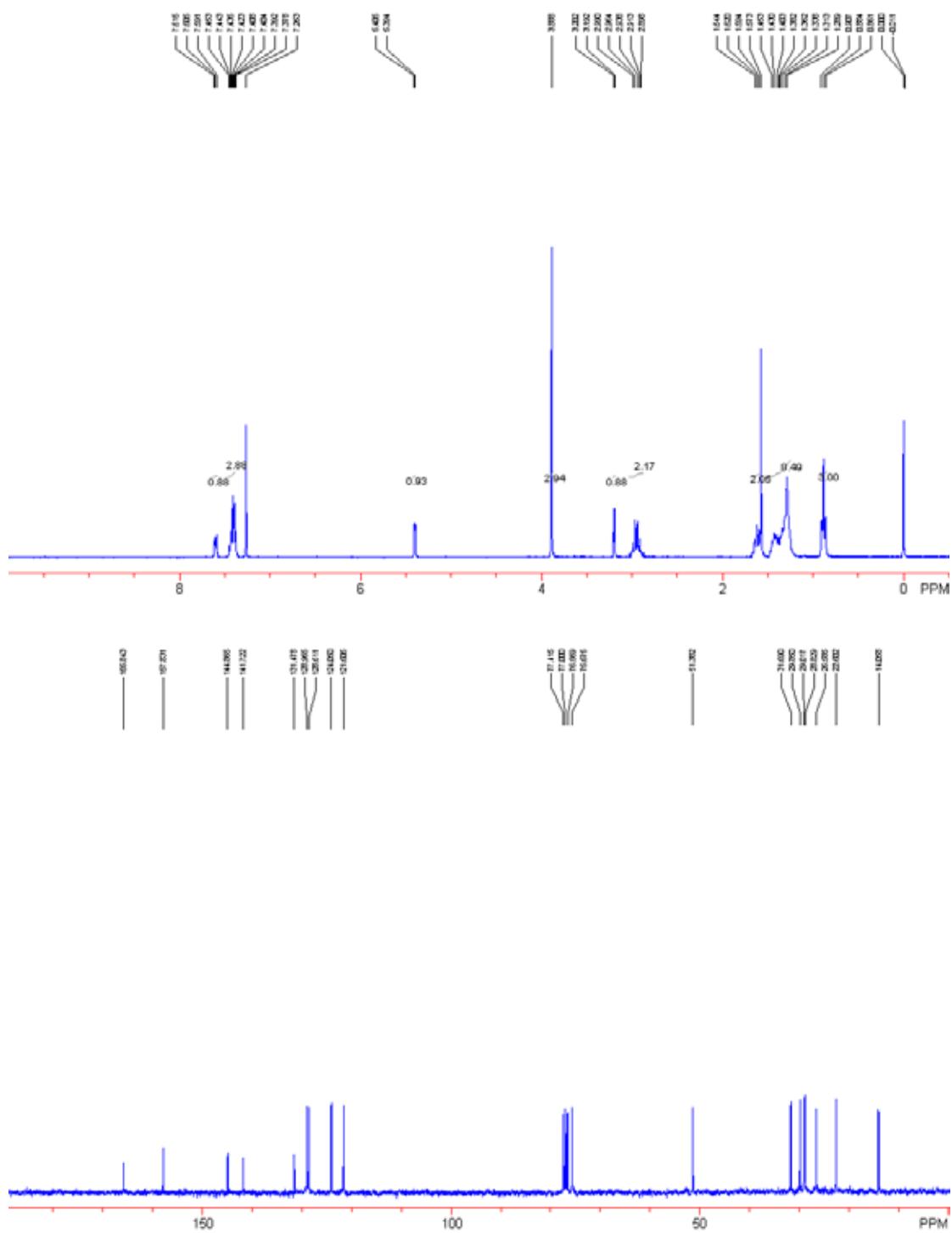
III. Copies of ^1H , ^{13}C NMR spectra of the annulation product

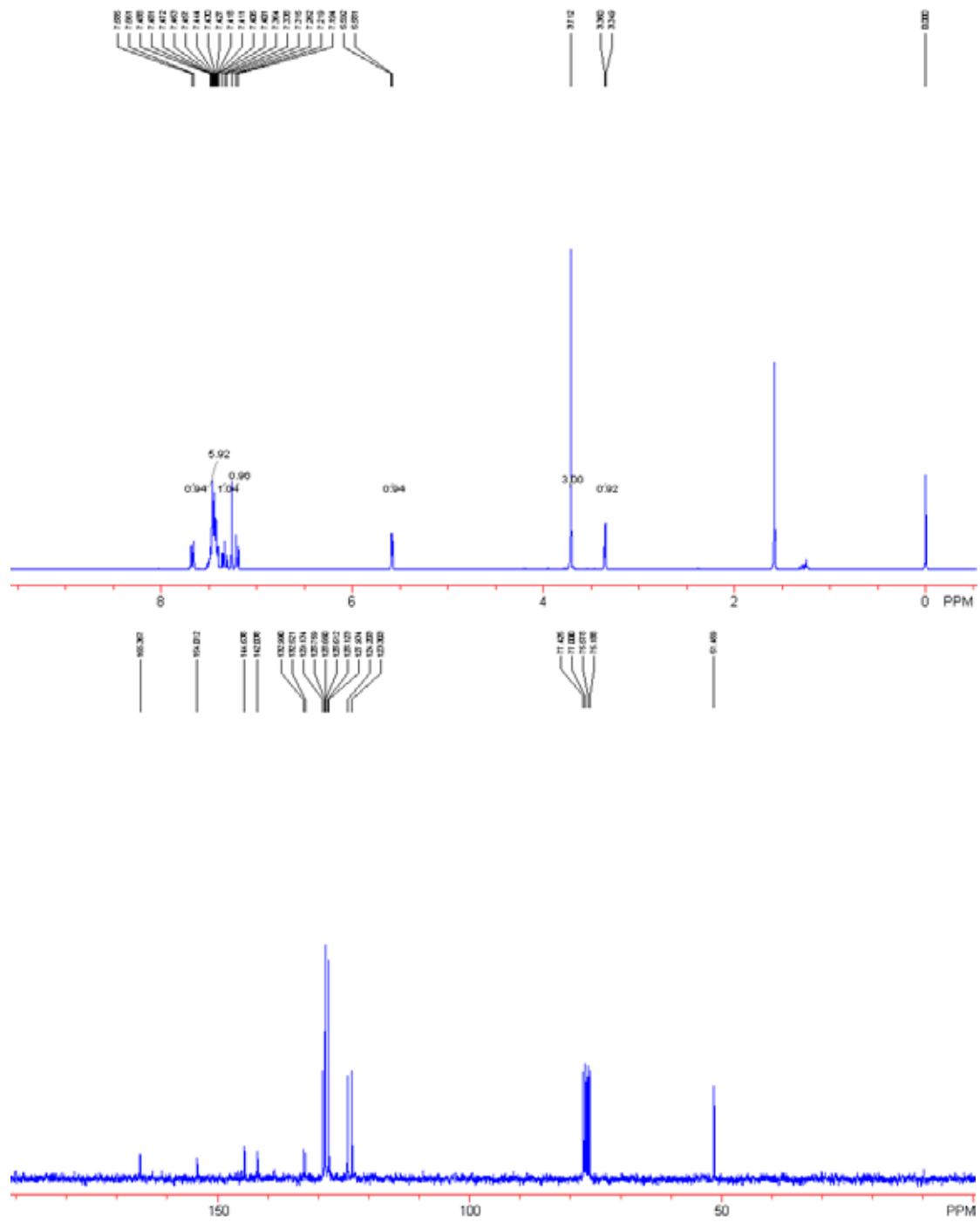
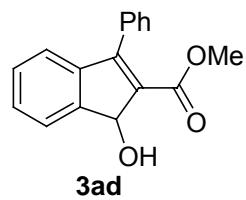


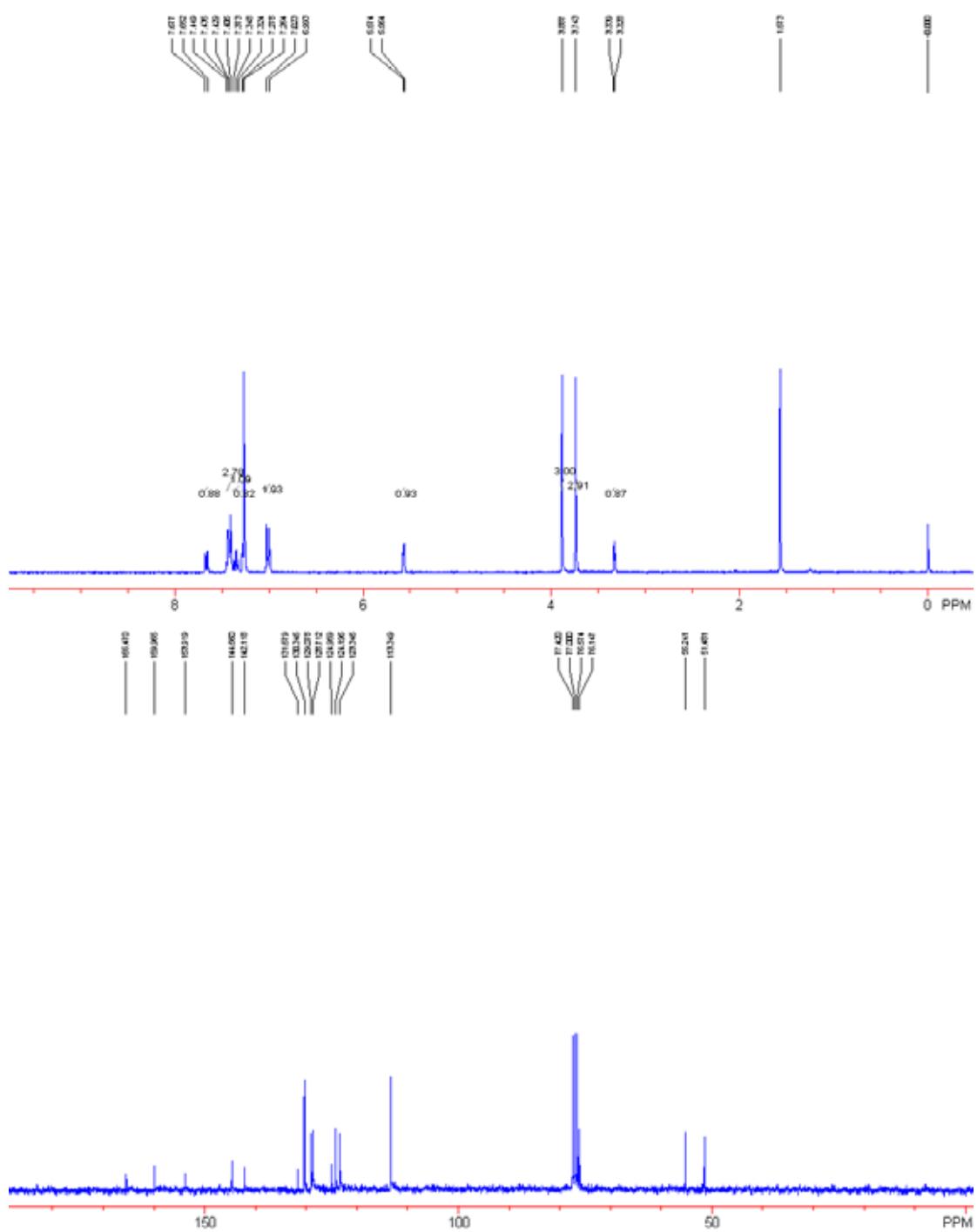
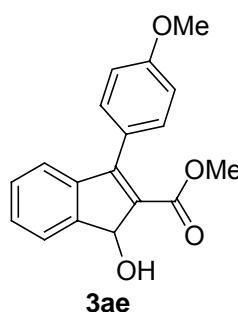


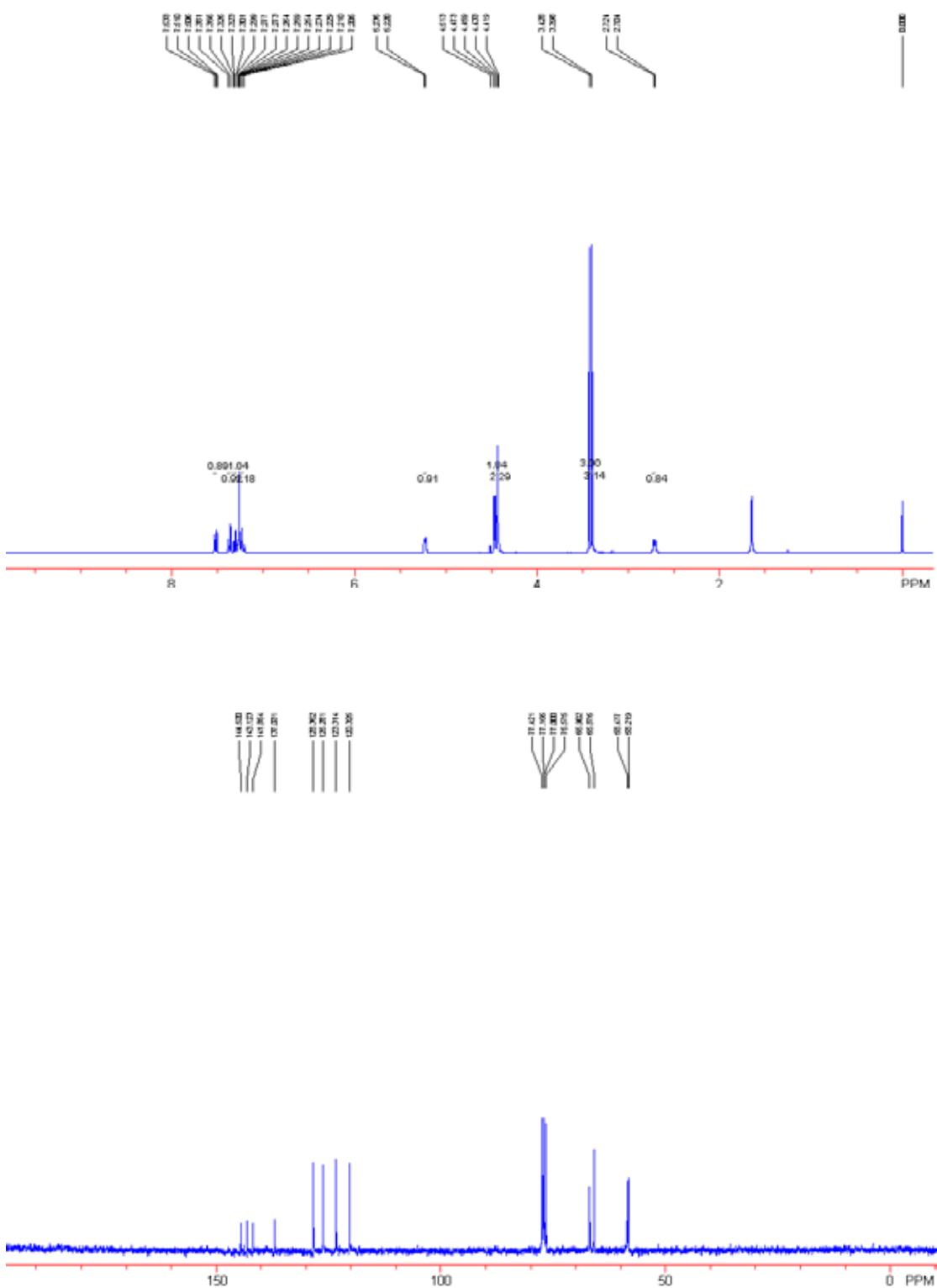
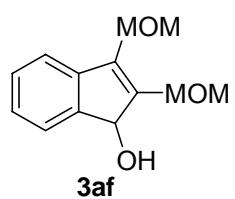


