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Intermolecular trapping of acylpalladium and related acylmetal derivatives with active C–H compounds

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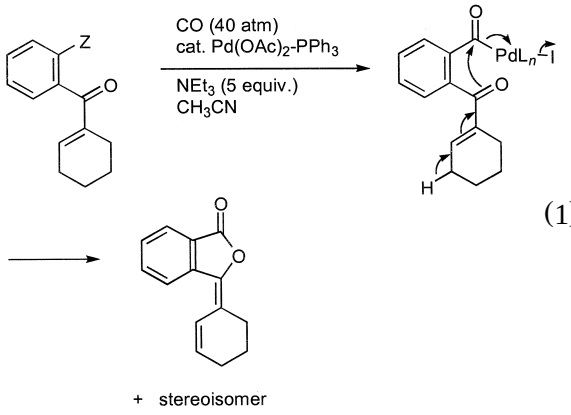
Abstract

The reaction of aryl and alkenyl iodides and bromides with highly acidic ketones in the presence of CO (40–45 atm), NEt_3 (1–2 equiv.), and 5 mol% of $Cl_2Pd(PPh_3)_2$ in DMF at 100°C provides the corresponding enol carboxylates formed via trapping of putative acylpalladiums with *O*-enolates. In cases where alkenyl halides are used, the initially formed products can cyclize to give the corresponding lactones.

Keywords: Palladium catalysis; Carbonylation; Enol esters; Active C–H compounds

1. Introduction

Although trapping of acylpalladiums with various nucleophiles including water, alcohols and amines is well documented [1–3], that with enolates had remained unknown until recently. In 1986, we unexpectedly observed the transformation shown in Eq. (1), which must have proceeded via intramolecular trapping of an acylpalladium intermediate with an *O*-enolate [4]. Also reported in the same year were some intermolecular versions involving trapping with both *C*- and *O*-enolates [5].



(1)

We have since delineated the intramolecular trapping reaction of acylpalladiums and related

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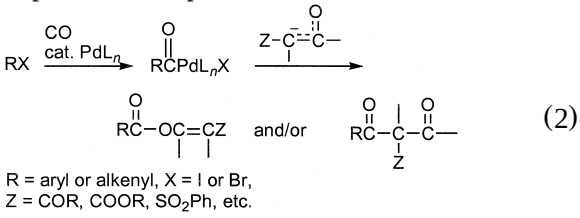
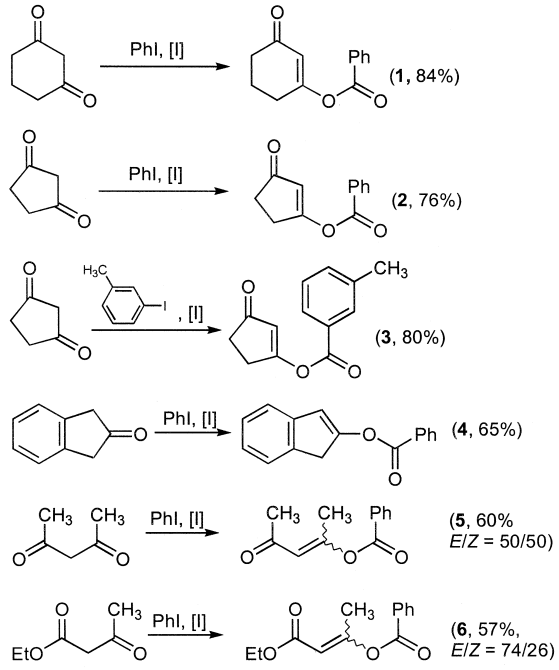
acylmetals with *O*- and *C*-enolates [6–16], and related studies by others [17–19] have also been published. In one of our studies [7], we briefly investigated intermolecular trapping of acylpalladiums and reported some results that complemented those reported by Kobayashi and Tanaka [5]. In this paper, a more systematic delineation of the scope and limitations of intermolecular trapping of acylpalladiums with external enolates (Eq. (2)) including further details of earlier experiments is presented.



2. Results and discussion

To explore the scope of intermolecular trapping of acylpalladium derivatives with active C–H compounds, phenyl iodide and (*E*)-1-octenyl iodide were selected as two representative test substrates, and their Pd-catalyzed carbonylation in the presence of various ketone enolate precursors, i.e., 1,3-cyclohexanedione, 1,3-cyclopentanedione, 2-indanone, 1,3-pentanedione, 1,3-diphenyl-1,3-propanedione, and ethyl acetoacetate, was carried out at 100°C in DMF using 5 mol% of $Cl_2Pd(PPh_3)_2$ as a catalyst and 1–2 equiv. of NEt_3 as a base. Some other starting compounds were also used as deemed appropriate. The experimental results with PhI are summarized in Scheme 1.

