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Synthesis of 3-aminoindole derivatives: combination of Thorpe–Ziegler cyclization and unexpected allylindium-mediated decyanation

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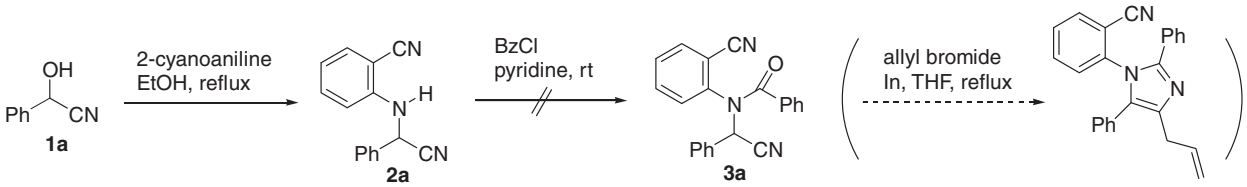
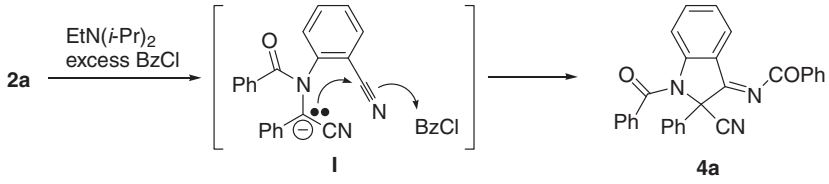
ABSTRACT

α-Anilinonitriles were unexpectedly converted to 3-iminodihydroindoles via the Thorpe–Ziegler cyclization during the benzoylation. 3-Iminodihydroindoles were transformed to 3-aminoindoles in good yields via an allylindium-mediated decyanative aromatization.

Allylindium reagents have been used extensively for the introduction of allyl groups in a Barbier type manner to various electrophiles.[1,2] Various electrophiles including aldehydes, ketones, imines, *N*-tosylimines, and nitriles have been used in the



Scheme 1.



Scheme 2.

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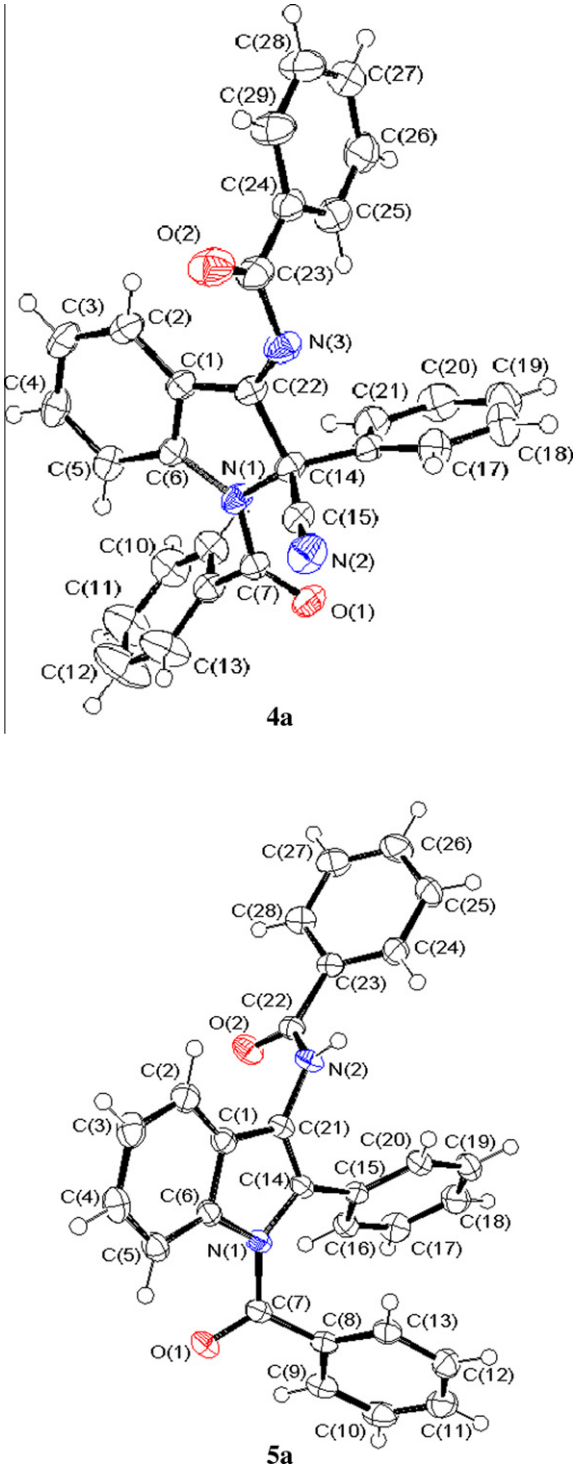