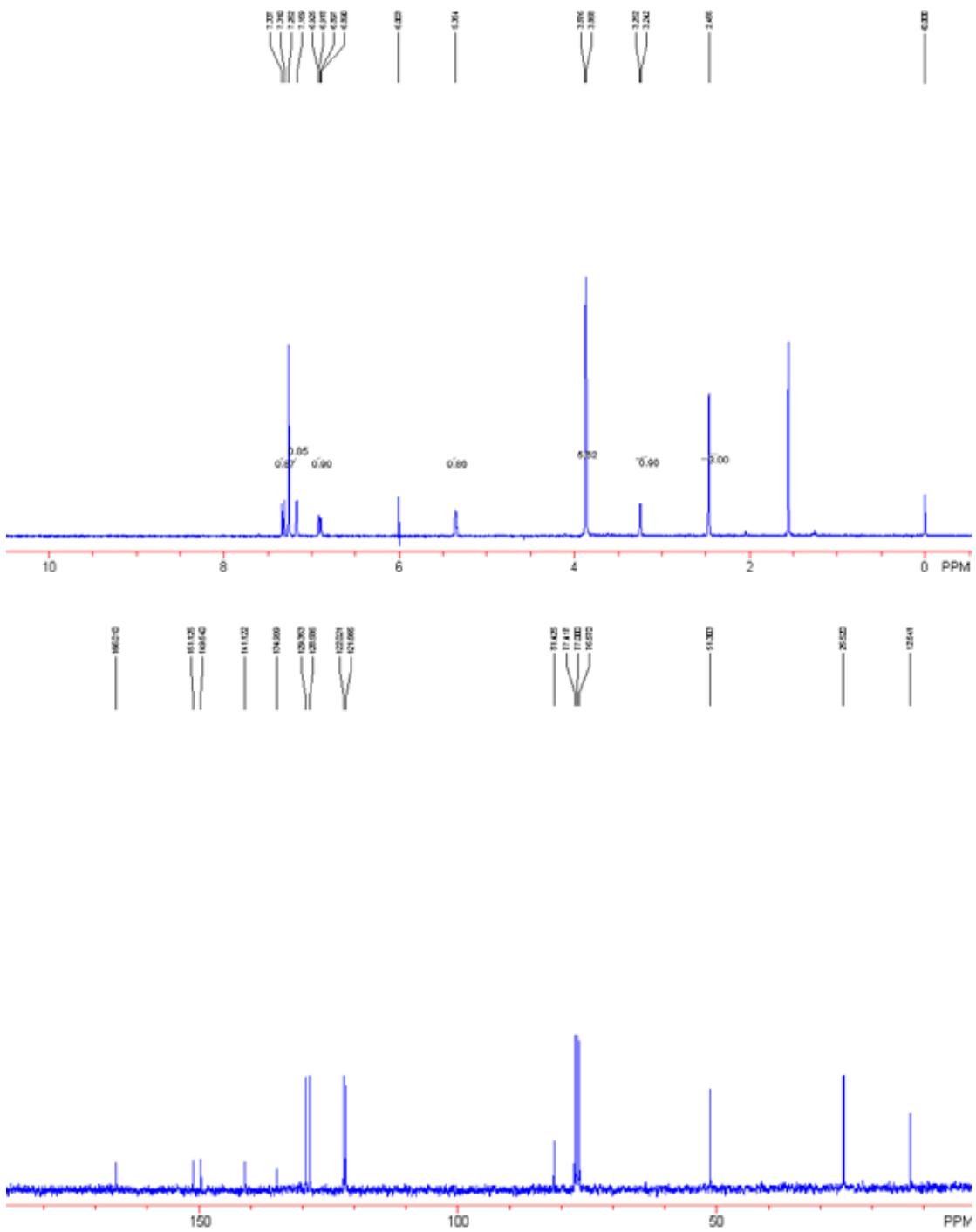
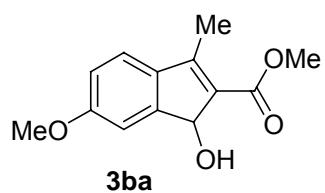
3ac

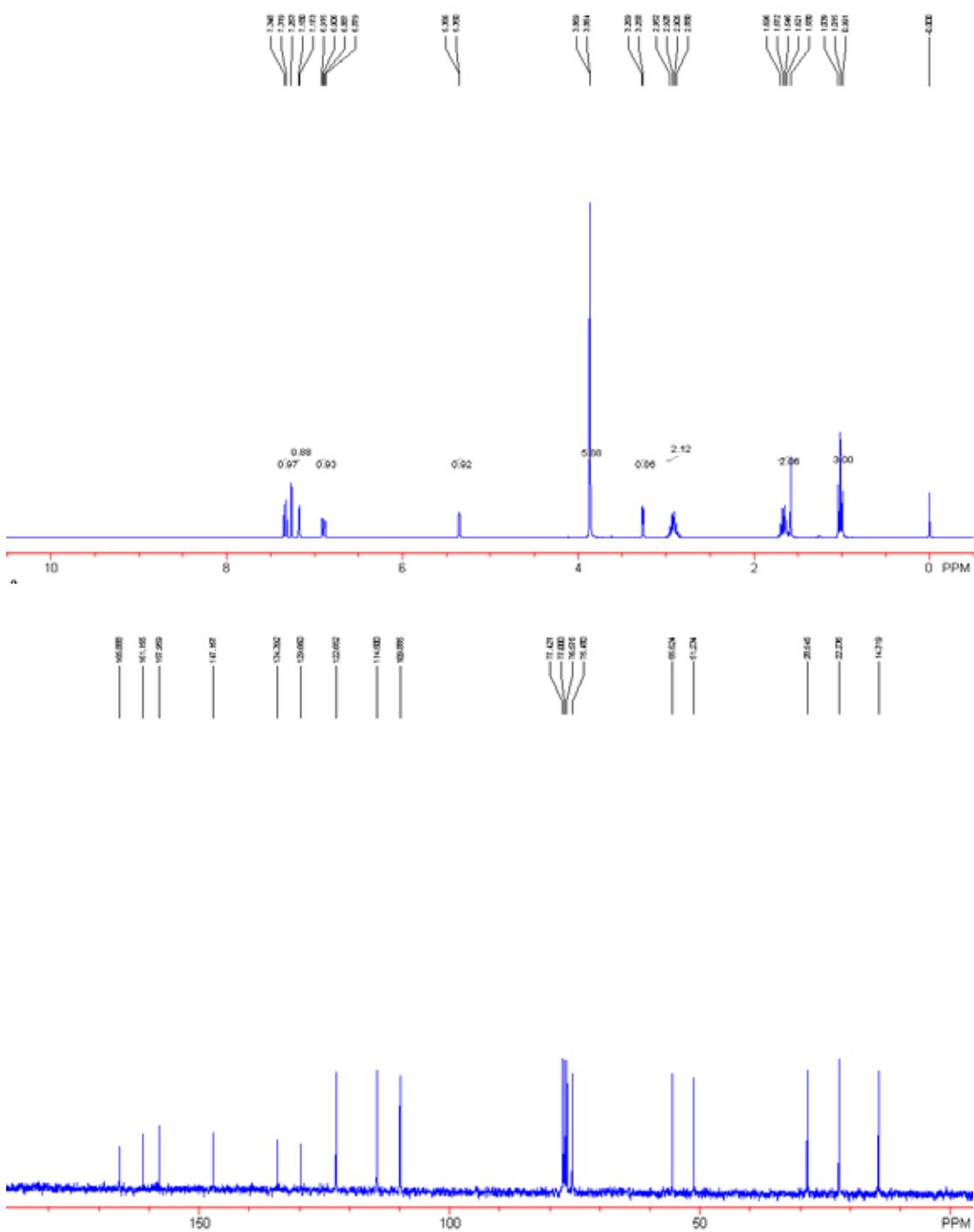
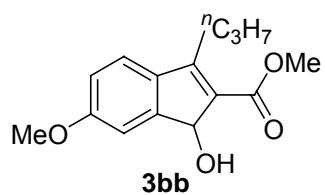


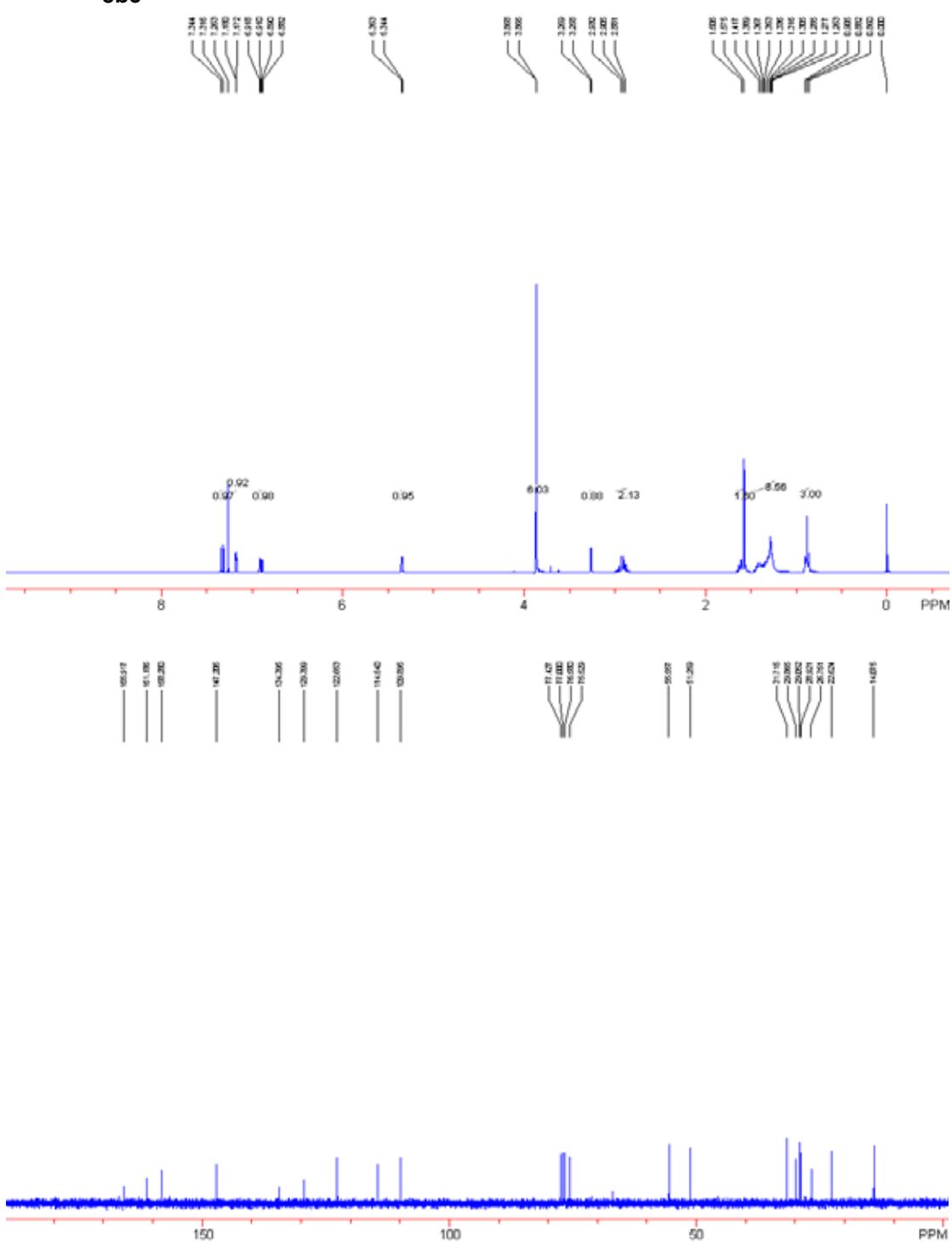
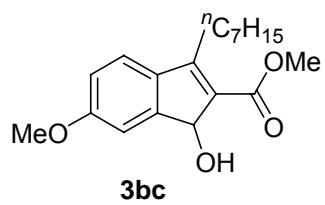


