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Enantioselective *N*-propargylation of indoles via Cu-catalyzed propargylic alkylation/dehydrogenation of indolines

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ABSTRACT

The synthesis of optically active *N*-propargylindoles has been accomplished via the Cu-catalyzed asymmetric propargylic alkylation of indolines with propargylic esters, followed by the dehydrogenation of the resulting *N*-substituted indolines with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone. The reaction proceeded in good yield with high enantioselectivity under mild conditions using a bulky and structurally rigid tridentate ketimine P,N,N-ligand, and exhibited a broad substrate scope.

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1. Introduction

Following of the pioneering works of Hattori et al. [1] and Detz et al. [2] in 2008, there has been significant progress towards the development of Cu-catalyzed asymmetric propargylic substitution reactions [3,4], with numerous *N*- and *C*-based nucleophiles, including primary and secondary amines, enamines and enolates, being identified as suitable reaction partners [5–21]. Despite these advances, several challenging issues still need to be addressed in the Cu-catalyzed asymmetric propargylic substitution reaction. One of the biggest issues with this transformation is the enantioselective *N*-propargylation of indole, in that the direct *N*-propargylation of indole with propargylic esters is effectively impossible because of the weakly acidic nature of the *N*-H group of the indole. Indeed, Detz et al. [9] reported the development of a highly enantioselective Cu-catalyzed propargylation of indole with propargylic acetates that used a copper-pybox complex as the catalyst.

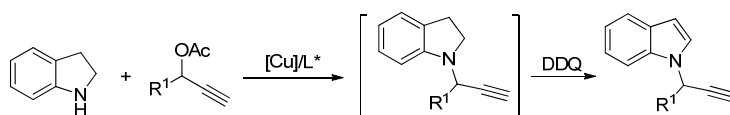
However, the propargylation reaction in this particular case occurred at the *C*3-position of the indole instead of the *N*1-position. This result was consistent with the observation that the *C*3-position of indole is more reactive than its *N*1 and *C*2 positions towards the Friedel-Crafts alkylation reaction [22]. The development of an alternative strategy for the construction of optically active *N*-propargylindoles is therefore highly desirable.

In 2003, Corey's group [23] reported a strategy for the construction of *N*-propargylindole via the sequential *N*-propargylation and dehydrogenation of the corresponding indoline in their total synthesis of okaramines, which are a family of biologically active tryptophan-derived heptacyclic and octacyclic alkaloids that are produced by the fungus *Penicillium simplicissimum* [24]. Although an asymmetric version of this reaction has never been reported, this strategy provided a platform for the enantioselective construction of optically active *N*-propargylindole. Employing a similar strategy, Liu et al. [25] recently

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Scheme 1. The enantioselective synthesis of *N*-propargylindoles via a sequential propargylic alkylation and dehydrogenation strategy.

developed a general process for the synthesis of *N*-allylindoles via the Ir-catalyzed allylic alkylation of indolines followed by an oxidation reaction. Compared with the Ir-catalyst used in this reaction, Cu salts are much cheaper and easier to handle, as well as being much less toxic. Herein, we wish to report the development of a highly enantioselective reaction for the Cu-catalyzed propargylic alkylation of indolines with propargylic esters, followed by dehydrogenation of the resulting *N*-substituted indolines with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) (Scheme 1). This method can be used to provide facile and efficient access to optically active *N*-substituted indoles, which are privileged structural motifs found in numerous natural products and biologically active compounds [26].

2. Experimental

2.1. General

All reactions were carried out under N₂ atmosphere. All of the solvents were purified by standard procedures before being used. Commercial reagents were used as supplied without further purification. Flash column chromatography (FCC) was performed over silica gel 60 (40–63 μm; Qingdao Makall Group Co., LTD, Qingdao, China). Thin layer chromatography (TLC) was performed on glass plates coated with silica gel 60 with an F254 indicator (Yantai Jianguyou Silica Gel Development Co., LTD, Yantai, China). Proton nuclear magnetic resonance (¹H NMR) spectra were recorded on a Bruker 400 MHz spectrometer (Bruker, Switzerland). The chemical shifts (δ) of the protons have been reported in parts per million (ppm) downfield of tetramethylsilane, which was used as a reference together with the residual proton of the deuterated NMR solvent (i.e., CHCl₃ = δ 7.28). ¹³C NMR spectra were recorded on a Bruker 101 MHz spectrometer. The chemical shifts (δ) for carbon signals have been reported in ppm downfield from tetramethylsilane, which was used as a reference together with the carbon resonances of the deuterated solvent (i.e., CDCl₃ = δ 77.07). NMR data have been presented as follows: chemical shift, multiplicity (br = broad, s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet), coupling constants (*J*) in Hz and integration. Enantiomeric ratios were determined by chiral HPLC using *n*-hexane and *i*-PrOH as the mobile phases. Optical rotations were recorded on a JASCO P-1020 polarimeter (JASCO Corporation, Tokyo, Japan).