Figure 1. ORTEP drawing of compounds **4a** and **5a**.

indium-mediated allylation[1,2] with the allyl transfer to the electrophilic carbon atom occurring via a six-membered transition state.[1,2]

Recently we reported the synthesis of alkenylimidazoles via an In-mediated allylation of various α-aminonitrile derivatives.[3] As a continuation, we tried to prepare compound **3a** having an *ortho*-cyanoaniline moiety in order to synthesize allylimidazole derivatives by the reaction of an allylindium reagent (Scheme 1). However, the benzoylation of **2a** with benzoyl chloride in pyridine failed at room temperature.[3,4] The benzoylation reaction was also ineffective even at elevated temperature (70 °C, 3 h) in pyridine or in the presence of Et_3N in CH_2Cl_2. The failure might be ascribed to the steric hindrance around the nucleophilic nitrogen atom of **2a** and the presence of an electron-withdrawing *ortho*-CN group in part.

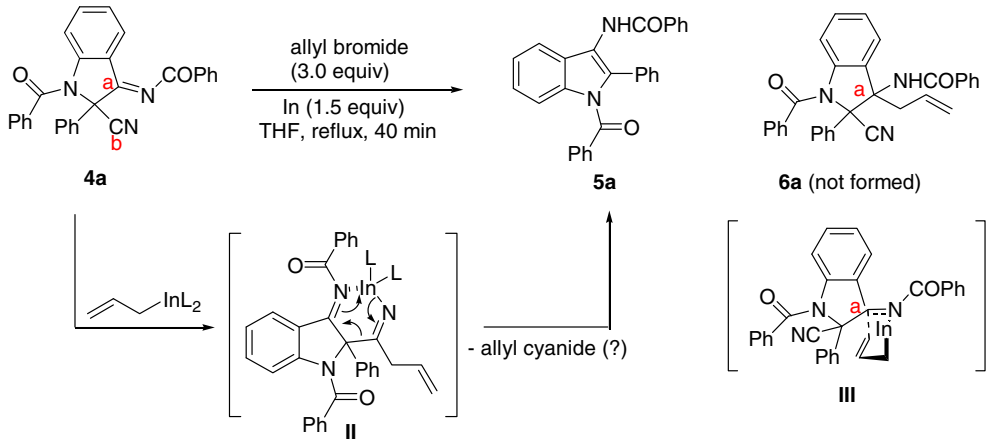
After many trials, the 3-iminodihydroindole derivative **4a** was obtained unexpectedly from **2a** in 87% in the presence of benzoyl chloride and *N,N*-diisopropylethylamine in toluene at elevated temperature (70 °C, Scheme 2).[5] Compound **4a** might be formed via N-benzoylation, subsequent Thorpe–Ziegler cyclization[6] of α-carbanion **I** and benzoylation of the imine intermediate. It is unclear at this stage as which step occurs first, the benzoylation or the tandem Thorpe–Ziegler cyclization accompanying benzoylation of imine intermediate.[4e,f] The structure of **4a** was confirmed unequivocally by X-ray diffraction (Fig. 1), and the spectroscopic data.[7,8]

