Supporting Information

Radical Alkenylation of α -Halo Carbonyl Compounds with Alkenylindiums

Kazuaki Takami, Hideki Yorimitsu, and Koichiro Oshima*

*Department of Material Chemistry, Graduate School of Engineering, Kyoto University,
Katsura, Nishikyo-ku, Kyoto 615-8510, Japan*

Instrumentation

^1H NMR (300 MHz) and ^{13}C NMR (75.3 MHz) spectra were taken on a Varian GEMINI 300 spectrometer in CDCl_3 as a solvent, and chemical shifts were given in δ value with tetramethylsilane as an internal standard. ^1H NMR (500 MHz) and ^{13}C NMR (125 MHz) data were obtained with a Varian UNITY INOVA 500 spectrometer. IR spectra were determined on a SHIMADZU FTIR-8200PC spectrometer. TLC analyses were performed on commercial glass plates bearing a 0.25-mm layer of Merck Silica gel 60F₂₅₄. Silica gel (Wakogel 200 mesh) was used for column chromatography. The analyses were carried out at the Elemental Analysis Center of Kyoto University.

Materials

Unless otherwise mentioned, all materials were procured commercially and used without further purification. Anhydrous indium trichloride was purchased from Aldrich Chemicals and was thoroughly dried in a reaction flask under reduced pressure (0.5 torr) by heating with a hair drier for 2 min before use. Neat triethylborane and diisobutylaluminium hydride (DIBAL-H) were obtained from Aldrich and were diluted with dry hexane to prepare 1.0 M solutions. *tert*-Butyllithium was purchased from

Kanto Chemical Inc. as a pentane solution and stored in a refrigerator.

Starting Alkenyl Halides

According to literature procedures, (*Z*)- β -bromostyrene ((*Z*)-**1**)¹, (*E*)-1-iodo-1-octene (**13**)², (*Z*)-1-iodo-1-dodecene (**16**)³, (*E*)-1-iodo-2-phenyl-1-propene (**19**)⁴ and (*E*)-1-iodo-2-methyl-1-octene (**22**)⁴ were prepared. The stereochemistry of these compounds was determined by comparison of proper signals of ¹H NMR spectra.

Experimental Section

All reactions were performed in a reaction flask connected with a toy balloon that was filled out with argon. Oxygen molecule, which is indispensable to cause an initiation reaction with triethylborane, penetrates the balloon moderately.

A General Procedure for Radical Alkenylation of α -Halo Carbonyl Compounds

To a solution of β -bromostyrene (**1**, 211 mg, 1.15 mmol) in 6 mL of dry ether at $-78\text{ }^{\circ}\text{C}$ was added a pentane solution of *tert*-butyllithium (1.5 M, 1.5 mL, 2.2 mmol). The solution was immediately warmed to $25\text{ }^{\circ}\text{C}$. Stirring at the same temperature for 30 min changed the color to clear reddish yellow. Then, this solution was added to a stirred white suspension of indium trichloride (243 mg, 1.1 mmol) in dry ether (4 mL) that was prepared in another reaction flask beforehand. After 30 min at $25\text{ }^{\circ}\text{C}$, ethyl iodoacetate (**3**, 214 mg, 1.0 mmol) and triethylborane (1.0 M hexane solution, 0.50 mL, 0.50 mmol) were successively added and the resulting mixture was vigorously stirred for 14 h. The reaction was quenched with 1.0 M HCl (10 mL) and extracted with

¹ Kuang, C.; Senboku, H.; Tokuda, M. *Tetrahedron Lett.* **2001**, 42, 3893–3896.

² Mole, T.; Jeffery, E. A. *Organoaluminium Compounds*; Elsevier: Amsterdam, 1972.

³ Takami, K.; Yorimitsu, H.; Oshima, K. *Org. Lett.* **2002**, 4, 2993–2995.

⁴ Van Horn, D. E.; Negishi, E. *J. Am. Chem. Soc.* **1978**, 100, 2252–2254.

hexane/ethyl acetate (10/1, 10 mL $\times$ 3). The organic extracts were dried over Na₂SO₄ and concentrated in vacuo. A purification by silica gel using hexane/ethyl acetate (10/1) as eluant afforded ethyl 4-phenyl-3-butenate (**4a**, *E/Z* = 90/10, 173 mg, 0.91 mmol) as a colorless oil.

