Nichekl-catalyzed Tishchenko Reaction via Hetero-nickelacycles by Oxidative Cyclization of Aldehydes with Nickel(0) Complex
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Supporting Information

[General]
All manipulations were conducted under a nitrogen atmosphere using standard Schlenk or dry box techniques. $^1$H, $^{31}$P, and $^{13}$C nuclear magnetic resonance spectra were recorded on JEOL GSX–270S, JEOL AL–400, Brucker DPX 400, Brucker AVANCE 400 and Varian UNITY INOVA 600 spectrometers at 25 °C unless otherwise stated. The chemical shifts in $^1$H nuclear magnetic resonance spectra were recorded relative to Me$_4$Si or residual protiated solvent (C$_6$D$_5$H ($\delta$ 7.16) or C$_7$D$_7$H ($\delta$ 7.02 or 7.13)). The chemical shifts in the $^{13}$C spectra were recorded relative to Me$_4$Si. Assignment of the resonances in $^1$H and $^{13}$C NMR spectra was based on $^1$H–$^1$H COSY, HMQC, and HMBC experiments. High resolution mass spectrometer (HRMS) and elemental analyses were performed at Instrumental Analysis Center, Faculty of Engineering, Osaka University. X-ray crystal data were collected by a Rigaku RAXIS–RAPID Imaging Plate diffractometer.

[Materials]
Toluene, C$_6$D$_6$, and toluene–$d_8$ were distilled from sodium benzophenone ketyl. All commercially available reagents were distilled and degassed prior to use. IPr (1,3–bis–(2,6–diisopropylphenyl)imidazol–2–ylidene), IPrCl (1,3–bis–(2,6–diisopropylphenyl) – 4,5–dichlorimidazol–2–ylidene) and 2-naphthaldehyde–$d_1$ were furnished by known procedures.$^{1,2}$
[NMR-scale experiments (Table 1)]

To a solution of Ni(cod)$_2$ (5.5 mg, 0.020 mmol) and PCy$_3$ (11.2 mg, 0.040 mmol) in 0.50 mL of toluene-$d_8$ was added benzaldehyde (20.4 mg, 0.20 mmol) at 23 °C. The reaction mixture was heated at 100 °C for 24 h. The solution changed from red to orange. The reaction was monitored by $^1$H and $^{31}$P NMR. Benzyl benzoate and C1 ($^{31}$P NMR: $\delta$ 41.7) were generated as red crystals (100% conversion vs Ni). Anal Calcd for C$_{72}$H$_{132}$NiOP (C1): C, 60.88; H, 9.38. Found: C, 61.34; H, 8.66.

To a solution of Ni(cod)$_2$ (5.5 mg, 0.020 mmol) and PCy$_3$ (5.6 mg, 0.020 mmol) in 0.50 mL of C$_6$D$_6$ was added benzyl benzoate (42.4 mg, 0.20 mmol) at 23 °C. The reaction mixture was heated at 80 °C for 60 h. The reaction was monitored by $^1$H and $^{31}$P NMR. C1 ($^{31}$P NMR: $\delta$ 41.7) was not formed at all, but unidentified new peaks were observed in $^1$H and $^{31}$P NMR spectra of the crude reaction mixture.

To a solution of Ni(cod)$_2$ (5.5 mg, 0.020 mmol) and PCy$_3$ (5.6 mg, 0.020 mmol) in 0.50 mL of C$_6$D$_6$ was added benzyl benzoate (42.4 mg, 0.20 mmol) at 23 °C. The reaction mixture was heated at 80 °C for 60 h. The reaction was monitored by $^1$H and $^{31}$P NMR. C1 ($^{31}$P NMR: $\delta$ 41.7) was not formed at all, but unidentified new peaks were observed in $^1$H and $^{31}$P NMR spectra of the crude reaction mixture.