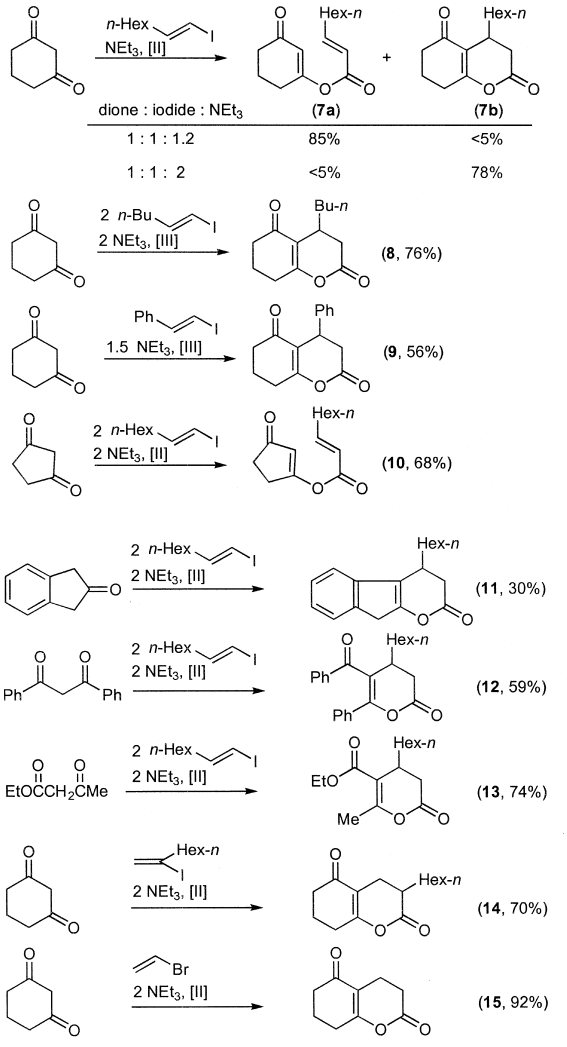
The results shown in Scheme 1 indicate the following. (1) The reaction appears to be reasonably general in cases where highly acidic ketones are used as enolate precursors. (2) The only detectable monomeric products in these cases are those obtained via trapping of putative acylpalladium intermediates with *O*-enolates. There was no sign for the formation of *C*-enolate trapping products. Although these results



Scheme 1.

do not contradict, they are in sharp contrast with those results involving mostly *C*-enolate trapping reported earlier by Kobayashi and Tanaka [5], which were mostly observed with diesters. (3) With acyclic ketones, both *E* and *Z* isomers are obtained, and the *E*/*Z* ratios have been relatively low ($\leqslant$ 3–4). As expected, *m*-iodotoluene gives **3** in 80% as the only regioisomer, indicating that no regiochemical scrambling occurs during the reaction. (5) Although not indicated in Scheme 1, the use of less acidic ketones, such as acetophenone and cyclohexanone, has not yielded the expected enolate trapping products in detectable yields, even when stronger bases, such as NaH and LDA, are used.

The reactions of (*E*)-1-octenyl iodide have displayed an interesting dichotomy. The experimental results summarized in Scheme 2 indicate the following. With alkenyl iodides, the expected *O*-enolate trapping products may undergo cyclization to give six-membered lac-



Scheme 2.

tones, and the product composition critically depends on the amount of a base, i.e., NEt_3 in this study, and the structure of the ketones. In the presence of 2 equiv. of NEt_3, lactones are either the predominant or the exclusive products in all cases except the reaction of 1,3-cyclopentanedione. When the Pd-catalyzed carbonylation reaction of (*E*)-1-octenyl iodide with 1 equiv. of 1,3-cyclohexanedione was carried out in the presence of only 1.2 equiv. of NEt_3 under otherwise the same conditions, the corresponding non-cyclic *O*-enolate trapping product was obtained along with a very minor amount, if any, of the lactone. Since the non-cyclic product from 1,3-cyclohexanedione can be readily cyclized in essentially quantitative yield in the presence of NEt_3 (1.2 equiv.) in DMF at 50°C within 10 h, this step does not require a Pd catalyst. In the absence of NEt_3, however, no cyclization occurs even at 100°C. Vinyl bromide and 2-iodo-1-octene also readily participate in the reaction, indicating that the reaction must be of considerable generality with respect to the alkenyl halides.