We found an interesting reactivity of **4a** toward allylindium reagents (Scheme 3). To our surprise, the 3-aminoindole derivative **5a** was obtained in 73% under the influence of allyl bromide and indium metal (THF, reflux, 40 min).[7–10] We expected originally the formation of compound **6a** by allylation at the imine double bond (*allylation to position-a*) via the six-membered chelated transition state **III**; however, we did not observe any trace of **6a**. Instead, the allyl group was transferred from allylindium to the nitrile moiety (*allylation to position-b*) to form an intermediate **II** in which indium is chelated by two atoms of nitrogen in a six-membered transition state. This intermediate **II** was converted to the aromatic indole derivative **5a** by liberation of allyl cyanide.[11] The structure of **5a** was also confirmed by X-ray diffraction (Fig. 1), and the spectroscopic data.[7,8]

The reaction of **4a** and methallyl bromide instead of allyl bromide under the same conditions produced **5a** in a similar yield (68%).[11] We thought that an appropriate nucleophile could attack the nitrile moiety and cause the decyanative aromatization; however, various trials for the conversion of **4a** to **5a** failed including the use of $NaHCO_3$/aq THF, THF/*c*-HCl, $NaBH_4$/EtOH, $InCl_3$/THF, $FeCl_3$/THF, $ZnBr_2$/THF, NaI/DMSO, and $(MeO)_3P$/toluene.

Encouraged by the results, we prepared α-aminonitriles **2a–d**[3,4] and generated the dihydroindoles **4a–f**. Subsequent treatment with indium and allyl bromide afforded the 3-aminoindoles **5a–f**. The results are summarized in Table 1. The reactions of **2a** with *p*-toluoyl chloride and 2,6-difluorobenzoyl chloride afforded the corresponding dihydroindoles **4b** and **4c**, respectively (entries 2 and 3). The reactions of **2b–d** and benzoyl chloride produced **4d–f** in good yields similarly (entries 4–6). All of the dihydroindoles **4a–f** were transformed to 3-aminoindoles **5a–f** in moderate to good yields (56–76%) under the influence of allylindium reagents.

In summary, we disclose a novel synthesis of 3-aminoindole derivatives from α-aminonitriles via Thorpe–Ziegler cyclization followed by an allylindium-mediated decyanative aromatization process.



Scheme 3.

Table 1
Synthesis of 3-aminoindole derivatives

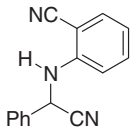
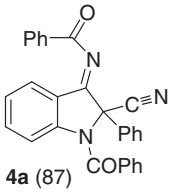
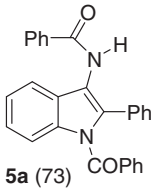
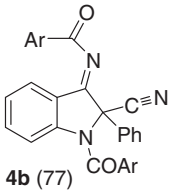
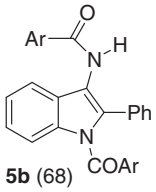
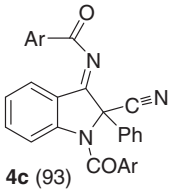
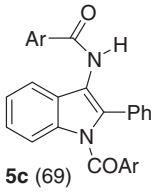
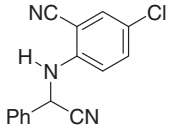
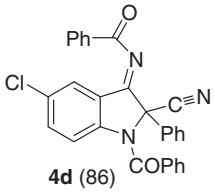
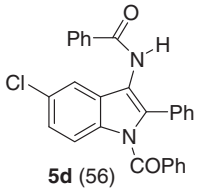
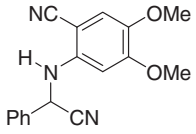
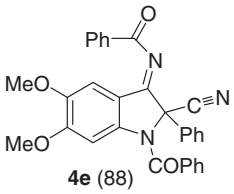
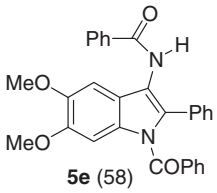
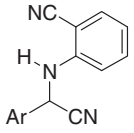
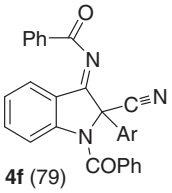
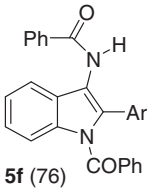
Entry	Substrate **2**[a] (%)	Product **4**[b] (%)	Indole **5**[c] (%)
1	 **2a** (65)	 **4a** (87)	 **5a** (73)
2[d]	**2a**	 **4b** (77)	 **5b** (68)
3[e]	**2a**	 **4c** (93)	 **5c** (69)
4	 **2b** (54)	 **4d** (86)	 **5d** (56)
5	 **2c** (80)	 **4e** (88)	 **5e** (58)