To a solution of Ni(cod)$_2$ (11.0 mg, 0.040 mmol) and Ligand (0.040 mmol; IPr 15.5 mg or IPrCl 18.3 mg) in 0.50 mL of toluene-$d_8$ was added benzaldehyde (212.4 mg, 2.0 mmol or 414.8 mg, 4.0 mmol) at 23 °C. The reaction mixture was heated at 60 °C. The reaction was monitored by $^1$H NMR. Benzyl benzoate was obtained quantitatively.
[General experimental procedures of Ni(0)/IPrCl–catalyzed Tishchenko reaction (Table 2)]

To a solution of Ni(cod)₂ (11.0 mg, 0.040 mmol) and IPrCl (18.3 mg, 0.040 mmol) in 2 mL of toluene was added the aldehyde under inert atmosphere at 23 °C. The reaction mixture was heated at 60 °C or 80 °C for 1–24 h. The reaction was monitored by GC analysis. GC yields were determined using pentadecane as an internal standard. The product was isolated by a silica gel chromatography (eluted with EtOAc, unless otherwise noted). Spectroscopic data of the products (1, 6, 7, 8, 9, 10, 12, 13 and 14) were identical to that previously reported.³

[Spectroscopic data for prepared esters]

**Benzyl benzoate (1):**

The general procedure was followed with benzaldehyde (429.0 mg, 4.04 mmol) and reaction mixture was stirred at 60 °C for 3 h. Purification by column chromatography gave 1 (429.5 mg, 2.02 mmol, > 99%) as pale yellow oil.

**2,4-Dimethylbenzyl 2,4-dimethylbenzoate (2):**

The general procedure was followed with 2,4-dimethylbenzaldehyde (536.4 mg, 4.00 mmol) and reaction mixture was stirred at 60 °C for 3 h. Purification by column chromatography gave 2 (532.8 mg, 1.99 mmol, > 99%) as colorless oil. **¹H NMR** (400 MHz, CDCl₃): δ 7.85 (d, J = 8.0 Hz, 1H, ArH), 7.31 (d, J = 8.0 Hz, 1H, ArH), 7.04 (m, 4H, ArH), 5.31 (s, 2H, OCH₂Ar), 2.59 (s, 3H, C₃H₃), 2.39 (s, 3H, C₃H₃), 2.35 (s, 3H, C₃H₃), 2.34 (s, 3H, C₃H₃). **¹³C NMR** (100 MHz, CDCl₃): δ 167.5, 142.7, 140.7, 138.4, 137.1, 132.7, 131.4, 131.3, 131.1, 129.7, 126.8, 126.7, 126.6, 64.8, 22.0, 21.5, 21.2, 19.1. **HRMS**: Calcd. for C₁₈H₂₀O₂ 268.1463, Found 268.1465.

**3,5-Dimethylbenzyl 3,5-dimethylbenzoate (3):**
The general procedure was followed with 3,5-dimethylbenzaldehyde (542.8 mg, 4.05 mmol) and reaction mixture was stirred at 60 °C for 3 h. Purification by column chromatography gave 3 (531.5 mg, 1.98 mmol, > 99%) as colorless oil. \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) 7.75 (s, 2H, ArH), 7.22 (s, 1H, ArH), 7.11 (s, 2H, ArH), 7.02 (s, 1H, ArH), 5.33 (s, 2H, OCH\(_2\)Ar), 2.39 (s, 6H, CH\(_3\)). \(^{13}\)C NMR (100 MHz, CDCl\(_3\)): \(\delta\) 166.9, 138.2, 138.0, 136.1, 134.7, 130.2, 130.0, 127.5, 126.2, 66.8, 21.3, 21.2. HRMS: Calcd. for C\(_{18}\)H\(_{20}\)O\(_2\) 268.1463, Found 268.1458.

3,5-Di-tert-butylbenzyl 3,5-di-tert-butylbenzoate (5):  

The general procedure was followed with 3,5-di-tert-butylbenzaldehyde (439.1 mg, 2.01 mmol) and reaction mixture was stirred at 80 °C for 2 h. Purification by column chromatography gave 5 (441.2 mg, 2.01 mmol, > 99%) as yellow oil. \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) 8.22 (s, 2H, ArH), 7.85 (s, 1H, ArH), 7.62 (s, 1H, ArH), 7.55 (s, 2H, ArH), 5.63 (s, 2H, OCH\(_2\)Ar), 1.55 (s, 36H, CH\(_3\)). \(^{13}\)C NMR (100 MHz, CDCl\(_3\)): \(\delta\) 167.0, 151.0, 150.9, 135.7, 129.9, 127.1, 124.0, 122.0, 121.9, 67.0, 34.9, 34.8, 31.6, 31.5. HRMS: Calcd. for C\(_{30}\)H\(_{44}\)O\(_2\) 436.3341, Found 436.3344.