Since the reaction of benzoyl chloride with 1,3-cyclopentanedione in DMF at 100°C in the absence of a Pd complex gives the expected **2** in $\geq$ 95% yield, [3] the only role of Pd is to convert organic halides to electrophilic acyl derivatives, i.e., acylpalladiums, as in other Pd-catalyzed conversions of organic halides into acyl derivatives [1–3]. In principle, other transition metal complexes should also be able to serve as catalysts. However, the use of a catalytic amount (5 mol%) of $ClCu(PPh_3)_3$ or $Cl_2Ni(PPh_3)_2$ in the reaction of PhI with 1,3-cyclohexanedione under otherwise the same conditions has led only to the production of **1** in several % yields with about 90% of PhI remaining unreacted. On the other hand, the use of 1 equiv. of $Cl_2Ni(PPh_3)_2$ did produce **1** in 93% yield. So, Ni is capable of inducing the desired reaction, but further development is necessary to devise its catalytic version.

3. Experimental

3.1. Reagents and physical measurements

All reactions except for the high pressure carbonylation were carried out under a dry N_2

[3] For a related reaction of α,β-unsaturated acyl chlorides, see Ref. [20].

or Ar atmosphere. The Pd-catalyzed high-pressure carbonylation reactions were carried out in a 22-ml autoclave (Parr Instrument) using a cylinder of 99.99% pure CO (Matheson). All commercially available reagents and catalysts including $ClCu(PPh_3)_3$ and $Cl_2Ni(PPh_3)_2$ were used without further purification unless otherwise noted. DMF and NEt_3 were dried over molecular sieves 4 Å. $Cl_2Pd(PPh_3)_2$ [21], (*E*)-1-iodo-1-octene [22,23], (*E*)-β-iodostyrene [22,23] and 2-iodo-1-octene [24] were synthesized by following the known procedures. Gas chromatographic measurements were performed on SE-30 (Chromosorb W) columns with appropriate saturated hydrocarbon internal standards. ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$ on Varian Gemini-200 and Innova-300 NMR spectrometers using Me_4Si as an internal standard unless otherwise noted. NMR yields were determined by using dibromomethane as an internal reference.

3.2. Palladium-catalyzed carbonylation of iodobenzene and m-iodotoluene in the presence of highly acidic ketones and triethylamine

*3.2.1. Carbonylation of iodobenzene in the presence of 1,3-cyclohexanedione to produce 3-benzoyloxy-2-cyclohexene-1-one (**1**)*

General procedure: To a solution of 1,3-cyclohexanedione (112 mg, 1.0 mmol), NEt_3 (0.28 ml, 2.0 mmol) in 2 ml of DMF were added sequentially PhI (0.41 g, 2.0 mmol) and $Cl_2Pd(PPh_3)_2$ (35 mg, 50 μmol). The resultant mixture was placed in an autoclave under N_2 or Ar, which was charged with CO (40–45 atm), heated to 100°C, and stirred overnight (12–24 h). After cooling, the mixture was worked up with ether and brine, and dried over Na_2SO_4. Evaporation of the volatiles and column chromatography (hexane/ethyl acetate = 4/1) provided 186 mg (86%, 84% by NMR) of **1**: IR (neat) 1744, 16,979 cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 2.0–2.2 (m, 2H), 2.49 (t, $J = 6.4$ Hz, 2H), 2.69 (t, $J = 6.4$ Hz, 2H), 6.07 (s, 1H), 7.4–8.2 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 21.22, 28.31, 36.65, 117.69, 128.26, 128.60, 130.10, 134.02, 163.05, 170.19, 199.55. HRMS calcd. for $C_{13}H_{12}O_3$ 216.0786, found 216.0786.

*3.2.2. 3-Benzoyloxy-2-cyclopenten-1-one (**2**)*

This compound [25] was obtained in 74% yield (0.30 g, 76% by NMR) from 1,3-cyclopentanedione (0.20 g, 2.0 mmol), iodobenzene (0.82 g, 0.45 ml, 4.0 mmol), NEt_3 (0.40 g, 0.56 ml, 4.0 mmol), and $Cl_2Pd(PPh_3)_2$ (70 mg, 0.1 mmol) following the representative procedure: ^1H NMR ($CDCl_3$, Me_4Si) δ 2.4–2.6 (m, 2H), 2.8–3.0 (m, 2H), 6.35 (s, 1H), 7.4–8.2 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 28.74, 33.33, 116.67, 127.96, 128.77, 130.28, 134.43, 167.05, 179.73, 206.64.