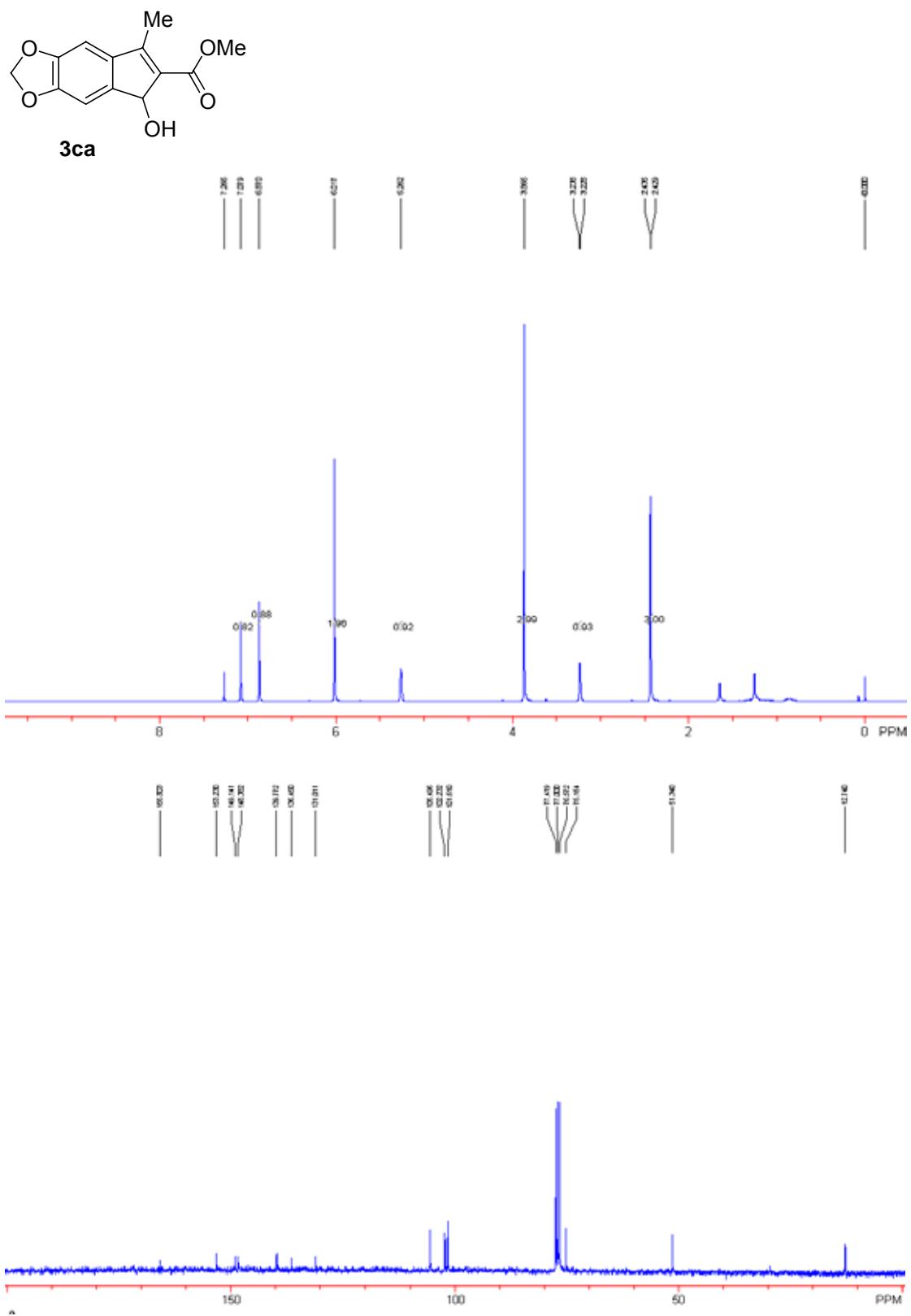


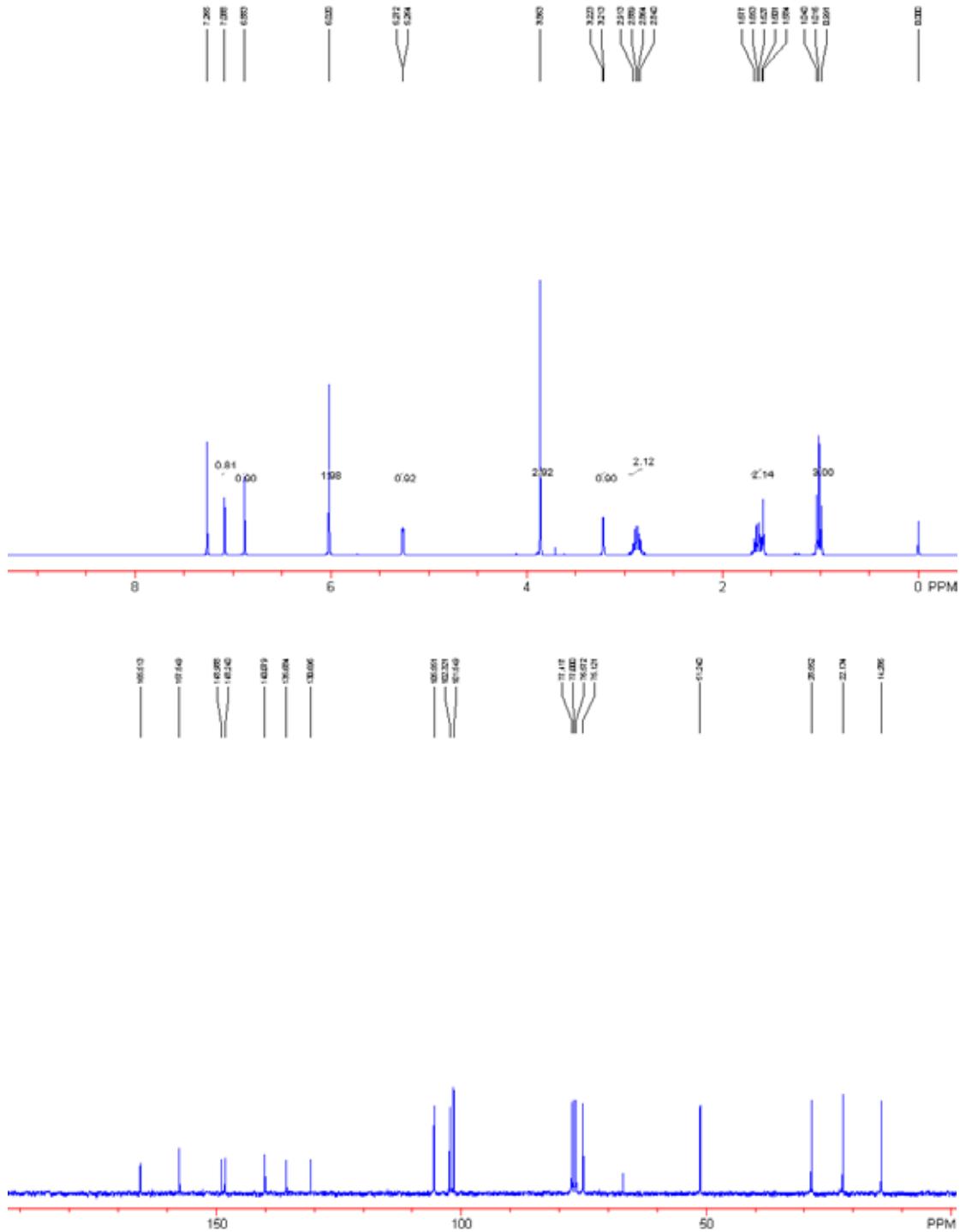
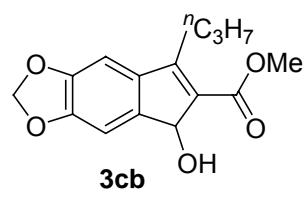


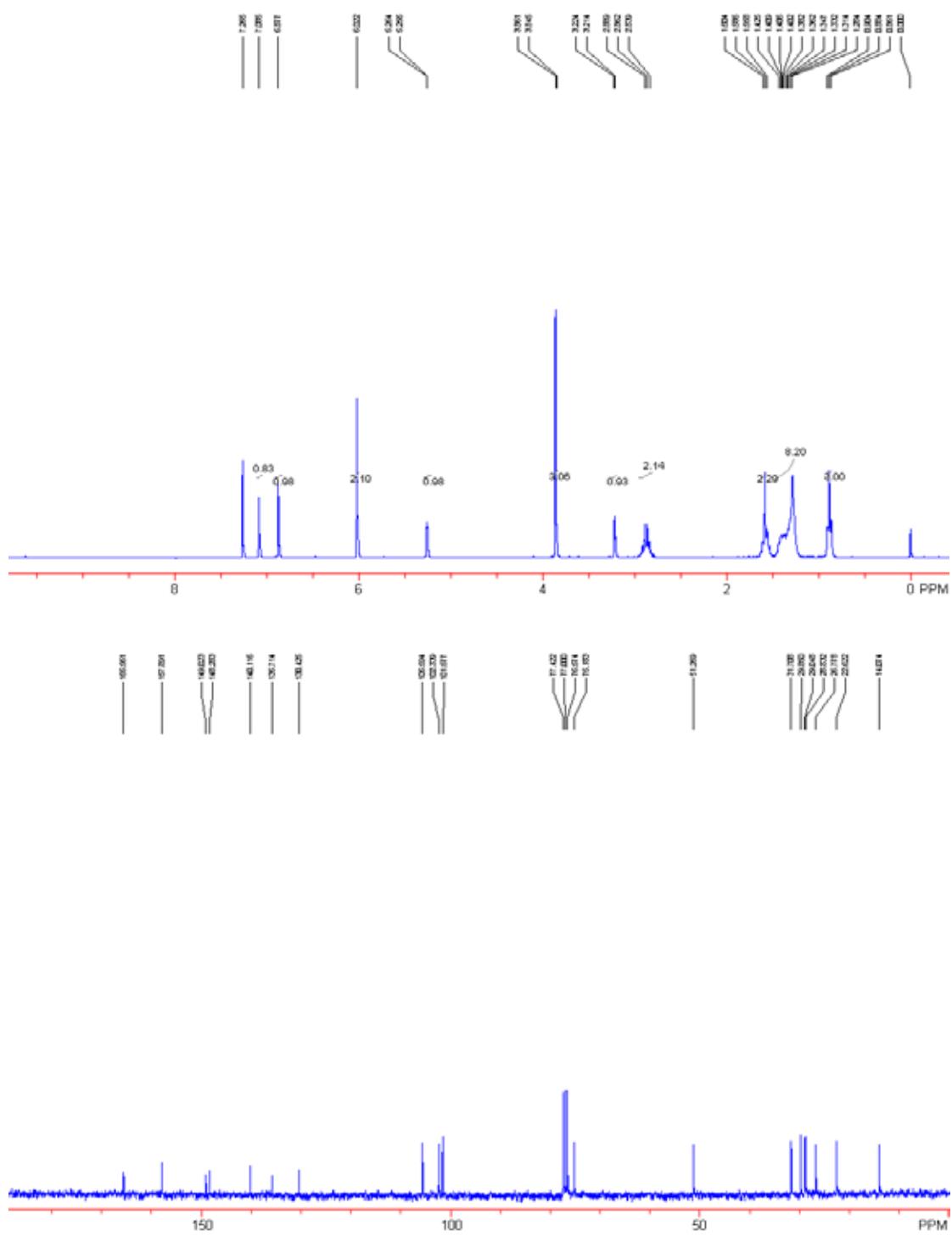
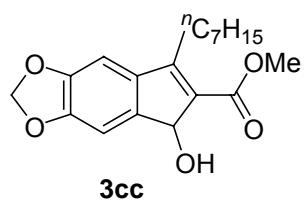


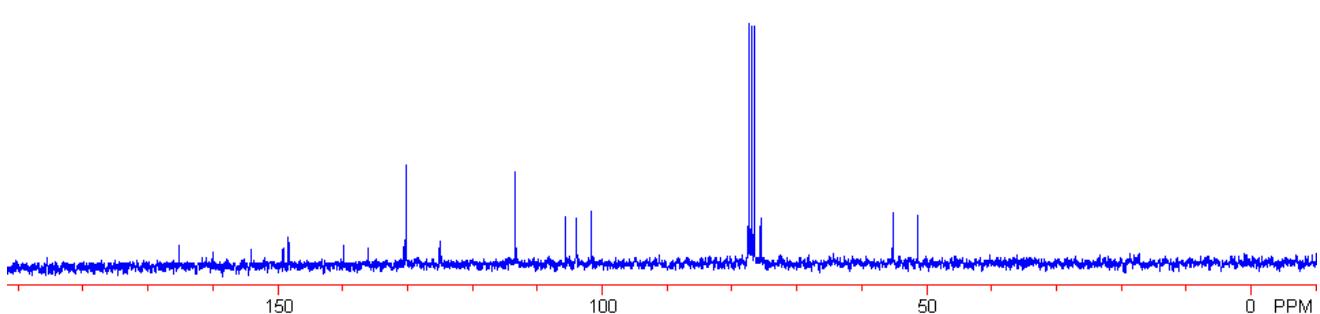
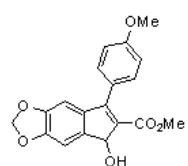
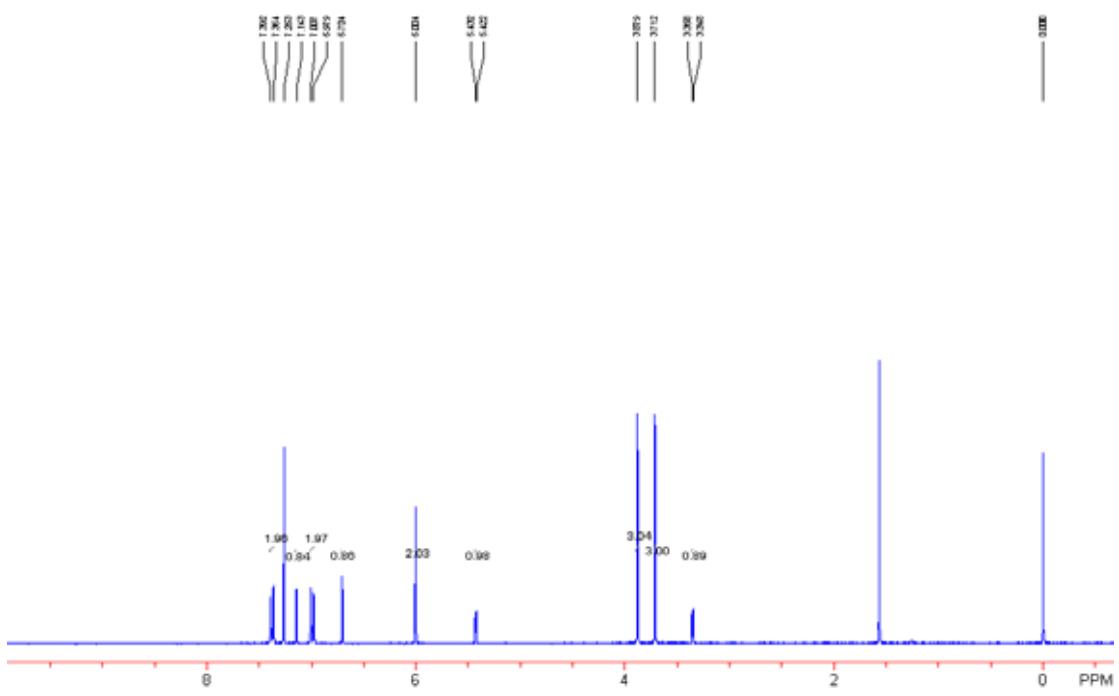
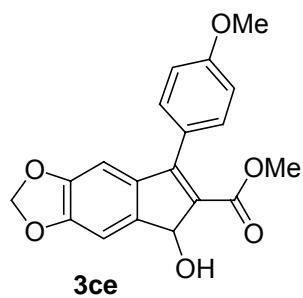


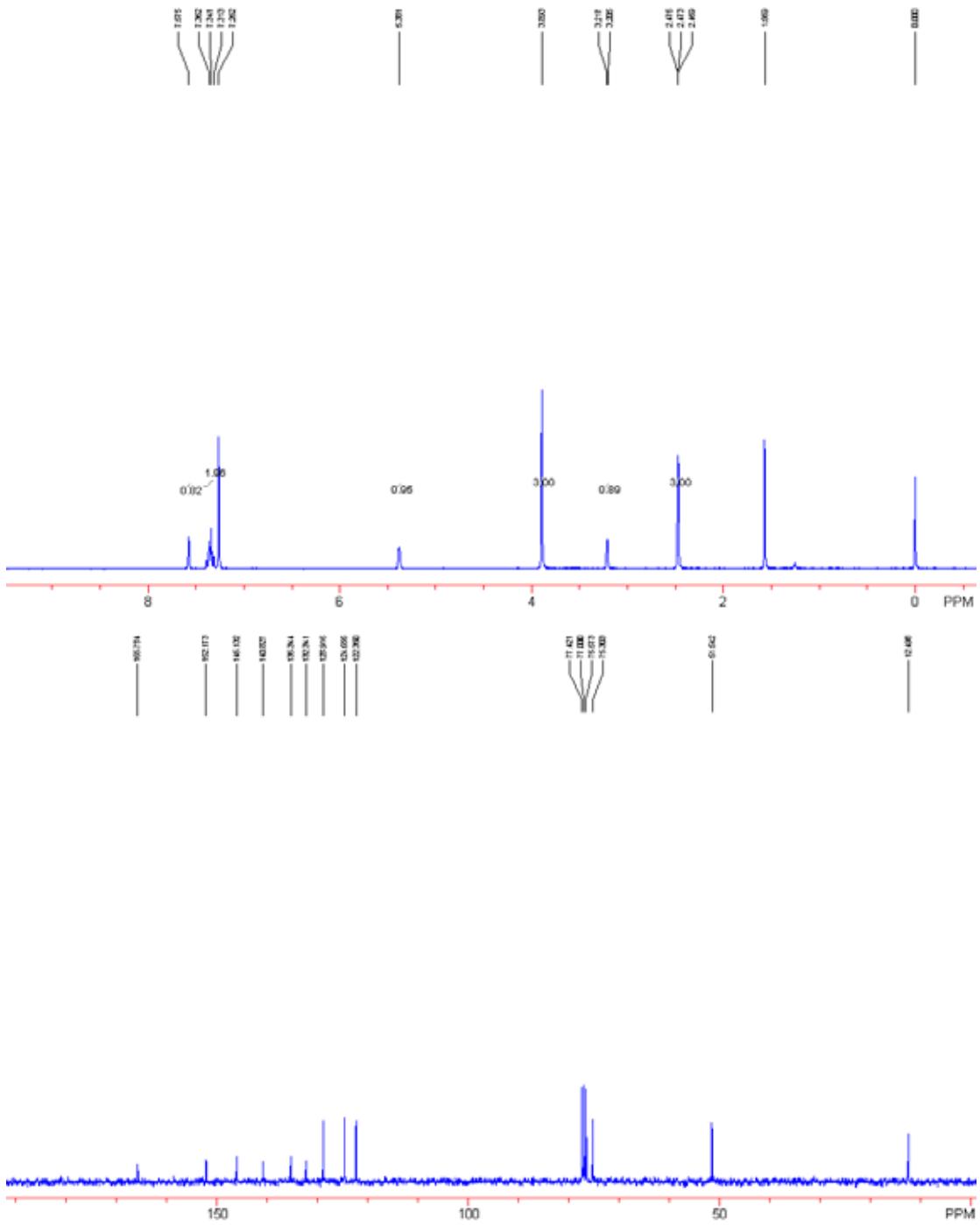
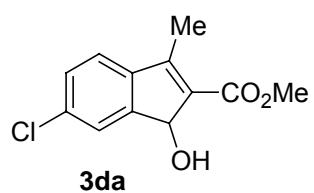