2.2. General procedure for the synthesis of optically active *N*-propargylindoles via a one-pot propargylation/dehydrogenation process

Cu(OAc)₂·H₂O (3.0 mg, 0.015 mmol) and (*S*)-**L5** (7.8 mg,

0.0165 mmol) were added to anhydrous methanol (1 mL), and the resulting mixture was stirred at room temperature under N₂ atmosphere for 1 h. The solution was then cooled to 0 °C and treated with a solution of indoline **1** (0.33 mmol), propargylic ester **2** (0.3 mmol) and *i*-Pr₂NEt (62 μL, 0.36 mmol) in anhydrous methanol (2 mL). The resulting mixture was stirred at 0 °C for 5 h before being warmed to room temperature and passed over a short pad of silica. The silica pad was eluted with a mixture of hexanes and ethyl acetate to give the crude *N*-propargylindoline product, which was treated with a solution of DDQ (0.33 mmol) in CH₂Cl₂ (3 mL) at room temperature for 5 min to give the oxidized product as a crude mixture. The desired *N*-propargylindole product **3** was purified by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate.

(*R*)-1-(1-Phenylprop-2-yn-1-yl)-1*H*-indole (**3aa**). Obtained as a colorless oil in 90% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate (*V/V* = 100/1); 92% ee was determined by chiral HPLC (Chiralcel OJ-H, *n*-hexane/*i*-PrOH = 50/50, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): *t*_R (major) = 25.4 min, *t*_R (minor) = 19.9 min; [α]_D²⁹ = 121.3 (*c* 0.48, CH₂Cl₂); ¹H NMR (400 MHz, CDCl₃): δ = 7.64–7.62 (m, 1H), 7.35–7.25 (m, 7H), 7.18–7.09 (m, 2H), 6.55 (dd, *J* = 3.3, 0.6 Hz, 1H), 6.39 (d, *J* = 2.4 Hz, 1H), 2.67 (d, *J* = 2.5 Hz, 1H); ¹³C NMR (101 MHz, CDCl₃): δ = 137.5, 135.6, 129.2, 128.9, 128.5, 126.7, 126.5, 121.9, 121.2, 120.0, 110.0, 102.5, 80.1, 75.5, 51.6; HRMS calculated for C₁₇H₁₃N [M+H]⁺, *M_r* = 232.1126, found *M_r* = 232.1128.

(*R*)-1-(1-(2-Chlorophenyl)prop-2-yn-1-yl)-1*H*-indole (**3ab**). Obtained as a colorless oil in 79% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate (*V/V* = 70/1); 85% ee was determined by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): *t*_R (major) = 8.4 min, *t*_R (minor) = 7.7 min; [α]_D²⁹ = 1.31 (*c* 0.48, CH₂Cl₂); ¹H NMR (400 MHz, CDCl₃): δ = 7.63–7.61 (m, 1H), 7.41–7.09 (m, 8H), 6.73 (d, *J* = 2.4 Hz, 1H), 6.56 (d, *J* = 3.3 Hz, 1H), 2.67 (d, *J* = 2.5 Hz, 1H); ¹³C NMR (101 MHz, CDCl₃): δ = 135.5, 135.2, 133.1, 130.0, 130.0, 129.2, 128.5, 127.5, 126.2, 122.0, 121.2, 120.2, 109.8, 102.4, 79.1, 75.8, 49.0; HRMS calculated for C₁₇H₁₂ClN [M+H]⁺, *M_r* = 266.0737, found *M_r* = 266.0735.

(*R*)-1-(1-(3-Chlorophenyl)prop-2-yn-1-yl)-1*H*-indole (**3ac**). Obtained as a colorless oil in 88% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate (*V/V* = 100/1); 93% ee was determined by chiral HPLC (Chiralcel OJ-H, *n*-hexane/*i*-PrOH = 50/50, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): *t*_R (major) = 17.3 min, *t*_R (minor) = 14.2 min; [α]_D²⁹ = 145.9 (*c* 0.48, CH₂Cl₂); ¹H NMR (400 MHz, CDCl₃): δ = 7.65–7.63 (m, 1H), 7.40 (d, *J* = 1.4 Hz, 1H), 7.30–7.10 (m, 7H), 6.58 (dd, *J* = 2.6, 2.2 Hz, 1H), 6.35 (d, *J* = 1.9 Hz, 1H), 2.71 (dd, *J* = 2.5, 0.9 Hz, 1H); ¹³C NMR (101 MHz, CDCl₃): δ = 139.6, 135.5, 134.9, 130.1, 129.2, 128.7, 126.9,

126.3, 124.8, 122.1, 121.3, 120.2, 109.8, 102.9, 79.4, 76.1, 51.1; HRMS calculated for $C_{17}H_{12}ClN$ $[M+H]^+$, $M_r = 266.0737$, found $M_r = 266.0733$.