*3.2.3. 3-(m-Toluoyloxy)-2-cyclopenten-1-one (**3**)*

This compound was obtained in 75% yield (0.16 g, 80% by NMR) from 1,3-cyclopentanedione (0.10 g, 1.0 mmol), iodotoluene (0.44 g, 2.0 mmol), NEt_3 (0.20 g, 0.28 ml, 2.0 mmol), and $Cl_2Pd(PPh_3)_2$ (35 mg, 50 μmol) following the representative procedure: ^1H NMR ($CDCl_3$, Me_4Si) δ 2.4 (s, 3H), 2.5–2.6 (m, 2H), 2.8–3.0 (m, 2H), 6.40 (s, 1H), 7.3–8. (m, 4H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 21.76, 29.37, 33.91, 117.17, 128.05, 128.45, 129.23, 131.34, 135.82, 139.29, 162.78, 172.92, 180.57. HRMS calcd. for $C_{13}H_{12}O_3 + H$ 217.0865, found 217.1865.

*3.2.4. 1H-Inden-2-yl benzoate (**4**)*

This compound was obtained in 63% yield (0.15 g, 65% by NMR) from 2-indanone (0.13 g, 1.0 mmol), iodobenzene (0.41 g, 2.0 mmol), NEt_3 (0.20 g, 0.28 ml, 2.0 mmol), and $Cl_2Pd(PPh_3)_2$ (35 mg, 50 μmol) following the representative procedure: ^1H NMR ($CDCl_3$, Me_4Si) δ 3.70 (s, 2H), 6.77 (s, 1H), 7.1–8.2 (m, 9H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 38.04, 115.51, 121.40, 123.79 124.78, 127.07, 128.96, 129.71, 130.43, 134.00, 137.71, 143.30, 156.33, 164.35. HRMS calcd. for $C_{16}H_{12}O_2$ 236.0837, found 236.0836.

*3.2.5. (E)- and (Z)-4-Benzoyloxy-3-penten-2-ones (**5E** and **5Z**)*

5*E* and **5*Z*** [26] were formed in 60% combined NMR yield based on vinyl proton signals at $\delta = 6.24$ and 5.92 ppm ($E/Z = 1/1$) from 2,4-pentanedione (0.10 g, 1.0 mmol), iodobenzene (0.41 g, 2.0 mmol), NEt_3 (0.20 g, 0.28 ml, 2.0 mmol), and $Cl_2Pd(PPh_3)_2$ (35 mg, 50 μmol) following the representative procedure: **5*E***: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 2.26 (s, 3H), 2.45 (s, 3H), 6.24 (s, 1H), 7.4–8.2 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 18.74, 32.25, 116.97, 129.03, 129.41, 130.47, 134.26, 163.42, 164.47, 197.93. **5*Z***: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 2.01 (s, 3H), 2.19 (d, $J = 8$ Hz, 3H), 5.92 (s, 1H), 7.4–8.2 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 21.56, 31.12, 117.74, 129.05, 129.42, 130.60, 134.22, 158.61, 163.98, 196.10.

*3.2.6. Ethyl (E)- and (Z)-3-benzoyloxy-2-butenoate (**6E** and **6Z**)*

6*E* and **6*Z*** [27] were formed in 57% combined NMR yield based on vinyl proton signals at $\delta = 5.81$ and 5.69 ppm ($E/Z = 3/1$) from ethyl acetoacetate (0.13 g, 1.0 mmol), iodobenzene (0.41 g, 2.0 mmol), NEt_3 (0.20 g, 0.28 ml, 2.0 mmol), and $Cl_2Pd(PPh_3)_2$ (35 mg, 50 μmol) following the representative procedure. **6*E***: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.28 (t, $J = 7.2$ Hz, 3H), 2.47 (s, 3H), 4.19 (q, $J = 7.2$ Hz, 2H), 5.81 (s, 1H), 7.4–8.2 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 14.13, 18.12, 60.10, 110.30, 128.50, 128.93, 129.97, 133.71, 163.78, 164.04, 165.86. **6*Z***: ^{1}H NMR ($CDCl_3$, Me_4Si) δ 1.10 (t, $J = 7.2$ Hz, 3H), 2.14 (s, 3H), 4.06 (q, $J = 7.2$ Hz, 2H), 5.69 (s, 1H), 7.4–8.2 (m, 5H).