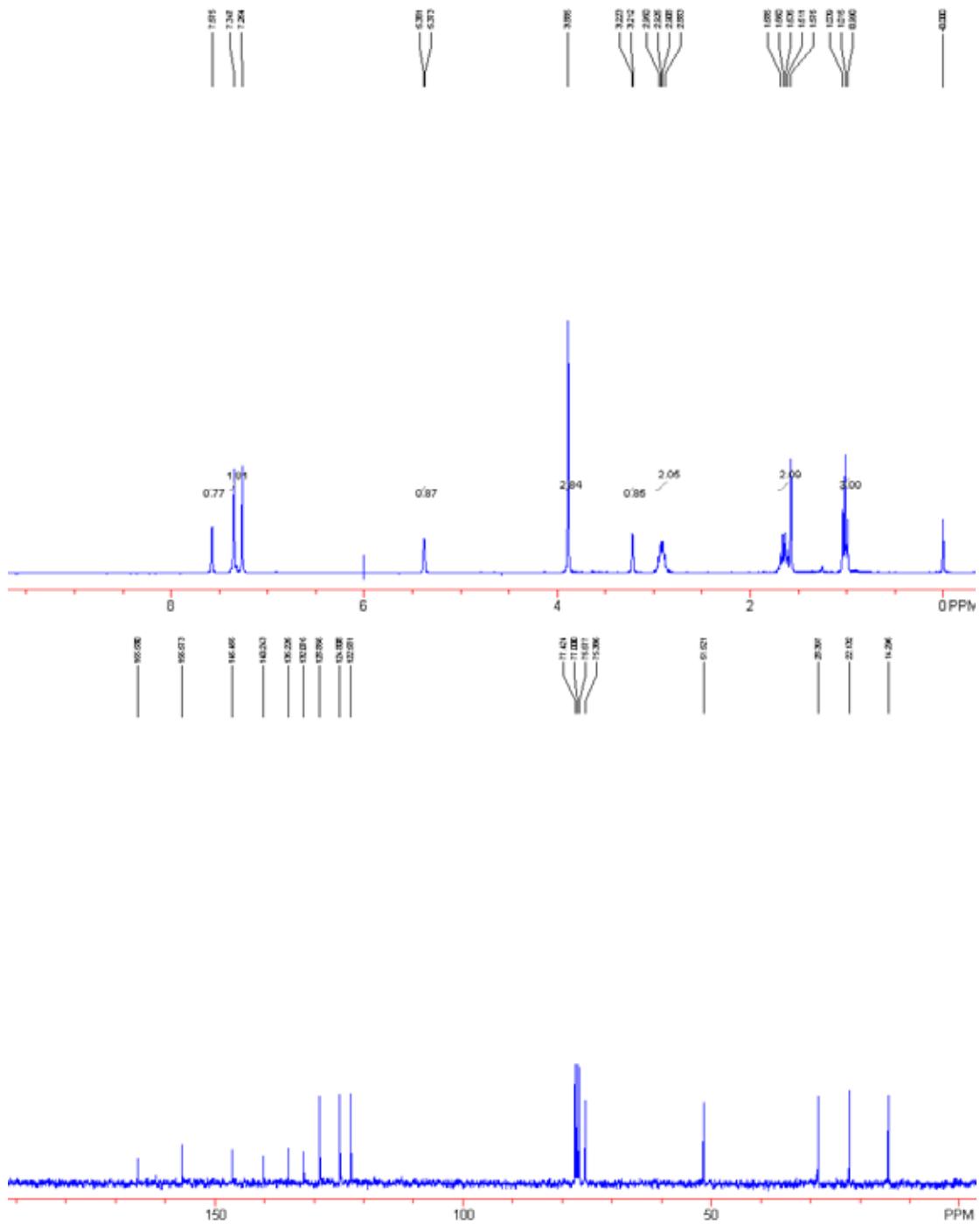
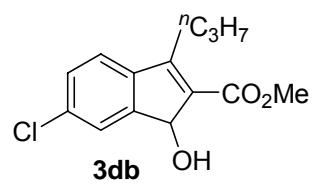


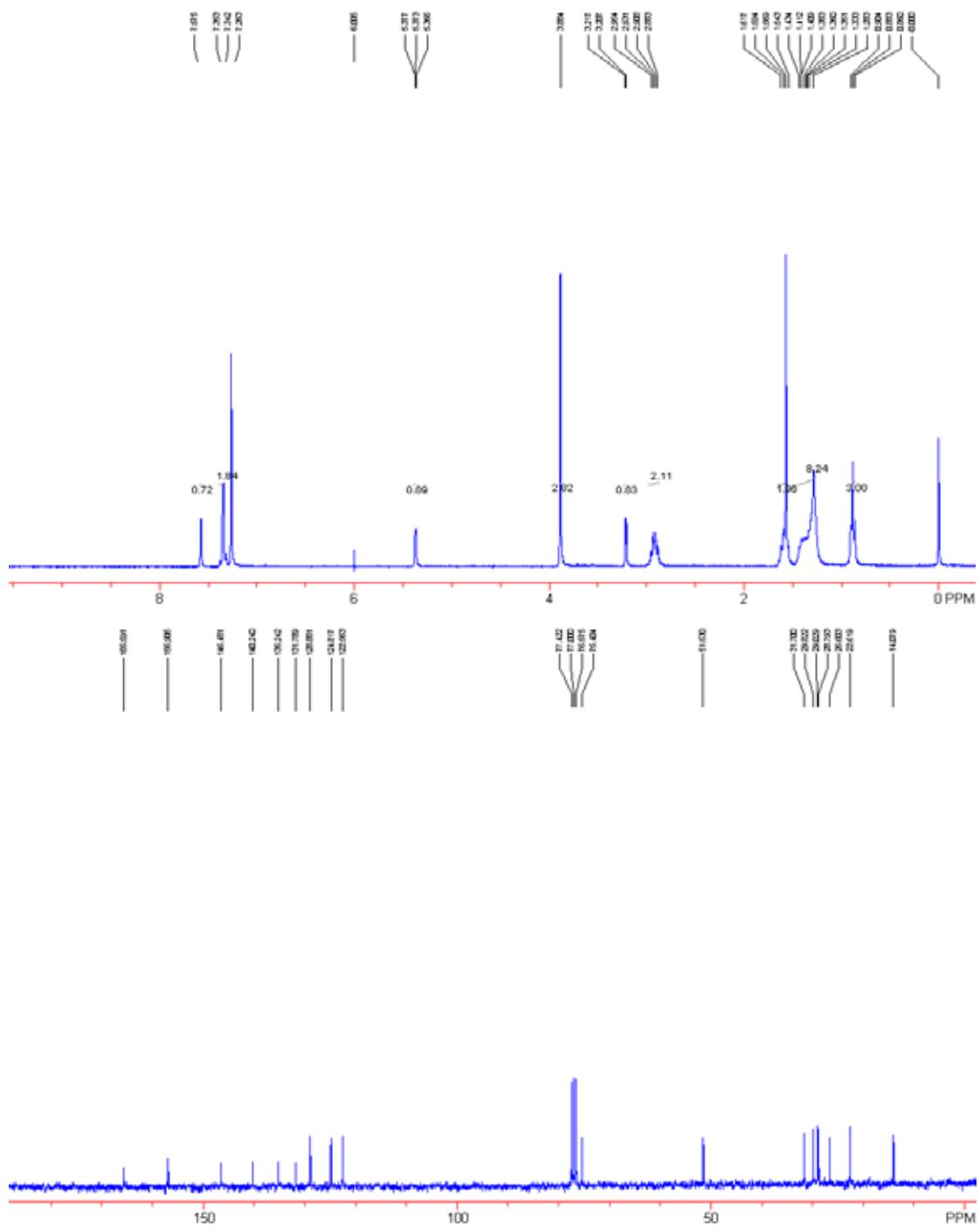
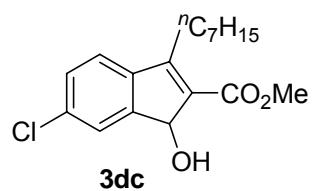


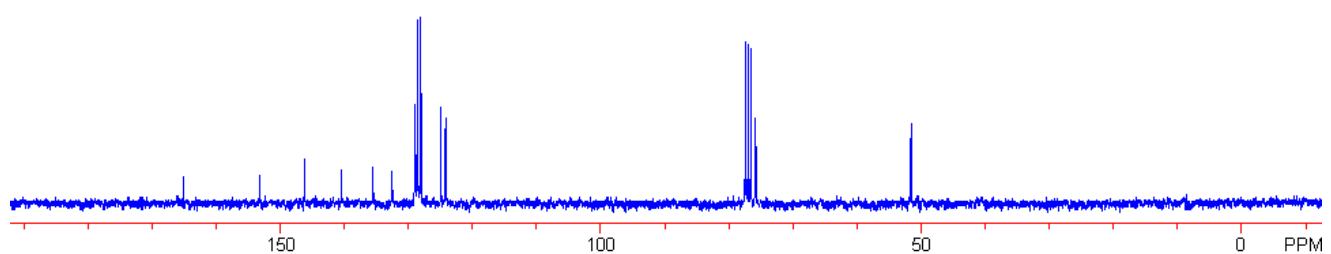
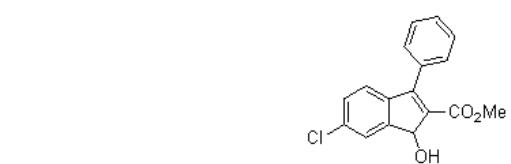
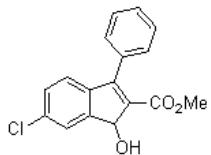
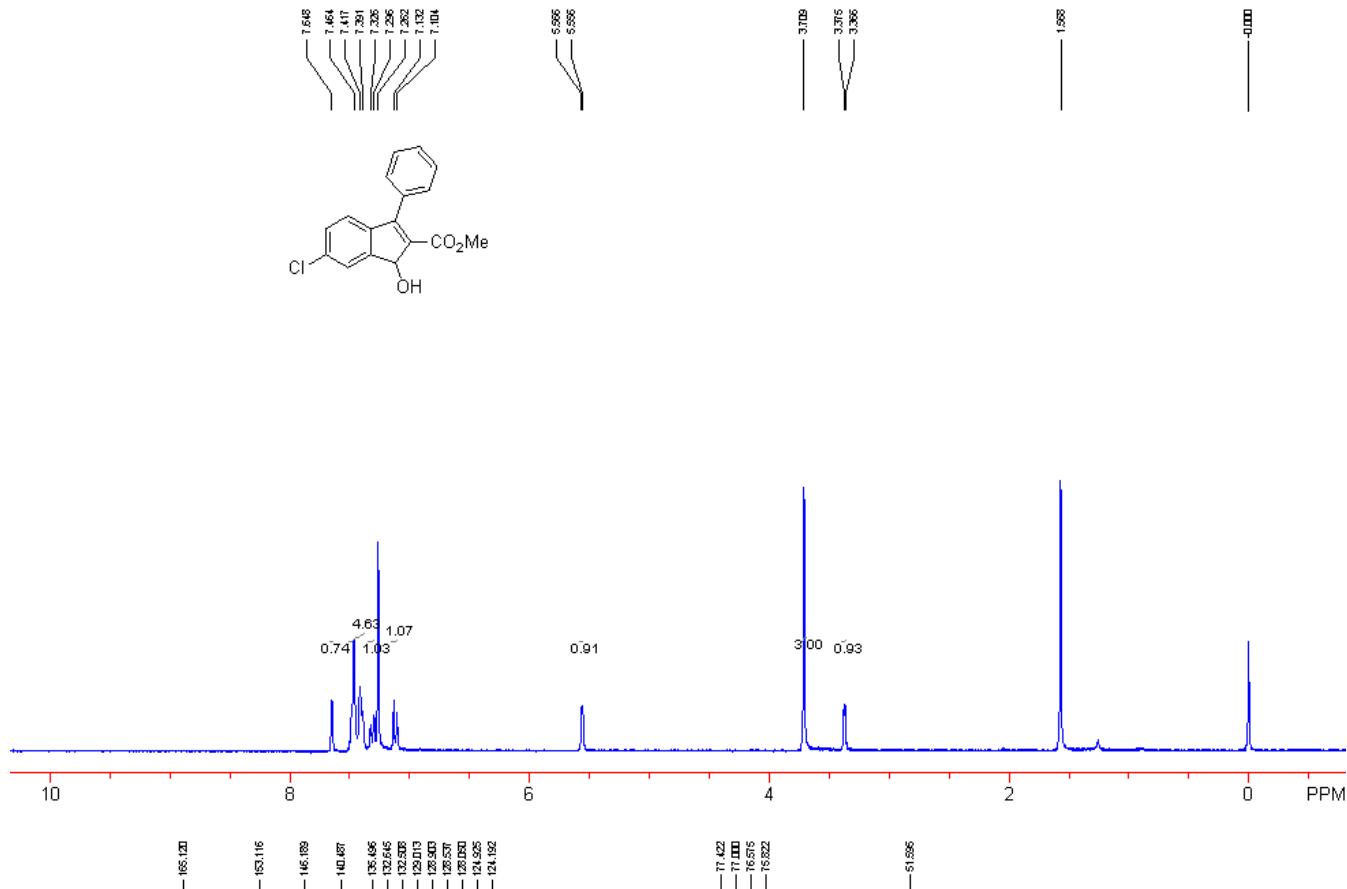
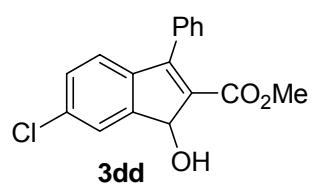


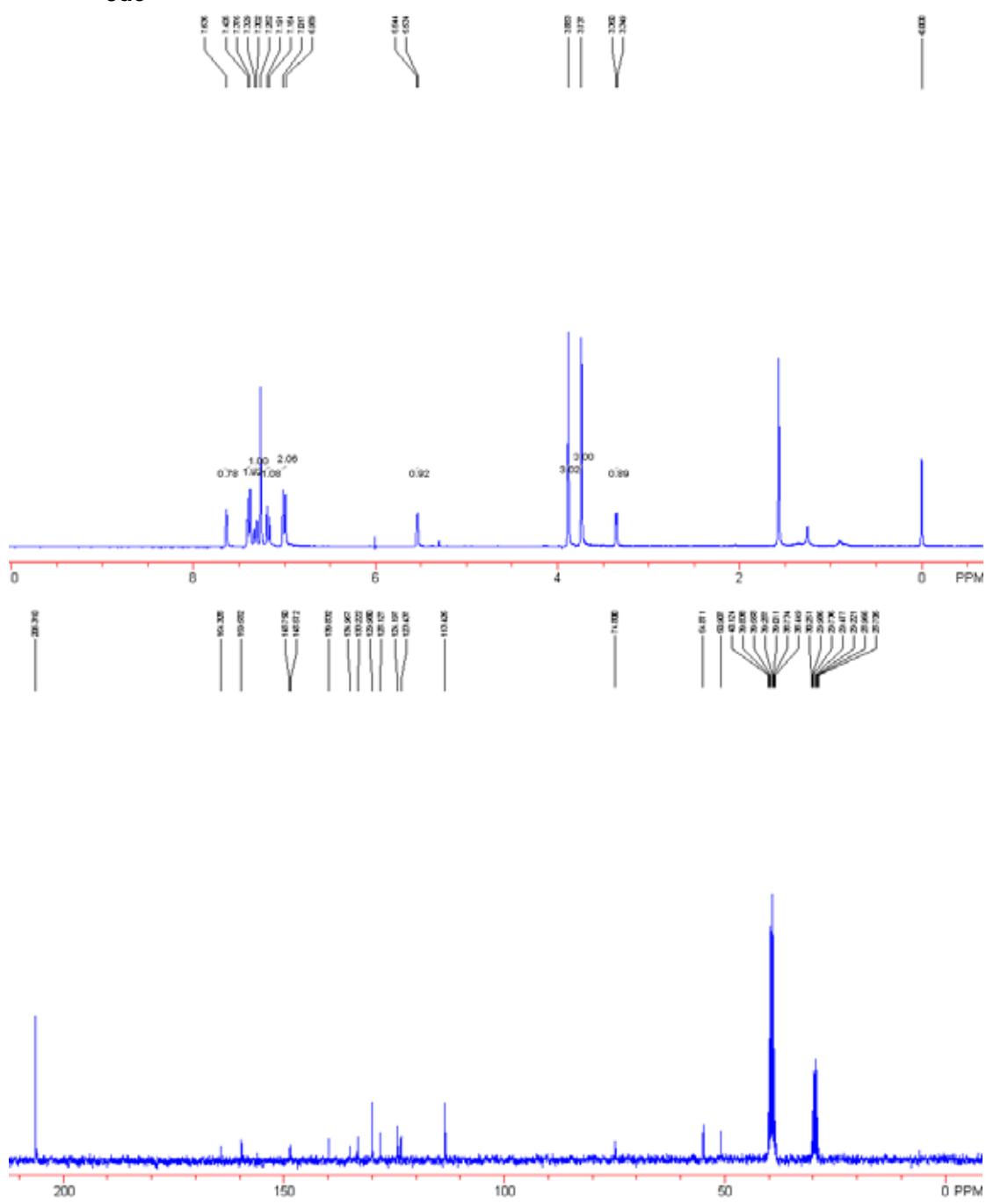
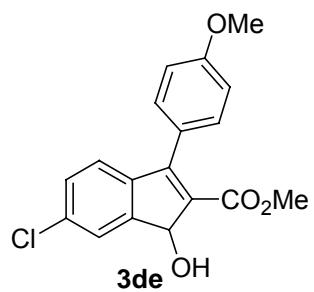