(*R*)-1-(1-(4-Chlorophenyl)prop-2-yn-1-yl)-1*H*-indole (**3ad**). Obtained as a colorless oil in 91% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 100/1$); 91% ee was determined by chiral HPLC (Chiralcel OJ-H, *n*-hexane/*i*-PrOH = 90/10, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 21.9 min, t_R (minor) = 20.3 min; $[\alpha]_D^{29} = 161.7$ (*c* 0.58, CH_2Cl_2); 1H NMR (400 MHz, $CDCl_3$): $\delta = 7.64$ – 7.62 (m, 1H), 7.28–7.09 (m, 8H), 6.56–6.55 (m, 1H), 6.34 (d, $J = 2.4$ Hz, 1H), 2.68 (d, $J = 2.5$ Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta = 136.1$, 135.5, 134.4, 129.3, 129.1, 128.1, 126.4, 122.1, 121.3, 120.2, 109.9, 102.8, 79.6, 75.9, 51.1; HRMS calculated for $C_{17}H_{12}ClN$ $[M+H]^+$, $M_r = 266.0737$, found $M_r = 266.0733$.

(*R*)-1-(1-(4-Bromophenyl)prop-2-yn-1-yl)-1*H*-indole (**3ae**). Obtained as a colorless oil in 92% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 100/1$); 89% ee was determined by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 10.5 min, t_R (minor) = 17.0 min; $[\alpha]_D^{29} = 138.0$ (*c* 0.70, CH_2Cl_2); 1H NMR (400 MHz, $CDCl_3$): $\delta = 7.64$ – 7.62 (m, 1H), 7.42 (d, $J = 8.3$ Hz, 2H), 7.27–7.11 (m, 6H), 6.56 (dd, $J = 2.2$, 1.0 Hz, 1H), 6.32 (d, $J = 2.3$ Hz, 1H), 2.68 (dd, $J = 2.5$, 0.9 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta = 136.6$, 135.5, 132.0, 129.3, 128.4, 126.4, 122.6, 122.1, 121.3, 120.2, 109.9, 102.8, 79.5, 76.0, 51.1; HRMS calculated for $C_{17}H_{12}BrN$ $[M+H]^+$, $M_r = 310.0231$, found $M_r = 310.0231$.

(*R*)-1-(1-(4-(Trifluoromethyl)phenyl)prop-2-yn-1-yl)-1*H*-indole (**3af**). Obtained as a colorless oil in 86% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 100/1$); 90% ee was determined by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 9.8 min, t_R (minor) = 14.2 min; $[\alpha]_D^{29} = 97.8$ (*c* 0.56, CH_2Cl_2); 1H NMR (400 MHz, $CDCl_3$): $\delta = 7.66$ – 7.56 (m, 3H), 7.42–7.11 (m, 6H), 6.60 (d, $J = 3.3$ Hz, 1H), 6.43 (d, $J = 2.3$ Hz, 1H), 2.73 (d, $J = 2.5$ Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta = 141.5$, 135.4, 130.8 (q, $J = 32.5$ Hz), 129.3, 127.0, 126.3, 125.9 (q, $J = 3.7$ Hz), 123.9 (q, $J = 272.1$ Hz), 122.1, 121.4, 120.3, 109.8, 103.0, 79.2, 76.3, 51.3; HRMS calculated for $C_{18}H_{12}F_3N$ $[M+H]^+$, $M_r = 300.1000$, found $M_r = 300.1003$.

(*R*)-1-(1-(*p*-Tolyl)prop-2-yn-1-yl)-1*H*-indole (**3ag**). Obtained as a colorless oil in 87% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 100/1$); 90% ee was determined by chiral HPLC (Chiralcel OJ-H, *n*-hexane/*i*-PrOH = 50/50, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 25.6 min, t_R (minor) = 17.0 min; $[\alpha]_D^{29} = 81.7$ (*c* 0.45, CH_2Cl_2); 1H NMR (400 MHz, $CDCl_3$): $\delta = 7.63$ – 7.61 (m, 1H), 7.35–7.09 (m, 8H), 6.54 (d, $J = 3.3$ Hz, 1H), 6.36 (d, $J = 1.8$ Hz, 1H), 2.66 (dd, $J = 2.5$, 0.9 Hz, 1H), 2.31 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta = 138.3$, 135.6, 134.5, 129.5, 129.2, 126.7, 126.4, 121.8, 121.1, 119.9, 110.0, 102.3, 80.3, 75.3, 51.4, 21.1; HRMS calculated for $C_{18}H_{15}N$ $[M+H]^+$, $M_r = 246.1283$, found $M_r = 246.1281$.

