

Efficient intramolecular hydroamination of aminoalkynes catalyzed by a zirconium(IV) complex

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Abstract

The neutral zirconium(IV) bis(thiophosphinic amidate) complex was demonstrated to be an effective precatalyst for 5-*exo*-, 6-*exo*-, and 7-*exo*-dig intramolecular hydroamination of aminoalkynes, producing the cyclic imines in excellent yields (92–98%).

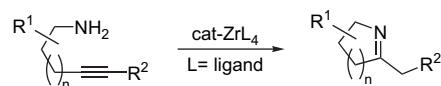
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1. Introduction

Transition metal-catalyzed intramolecular hydroamination of aminoalkynes has been recognized as an effective method for the synthesis of nitrogen-containing heterocyclic compounds.¹ A variety of metallocenes as well as nonmetallocene complexes of the group 3 metals have been developed as efficient catalysts in hydroamination of aminoalkenes, aminoalkynes, and aminoallenes.² Recently, there have been several reports describing inter- and intramolecular hydroamination of these compounds with the group 4 metals.³ However, these procedures suffer from some disadvantages such as inconvenient preparation and instability of the catalysts and limited substrate scope. Therefore, there is still a strong need for a highly efficient catalytic synthesis of azacycles common to naturally occurring alkaloids through hydroamination. We have previously described that chelating bis(thiophosphinic amidate) complexes of the group 3 metals (particularly Y and Nd) are powerful catalysts for intramolecular hydroamination of

aminoalkenes.^{2j} Very recently, we reported that a neutral zirconium(IV) complex was an effective precatalyst for intramolecular hydroamination of aminoalkenes and aminoallenes to give cyclic amines in good to excellent yields.⁴ In continuation of our studies directed toward the development of efficient group 4 metal-catalyzed-hydroamination of aminoalkynes, we now report the realization of this goal with zirconium complex (Scheme 1).



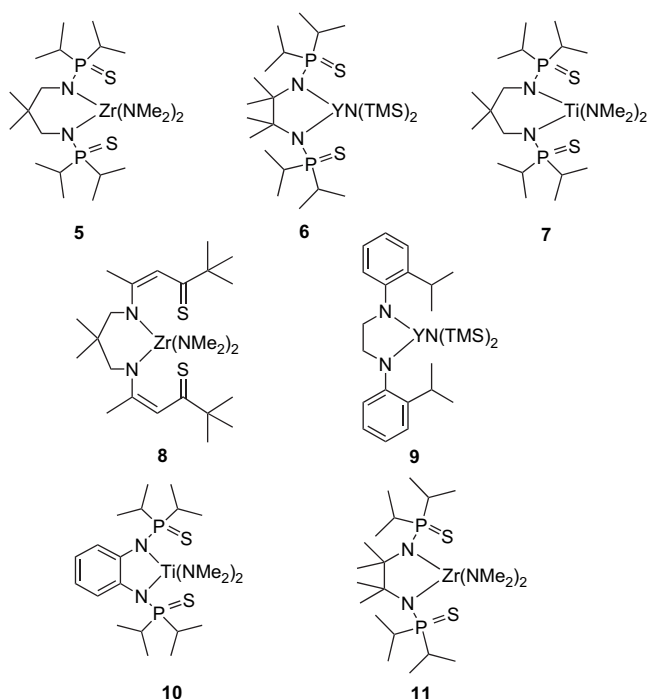
Scheme 1. Zirconium-catalyzed intramolecular hydroamination of aminoalkynes.

2. Results and discussion

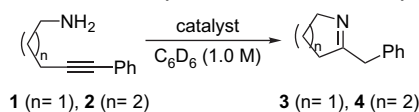
The catalytic activity of several group 3 and 4 metal complexes in Scheme 2 was first examined in the hydroamination of 5-phenyl-4-pentynyl-1-amine (**1**) and 5-decynyl-1-amine (**2**) and the results are summarized in Table 1. $\text{TiCl}(\text{NMe}_2)_3$ gave the desired product in 91% yield (by NMR in benzene- d_6) at 75 °C for 17 h (entry 1). However, $\text{Ti}(\text{NMe}_2)_4$ required

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Scheme 2. Representative group 3 and 4 complexes.