IV HPLC analysis reports

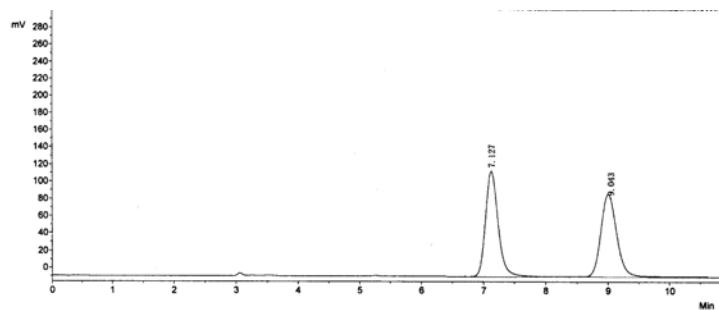
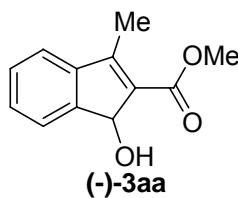


Table 1, entry 1

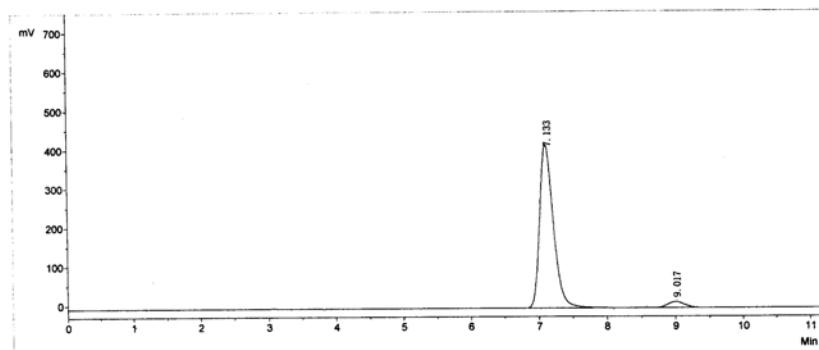
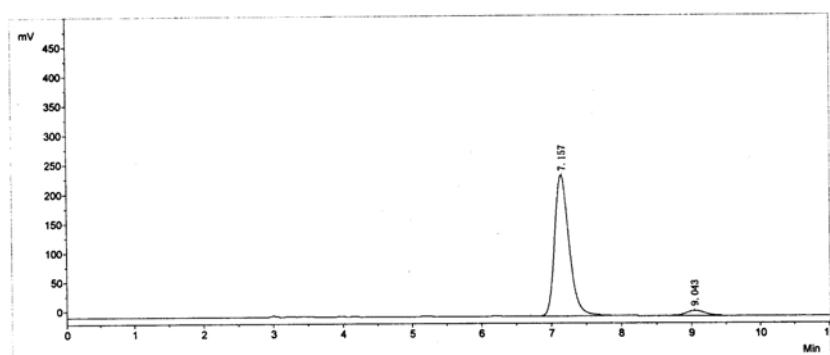
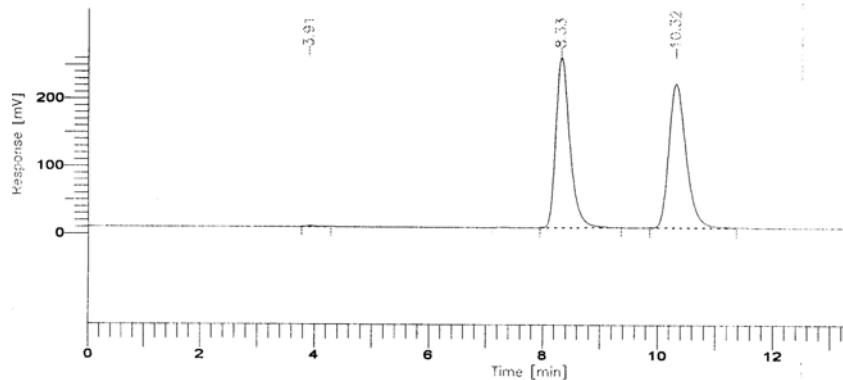
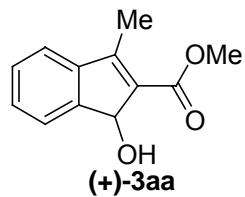


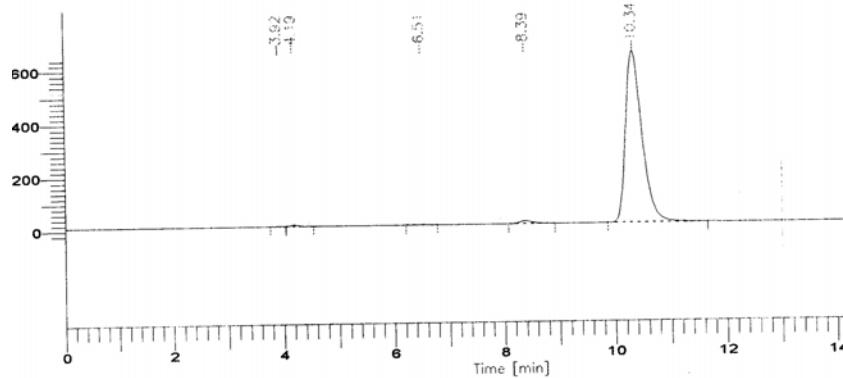
Table 1 entry 4





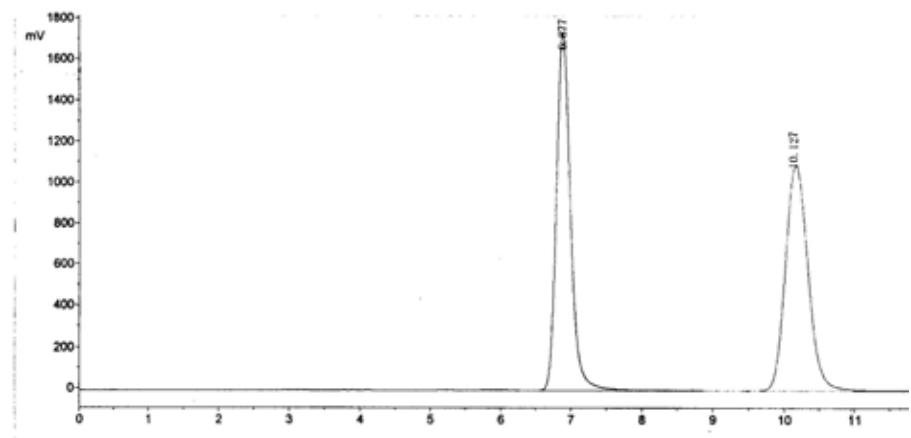
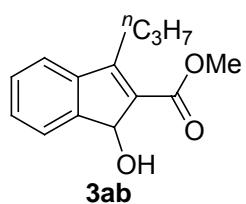
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	Area BL [sec]	Area/Height
1	3.910	12558.50	1059.96	0.14	0.00	BB	11.8481
2	8.329	4292613.00	252686.93	49.14	0.00	BB	16.9879
3	10.320	4431053.50	214110.86	50.72	0.00	BB	20.6951
<hr/>							
8736225.00 467857.76 100.00							0.00

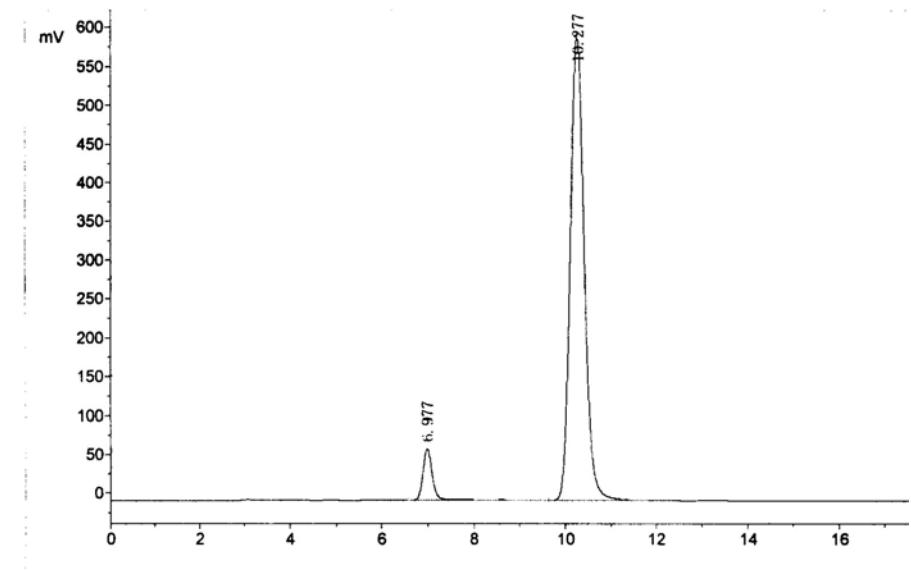


REPORT

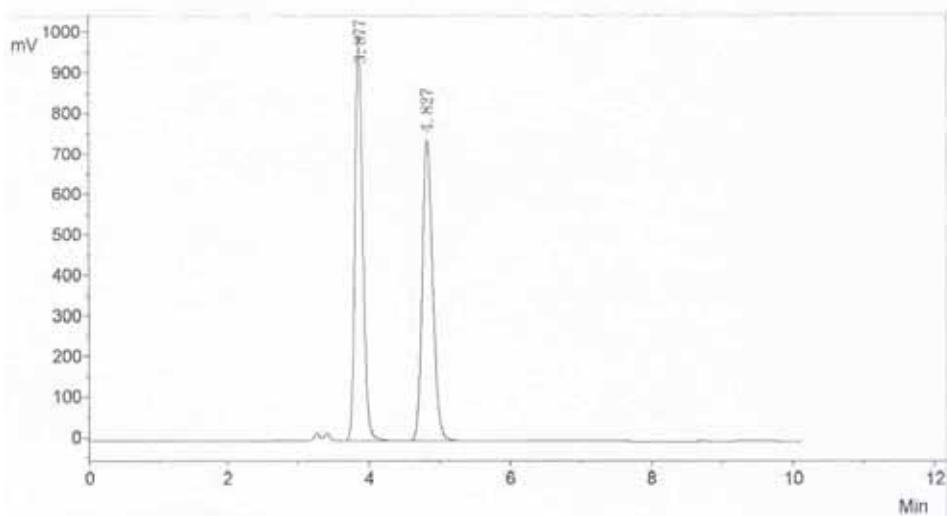
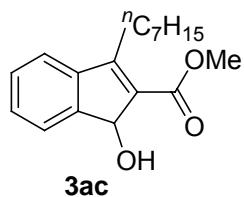
Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	Area BL [sec]	Area/Height
1	3.922	10102.98	1159.85	0.08	0.00	BV	8.7106
2	4.191	54378.52	5625.97	0.40	0.00	VB	9.6656
3	6.510	13750.00	1133.74	0.10	0.00	BB	12.1280
4	8.388	174600.00	10772.33	1.30	0.00	BB	16.2082
5	10.338	13178632.50	645316.77	98.12	0.00	BB	20.4220
<hr/>							
13431464.00 664008.67 100.00							0.00



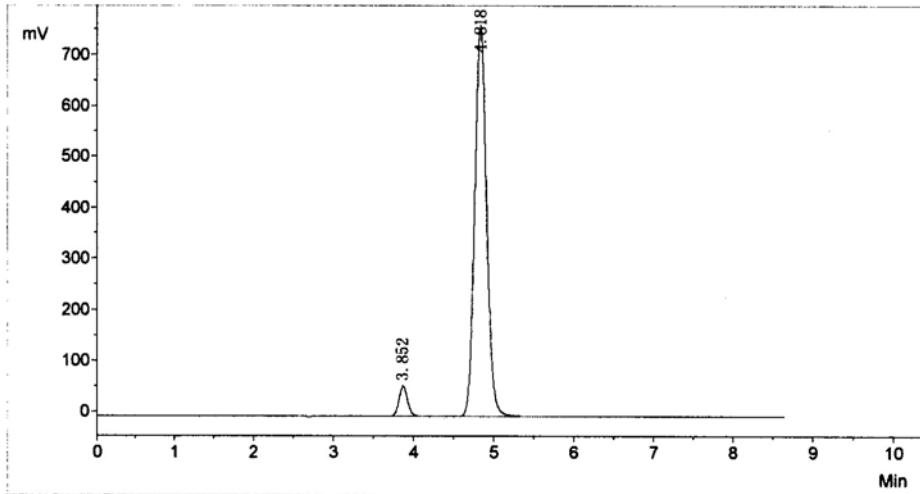
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	6.877	1723150.6	24163775.7	49.9010
2	2	10.127	1053475.9	24259693.8	50.0990
Total			2776626.5	48423469.5	100.0000



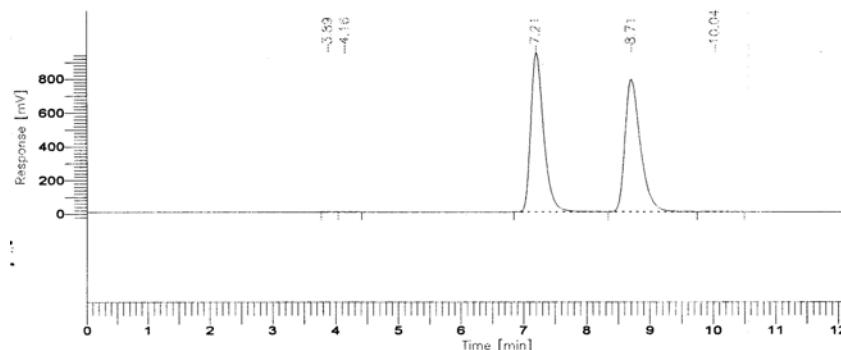
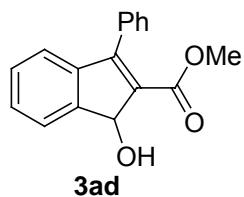
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	6.977	65809.0	975927.5	7.1015
2	2	10.277	594427.6	12766685.3	92.8985
Total			660236.7	13742612.8	100.0000



No.	PeakNo	ID. Name	R. Time	PeakHeight	PeakArea	PerCent
1	1	Unknown	3.877	971038.3	7581163.5	49.8646
2	2	Unknown	4.827	740931.7	7622336.0	50.1354