(*R*)-1-(1-(4-Methoxyphenyl)prop-2-yn-1-yl)-1*H*-indole (**3ah**). Obtained as a colorless oil in 85% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 70/1$); 83% ee was determined by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 11.7 min, t_R (minor) = 19.9 min; $[\alpha]_D^{29} = 134.5$ (*c* 0.25, CH_2Cl_2); 1H NMR (400 MHz, $CDCl_3$): $\delta = 7.63$ – 7.61 (m, 1H), 7.36–7.09 (m, 6H), 6.86–6.84 (m, 2H), 6.54 (d, $J = 3.2$ Hz, 1H), 6.36 (d, $J = 2.2$ Hz, 1H), 3.77 (s, 3H), 2.67 (d, $J = 2.5$ Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta = 159.7$, 135.5, 129.5, 129.2, 128.1, 126.3, 121.8, 121.2, 119.9, 114.2, 110.0, 102.3, 80.3, 75.2, 55.3, 51.1; HRMS calculated for $C_{18}H_{15}NO$ $[M+H]^+$, $M_r = 262.1232$, found $M_r = 262.1229$.

(*R*)-1-(1-(Naphthalen-2-yl)prop-2-yn-1-yl)-1*H*-indole (**3ai**). Obtained as a colorless oil in 88% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 70/1$); 87% ee was determined by chiral HPLC (Chiralcel OJ-H, *n*-hexane/*i*-PrOH = 50/50, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 36.3 min, t_R (minor) = 26.9 min; $[\alpha]_D^{29} = 205.4$ (*c* 0.46, CH_2Cl_2); 1H NMR (400 MHz, $CDCl_3$): $\delta = 7.90$ – 7.63 (m, 5H), 7.48–7.09 (m, 7H), 6.57–6.54 (m, 2H), 2.73 (dd, $J = 2.4$, 1.0 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta = 135.7$, 134.7, 133.2, 133.2, 129.3, 128.9, 128.3, 127.7, 126.6, 126.6, 126.5, 125.9, 124.4, 122.0, 121.2, 120.1, 110.0, 102.6, 80.0, 75.9, 51.8; HRMS calculated for $C_{21}H_{15}N$ $[M+H]^+$, $M_r = 282.1283$, found $M_r = 282.1280$.

(*R*)-1-(1-(Thiophen-2-yl)prop-2-yn-1-yl)-1*H*-indole (**3aj**). Obtained as a colorless oil in 89% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 100/1$); 91% ee was determined by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 11.3 min, t_R (minor) = 19.4 min; $[\alpha]_D^{29} = 162.6$ (*c* 0.14, CH_2Cl_2); 1H NMR (400 MHz, $CDCl_3$): $\delta = 7.62$ (d, $J = 7.8$ Hz, 1H), 7.42 (d, $J = 8.1$ Hz, 1H), 7.29–7.08 (m, 5H), 6.90 (dd, $J = 5.1$, 3.6 Hz, 1H), 6.56–6.54 (m, 2H), 2.67 (d, $J = 2.5$ Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta = 141.0$, 135.4, 129.3, 126.9, 126.4, 126.2, 126.0, 122.0, 121.3, 120.2, 109.9, 102.9, 79.6, 74.9, 47.5; HRMS calculated for $C_{15}H_{11}NS$ $[M+H]^+$, $M_r = 238.0690$, found $M_r = 238.0689$.

(*R*)-3-Methyl-1-(1-phenylprop-2-yn-1-yl)-1*H*-indole (**3ba**). Obtained as a colorless oil in 89% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 100/1$); 94% ee was determined by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 10.1 min, t_R (minor) = 12.7 min; $[\alpha]_D^{29} = 116.4$ (*c* 0.46, CH_2Cl_2); 1H NMR (400 MHz, $CDCl_3$): $\delta = 7.57$ – 7.55 (m, 1H), 7.36–7.09 (m, 8H), 7.03 (s, 1H), 6.34 (s, 1H), 2.64 (dd, $J = 2.4$, 0.9 Hz, 1H), 2.32–2.31 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): $\delta = 137.7$, 136.0, 129.5, 128.8, 128.4, 126.8, 123.9, 121.9, 119.4, 119.3, 111.8, 109.7, 80.4, 75.2, 51.3, 9.7; HRMS calculated for $C_{18}H_{15}N$ $[M+H]^+$, $M_r = 246.1283$, found $M_r = 246.1281$.