Table 1 (*continued*)

Entry	Substrate **2**[a] (%)	Product **4**[b] (%)	Indole **5**[c] (%)
6[f]	 **2d** (51)	 **4f** (79)	 **5f** (76)

[a] Prepared from mandelonitrile and 2-cyanoaniline derivatives in EtOH (reflux, 30 h).
[b] Prepared from **2** and aroyl chloride (4.0 equiv), EtN(*i*-Pr)$_2$ (4.0 equiv), toluene, 70 °C, 2 h.
[c] Allyl bromide (3.0 equiv), In (1.5 equiv), THF, reflux, 40 min.
[d] Ar is *p*-tolyl.
[e] Ar is 2,6-difluorophenyl.
[f] Ar is *p*-tolyl.

Acknowledgments

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References and notes

1. For the general review on indium-mediated reactions, see: (a) Auge, J.; Lubin-Germain, N.; Uziel, J. *Synthesis* **2007**, 1739–1764; (b) Kargbo, R. B.; Cook, G. R. *Curr. Org. Chem.* **2007**, *11*, 1287–1309; (c) Lee, P. H. *Bull. Korean Chem. Soc.* **2007**, *28*, 17–28; (d) Li, C.-J.; Chan, T.-H. *Tetrahedron* **1999**, *55*, 11149–11176; (e) Pae, A. N.; Cho, Y. S. *Curr. Org. Chem.* **2002**, *6*, 715–737; (f) Kim, S. H.; Lee, H. S.; Kim, K. H.; Kim, S. H.; Kim, J. N. *Tetrahedron* **2010**, *66*, 7065–7076.
2. For the In-mediated Barbier-type allylation of nitrile-containing substrates, see: (a) Kim, S. H.; Lee, H. S.; Kim, K. H.; Kim, J. N. *Tetrahedron Lett.* **2009**, *50*, 1696–1698; (b) Kim, S. H.; Kim, S. H.; Lee, K. Y.; Kim, J. N. *Tetrahedron Lett.* **2009**, *50*, 5744–5747; (c) Kim, S. H.; Lee, H. S.; Kim, K. H.; Kim, J. N. *Tetrahedron Lett.* **2009**, *50*, 6476–6479; (d) Kim, S. H.; Kim, S. H.; Kim, K. H.; Kim, J. N. *Tetrahedron Lett.* **2010**, *51*, 860–862; (e) Kim, S. H.; Kim, S. H.; Kim, T. H.; Kim, J. N. *Tetrahedron Lett.* **2010**, *51*, 2774–2777.
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5. The reaction of **2a** and benzoyl chloride (4.0 equiv) in the presence of Et_3N (4.0 equiv) in toluene (90–100 °C, 3 h) also afforded **4a**, albeit in low yield (48%). In contrast, the reactions under the influence of Cs_2CO_3/DMF (rt–70 °C, 2 h), K_2CO_3/CH_3CN (rt, 10 h), or *t*-BuOK/THF (rt, 2 h) were all ineffective for the synthesis of **4a**.
6. For Thorpe–Ziegler dinitrile cyclization, see: (a) Fleming, F. F.; Shook, B. C. *Tetrahedron* **2002**, *58*, 1–23. and further references cited therein; (b) Schaefer, J. P.; Bloomfield, J. J. *Org. React.* **1967**, *15*, 1–203; (c) Takaya, H.; Naota, T.; Murahashi, S.-I. *J. Am. Chem. Soc.* **1998**, *120*, 4244–4245; (d) Toro, A.; Nowak, P.; Deslongchamps, P. *J. Am. Chem. Soc.* **2000**, *122*, 4526–4527; (e) Winkler, M.; Martinkova, L.; Knall, A. C.; Krahulec, S.; Klempier, N. *Tetrahedron* **2005**, *61*, 4249–4260.
7. *Crystal data of 3-iminodihydroindole* **4a**: solvent of crystal growth (hexane); empirical formula $C_{29}H_{19}N_3O_2$, *Fw* = 441.47, crystal dimensions 0.28 × 0.15 × 0.14 mm^3, monoclinic, space group *P*2(1)/*c*, *a* = 8.959(2) Å, *b* = 21.637(5) Å, *c* = 11.593(3) Å, α = 90°, β = 93.785(14)°, γ = 90°, *V* = 2242.5(9) Å^3, *Z* = 4, D_{calcd} = 1.308 mg/m^3, F_{000} = 920, Mo Kα (λ = 0.71073 Å), R_1 = 0.0559, wR_2 = 0.1272 ($I > 2\sigma(I)$). The X-ray data has been deposited in CCDC with number 802632.