3.3. Palladium-catalyzed carbonylation of alkenyl iodides and bromides in the presence of highly acidic ketones and triethylamine producing enol carboxylates

*3.3.1. (E)-3-(2-Nonenoyloxy)-2-cyclohexenone (**7a**)*

This compound was prepared from (*E*)-1-ido-1-octene (0.48 g, 2.0 mmol), 1,3-cyclohexanedione (0.225 g, 2.0 mmol), NEt_3 (0.34 ml, 2.4 mmol), $Cl_2Pd(PPh_3)_2$ (70 mg, 0.1 mmol), and CO (40 atm) in DMF (4.0 ml). Flash chromatography (hexane/EtOAc = 10/1) provided a 65% yield (86% by NMR) of **7a**: IR (neat) 1745, 1678, 1640, 1123 cm^{-1}. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.89 (t, $J = 7.0$ Hz, 3H), 1.1–1.6 (m, 8H), 2.07 (tt, $J = 6.1$, 6.6 Hz, 2H), 2.2–2.35 (m, 2H), 2.42 (t, $J = 6.6$ Hz, 2H), 2.57 (t, $J = 6.1$ Hz, 2H), 5.89 (d, $J = 15.7$ Hz, 1H), 5.95 (s, 1H), 7.13 (dt, $J = 15.7$ and 7.0 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.87, 22.15, 22.35, 27.61, 28.25, 28.65, 31.38, 32.31, 36.58, 117.14, 119.61, 153.34, 162.69, 169.96, 199.50. HRMS calcd. for $C_{15}H_{22}O_3$ + H 251.1647, found 251.1647.

*3.3.2. 4-(n-Hexyl)-3,4,5,6,7,8-hexahydro-2H-benzopyran-2,5-dione (**7b**)*

This compound was prepared in a manner similar to that for the preparation of **7a** except that 0.56 ml (4.0 mmol) of NEt_3 was used. Flash chromatography (hexane/EtOAc = 10/1) provided a 78% yield of **7b**: IR (neat) 1787, 1668, 1651, 1382, 1122 cm^{-1}. ^{1}H NMR ($CDCl_3$, Me_4Si) δ 0.87 (t, $J = 6.9$ Hz, 3H), 1.1–1.5 (m, 10H), 2.0–2.2 (m, 2H), 2.4–2.8 (m, 6H), 2.95–3.1 (m, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.84, 20.47, 22.34, 26.10, 26.99, 27.91, 28.90, 31.38, 33.27 (2C), 36.51, 118.53, 166.47, 166.60, 196.47. HRMS calcd. for $C_{15}H_{22}O_3$ + H 251.1647, found 251.1646.

*3.3.3. 4-(n-Butyl)-3,4,5,6,7,8-hexahydro-2H-benzopyran-2,5-dione (**8**)*

(*E*)-1-Iodo-1-hexene (0.42 g, 2 mmol), 1,3-cyclohexanedione (0.34 g, 3.0 mmol), NEt_3 (0.30 g, 0.42 ml, 3 mmol), MeCN (1 ml), THF (1 ml) and $Cl_2Pd(PPh_3)_2$ (70 mg, 0.1 mmol) were placed in an autoclave and CO (40 atm) was introduced. The mixture was heated to 100°C and stirred for 19 h. After cooling, the mixture was worked up with ether and aqueous $NaHCO_3$, washed with brine, and dried over $MgSO_4$. Bulb-to-bulb distillation provided 0.30 g (76%, 88% by GLC) of the title compound:

IR (neat) 2960, 2935, 1790, 1653, 1381, 1185, 1141, 1130 cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 0.87 (t, $J = 6.7$ Hz, 3H), 1.1–1.5 (m, 6H), 2.0–2.2 (m, 2H), 2.4–2.8 (m, 6H), 2.9–3.1 (m, 1H). ^{13}C NMR ($CDCl_3$) δ 13.92, 20.75, 22.62, 27.31, 28.20, 28.59, 33.32, 33.63, 36.85, 119.14,167.25, 167.34, 197.40.