(*R*)-2-Methyl-1-(1-phenylprop-2-yn-1-yl)-1*H*-indole (**3ca**). Obtained as a yellow solid in 90% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate ($V/V = 100/1$); m.p. = 53–55 °C; 89% ee was de-

terminated by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 7.8 min, t_R (minor) = 9.5 min; $[\alpha]_{D}^{29} = 208.5$ (*c* 0.76, CH₂Cl₂); ¹H NMR (400 MHz, CDCl₃): δ = 7.53–7.50 (m, 1H), 7.28–7.24 (m, 6H), 7.07–7.03 (m, 2H), 6.51 (s, 1H), 6.32 (s, 1H), 2.64 (dd, *J* = 2.4, 2.0 Hz, 1H), 2.38–2.37 (m, 1H); ¹³C NMR (101 MHz, CDCl₃): δ = 137.2, 136.5, 136.3, 128.7, 128.6, 128.1, 126.3, 126.3, 120.8, 119.9, 110.6, 101.9, 79.7, 75.2, 48.9, 13.5; HRMS calculated for C₁₈H₁₅N [M+H]⁺, $M_r = 246.1283$, found $M_r = 246.1279$.

(*R*)-4-Methyl-1-(1-phenylprop-2-yn-1-yl)-1*H*-indole (**3da**). Obtained as a colorless oil in 86% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate (*V/V* = 100/1); 88% ee was determined by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 8.5 min, t_R (minor) = 10.4 min; $[\alpha]_{D}^{29} = 98.9$ (*c* 0.50, CH₂Cl₂); ¹H NMR (400 MHz, CDCl₃): δ = 7.35–7.28 (m, 6H), 7.20–7.05 (m, 2H), 6.92–6.90 (m, 1H), 6.58–6.57 (m, 1H), 6.38 (s, 1H), 2.66 (dd, *J* = 2.4, 2.0 Hz, 1H), 2.54 (d, *J* = 2.2 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃): δ = 137.5, 135.4, 130.7, 129.0, 128.9, 128.4, 126.7, 125.8, 122.1, 120.3, 107.6, 101.0, 80.2, 75.5, 51.7, 18.7; HRMS calculated for C₁₈H₁₅N [M+H]⁺, $M_r = 246.1283$, found $M_r = 246.1282$.

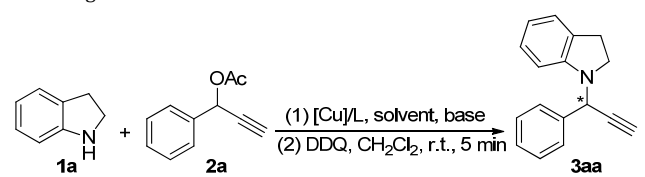
(*R*)-6-Fluoro-1-(1-phenylprop-2-yn-1-yl)-1*H*-indole (**3ea**). Obtained as a colorless oil in 91% yield following purification by FCC over silica gel eluting with a mixture of hexanes and ethyl acetate (*V/V* = 100/1); 90% ee was determined by chiral HPLC (Chiralcel OD-H, *n*-hexane/*i*-PrOH = 95/5, 0.8 mL/min, detection at 230 nm, column temperature 40 °C): t_R (major) = 8.3 min, t_R (minor) = 9.2 min. $[\alpha]_{D}^{29} = 94.7$ (*c* 0.80, CH₂Cl₂); ¹H NMR (400 MHz, CDCl₃): δ = 7.53–7.50 (m, 1H), 7.33–7.23 (m, 6H), 7.01 (d, *J* = 9.9 Hz, 1H), 6.89–6.84 (m, 1H), 6.52 (d, *J* = 3.3 Hz, 1H), 6.28 (d, *J* = 2.4 Hz, 1H), 2.70 (d, *J* = 2.5 Hz, 1H); ¹³C NMR (101 MHz, CDCl₃): δ = 159.7 (d, *J* = 237.9 Hz), 137.0, 135.5 (d, *J* = 12.2 Hz), 128.9, 128.6, 127.0 (d, *J* = 3.7 Hz), 126.7, 125.6, 121.8 (d, *J* = 10.2 Hz), 108.8 (d, *J* = 24.6 Hz), 102.5, 96.8 (d, *J* = 26.8 Hz), 79.6, 75.9, 52.0; HRMS calculated for C₁₇H₁₂FN [M+H]⁺, $M_r = 250.1032$, found $M_r = 250.1026$.

3. Results and discussion

The optically active *N*-propargylindoles were prepared according to the strategy reported by Corey et al. [23] via an *N*-propargylation/dehydrogenation sequence (Scheme 1). The optical purity of the *N*-propargylindole products was found to be determined during the propargylic alkylation step. With this in mind, we screened a variety of chiral ligands in this reaction that have been proven to be performed effectively as ligands in various other Cu-catalyzed asymmetric propargylic substitution reactions [1,2,12,16]. Indoline (**1a**) and 1-phenylprop-2-yn-1-yl acetate (**2a**) were selected as model substrates for this reaction, which was performed in the presence of 5 mol% Cu catalyst (prepared in situ from 5 mol% Cu(OAc)₂·H₂O and 5.5 mol% chiral ligand) and 1.2 equiv of *i*-Pr₂NEt in MeOH (3 mL) at 0 °C for 5 h. Upon completion of the propargylation reaction, the Cu catalyst was removed by filtration. Evaporation of the