Crystal data of 3-aminoindole **5a**: solvent of crystal growth (EtOH); empirical formula $C_{28}H_{20}N_2O_2$, *Fw* = 416.46, crystal dimensions 0.29 × 0.22 × 0.09 mm^3, monoclinic, space group *P*2(1)/*c*, *a* = 14.2679(4) Å, *b* = 9.1186(3) Å, *c* = 16.2940(4) Å, α = 90°, β = 103.187(2)°, γ = 90°, *V* = 2064.00(10) Å^3, *Z* = 4, D_{calcd} = 1.340 mg/m^3, F_{000} = 872, Mo Kα (λ = 0.71073 Å), R_1 = 0.0389, wR_2 = 0.0888 ($I > 2\sigma(I)$). The X-ray data has been deposited in CCDC with number 802633.
8. *Typical procedure for the synthesis of compound* **4a**: To a stirred solution of compound **2a** (117 mg, 0.5 mmol) in toluene (1.0 mL) was added EtN(*i*-Pr)$_2$ (258 mg, 2.0 mmol) and benzoyl chloride (280 mg, 2.0 mmol) at room temperature. The reaction mixture was heated to 70 °C for 2 h. After the usual aqueous extractive workup and column chromatographic purification process (hexanes/CH_2Cl_2/EtOAc, 10:1:1), compound **4a** was obtained as a white solid, 192 mg (87%). Other compounds were synthesized similarly, and the spectroscopic data of **4a**–**f** are as follows.
Compound **4a**: 87%; white solid, mp 182–184 °C; IR (KBr) 1688, 1667, 1466, 1338 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 6.89 (d, *J* = 7.5 Hz, 1H), 7.07 (t, *J* = 7.5 Hz, 1H), 7.34–7.57 (m, 15H), 7.80 (d, *J* = 7.5 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 68.39, 115.46, 116.73, 119.59, 125.15, 125.73, 127.04, 127.71, 128.65, 128.88, 129.24, 129.32, 129.69, 131.89, 131.96, 133.77, 134.06, 134.42, 135.79, 149.21, 161.99, 167.49, 177.42; ESIMS *m/z* 442 (M$^+$+H). Anal. Calcd for $C_{29}H_{19}N_3O_2$: C, 78.90; H, 4.34; N, 9.52. Found: C, 79.07; H, 4.56; N, 9.33.
Compound **4b**: 77%; yellow solid, mp 96–98 °C; IR (KBr) 1688, 1666, 1466, 1335 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 2.34 (s, 3H), 2.39 (s, 3H), 6.79 (d, *J* = 8.4 Hz, 1H), 7.00 (t, *J* = 8.1 Hz, 1H), 7.13–7.41 (m, 10H), 7.47–7.58 (m, 3H), 7.66–7.69 (d, *J* = 8.1 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.45, 21.52, 68.24, 115.40, 116.37, 119.26, 124.78, 125.50, 126.89, 127.75, 129.01, 129.09 (2C), 129.23, 129.39, 131.28, 134.11, 135.49, 142.70, 144.61, 149.02, 161.69, 167.19, 171.32 (one carbon is missing); ESIMS *m/z* 470 (M$^+$+H). Anal. Calcd for $C_{31}H_{23}N_3O_2$: C, 79.30; H, 4.94; N, 8.95. Found: C, 79.51; H, 4.98; N, 8.69.
Compound **4c**: 93%; yellow solid, mp 172–174 °C; IR (KBr) 1678, 1622, 1468, 1354 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 6.32–6.46 (br m, 1H), 6.90 (t, *J* = 8.4 Hz, 2H), 6.96–7.72 (m, 11 H), 7.76 (d, *J* = 8.1 Hz, 1H); ESIMS *m/z* 514 (M$^+$+H). Anal. Calcd for $C_{29}H_{15}F_4N_3O_2$: C, 67.84; H, 2.94; N, 8.18. Found: C, 67.89; H, 3.25; N, 7.99.