Another Procedure for Radical Alkenylation: An Increased Amount of Styrylindium and Injection of Air

According to the procedure mentioned above, β -styrylindium dichloride was prepared from β -bromostyrene (**1**, 284 mg, 1.55 mmol), *tert*-butyllithium (1.5 M pentane solution, 2.0 mL, 3.0 mmol), and dried indium trichloride (332 mg, 1.5 mmol) in ether (12 mL). At 25 °C, ethyl iodoacetate (**3**, 214 mg, 1.0 mmol), triethylborane (1.0 M hexane solution, 0.30 mL, 0.30 mmol) and air (10 mL) were syringed into the reaction flask. Resulting mixture was strongly stirred for 15 h. Extractive workup followed by purification as above gave ethyl 4-phenyl-3-butenate (**4a**, *E/Z* = 90/10, 185 mg, 0.97 mmol).

Procedure for the Reaction in the Presence of Tetramethylpiperidine-*N*-oxyl (TEMPO)

β -Styrylindium dichloride was prepared with β -bromostyrene (211 mg, 1.15 mmol), *tert*-butyllithium (1.5 M pentane solution, 1.5 mL, 2.2 mmol) and dry indium trichloride (243 mg, 1.1 mmol) in ether (10 mL) as mentioned above. To the solution, TEMPO (94 mg, 0.60 mmol), ethyl iodoacetate (**3**, 241 mg, 1.0 mmol) and triethylborane (1.0 M hexane solution, 0.50 mL, 0.50 mmol) were sequentially added at 25 °C. After being stirred for 12 h, the resulting mixture was quenched with 1 M HCl (10 mL). Extraction with hexane/ethyl acetate (10/1, 10 mL $\times$ 3) followed by silica gel column purification resulted in recovery of ethyl iodoacetate (**3**, 148 mg, 0.69 mmol).

A General Procedure for Iodolysis of Alkenylindiums

Preparation of styrylindium dichloride was carried out with β -bromostyrene ($E/Z = 1/99$, 183 mg, 1.0 mmol), *tert*-butyllithium (1.5 M pentane solution, 1.3 mL, 2.0 mmol) and dry indium trichloride (221 mg, 1.0 mmol) in ether (10 mL) according to the method aforementioned. After addition of iodine (254 mg, 1.0 mmol) at 25 °C, the mixture was stirred for 30 min. To the resulting mixture, 1 M HCl (10 mL) and saturated sodium hydrogen sulfite (1.0 mL) were sequentially added. Extraction with hexane (10 mL $\times$ 3) and following silica gel column chromatography provided iodostyrene ($E/Z = 1/99$, 228 mg, 0.99 mmol).

A Procedure for Hydroindation Followed by Radical Alkenylation

To a solution of dry indium trichloride (454 mg, 2.05 mmol) in THF (8.0 mL), diisobutylaluminium hydride (1.0 M hexane solution, 2.0 mL, 2.0 mmol) was added at -78 °C and the solution was stirred for 30 min. After addition of 1-octyne (231 mg, 2.1 mmol) and triethylborane (1.0 M hexane solution, 0.40 mL, 0.40 mmol), resulting mixture was stirred for 3 h at the same temperature. The solvent and volatile components were then removed under reduced pressure. Diethyl ether (5.0 mL), dimethyl sulfoxide (1.0 mL), ethyl iodoacetate (214 mg, 1.0 mmol) and triethylborane (1.0 M hexane solution, 0.50 mL, 0.50 mmol) were successively added at ambient temperature. After being stirred for 16 h, the reaction was quenched with 1.0 M HCl (10 mL). The organic layer extracted with hexane/ethyl acetate (10/1, 10 mL $\times$ 3) was dried over Na₂SO₄ and concentrated in vacuo. Silica gel column purification provided ethyl 3-decenoate (**15**, $E/Z = 9/91$, 93 mg, 0.47 mmol).