MeOH solvent gave the crude *N*-propargylindoline as a residue, which was treated with a solution of DDQ in CH₂Cl₂ at room temperature to give the corresponding dehydrogenated product in only 5 min. The desired 1-(1-phenylprop-2-yn-1-yl)-1*H*-indole (**3aa**) was obtained in good yield in all cases, although it is noteworthy that the structure of the ligand was found to have a significant impact on the enantioselectivity of the reaction (Table 1, entries 1–5). For example, BINAP (**L1**) and the P,N,N-ligands **L3** and **L4** gave moderate enantioselectivity (Table 1, entries 1, 3, and 4), whereas the tridentate N-ligand **L2** gave a low enantioselectivity (Table 1, entry 2). The bulky and structurally rigid chiral tridentate ketimine P,N,N-ligand (*S*)-**L5**, which was developed in our group, gave the best result of all of the ligands screened in this reaction in terms of its reactivity

Table 1
Screening the reaction condition.



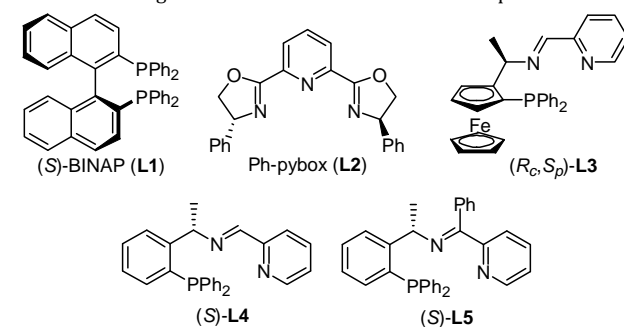
Entry	[Cu]	L	Base	Solvent	Yield ^a (%)	ee ^b (%)
1	Cu(OAc) ₂ ·H ₂ O	L1	<i>i</i> -Pr ₂ NEt	MeOH	87	72 (<i>R</i>)
2	Cu(OAc) ₂ ·H ₂ O	L2	<i>i</i> -Pr ₂ NEt	MeOH	87	38 (<i>S</i>)
3	Cu(OAc) ₂ ·H ₂ O	L3	<i>i</i> -Pr ₂ NEt	MeOH	85	79 (<i>S</i>)
4	Cu(OAc) ₂ ·H ₂ O	L4	<i>i</i> -Pr ₂ NEt	MeOH	89	76 (<i>R</i>)
5	Cu(OAc) ₂ ·H ₂ O	L5	<i>i</i> -Pr ₂ NEt	MeOH	90	92 (<i>R</i>)
6	Cu(OTf) ₂	L5	<i>i</i> -Pr ₂ NEt	MeOH	89	92 (<i>R</i>)
7	CuCl	L5	<i>i</i> -Pr ₂ NEt	MeOH	81	87 (<i>R</i>)
8	CuI	L5	<i>i</i> -Pr ₂ NEt	MeOH	82	83 (<i>R</i>)
9	Cu(CH ₃ CN) ₄ BF ₄	L5	<i>i</i> -Pr ₂ NEt	MeOH	87	91 (<i>R</i>)
10	Cu(OAc) ₂ ·H ₂ O	L5	DBU	MeOH	65	76 (<i>R</i>)
11	Cu(OAc) ₂ ·H ₂ O	L5	Et ₃ N	MeOH	88	92 (<i>R</i>)
12	Cu(OAc) ₂ ·H ₂ O	L5	—	MeOH	45	25 (<i>R</i>)
13	Cu(OAc) ₂ ·H ₂ O	L5	K ₂ CO ₃	MeOH	88	89 (<i>R</i>)
14	Cu(OAc) ₂ ·H ₂ O	L5	<i>i</i> -Pr ₂ NEt	CH ₂ Cl ₂	—	—
15	Cu(OAc) ₂ ·H ₂ O	L5	<i>i</i> -Pr ₂ NEt	Toluene	—	—
16	Cu(OAc) ₂ ·H ₂ O	L5	<i>i</i> -Pr ₂ NEt	THF	—	—
17	Cu(OAc) ₂ ·H ₂ O	L5	<i>i</i> -Pr ₂ NEt	DMF	—	—
18	Cu(OAc) ₂ ·H ₂ O	L5	<i>i</i> -Pr ₂ NEt	DMSO	—	—
19	Cu(OAc) ₂ ·H ₂ O	L5	<i>i</i> -Pr ₂ NEt	MeOH	35	92 (<i>R</i>) ^c

Reaction conditions: (1) **1a** (0.33 mmol), **2a** (0.3 mmol), [Cu] (0.015 mmol, 5 mol%), L (0.0165 mmol, 5.5 mol%) and base (0.36 mmol) in solvent (3 mL) at 0 °C for 5 h; (2) DDQ (0.33 mmol) in CH₂Cl₂ (3 mL) at r.t. for 5 min.