Compound **4d**: 86%; white solid, mp 100–102 °C; IR (KBr) 1688, 1668, 1463, 1329 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 6.94 (d, *J* = 7.5 Hz, 1H), 7.30–7.47 (m, 12H), 7.50–7.55 (m, 3H), 7.76 (d, *J* = 7.5 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 68.60, 115.07, 117.94, 121.12, 125.77, 126.12, 127.60, 128.62, 128.87, 129.23, 129.32, 129.82, 130.67, 131.68, 132.03, 133.46, 133.91, 134.07, 135.72, 147.77, 160.81, 167.41, 176.88; ESIMS *m/z* 476 (M$^+$+H), 478 (M$^+$+H+2). Anal. Calcd for $C_{29}H_{18}ClN_3O_2$: C, 73.19; H, 3.81; N, 8.83. Found: C, 73.44; H, 3.84; N, 8.95.
Compound **4e**: 88%; yellow solid, mp 218–220 °C; IR (KBr) 1681, 1660, 1502, 1339 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 3.62 (s, 3H), 3.70 (s, 3H), 6.57 (br s, 1H), 6.91 (s, 1H), 7.24–7.58 (m, 13H), 7.80 (d, *J* = 7.5 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 56.00, 56.03, 68.73, 99.85, 106.31, 111.58, 115.60, 125.62, 127.54, 128.55, 128.67, 129.13, 129.22, 129.55, 131.39, 132.68, 133.51, 134.22, 134.76, 145.88, 147.27, 155.83, 161.69, 177.82 (one carbon is missing); ESIMS *m/z* 502 (M$^+$+H). Anal. Calcd for $C_{31}H_{23}N_3O_4$: C, 74.24; H, 4.62; N, 8.38. Found: C, 74.51; H, 4.93; N, 8.32.
Compound **4f**: 79%; white solid, mp 204–206 °C; IR (KBr) 1677, 1663, 1465, 1342 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 2.28 (s, 3H), 6.81 (d, *J* = 6.6 Hz, 1H), 7.03–7.14 (m, 3H), 7.28–7.55 (m, 12H), 7.80 (d, *J* = 7.5 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.01, 68.06, 115.46, 116.52, 119.67, 125.00, 125.72, 126.81, 127.66, 128.49, 128.79, 129.14, 129.85, 130.81, 131.79, 131.94, 133.58, 134.35, 135.67, 139.73, 149.02, 162.01, 167.31, 177.46; ESIMS *m/z* 456 (M$^+$+H). Anal. Calcd for $C_{30}H_{21}N_3O_2$: C, 79.10; H, 4.65; N, 9.22. Found: C, 78.95; H, 4.81; N, 9.02.
Typical procedure for the synthesis of compound **5a**: A stirred mixture of compound **4a** (132 mg, 0.3 mmol), allyl bromide (109 mg, 0.9 mmol), and indium (52 mg, 0.45 mmol) in THF (0.5 mL) was heated to reflux for 40 min under N_2 atmosphere. After the usual aqueous extractive workup and column chromatographic purification process (hexanes/CH_2Cl_2/EtOAc, 10:1:2), compound **5a** was obtained as a white solid, 91 mg (73%). Other compounds were synthesized similarly, and the spectroscopic data of **5a**–**f** are as follows.
Compound **5a**: 73%; white solid, mp 228–230 °C; IR (KBr) 3210, 1680, 1649, 1451 cm^{-1}; ^{1}H NMR ($CDCl_3$ + DMSO-d_6, 300 MHz) δ 7.07–7.19 (m, 3H), 7.24–7.63 (m, 14H), 8.00 (d, *J* = 6.9 Hz, 2H), 9.75 (s, 1H); ^{13}C NMR ($CDCl_3$ + DMSO-d_6, 75 MHz) δ 112.67, 117.28, 118.21, 121.85, 123.57, 125.82, 126.47, 126.69, 126.85, 127.13 (2C), 128.07, 128.79, 129.73, 130.41, 131.73, 133.03, 133.61, 133.80, 134.76, 166.59, 168.24; ESIMS *m/z* 417 (M$^+$+H). Anal. Calcd for $C_{28}H_{20}N_2O_2$: C, 80.75; H, 4.84; N, 6.73. Found: C, 80.87; H, 4.57; N, 6.56.
Compound **5b**: 68%; yellow solid, mp 174–176 °C; IR (KBr) 3304, 1681, 1649,