Characterization Data

Ethyl (*E*)-4-Phenyl-3-butenolate ((*E*)-4a), $R_f = 0.29$ (hexane/ethyl acetate = 10/1): IR

(neat) 2981, 2925, 1738, 1603, 1497, 1448, 1369, 1250, 1159, 1028, 966, 746, 692 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.28 (t, $J = 7.0$ Hz, 3H), 3.24 (dd, $J = 1.5, 7.0$ Hz, 2H), 4.17 (q, $J = 7.0$ Hz, 2H), 6.30 (dt, $J = 16.0, 7.0$ Hz, 1H), 6.49 (dt, $J = 16.0, 1.5$ Hz, 1H), 7.22 (ddt, $J = 7.5, 7.5, 1.5$ Hz, 1H), 7.30 (dd, $J = 7.5, 7.5$ Hz, 2H), 7.37 (dd, $J = 1.5, 7.5$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 14.17, 38.43, 60.73, 121.81, 126.22, 127.47, 128.47, 133.29, 136.81, 171.55. HRMS Found: 190.0997. Calcd for $\text{C}_{12}\text{H}_{14}\text{O}_2$: 190.0994. Found: C, 75.89; H, 7.44%. Calcd for $\text{C}_{12}\text{H}_{14}\text{O}_2$: C, 75.76; H, 7.42%.

Ethyl (Z)-4-Phenyl-3-butenolate ((Z)-4a), $R_f = 0.32$ (hexane/ethyl acetate = 10/1): IR (neat) 2982, 2925, 1738, 1603, 1498, 1447, 1367, 1325, 1258, 1163, 1048, 772, 700 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.27 (t, $J = 7.0$ Hz, 3H), 3.34 (dd, $J = 2.0, 7.0$ Hz, 2H), 4.17 (q, $J = 7.0$ Hz, 2H), 5.90 (dt, $J = 11.5, 7.0$ Hz, 1H), 6.64 (dt, $J = 11.5, 2.0$ Hz, 1H), 7.24–7.29 (m, 3H), 7.35 (dd, $J = 7.5, 7.5$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 14.19, 34.13, 60.78, 123.32, 127.09, 128.29, 128.65, 131.92, 136.55, 171.77. HRMS Found: 190.0989. Calcd for $\text{C}_{12}\text{H}_{14}\text{O}_2$: 190.0994. Found: C, 75.80; H, 7.45%. Calcd for $\text{C}_{12}\text{H}_{14}\text{O}_2$: C, 75.76; H, 7.42%.

Benzyl 2-Methyl-4-phenyl-3-butenolate (4c, $E/Z = 90/10$): IR (neat) 3030, 2934, 1732, 1600, 1497, 1165, 964, 746, 694 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.31 (d, $J = 7.2$ Hz, 0.30H), 1.38 (d, $J = 7.2$ Hz, 2.70H), 3.37 (dq, $J = 7.8, 7.8$ Hz, 1H), 5.15 (s, 2H), 5.71 (dd, $J = 7.8, 11.7$ Hz, 0.10H), 6.29 (dd, $J = 7.8, 15.9$ Hz, 0.90H), 6.48 (d, $J = 15.9$ Hz, 0.90H), 6.56 (d, $J = 11.7$ Hz, 0.10H), 7.19–7.39 (m, 10H); ^{13}C NMR (CDCl_3) For major isomer: δ 17.37, 43.10, 66.26, 126.08, 127.29, 127.79, 127.92, 128.29 (2C), 128.33, 131.04, 135.77, 136.57, 173.87. HRMS Found: 266.1320. Calcd for $\text{C}_{18}\text{H}_{18}\text{O}_2$: 266.1307.

2-[(E)-2-Phenylethenyl]-4-butanolide ((E)-4d): IR (nujol) 2932, 2858, 1747, 1261,

1180, 1032 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.23–2.37 (m, 1H), 2.51 (m, 1H), 3.38–3.48 (m, 1H), 4.30 (ddd, $J = 6.6, 9.0, 9.0$ Hz, 1H), 4.44 (ddd, $J = 3.3, 9.0, 9.0$ Hz, 1H), 6.26 (dd, $J = 6.3, 15.9$ Hz, 1H), 6.58 (d, $J = 15.9$ Hz, 1H), 7.20–7.40 (m, 5H); ^{13}C NMR (CDCl_3) δ 29.23, 42.45, 66.67, 123.80, 126.30, 127.82, 128.49, 133.30, 136.13, 176.99. Found: C, 76.27; H, 6.47%. Calcd for $\text{C}_{12}\text{H}_{12}\text{O}_2$: C, 76.57; H, 6.43%.