^a Isolated yield.

^b Determined by chiral HPLC analysis.

^c A solution of DDQ in CH₂Cl₂ (3 mL) was added directly to the reaction mixture following the removal of MeOH under reduced pressure.

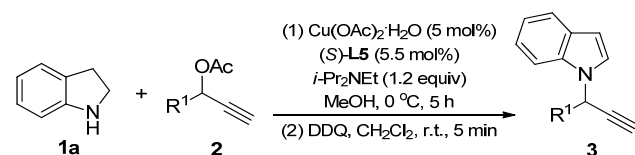


and enantioselectivity, and was selected as the optimum ligand for further evaluation (Table 1, entry 5).

A variety of different Cu sources were also screened in this model reaction, but the results revealed that the type of Cu salts used in the transformation had no discernible impact on the reactivity or enantioselectivity of the reaction (Table 1, entries 5–9). These results demonstrated that Cu(OAc)₂·H₂O was the best source of Cu for the reaction (Table 1, entry 5). The addition of a base was determined to be critical to the success of this reaction, with the product being formed in a very low yield and enantioselectivity when the reaction was performed in the absence of base (Table 1, entry 12). The addition of a stronger base, such as 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), had a detrimental impact on the yield and enantioselectivity of the reaction (Table 1, entry 10), whereas the use of Et₃N provided similar good result to that of *i*-Pr₂NEt (Table 1, entry 11). Interestingly, the inorganic base K₂CO₃ also performed efficiently in the reaction, with the desired product being formed in good yield and enantioselectivity (Table 1, entry 13). The effect of the solvent on the outcome of the model reaction was also investigated, and the results revealed a significant solvent dependency. For example, MeOH was found to be the only one of the six different solvents tested to be suitable for the transformation, with very little product being observed when the reaction was conducted in CH₂Cl₂, toluene, tetrahydrofuran, *N,N*-dimethylformamide or dimethyl sulfoxide (Table 1, entries 14–18). These results were found to be consistent with those observed in other Cu-catalyzed asymmetric propargylic substitution reactions [1,2]. Pleasingly, a one-pot version of this reaction also worked well, with 1.1 equivalents of DDQ being added directly to the reaction mixture upon the completion of

Table 2

Cu-catalyzed propargylation/dehydrogenation of indoline (**1a**) with propargylic esters (**2**).



Entry	2 (R ¹)	3	Yield ^a (%)	ee ^b (%)
1	2a : R ¹ = Ph	3aa	90	92 (R) ^c
2	2b : R ¹ = 2-ClC ₆ H ₄	3ab	79	85
3	2c : R ¹ = 3-ClC ₆ H ₄	3ac	88	93
4	2d : R ¹ = 4-ClC ₆ H ₄	3ad	91	91
5	2e : R ¹ = 4-BrC ₆ H ₄	3ae	92	89
6	2f : R ¹ = 4-CF ₃ C ₆ H ₄	3af	86	90
7	2g : R ¹ = 4-MeC ₆ H ₄	3ag	87	90
8	2h : R ¹ = 4-MeOC ₆ H ₄	3ah	85	83
9	2i : R ¹ = 2-naphthyl	3ai	88	87
10	2j : R ¹ = 2-thienyl	3aj	89	91

Reaction conditions: (1) **1a** (0.33 mmol), **2** (0.3 mmol), Cu(OAc)₂·H₂O (0.015 mmol, 5 mol%), (*S*)-**L5** (0.0165 mmol, 5.5 mol%) and *i*-Pr₂NEt (0.36 mmol) in MeOH (3 mL) at 0 °C for 5 h; (2) DDQ (0.33 mmol) in CH₂Cl₂ (3 mL) at r.t. for 5 min.

^a Isolated yields.

^b Determined by chiral HPLC analysis.

^c The absolute configuration was determined by comparing the specific rotation of the corresponding 1-(1-phenylprop-2-yn-1-yl)indoline compound with the data reported in Ref. [8].

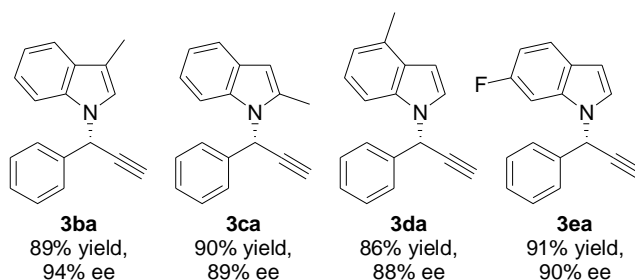


Fig. 1. Scope of indolines.