4-Methoxybenzyl 4-methoxybenzoate (6):
The general procedure was followed with 4-methoxybenzaldehyde (274.3 mg, 2.01 mmol) and reaction mixture was stirred at 60 °C for 2 h. Purification by column chromatography gave 6 (260.8 mg, 1.92 mmol, 95%) as yellow oil.

4-(Trifluoromethyl)benzyl 4-(trifluoromethyl)benzoate (7):

The general procedure was followed with 4-trifluoromethylbenzaldehyde (69.8 mg, 0.40 mmol) and reaction mixture was stirred at 60 °C for 4 h. Purification by column chromatography gave 7 (61.4 mg, 0.18 mmol, 88% as crude yield). Further purification by recrystallization gave 7 (57.2 mg, 0.17 mmol, 82%) as colorless solid.

4-(Methoxycarbonyl)benzyl methyl terephthalate (8):

The general procedure was followed with 4-methoxycarbonylbenzaldehyde (329.6 mg, 2.01 mmol) and reaction mixture was stirred at 80 °C for 4 h. Purification by column chromatography gave 8 (324.7 mg, 0.99 mmol, 99%). Further purification by recrystallization gave 8 as colorless solid.

Naphthalen-2-ylmethyl 2-naphthoate (9):

The general procedure was followed with 2-naphthadehyde (208.6 mg, 1.34 mmol) and reaction mixture was stirred at 60 °C for 3 h. Purification by column chromatography gave 9 (195.8 mg, 0.63
mmol, 94% as crude yield). Further purification by recrystallization gave 8 (170.8 mg, 0.55 mmol, 82%) as colorless solid. NMR scale experiment was conducted followed by procedure noted in p S12.

Furfuryl furoate (10):

![Furfuryl furoate](image)

The general procedure was followed with furfural (192.2 mg, 2.00 mmol) and reaction mixture was stirred at 60 °C for 3 h. Purification by column chromatography gave 10 (118.6 mg, 0.62 mmol, 62%) as yellow oil. The yellow solid was produced as unidentified byproduct.

3,5,5-Trimethylhexyl 3,5,5-trimethylhexanoate (11):

![3,5,5-Trimethylhexyl 3,5,5-trimethylhexanoate](image)

The general procedure was followed with 3,5,5-trimethylhexanal (569.9 mg, 4.01 mmol) and reaction mixture was stirred at 60 °C for 1 h. Purification by column chromatography gave 11 (543.3 mg, 1.91 mmol, 96%) as colorless oil. This product was obtained as a diasteromer mixture 11/11’ (60/40, estimated by 1H NMR). 1H NMR (400 MHz, CDCl3): δ 4.09–4.05 (m, 2H of 11 and 11’, OCH₂CH₂), 2.31–2.29 (m, 1H of 11’ BuCH₂CH(Me)CH₂), 2.28–2.26 (m, 1H of 11, ‘BuCH₂CH(Me)CH₂), 2.13-2.03 (m, 2H), 1.63–1.59 (m, 2H), 1.44-1.42 (m, 1H), 1.25 (t, J = 4.0 Hz, 2H of 11’, ‘BuCH₂CH(Me)CH₂), 1.21 (t, J = 4 Hz, 2H of 11, ‘BuCH₂CH(Me)CH₂), 1.13–1.01 (ddd, 2H), 0.97 (d, J = 4.0 Hz, 3H of 11’, Me-H), 0.95 (d, J = 4.0 Hz, 3H of 11’, Me-H), 0.89 (s, 9H of 11 and 11’, ‘Bu-H), 0.87 (s, 9H of 11 and 11’, ‘Bu-H). 13C NMR (CDCl3, 67 MHz): δ 173.4, 62.8, 51.1 (11’), 51.1 (11), 50.7, 44.3, 38.0, 31.2, 30.2 (11’), 30.1 (11), 27.1 (11), 26.9 (11’), 26.3, 22.8 (11’), 22.8 (11), 22.7 (11), 22.6(11’). HRMS: Calcd. for C₁₈H₃₆O₂ 284.2715, Found 284.2713.