2-[(Z)-2-Phenylethenyl]-4-butanolide ((Z)-4d): IR (nujol) 2926, 1755, 1600, 1448, 1377, 1159, 1020, 970, 952, 750, 694 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.11–2.24 (m, 1H), 2.39–2.49 (m, 1H), 3.74 (ddd, $J = 9.3, 9.3, 9.3$ Hz, 1H), 4.22 (m, 1H), 4.38–4.46 (m, 1H), 5.58 (dd, $J = 9.3, 11.1$ Hz, 1H), 6.82 (d, $J = 11.1$ Hz, 1H), 7.26–7.42 (m, 5H); ^{13}C NMR (CDCl_3) δ 30.78, 39.45, 66.60, 126.02, 127.52, 128.33, 128.40, 134.29, 136.01, 177.56. Found: C, 76.17; H, 6.50%. Calcd for $\text{C}_{12}\text{H}_{12}\text{O}_2$: C, 76.57; H, 6.43%.

2,N,N-Trimethyl-4-phenyl-3-butenamide (4h, E/Z = 95/5): IR (neat) 2932, 1634, 1495, 1375, 1138, 1059, 965 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.32 (d, $J = 6.9$ Hz, 2.85H), 1.34 (d, $J = 6.9$ Hz, 0.15H), 2.98 (bs, 3H), 3.08 (bs, 3H), 3.55 (dq, $J = 8.1, 6.9$ Hz, 1H), 5.73 (dd, $J = 8.1, 11.1$ Hz, 0.05H), 6.28 (dd, $J = 8.1, 15.9$ Hz, 0.95H), 6.42 (d, $J = 15.9$ Hz, 0.95H), 6.53 (d, $J = 11.1$ Hz, 0.05H), 7.22 (t, $J = 7.5$ Hz, 1H), 7.30 (t, $J = 7.5$ Hz, 2H), 7.36 (d, $J = 7.5$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 18.31, 35.75, 37.10, 40.22, 125.96, 127.18, 128.28, 129.94, 130.25, 136.67, 173.49. HRMS Found: 203.1320. Calcd for $\text{C}_{13}\text{H}_{17}\text{NO}$: 203.1311.

Benzyl 4-Methyl-3-pentenoate (12): IR (neat) 3034, 2930, 1738, 1456, 1377, 1312, 1153, 737, 696 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.63 (s, 3H), 1.75 (s, 3H), 3.09 (d, $J = 7.2$ Hz, 2H), 5.12 (s, 2H), 5.33 (t, $J = 7.2$ Hz, 1H), 7.31–7.41 (m, 5H); ^{13}C NMR (CDCl_3) δ 17.97, 25.61, 33.75, 66.17, 115.55, 127.94 (2C), 128.31, 135.41, 135.83,

171.91. Found: C, 76.17; H, 7.80%. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.90%.

Ethyl 3-Decenoate (15, *E/Z* = 88/12): IR (neat) 2928, 2856, 1740, 1466, 1369, 1250, 1159, 1032, 968 cm^{-1} ; 1H NMR ($CDCl_3$) δ 0.88 (t, J = 6.6 Hz, 3H), 1.22–1.45 (m, 11H), 2.03 (dt, J = 6.9, 5.4 Hz, 2H), 3.02 (d, J = 5.4 Hz, 1.76H), 3.08 (d, J = 5.4 Hz, 0.24H), 4.14 (q, J = 7.2 Hz, 2H), 5.46–5.61 (m, 2H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 14.13, 14.25, 22.66, 28.84, 29.16, 31.74, 32.51, 38.19, 60.44, 121.40, 134.65, 171.99. Found: C, 72.74; H, 11.27%. Calcd for $C_{12}H_{22}O_2$: C, 72.68; H, 11.18%.