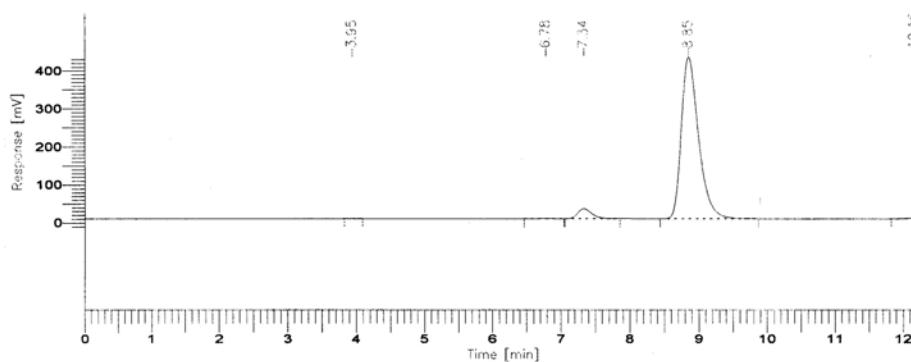


No.	PeakNo	ID. Name	R. Time	PeakHeight	PeakArea	PerCent
1	1	Unknown	3.852	55822.8	443781.3	5.3131
2	2	Unknown	4.818	758842.1	7908785.0	94.6869
Total				814664.9	8352566.3	100.0000



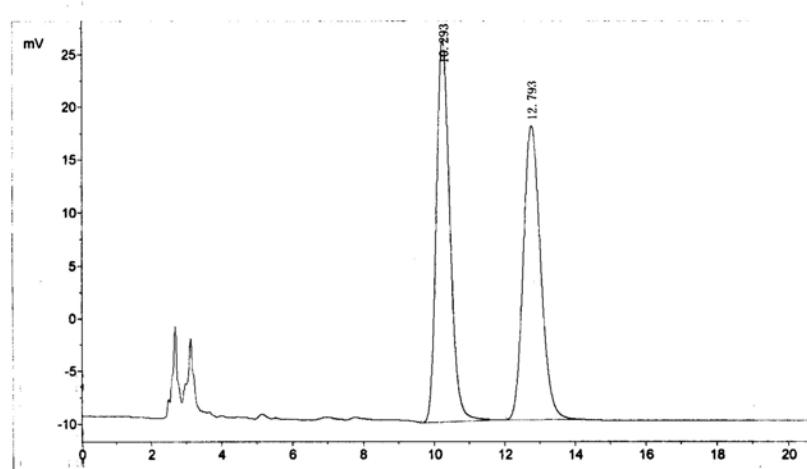
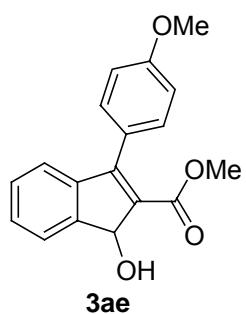
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	Area BL [sec]	Area/Height
1	3.891	7361.82	938.06	0.03	0.00	BV	7.8480
2	4.157	6643.18	539.58	0.02	0.00	VB	12.3117
3	7.207	13424291.50	942058.62	49.95	0.00	BB	14.2500
4	8.708	13381412.07	784923.64	49.79	0.00	BV	17.0480
5	10.036	55379.93	2804.78	0.21	0.00	VB	19.7449
26875088.50			1.73e+06	100.00	0.00		

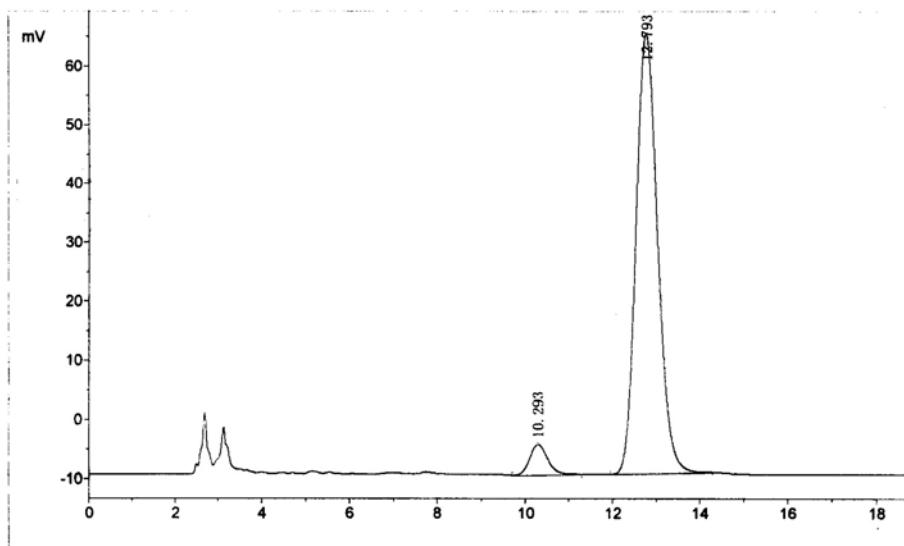


REPORT

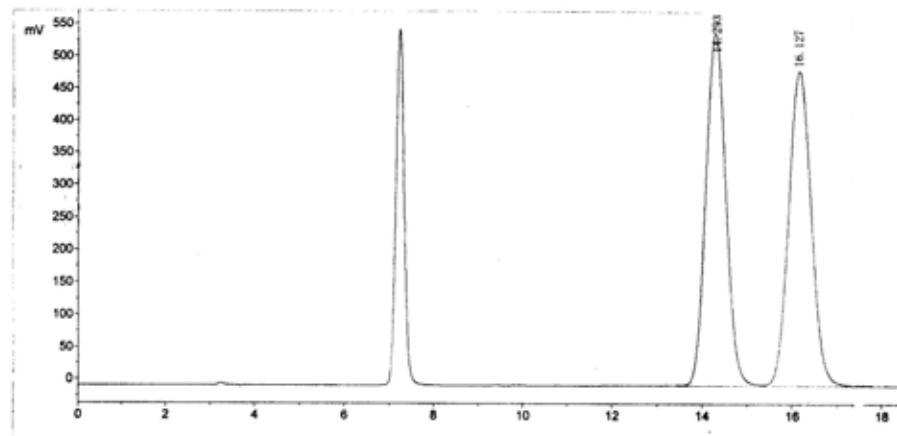
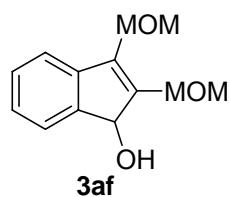
Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	Area BL [sec]	Area/Height
1	3.950	3230.00	455.00	0.04	0.00	BB	7.0989
2	6.783	12996.00	914.69	0.17	0.00	BB	14.2082
3	7.336	371504.00	26260.37	4.77	0.00	BB	14.1469
4	8.850	7385630.00	425973.81	94.76	0.00	BB	17.3382
5	12.157	20611.00	1297.12	0.26	0.00	BB	15.8898
7793971.00			454900.98	100.00	0.00		



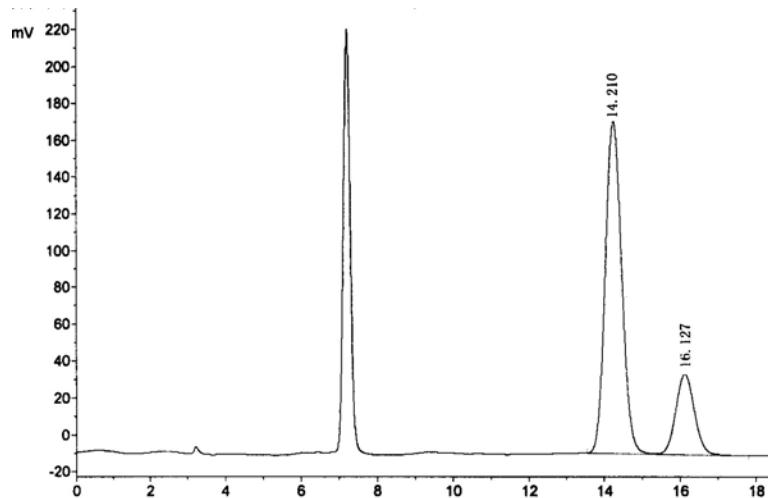
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	10.293	35244.7	963423.8	50.3045
2	2	12.793	27721.5	951761.1	49.6955
Total			62966.2	1915184.9	100.0000



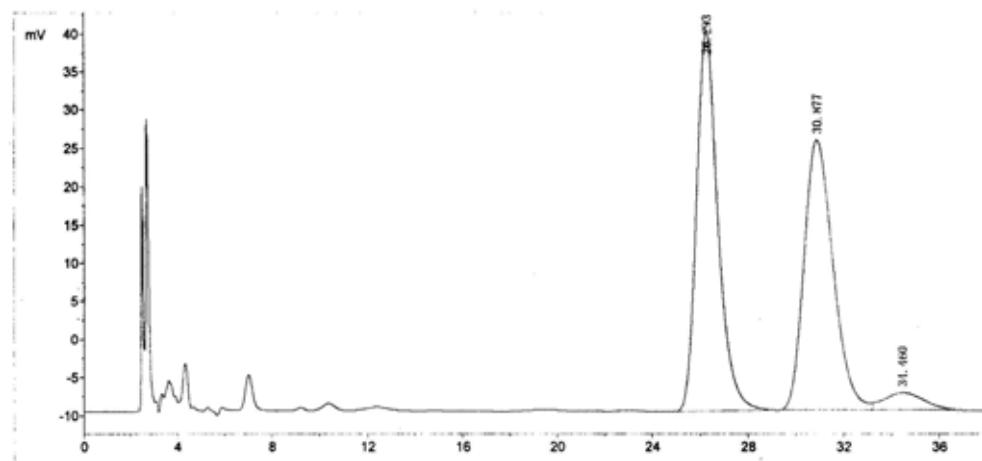
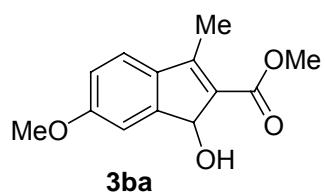
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	10.293	5197.2	145299.8	5.3697
2	2	12.793	74236.4	2560602.9	94.6303
Total			79433.6	2705902.7	100.0000



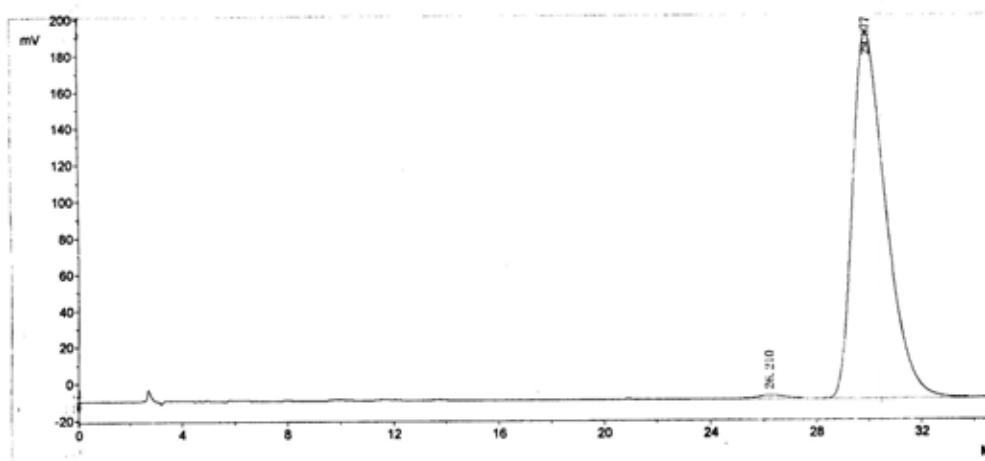
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	14.293	544616.0	16899499.2	49.8357
2	2	16.127	486139.4	17010926.1	50.1643
Total			1030755.4	33910425.3	100.0000



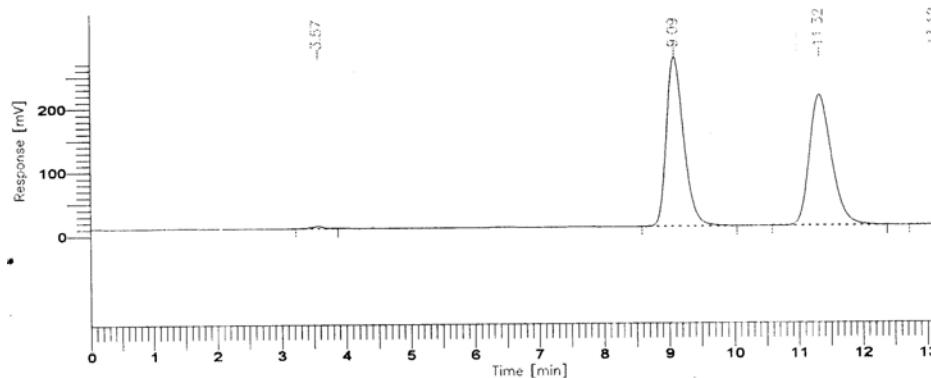
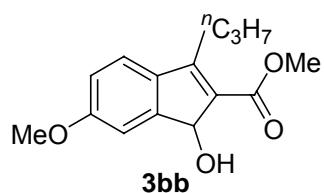
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	14.210	178420.5	5411654.8	78.6796
2	2	16.127	43425.8	1466435.0	21.3204
Total			221846.3	6878089.8	100.0000



No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	26.293	49568.1	3084854.1	48.8157
2	2	30.877	35272.7	2977564.8	47.1179
3	3	34.460	2201.7	256972.4	4.0664
Total			87042.6	6319391.3	100.0000

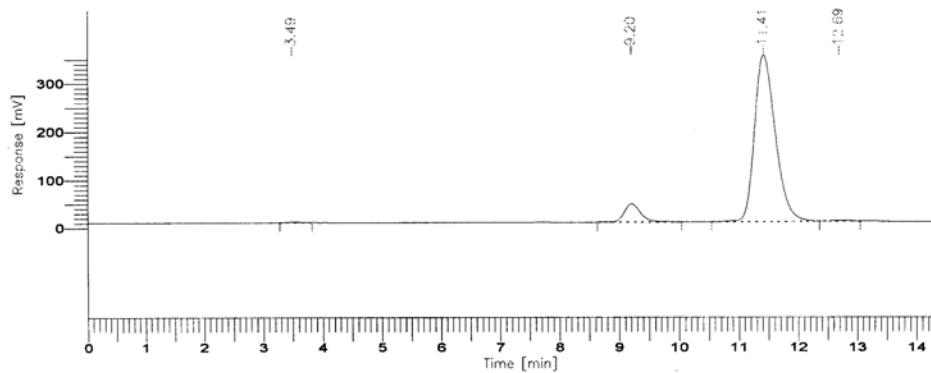


No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	26.210	1770.9	122698.7	0.6967
2	2	29.877	200328.5	17489255.2	99.3033
Total			202099.4	17611953.9	100.0000



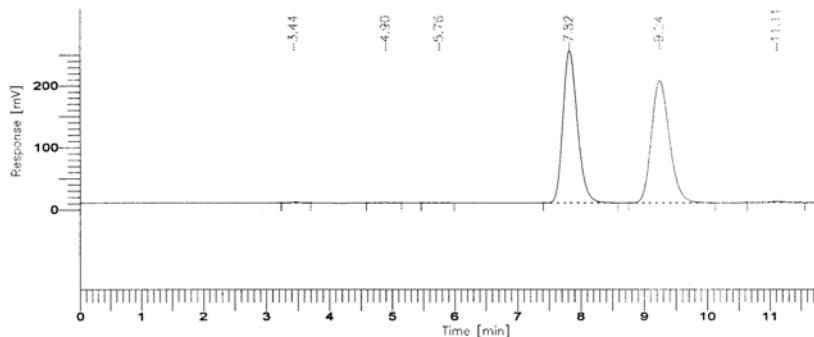
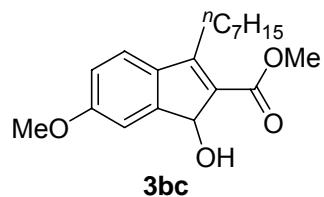
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. [%]	Area BL [sec]	Area/Height
1	3.574	37976.00	3426.21	0.38	0.00	BB	11.0840
2	9.089	4894895.50	265796.48	49.58	0.00	BB	18.4160
3	11.324	4917384.50	204745.97	49.81	0.00	BB	24.0170
4	13.117	21588.00	905.12	0.22	0.00	BB	23.8509