2-Ethylhexyl 2-ethylhexanoate (12):

![2-Ethylhexyl 2-ethylhexanoate](image)
The general procedure was followed with 2-ethylhexanal (519.3 mg, 4.05 mmol) and reaction mixture was stirred at 60 °C for 1 h. Purification by column chromatography gave 12 (483.3 mg, 1.88 mmol, 94%) as colorless oil.

**Cyclohexylmethyl cyclohexanecarboxylate (13):**

![Cyclohexylmethyl cyclohexanecarboxylate](image)

The general procedure was followed with cyclohexanecarbaldehyde (450.2 mg, 4.01 mmol) and reaction mixture was stirred at 60 °C for 1 h. Purification by column chromatography gave 13 (451.5 mg, 2.01 mmol, 99%) as colorless oil.

**Neopentyl pivalate (Scheme 2, Entry 14):**

![Neopentyl pivalate](image)

The general procedure was followed with pivalaldehyde (442 uL, 344.8 mg, 4.00 mmol) and reaction mixture was stirred at 60 °C for 1 h. Neopentyl pivalate (14) is difficult to isolate because of its low boiling point. Therefore, product yield was determined by GC.
[Mechanistic investigations]

NMR Monitoring of the Tishchenko reaction of 2-naphthaldehyde:

To a solution of Ni(cod)$_2$ (110.0 mg, 0.40 mmol) and IPrCl (183.2 mg, 0.40 mmol) in 2 mL of toluene-$d_8$ was added 2-naphthaldehyde (312.4 mg, 2.00 mmol) at 23 °C and the sample was transferred to an NMR tube equipped with a sealable teflon cap. The tube was sealed and inserted in a NMR spectrometer. The $^1$H NMR analysis was conducted at 25 °C (NMR S1) and then the sample was cooled to -60 °C. After the measurement of $^1$H NMR (NMR S2), $^{13}$C NMR (NMR S3) and HMBC (NMR S4) at -60 °C, the sample was allowed to warm to 25 °C. Then, $^1$H NMR analysis was conducted at 25 °C again to verify that the reaction is not proceeded from when the first $^1$H NMR analysis had been conducted at 25 °C. The reaction at room temperature was monitored by $^1$H NMR for 1 d and the 2-naphthaldehyde was consumed to the give corresponding ester quantitatively. Spectral data for C2: $^1$H NMR (600 MHz, toluene-$d_8$, -60 °C): $\delta$ 4.70 (brs, 2H, ArCHO), 3.12 (br, 2H, $^1$Pr-H), 2.97 (br, 2H, $^1$Pr-H), 1.61 (br, 6H, $^1$Pr-H), 1.17 (br, 6H, $^1$Pr-H), 1.07 (br, 6H, $^1$Pr-H), 1.02 (br, 6H, $^1$Pr-H). $^{13}$C NMR (150 MHz, toluene-$d_8$): $\delta$ 196.0, 109.3, 29.6, 28.8, 24.8, 24.3, 24.0, 23.6.
NMR Monitoring of the Tishchenko reaction of 2-naphthaldehyde-\textit{d}_1:

To a solution of Ni(cod)$_2$ (110.0 mg, 0.40 mmol) and IPrCl (183.2 mg, 0.40 mmol) in 2 mL of toluene-\textit{d}_8 was added 2-naphthaldehyde-\textit{d}_1 (314.4 mg, 2.00 mmol) at 23 °C and the sample was transferred to an NMR tube equipped with a sealable teflon cap. The tube was sealed and inserted in a NMR spectrometer. The $^1$H NMR analysis was conducted at 25 °C and then the sample was cooled to -60 °C. After the measurement of $^1$H NMR (NMR S5) and $^{13}$C NMR (NMR S6) at -60 °C, the sample was allowed to warm to 25 °C. Then, $^1$H NMR analysis was conducted at 25 °C again to verify that the reaction is not proceeded from when the first $^1$H NMR analysis had been conducted at 25 °C.
[Determination of reaction rate constant and KIE]

For all kinetic analyses, each measurement was repeated at least twice.