*3.3.4. 4-Phenyl-3,4,5,6,7,8-hexahydro-2H-benzopyran-2,5-dione (**9**)*

This compound was prepared from (*E*)-β-iodostyrene (1.10 g, 5.0 mmol), 1,3-cyclohexanedione (0.84 g, 7.5 mmol), NEt_3 (1.05 ml, 7.5 mmol) and 0.18 g (0.25 mmol) of $Cl_2Pd(PPh_3)_2$ in 1:1 MeCN–THF (8 ml) using 40 atm of CO in 56% yield (0.67 g): IR (neat) 2954, 1788, 1712, 1654, 1494, 1106, 732 cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 1.9–2.15 (m, 2H), 2.3–2.5 (m, 2H), 2.55–2.75 (m, 2H), 2.85–2.95 (m, 2H), 4.27 (d, $J = 6$ Hz, 1H), 7.1–7.4 (m, 5H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 20.35, 27.09, 33.55, 36.04, 36.46, 116.93, 126.33, 127.21, 128.80, 140.34, 165.64, 167.28, 196.11. HRMS calcd. for $C_{15}H_{14}O_3$ 242.0943, found 242.0943.

*3.3.5. (E)-3-(2-Nonenoyloxy)-2-cyclopentenone (**10**)*

This compound was obtained from 1,3-cyclopentanedione (0.20 g, 2.0 mmol), (*E*)-1-iodo-1-octene (0.95 g, 4.0 mmol), $Cl_2Pd(PPh_3)_2$ (70 mg, 0.1 mmol), NEt_3 (0.56 ml, 4.0 mmol), and DMF (4.0 ml) in 68% yield: IR (neat) 1756, 1713, 1600, 1153, 1105 cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 0.90 (t, $J = 7.0$ Hz, 3H), 1.2–1.7 (m, 8H), 2.2–2.5 (m, 4H), 2.7–2.9 (m, 2H), 5.94 (d, $J = 15.6$ Hz, 1H), 6.26 (s, 1H), 7.23 (dt, $J = 15.6$ and 7.0 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ 13.86, 22.34, 27.56, 28.63, 28.66, 31.36, 32.43, 33.08, 116.03, 119.20, 154.57, 161.64, 179.71, 206.64. HRMS calcd. for $C_{14}H_{20}O_3 + H$ 237.1491, found 237.1491.

*3.3.6. 4-(n-Hexyl)-9H-indeno[2,3-e]-3,4-dihydro-2H-pyran-2-one (**11**)*

This compound was prepared from 2-indanone (0.13 g, 1.0 mmol), (*E*)-1-iodo-1-octene (0.48 g, 2.0 mmol), $Cl_2Pd(PPh_3)_2$ (35 mg, 50 μmol), NEt_3 (0.28 ml, 2.0 mmol), and DMF (2.0 ml) in 30% yield (31% by NMR): IR (neat) 1778, 1136 cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 0.86 (t, $J = 7.1$ Hz, 3H), 1.1–1.7 (m, 10H), 2.8–3.1 (m, 2H), 3.94 (s, 2H), 7.1–7.4 (m, 5H). ^{13}C NMR ($CDCl_3$) δ 14.02, 22.57, 26.57, 29.29, 29.76, 31.61, 34.21, 34.47, 35.27, 118.38, 119.24, 123.91, 124.14, 126.82, 136.70, 141.65, 154.78, 168.64; HRMS calcd. for $C_{18}H_{22}O_2 +$ H 271.1698, found 271.1697.

*3.3.7. 4-(n-Hexyl)5-benzoyl-6-phenyl-3,4-dihydro-2H-pyran-2-one (**12**)*

This compound was prepared from 1,3-diphenyl-1,3-propanedione (0.45 g, 2.0 mol), (*E*)-1-iodo-1-octene (0.95 g, 4.0 mmol), $Cl_2Pd(PPh_3)_2$ (70 mg, 0.1 mmol), NEt_3 (0.56 ml, 4.0 mmol), and DMF (4.0 ml) in 59% yield: IR (neat) 1677, 1658, 1376, 1340 cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 0.91 (t, $J = 7.0$ Hz, 3H), 1.2–2.1 (m, 10H), 2.5–2.9 (m, 2H), 4.6–4.9 (m, 1H), 7.1–7.9 (m, 10H). ^{13}C NMR ($CDCl_3$) δ 13.91, 22.40, 24.79, 28.84, 31.49, 34.31, 41.12, 79.66, 117.06, 128.26 (4C), 128.63 (2C), 129.09 (2C), 131.57, 132.70, 132.97, 137.54, 171.29, 190.71, 194.46. HRMS calcd. for $C_{24}H_{26}O_3 + H$ 363.1960, found 363.1958.