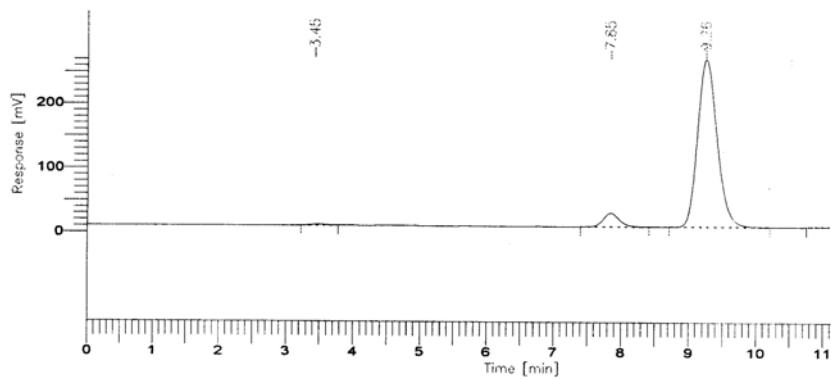
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. [%]	Area BL [sec]	Area/Height
1	3.487	17827.50	1694.03	0.19	0.00	BB	10.5237
2	9.202	716497.00	38104.70	7.79	0.00	BB	18.8034
3	11.412	8446964.51	346200.55	91.79	0.00	BV	24.3991
4	12.685	21331.49	976.53	0.23	0.00	VB	21.8442



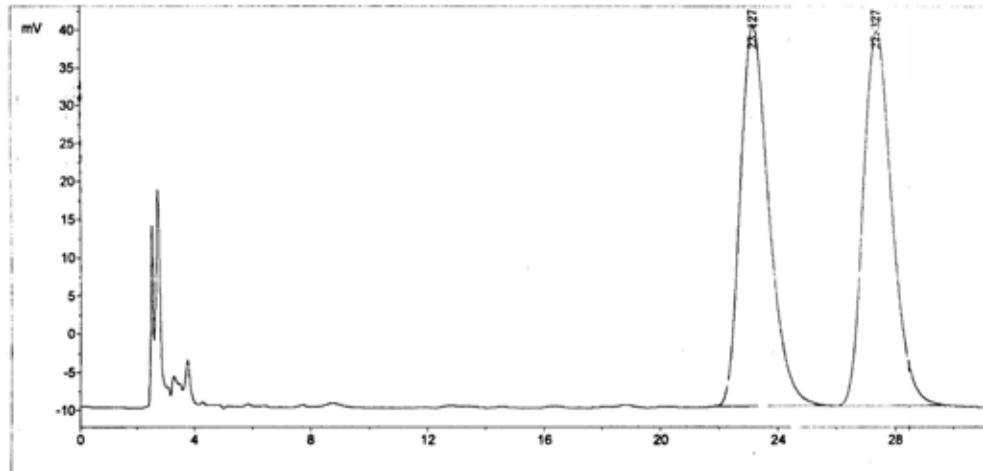
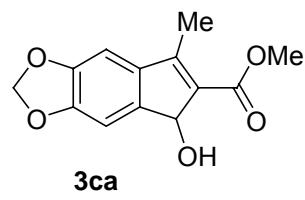
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	Area BL [sec]	Area/Height [sec]
1	3.442	12066.00	1533.16	0.15	0.00	BB	7.8700
2	4.904	7325.00	658.76	0.09	0.00	BB	11.1194
3	5.759	7007.00	537.48	0.09	0.00	BB	13.0368
4	7.822	3897668.50	246237.29	49.40	0.00	BB	15.8289
5	9.241	3902497.50	197452.00	49.46	0.00	BB	19.7643
6	11.110	41981.60	1930.47	0.53	0.00	BV	21.7468
7	11.854	21325.40	1122.77	0.27	0.00	VB	18.9936

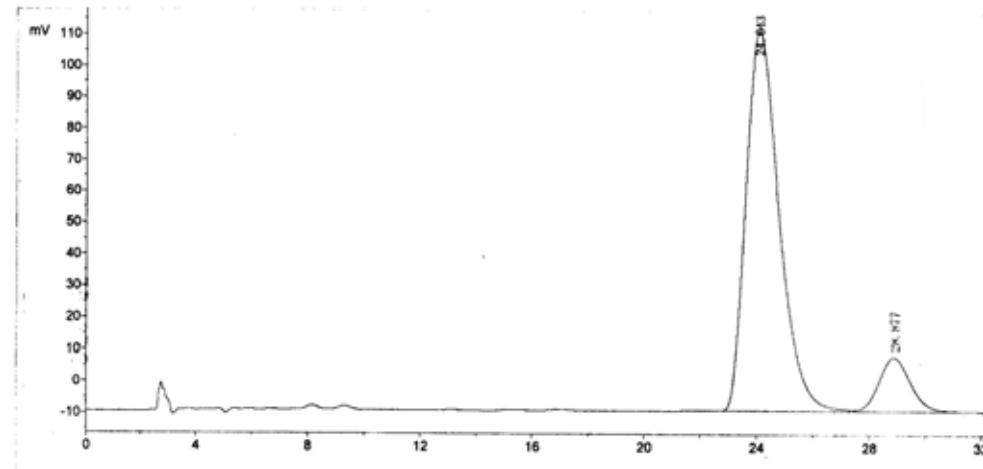


REPORT

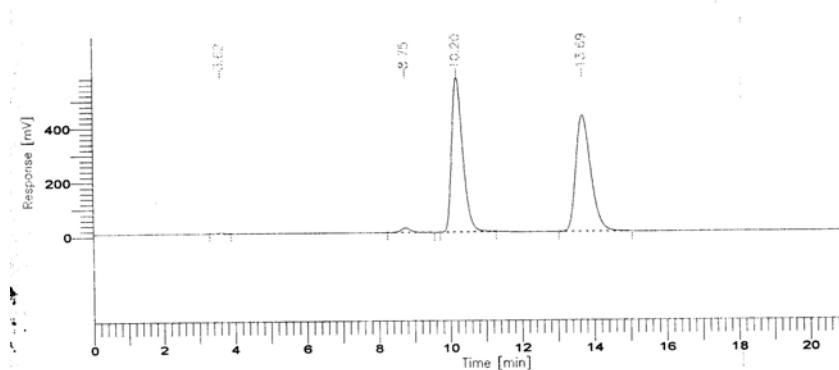
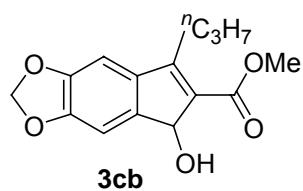
Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	Area BL [sec]	Area/Height [sec]
1	3.445	19278.00	1597.38	0.34	0.00	BB	12.0685
2	7.853	354906.50	21565.06	6.29	0.00	BB	16.4575
3	9.256	5246362.50	262446.28	92.91	0.00	BB	19.9902
4	11.293	26300.50	927.88	0.47	0.00	BB	28.3446



No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	23.127	49969.0	3365961.7	50.1286
2	2	27.327	49128.8	3348693.9	49.8714
Total			99097.8	6714655.6	100.0000

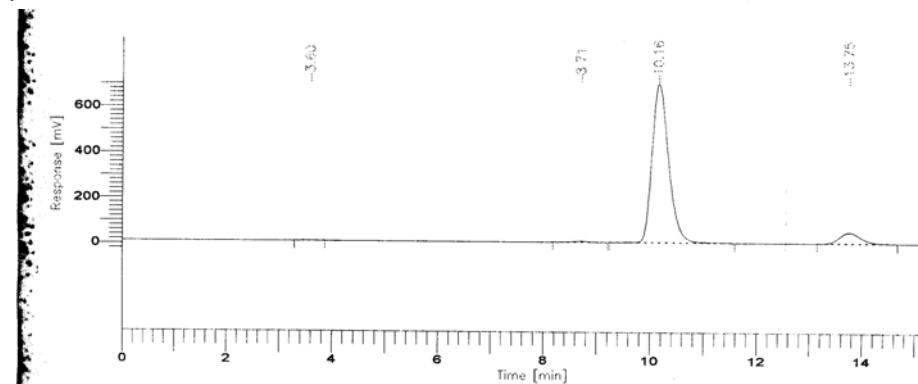


No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	24.043	120337.3	9808841.7	88.0486
2	2	28.877	17132.6	1331413.1	11.9514
Total			137469.9	11140254.8	100.0000



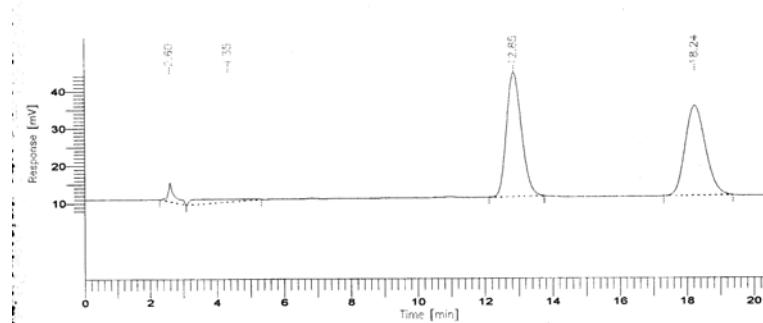
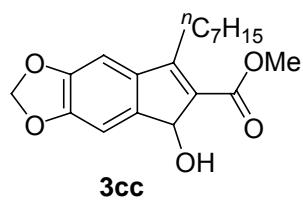
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	BL [sec]	Area/Height [sec]
1	3.616	37435.00	3944.06	0.15	0.00	BB	9.4915
2	8.750	314960.00	16874.41	1.27	0.00	BB	18.6650
3	10.195	12231135.00	569487.93	49.15	0.00	BB	21.4774
4	13.691	12304058.00	428083.91	49.44	0.00	BB	28.7422
			24887588.00	1.02e+06	100.00		0.00



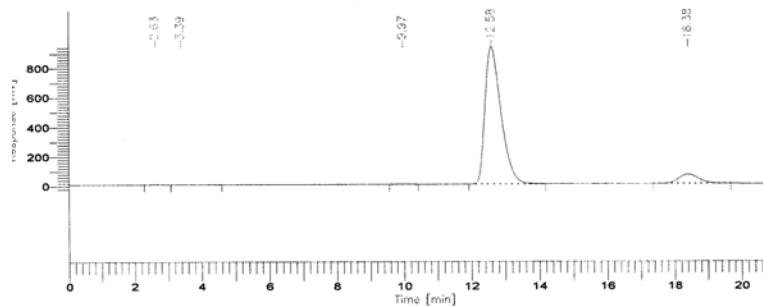
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	BL [sec]	Area/Height [sec]
1	3.604	21852.50	1797.09	0.13	0.00	BB	12.1600
2	8.711	104883.00	4571.68	0.63	0.00	BB	22.9419
3	10.161	15091796.00	697984.49	90.84	0.00	BB	21.6220
4	13.747	1394745.00	49078.38	8.40	0.00	BB	28.4187
			16613276.50	753431.64	100.00		0.00



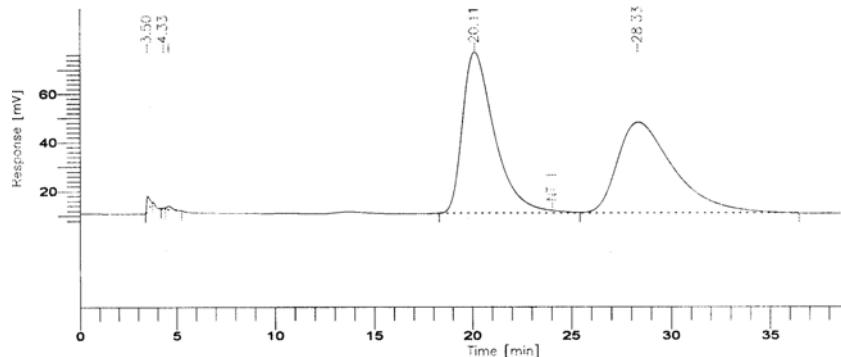
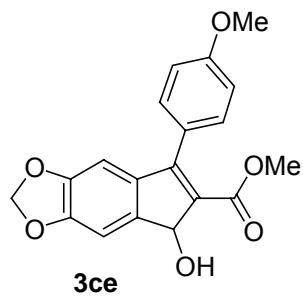
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	Area BL [sec]	Area/Height [sec]
1	2.602	67154.00	5023.25	3.03	0.00	BB	13.3686
2	4.348	97221.50	728.21	4.39	0.00	BB	133.5080
3	12.851	1025021.00	33215.65	46.24	0.00	BB	30.8596
4	18.236	1027281.00	24075.70	46.34	0.00	BB	42.6688
			2216677.50	63042.81	100.00		0.00



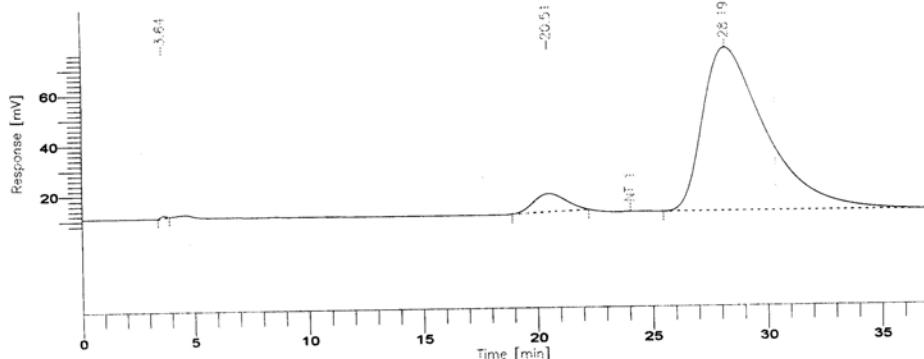
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	Area BL [sec]	Area/Height [sec]
1	2.625	50443.00	3333.28	0.15	0.00	BB	15.1332
2	3.388	48736.00	1001.15	0.15	0.00	BB	48.6800
3	9.971	34254.00	1553.99	0.10	0.00	BB	22.0427
4	12.583	30448712.00	932612.47	91.47	0.00	BB	32.6488
5	18.383	2707140.00	63604.30	8.13	0.00	BB	42.5622
			33289285.00	1.00e+06	100.00		0.00



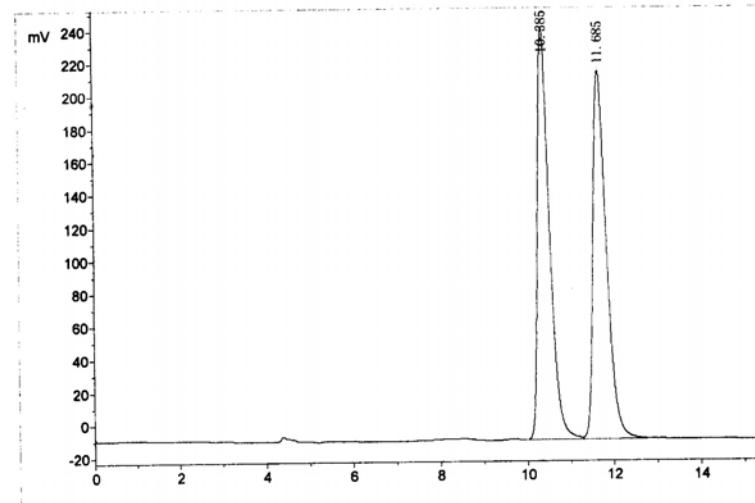
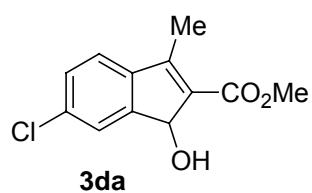
REPORT

Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	BL [sec]	Area/Height [sec]
1	3.502	65946.00	5927.19	0.44	0.00	BB	11.1260
2	4.327	4425.19	589.92	0.03	0.00	BV	7.5013
3	4.592	25430.81	1396.59	0.17	0.00	VB	18.2093
4	20.108	7495478.65	66151.80	50.39	0.00	*BV	113.3073
5	28.333	7284958.35	37240.17	48.97	0.00	*VB	195.6210

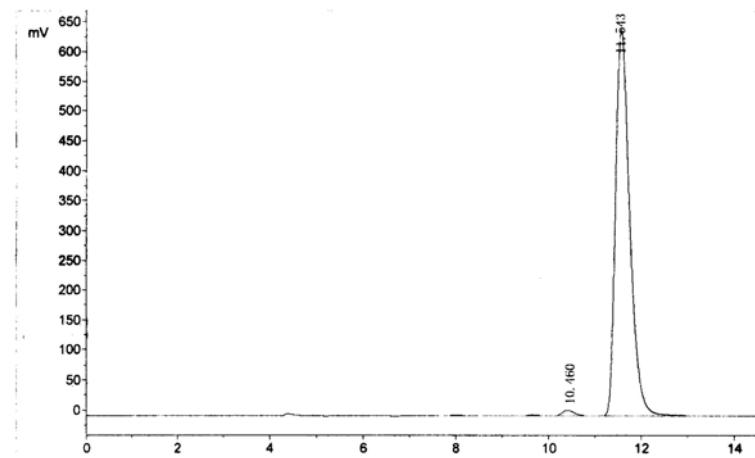


REPORT

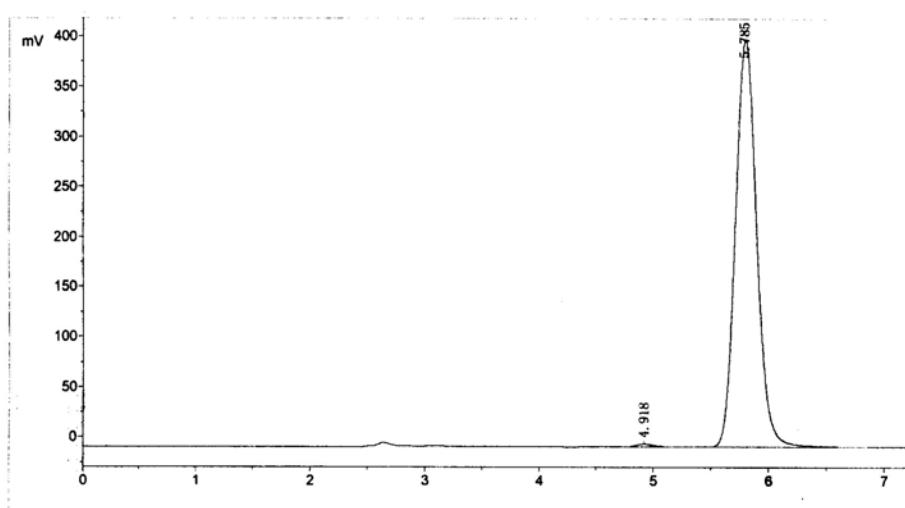
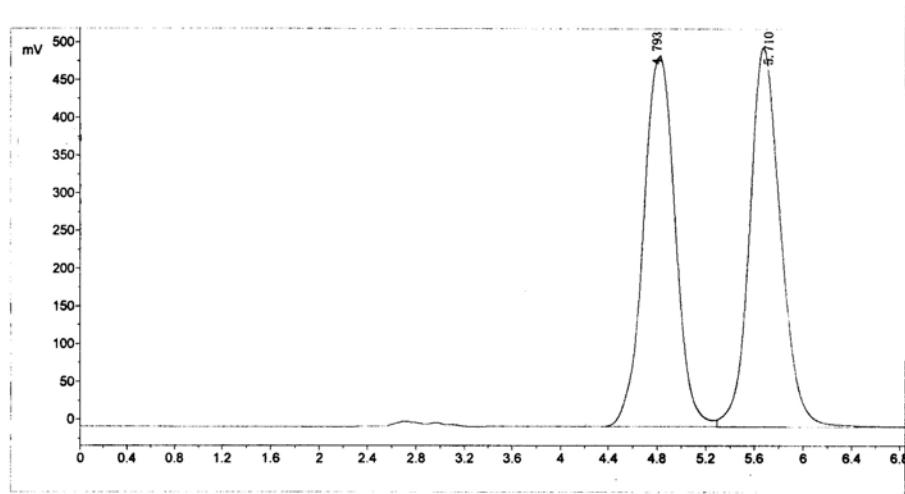
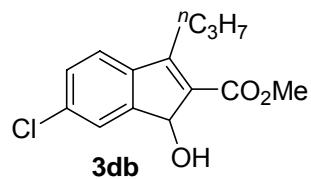
Peak #	Time [min]	Area [uV*sec]	Height [uV]	Area [%]	Norm. Area [%]	BL [sec]	Area/Height [sec]
1	3.640	15440.00	848.55	0.12	0.00	BB	18.1957
2	20.512	705113.00	7221.33	5.38	0.00	BB	97.6431
3	28.188	12379155.50	64867.14	94.50	0.00	*BB	190.8386



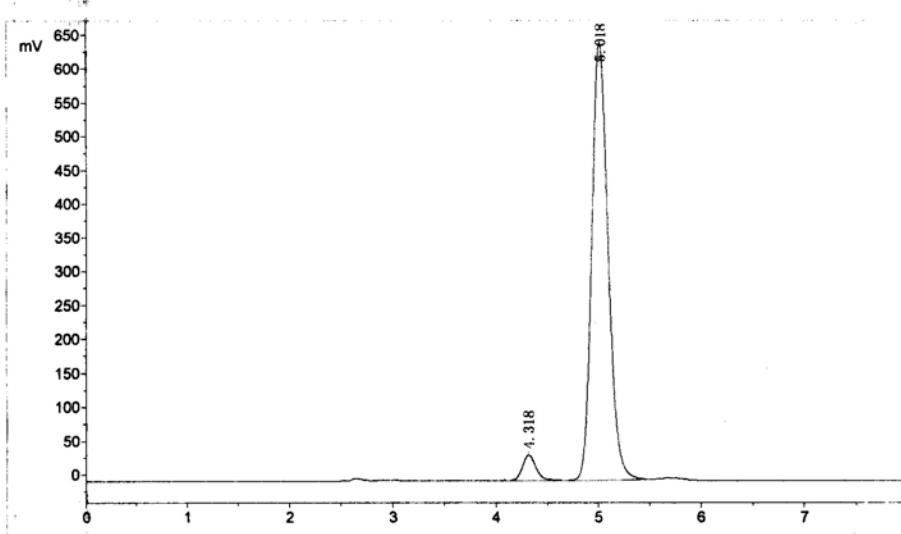
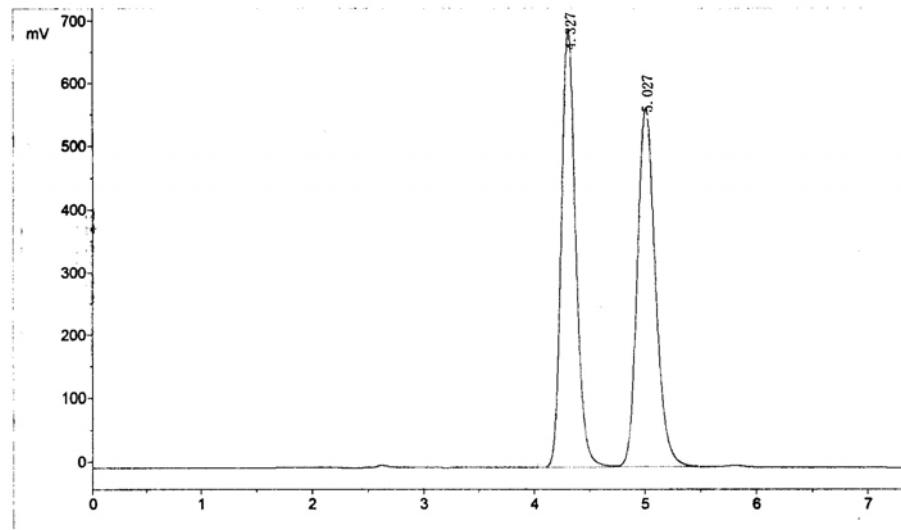
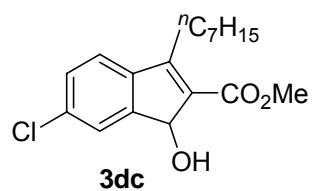
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	10.385	249932.3	4806263.2	49.9564
2	2	11.685	224012.9	4814647.2	50.0436
Total			473945.2	9620910.4	100.0000



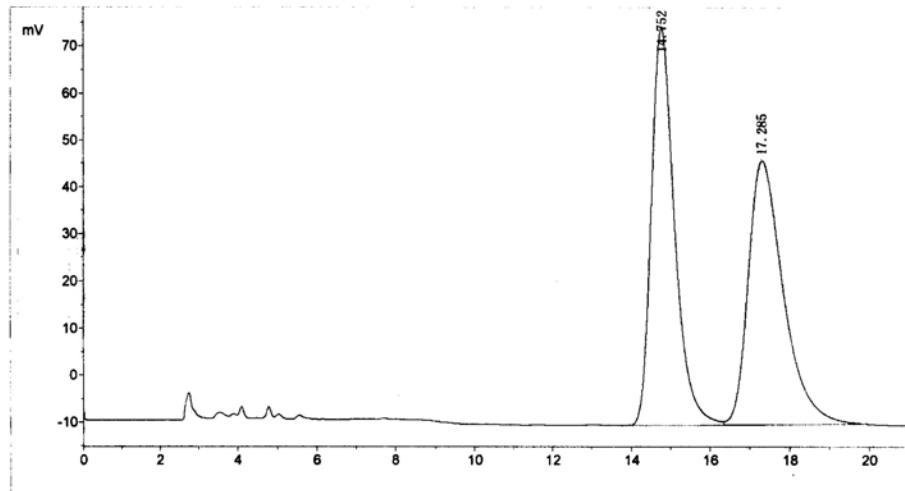
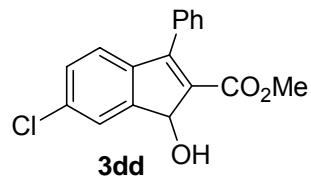
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	10.460	9098.1	249592.3	1.7813
2	2	11.543	628758.1	13762318.1	98.2187
Total			637856.3	14011910.4	100.0000



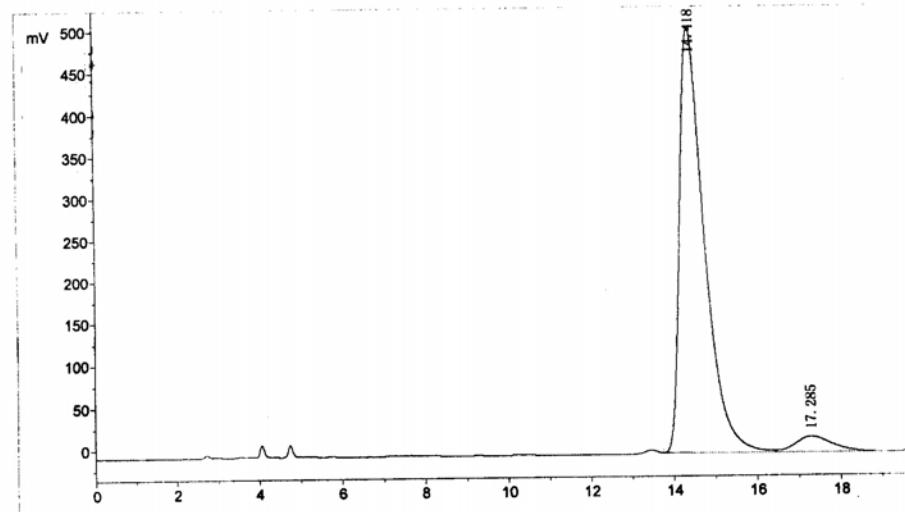
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	4.918	3094.2	34191.4	0.6526
2	2	5.785	401800.6	5205383.1	99.3474
Total			404894.8	5239574.5	100.0000



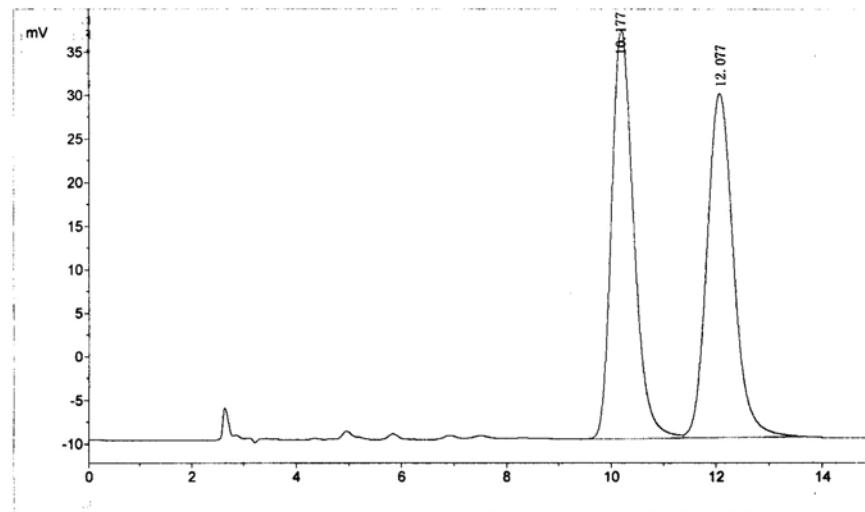
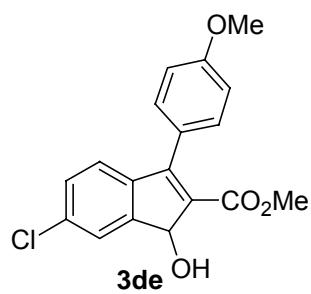
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	4.318	37186.9	338038.1	4.5102
2	2	5.018	643988.4	7156936.6	95.4898
Total			681175.3	7494974.7	100.0000



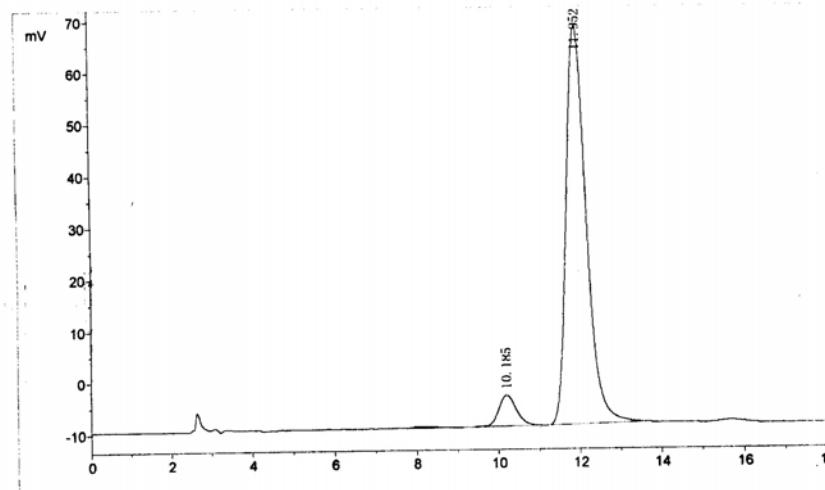
No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	14.752	84470.7	3458727.2	50.2700
2	2	17.285	55924.8	3421568.1	49.7300
Total			140395.4	6880295.3	100.0000



No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	14.418	507010.7	20787950.1	94.9275
2	2	17.285	18141.3	1110818.3	5.0725
Total			525152.0	21898768.4	100.0000



No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	10.177	46535.0	1380842.9	50.1894
2	2	12.077	39402.4	1370419.8	49.8106
Total			85937.4	2751262.7	100.0000



No.	PeakNo	R. Time	PeakHeight	PeakArea	PerCent
1	1	10.185	5822.0	175884.5	6.3126
2	2	11.952	76970.6	2610350.0	93.6874
Total			82792.7	2786234.5	100.0000