**Reaction rate constant of the Tishchenko reaction of 2-naphthaldehyde, \( k_{H} \):**

To a solution of Ni(cod)\(_2\) (11.0 mg, 0.040 mmol) and IPrCl (18.3 mg, 0.040 mmol) in 0.5 mL of C\(_6\)D\(_6\) was added 2-naphthaldehyde (206.2 mg, 1.32 mmol) and 1,4-dioxane (39.5 mg, 0.45 mmol) as an internal standard at 25 °C. The reaction mixture was thermostated at 60 °C, and then the integral values at \( \delta_{H} 8.12 \text{ ppm} \) and 3.32 ppm, the resonances attributable to the aromatic proton in 9 and to 1,4-dioxane, respectively, were monitored periodically (every 5 minutes) by means of \(^1\text{H}\) NMR spectroscopy (Table S1). The rate constant of disappearance of C\(_{10}\)H\(_7\)CHO (\( k_{H} \)) was evaluated by least-squares fitting of the conversion-time profiles to a zero-order rate equation (eq. S1).

\[
-d[C_{10}H_7CHO]/dt = k_{H} = 3.55(3) \times 10^{-4} \text{ [mol m}^{-3}\text{-sec}^{-1}] 
\]

**Reaction rate constant of the Tishchenko reaction of 2-naphthaldehyde-\(d_1\), \( k_{D} \):**

To a solution of Ni(cod)\(_2\) (11.0 mg, 0.040 mmol) and IPrCl (18.3 mg, 0.040 mmol) in 0.5 mL of C\(_6\)D\(_6\) was added 2-naphthaldehyde-\(d_1\) (207.5 mg, 1.32 mmol) and 1,4-dioxane (40.5 mg, 0.46 mmol) as an internal standard at 25 °C. The reaction mixture was thermostated at 60 °C, and then the integral values at \( \delta_{H} 8.12 \text{ ppm} \) and 3.32 ppm, the resonances attributable to the aromatic proton in 9 and to 1,4-dioxane, respectively, were monitored periodically (every 5 minutes) by means of \(^1\text{H}\) NMR spectroscopy (Table S2). The rate constant of disappearance of C\(_{10}\)H\(_7\)CDO (\( k_{D} \)) was evaluated by least-squares fitting of the conversion-time profiles to a zero-order rate equation (eq. S2).

\[
-d[C_{10}H_7CDO]/dt = k_{D} = 1.87(1) \times 10^{-4} \text{ [mol m}^{-3}\text{-sec}^{-1}] 
\]
where \([C_{10}H_7CDO] = [C_{10}H_7CDO]_0 - 2[9-d_2]_t\), \([C_{10}H_7CDO]_0 = 1.180(4) \text{ mol m}^{-3}\)

([C_{10}H_7CDO]_0 means the concentration of [C_{10}H_7CDO] at \(t = 0\).)

These two experiments show a KIE value of reaction rate \((k_H/k_D = 3.55 \times 10^{-4}/1.87 \times 10^{-4} = 1.9)\).

Table S1

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\([C_{10}H_7CHO] = -3.55(3) \times 10^{-4}t + 1.169(5)\)

\(R^2 = 0.999\)
Table S2

$$[C_{10}H_7CDO] = -1.87(1) \times 10^{-4} t + 1.180(4)$$

$$R^2 = 0.999$$

References

2,4-dimethylbenzyl 2,4-dimethylbenzoate

Supplementary Material (ESI) for Chemical Communications
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3,5-dimethylbenzyl 3,5-dimethylbenzoate

[Chemical structure diagram]
3,5-dimethylbenzyl 3,5-dimethylbenzoate
2,4,6-trimethylbenzyl 2,4,6-trimethylbenzoate

\HD300G\share\hoshimoto\H-NMR after\R.600-R.699\R.611\1HNMR CD3CL.als
2,4,6-trimethylbenzyl 2,4,6-trimethylbenzoate

\HD300G\share\hoshimoto\H-NMR after\R.600-R.699\R.611\13CNMR CD3CL.als
3,5-di-tert-butylbenzyl 3,5-di-tert-butylbenzoate
3,5-di-tert-butylbenzyl 3,5-di-tert-butylbenzoate
3,5,5-trimethylhexyl 3,5,5-trimethylhexanoate