1453 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 2.29 (s, 3H), 2.40 (s, 3H), 7.03 (d, J = 7.8 Hz, 2H), 7.12–7.29 (m, 9H), 7.51–7.54 (m, 3H), 7.63–7.66 (m, 2H), 7.75 (d, J = 7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.47, 21.58, 114.06, 117.66, 120.12, 123.09, 124.87, 125.92, 127.37, 127.91, 128.36, 128.93, 129.36 (2C), 130.39, 130.63, 131.03, 132.06, 133.51, 136.22, 142.51, 143.72, 166.98, 169.38; ESIMS m/z 431 (M^++H). Anal. Calcd for $C_{30}H_{24}N_2O_2$: C, 81.06; H, 5.44; N, 6.30. Found: C, 81.41; H, 5.65; N, 6.19.

Compound **5c**: 69%; white solid, mp 248–250 °C; IR (KBr) 3347, 1677, 1667, 1467 cm^{-1}; ^1H NMR (DMSO-d_6, 300 MHz) δ 6.89 (t, J = 8.4 Hz, 2H), 7.05–7.25 (m, 5H), 7.26–7.40 (m, 3H), 7.41–7.62 (m, 4H), 8.32 (d, J = 7.2 Hz, 1H), 10.34 (s, 1H); ^{13}C NMR (DMSO-d_6, 75 MHz) δ 111.84, 112.09, 112.11, 114.35, 114.60, 114.68, 114.99, 115.22, 119.03, 119.19, 124.79, 126.26, 126.81, 127.89, 128.85, 129.01, 129.25, 131.95, 132.08, 132.21, 134.10, 134.19, 134.34, 134.48, 135.03, 156.64, 156.72, 157.12, 157.20, 159.97, 160.05, 160.20, 160.41, 160.50; ESIMS m/z 489 (M^++H). Anal. Calcd for $C_{28}H_{16}F_4N_2O_2$: C, 68.85; H, 3.30; N, 5.74. Found: C, 68.77; H, 3.29; N, 5.46.