Cu-catalyzed propargylic amination step. Disappointingly, however, this process gave a much lower yield of the desired product, albeit with a high enantioselectivity (Table 1, entry 19). This result suggested that the Cu salt had an adverse impact on the DDQ-mediated dehydrogenation process.

With optimized conditions in hand, we proceeded to investigate the scope of the reaction using a variety of different propargylic esters (Table 2). The results of the reactions indicated that the substitution pattern of the phenyl ring had an impact on the outcome of the reaction (Table 2, entries 2–4). For example, the 3- and 4-Cl substituted substrates (**2c** and **2d**, respectively) provided the corresponding indole products in good yields and high enantioselectivities (Table 2, entries 3 and 4), whereas the 2-Cl substituted substrate **2b** gave the corresponding product with a decreased yield and lower enantioselectivity (Table 2, entry 2). The electronic properties of the substituent at the para position of the phenyl ring also had a significant impact on the performance of the reaction. In most cases, the reaction gave good results, although the 4-MeO-substituted substrate **2h** gave a slight decrease in the enantioselectivity of the product to 83% ee (Table 2, entry 8). The 2-naphthyl substrate **2i** reacted smoothly to give 1-(1-(naphthalen-2-yl)prop-2-yn-1-yl)-1*H*-indole (**3ai**) in 88% yield and 87% ee (Table 2, entry 9). The 2-thienyl substrate **2j** also performed well in the reaction, with the corresponding *N*-propargylindole product **3aj** being formed in 89% yield and 91% ee (Table 2, entry 10).

The scope of the indolines was also evaluated (Fig. 1), and the results revealed that the optimized reaction could be successfully applied to a variety of substituted indolines. For example, 2-, 3- and 4-methyl indolines all reacted smoothly under the optimized conditions to give the corresponding *N*-propargylated indoles **3ba**, **3ca**, and **3da**, respectively, in good yields and high enantioselectivities. Electron-withdrawing substituents were also well tolerated on the indoline ring with 6-fluoroindoline reacting smoothly to give the *N*-propargylated fluoroindole product **3ea** in a high yield and enantioselectivity.

4. Conclusions

We have developed an efficient and highly enantioselective process for the construction of optically active *N*-propargylindoles via the Cu-catalyzed asymmetric propargylic amination of indolines with propargylic esters followed by the dehydrogenation of the resulting *N*-substituted indolines with DDQ. This reaction can be performed under mild conditions using a

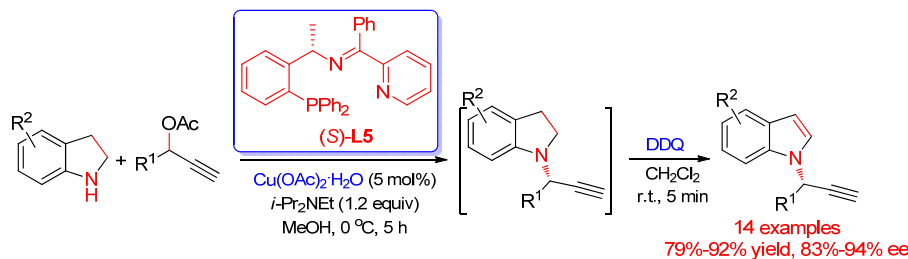
Graphical Abstract

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Enantioselective *N*-propargylation of indoles via Cu-catalyzed propargylic alkylation/dehydrogenation of indolines

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A new strategy has been developed for the sequential Cu-catalyzed asymmetric propargylic alkylation and DDQ-mediated dehydrogenation of indolines using a bulky and structurally rigid ketimine P,N,N-ligand. This reaction allowed for the enantioselective synthesis of optically active *N*-propargylindoles.

broad range of different substrates, with the resulting chiral *N*-propargylindole products being formed in good yields and high enantioselectivities. Further work towards the development and application of this reaction is currently underway in our laboratory.

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Cu催化吲哚啉的炔丙基烷基化/脱氢对映选择性合成手性*N*-炔丙基吲哚化合物朱付林^{a,b}, 胡向平^{a,*}^a中国科学院大连化学物理研究所, 辽宁大连116023^b中国科学院大学, 北京100049

摘要: 基于吲哚啉的Cu催化不对称炔丙基烷基化及DDQ脱氢策略, 成功合成了手性*N*-炔丙基吲哚化合物. 通过使用一个结构刚性的酮亚胺三齿P,N,N-配体, 反应获得了很好的对映选择性. 该方法反应条件温和、底物适用范围广、产物收率高、立体选择性好, 为手性*N*-炔丙基吲哚化合物的合成提供了一条简捷、高效的新途径.

关键词: 不对称合成; 铜; 炔丙基取代; 脱氢; *N*-炔丙基吡啶

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