Ethyl 3-Tetradecenoate (18, *E/Z* = 8/92): IR (neat) 2926, 2855, 1742, 1466, 1367, 1323, 1252, 1163, 1036 cm^{-1} ; 1H NMR ($CDCl_3$) δ 0.88 (t, J = 6.6 Hz, 3H), 1.22–1.40 (m, 19H), 2.03 (q, J = 6.6 Hz, 2H), 3.01 (d, J = 5.7 Hz, 0.16H), 3.08 (d, J = 5.7 Hz, 1.84H), 4.14 (q, J = 7.2 Hz, 2H), 5.49–5.63 (m, 2H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 14.22, 14.30, 22.77, 27.49, 29.32, 29.41 (2C), 29.59, 29.69 (2C), 31.98, 33.10, 60.58, 120.68, 133.38, 171.89. Found: C, 75.24; H, 12.19%. Calcd for $C_{16}H_{30}O_2$: C, 75.54; H, 11.89%.

Ethyl 4-Phenyl-3-pentenoate (21, *E/Z* = 87/13): IR (neat) 2982, 2934, 1738, 1600, 1495, 1445, 1369, 1258, 1163, 1028, 756, 696 cm^{-1} ; 1H NMR ($CDCl_3$) δ 1.28 (t, J = 7.2 Hz, 3H), 2.05 (d, J = 1.2 Hz, 3H), 3.24 (d, J = 7.2 Hz, 2H), 4.17 (q, J = 7.2 Hz, 2H), 5.81 (t, J = 7.2 Hz, 0.13 $\times$ 1H), 5.95 (tq, J = 7.2, 1.2 Hz, 0.87 $\times$ 1H), 7.24 (ddt, J = 7.2, 7.2, 1.5 Hz, 1H), 7.31 (dd, J = 7.2, 7.2 Hz, 2H), 7.40 (dd, J = 1.5, 7.2 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 14.22, 16.21, 34.53, 60.69, 119.34, 125.78, 127.02, 128.19, 137.96, 143.09, 171.90. HRMS Found: 204.1141. Calcd for $C_{13}H_{16}O_2$: 204.1150. Found: C, 76.60; H, 7.96%. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.90%.

Ethyl (*E*)-4-Methyl-3-decenoate (24): IR (neat) 2930, 2858, 1740, 1466, 1369, 1315,

1258, 1159, 1034 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.88 (t, $J = 6.9$ Hz, 3H), 1.26 (t, $J = 7.2$ Hz, 3H), 1.24–1.33 (m, 6H), 1.34–1.45 (m, 2H), 1.62 (s, 3H), 2.02 (t, $J = 7.2$ Hz, 2H), 3.03 (d, $J = 6.9$ Hz, 2H), 4.13 (q, $J = 7.2$ Hz, 2H), 5.31 (t, $J = 6.9$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 14.20, 14.32, 16.33, 22.71, 27.78, 28.98, 31.81, 33.85, 39.57, 60.41, 115.37, 139.14, 172.24. HRMS Found: 212.1778. Calcd for $\text{C}_{13}\text{H}_{24}\text{O}_2$: 212.1777.

500 MHz ^1H NMR of compound **4b** in CDCl_3

282 MHz ^{19}F NMR of compound **4b** in CDCl_3

500 MHz ^1H NMR of compound (E)-4e in CDCl_3

125 MHz ^{13}C NMR of compound (E)-4e in CDCl_3

500 MHz ^1H NMR of compound (Z)-4e in CDCl_3

125 MHz ^{13}C NMR of compound (Z)-4e in CDCl_3

500 MHz ^1H NMR of compound (*E*)-**4f** in CDCl_3

125 MHz ^{13}C NMR of compound (E)-4f in CDCl_3

500 MHz ^1H NMR of compound (Z)-4f in CDCl_3

125 MHz ^{13}C NMR of compound (Z)-4f in CDCl_3

300 MHz ¹H NMR of compound **4g** in CDCl₃

125 MHz ^{13}C NMR of compound **4g** in CDCl_3

500 MHz ^1H NMR of compound 8 in CDCl_3

125 MHz ^{13}C NMR of compound **8** in CDCl_3

500 MHz ¹H NMR of compound **10** in CDCl₃

125 MHz ^{13}C NMR of compound **10** in CDCl_3