Compound **5d**: 56%; white solid, mp 266–268 °C; IR (KBr) 3212, 1677, 1656, 1449 cm^{-1}; ^1H NMR (DMSO-d_6, 300 MHz) δ 7.12–7.24 (m, 3H), 7.34–7.39 (m, 5H), 7.49–7.61 (m, 8H), 7.97 (d, J = 6.9 Hz, 2H), 10.10 (s, 1H); ^{13}C NMR (DMSO-d_6, 75 MHz) δ 115.19, 117.45, 118.60, 124.69, 127.54, 127.75, 128.03, 128.13, 128.20, 128.47, 128.62, 129.05, 129.85, 130.10, 131.83, 133.43, 133.72, 133.87, 134.05, 136.49, 166.98, 169.00; ESIMS m/z 451 (M^++H), 453 (M^++H+2). Anal. Calcd for $C_{28}H_{19}ClN_2O_2$: C, 74.58; H, 4.25; N, 6.21. Found: C, 74.76; H, 4.34; N, 6.35.

Compound **5e**: 58%; white solid, mp 214–216 °C; IR (KBr) 3322, 1679, 1649, 1482 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 3.87 (s, 3H), 3.93 (s, 3H), 7.02–7.31 (m, 9H), 7.44–7.55 (m, 7H), 7.87 (d, J = 6.9 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 56.08, 56.23, 97.92, 101.50, 117.99, 118.67, 127.36, 127.62, 127.96, 128.31, 128.75, 129.43, 130.04, 130.77, 130.87, 131.26, 132.01, 132.33, 133.86, 135.01, 147.01, 148.68, 166.94, 169.79; ESIMS m/z 477 (M^++H). Anal. Calcd for $C_{30}H_{24}N_2O_4$: C, 75.61; H, 5.08; N, 5.88. Found: C, 75.68; H, 5.32; N, 5.68.

Compound **5f**: 76%; white solid, mp 160–162 °C; IR (KBr) 3305, 1680, 1660, 1451 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 2.12 (s, 3H), 6.97 (d, J = 7.8 Hz, 2H), 7.11–7.69 (m, 15H), 7.86 (d, J = 7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.15, 114.12, 117.49, 120.05, 123.23, 124.88, 125.93, 127.34, 127.49, 128.17, 128.71, 129.11, 129.25, 130.16, 131.94, 132.65, 133.63, 133.88, 134.91, 136.13, 137.96, 166.97, 169.56; ESIMS m/z 431 (M^++H). Anal. Calcd for $C_{29}H_{22}N_2O_2$: C, 80.91; H, 5.15; N, 6.51. Found: C, 80.79; H, 5.43; N, 6.66.

9. For some leading reviews on indole derivatives, see: (a) Kochanowska-Karamyan, A. J.; Hamann, M. T. *Chem. Rev.* **2010**, *110*, 4489–4497; (b) Trost, B. M.; Brennan, M. K. *Synthesis* **2009**, 3003–3025.
10. For the synthesis of similar indole derivatives, see: (a) Qu, J.; Kumar, N.; Alamgir, M.; Black, D. S. C. *Tetrahedron Lett.* **2009**, *50*, 5628–5630; (b) Przheval'skii, N. M.; Skvortsova, N. S.; Magedov, I. V. *Khim. Geterotsikl. Soedin.* **2003**, *12*, 189–195 (*Chem. Heterocycl. Compd.* **2003**, *39*, 161–167); (c) Petasis, N. A.; Myslinska, M. WO 2009/121033, 2009.; (d) Michaelidou, S. S.; Koutentis, P. A. *Tetrahedron* **2010**, *66*, 3016–3023; (e) Seong, C. M.; Park, C. M.; Choi, J.; Park, N. S. *Tetrahedron Lett.* **2009**, *50*, 1029–1031; (f) Ryabova, S. Y.; Alekseeva, L. M.; Lisitsa, E. A.; Granik, V. G. *Russ. Chem. Bull. Int. Ed.* **2006**, *55*, 1248–1254.
11. The formation of allyl cyanide in the reaction was difficult to confirm. Thus, we performed the reaction of **4a** with benzyl bromide or cinnamyl bromide in order to confirm the formation of benzyl cyanide or 2-phenylbut-3-enenitrile; however, the reaction failed to form **5a**.