*3.3.8. 4-(n-Hexyl)-5-ethoxycarbonyl-6-methyl-3,4-dihydro-2H-pyran-2-one (**13**)*

This compound was prepared from ethyl acetoacetate (0.25 ml, 2.0 mmol), (*E*)-1-iodo-1-octene (0.95 g, 4.0 mmol), $Cl_2Pd(PPh_3)_2$ (70 mg, 0.1 mmol), NEt_3 (0.56 ml, 4.0 mmol), and DMF (4.0 ml) in 74% yield: IR (neat) 1788, 1715, 1648, 1134, 1073 cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 0.84 (t, $J = 7.1$ Hz, 3H), 1.2–1.5 (m, 13H), 2.34 (s, 3H), 2.57 (dd, $J = 6.3$ and 15.9 Hz, 1H), 2.70 (dd, $J = 2.2$ and 15.9 Hz, 1H), 2.9–3.05 (m, 1H), 4.24 (q, $J = 7.1$ Hz, 2H). ^{13}C NMR ($CDCl_3$) δ 13.91, 14.09, 18.65, 22.43, 26.26, 28.90, 31.47, 31.65, 32.96, 33.25, 60.56, 111.69, 160.07, 166.24, 167.22. HRMS calcd. for $C_{15}H_{24}O_4 + H$ 269.1753, found 269.1752.

*3.3.9. 3-(n-Hexyl)-2H-benzopyran-2,5-dione (**14**)*

This compound was prepared from 2-iodo-1-hexene (0.24 g, 1.0 mmol), 1,3-cyclohexanedione (0.17 g, 1.5 mmol), NEt_3 (0.28 ml, 2.0 mmol), $Cl_2Pd(PPh_3)_2$ (35 mg, 50 μmol), and DMF (2.0 ml). Column chromatography (hexane/ethyl acetate = 3/1) provided **14** (126 mg, 51%, 70% by NMR): IR (neat) 1790 (s), 1653 (s) cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 0.88 (t, $J = 6.7$ Hz, 3H), 1.2–1.6 (m, 10H), 1.8–2.3 (m, 4H), 2.4–2.65 (m 4H), 2.85 (dd, $J = 16$ and 7 Hz, 1H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 13.93, 20.59, 21.97, 22.44, 26.45, 26.92, 28.91, 29.67, 31.46, 36.35, 38.24, 113.89, 166.87, 169.35, 197.10. HRMS calcd. for $C_{15}H_{22}O_3 + H$ 251.1647, found 251.1644.

*3.3.10. 3,4,5,6,7,8-Hexahydro-2H-benzopyran-2,5-dione (**15**)*

This compound was prepared from vinyl bromide (0.71 ml, 1.0 mmol), 1,3-cyclohexanedione (0.17 g, 1.5 mmol), NEt_3 (0.28 ml, 2.0 mmol), $Cl_2Pd(PPh_3)_2$ (35 mg, 50 μmol), and DMF (2.0 ml). Column chromatography (hexane/ethyl acetate = 2/1) provided **15** [28] (118 mg, 71%, 92% by NMR): IR (neat) 1785 (s), 1650 (s) cm^{-1}. ^1H NMR ($CDCl_3$, Me_4Si) δ 2.0–2.2 (m, 2H), 2.35-2.75 (m, 8H). ^{13}C NMR ($CDCl_3$, Me_4Si) δ 16.24, 20.40, 26.94, 27.94, 36.23, 113.90, 166.38, 167.14, 196.77.

3.4. Miscellaneous

*3.4.1. Conversion of **7a** to **7b***

Heating **7a** (50 mg, 0.2 mmol) in 0.4 ml of DMF at 100°C for 1–2 h did not induce any significant change. After cooling, NEt_3 (32 μl, 0.24 mmol) was added, and the mixture was heated to 50°C for 12 h. GLC analysis indicated the formation of **7b** in quantitative yield.

3.4.2. Reaction of benzoyl chloride with 1,3-cyclopentanedione

The reaction of 1,3-cyclopentanedione (147 mg, 1.5 mmol) with benzyl chloride (0.17 ml, 1.5 mmol) and NEt_3 (0.28 ml, 2 mol) in DMF at 100°C produced **2** in ≥95% yield either in the presence or absence of 5 mol% of $Cl_2Pd(PPh_3)_2$.

3.4.3. Use of other metal complexes in Section 3.2.1

3.4.3.1. Use of a catalytic amount of $Cl_2Ni(PPh_3)_2$. The use of $Cl_2Ni(PPh_3)_2$ (33 mg, 50 μmol) in place of $Cl_2Pd(PPh_3)_2$ in Section 3.2.1 led to the formation of **1** in 8% yield with 90% of PhI remaining unreacted.

3.4.3.2. Use of the stoichiometric amount of $Cl_2Ni(PPh_3)_2$. The use of $Cl_2Ni(PPh_3)_2$ (0.65 g, 1 mmol) in place of $Cl_2Pd(PPh_3)_2$ in Section 3.2.1 led to the formation of 0.19 g (89%, 93% by NMR) of **1**.

3.4.3.3. Use of a catalytic amount of $ClCu(PPh_3)_3$. The use of $ClCu(PPh_3)_3$ (44 mg, 50 μmol) in place of $Cl_2Pd(PPh_3)_2$ in Section 3.2.1 led to the formation of **1** in 8% yield with 90% PhI remaining unreacted.

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References

[1] R.F. Heck, Palladium Reagents in Organic Syntheses, Academic Press, New York, 1985.
[2] H.M. Colquhoun, D.J. Thompson, M.V. Twigg, Carbonylation, Plenum, New York, 1991.
[3] J. Tsuji, Palladium Reagents and Catalysts, Wiley, New York, 1995.

[4] E. Negishi, J.M. Tour, Tetrahedron Lett. 27 (1986) 4869.
[5] T. Kobayashi, M. Tanaka, Tetrahedron Lett. 27 (1986) 4745.
[6] E. Negishi, Y. Zhang, I. Shimoyama, G. Wu, J. Am. Chem. Soc. 111 (1989) 8018.
[7] I. Shimoyama, Y. Zhang, G. Wu, E. Negishi, Tetrahedron Lett. 31 (1990) 2841.
[8] G. Wu, I. Shimoyama, E. Negishi, J. Org. Chem. 56 (1991) 6506.
[9] E. Negishi, Pure Appl. Chem. 74 (1992) 323.
[10] E. Negishi, C. Copéret, T. Sugihara, I. Shimoyama, Y. Zhang, G. Wu, J.M. Tour, Tetrahedron 50 (1994) 425.
[11] T. Sugihara, C. Copéret, Z. Owczarczyk, L.S. Harring, E. Negishi, J. Am. Chem. Soc. 116 (1994) 7923.
[12] C. Copéret, T. Sugihara, G. Wu, I. Shimoyama, E. Negishi, J. Am. Chem. Soc. 117 (1995) 3422.
[13] E. Negishi, C. Copéret, S.Y. Liou, F. Liu, S. Ma, Chem. Rev. 96 (1996) 365.
[14] E. Negishi, C. Copéret, S. Ma, T. Mita, T. Sugihara, J.M. Tour, J. Am. Chem. Soc. 118 (1996) 5904.
[15] E. Negishi, S. Ma, J. Amanfu, C. Copéret, J.A. Miller, T. Sugihara, J.M. Tour, J. Am. Chem. Soc. 118 (1996) 5919.
[16] E. Negishi, H. Makabe, I. Shimoyama, G. Wu, Y. Zhang, Tetrahedron 54 (1998) 1095.
[17] D. Roberto, M. Catellani, G.P. Chiusoli, Tetrahedron Lett. 29 (1988) 2115.
[18] Y. Uozumi, E. Mori, M. Mori, M. Shibasaki, J. Organomet. Chem. 399 (1990) 93.
[19] E. Dalcanale, Z. An, L.P. Battaglia, M. Catellani, G.P. Chiusoli, J. Organomet. Chem. 437 (1992) 375.
[20] B.M. Monroe, J. Heterocycl. Chem. 6 (1969) 917.
[21] J.M. Jenkins, J.G. Verkade, Inorg. Synth. 11 (1968) 108.
[22] C.J. Sih, R.G. Salomon, P. Price, R. Sood, G. Peruzzotti, J. Am. Chem. Soc. 97 (1975) 857.
[23] G. Zweifel, J.A. Miller, Org. React. 32 (1984) 375.
[24] N. Kamiya, Y. Chikami, Y. Ishii, Synlett (1990) 675.
[25] F.A. Lakhvich, T.S. Khlebnikova, A.A. Akrhem, J. Org. Chem. USSR (Engl. Transl.) (1989) 2280.
[26] J. Larkin, M.G. Murray, D.C. Nonhebel, A.D. Mitchell, J. Chem. Soc. Perkin Trans. I (1976) 380.
[27] R. Gelin, A. Gallaud. Bull. Soc. Chim. Fr. (1973) 3416.
[28] P.Y. Johnson, M.A. Priest, Tetrahedron Lett. (1975) 3133.