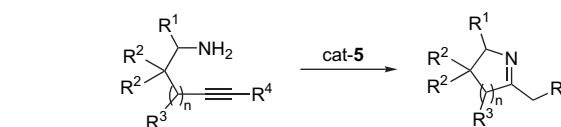
Table 1
Optimization of intramolecular hydroamination of aminoalkynes^a

Entry	<i>n</i>	Catalyst	Temp (°C)	Time (h)	Yield ^b (%)
1	2	TiCl(NMe ₂) ₃	75	17	91
2	2	Ti(NMe ₂) ₄	75	58	87
3	2	Zr(NMe ₂) ₄	75	24	0
4	2	Zr(NMe ₂) ₄	125	24	86
5	2	5	75	5.5	95
6	2	6	75	21	0
7	2	6	100	30	0
8	2	7	75	43	73
9	2	8	125	41	0
10	1	5	60	1.5	95
11	1	9	60	9	94
12	1	10	60	9	0
13	1	10	125	9	95
14	1	11	60	9	91
15	1	Y[N(TMS) ₂] ₃	60	80	96

^a Reactions were carried out in the presence of 5 mol % of catalyst in benzene-*d*₆.^b NMR yields based on *p*-xylene as an internal standard.

a longer reaction time (75 °C, 58 h) to produce the cyclic imine (**4**) in 87% yield (entry 2). Although reaction of aminoalkyne **2** with 5 mol % of Zr(NMe₂)₄ did not proceed at 75 °C for 24 h (entry 3), compound **4** was obtained in 86% yield at 125 °C after 24 h (entry 4), indicating that reactivity of TiCl(NMe₂)₃ and Ti(NMe₂)₄ in hydroamination is better than Zr(NMe₂)₄. With these results, a variety of precatalysts generated in situ from

the direct metalation of several 1,2- or 1,3-diamino proligands with titanium, zirconium, or yttrium complexes were applied to intramolecular hydroamination. Of the catalytic systems examined, the best results were obtained with 5 mol % of catalyst **5** in benzene-*d*₆ at 75 °C for 5.5 h, producing the desired product in 95% yield (entry 5). Although the use of catalysts **6** and **8** did not provide the cyclic compound (entries 6, 7, and 9), 5 mol % of catalyst **7** afforded compound **4** in 73% yield at 75 °C for 43 h (entry 8). Treatment of **1** with 5 mol % of **5** gave rise to the cyclic imine **3** in 95% yield through 5-*exo-dig* intramolecular hydroamination (entry 10). The hydroamination of **1** was also examined using Y[N(TMS)₂]₃, **9**, **10**, and **11**. When aminoalkyne **1** was treated with 5 mol % of Y[N(TMS)₂]₃ at 60 °C for 80 h, the desired product **3** was produced in 96% yield (entry 15). Although the hydroamination of **1** using catalysts **9**, **10**, and **11** gave the cyclic imine **3** in 94%, 95% and 91% yields,

Table 2
Zirconium-catalyzed intramolecular hydroamination of aminoalkynes^a

Entry	Aminoalkyne	Time (h)	Product	Yield ^b (%)
1	1	1.5	3	95 (91) ^c
2	12	2.5	17	98
3	13	2.5	18	93
4	14	11	19 (R: SiMe ₃) 20 (R: H)	96 ^d 90 ^e
5	2	5.5	4	95
6	15	10	21	92
7 ^f	16	7	22	93

^a Reactions were carried out in the presence of 5 mol % of catalyst **5** in benzene-*d*₆ at 75 °C.^b NMR yields based on *p*-xylene as an internal standard.^c Isolated yield (3.0 mmol scale). Reaction was carried out at 60 °C.^d NMR yield of **19**.^e Isolated yield of **20** after quenching with NaOH in methanol.^f The reaction was carried out at 100 °C.

respectively, a longer reaction time (9 h) was needed at 60 and 125 °C (entries 11–14). These results show that zirconium(IV) bis(thiophosphinic amidate) complex **5** is the best catalyst for the hydroamination of both aminoalkynes **1** and **2** in terms of yield and reaction time.

To demonstrate the efficiency and scope of the present method, we applied this catalyst **5** to intramolecular hydroamination of a variety of aminoalkynes. The results of this study are summarized in Table 2. Aminoalkyne **12** bearing a methyl group at carbon adjacent to nitrogen was smoothly cyclized to give **17** in 98% yield (75 °C, 2.5 h, entry 2). Subjecting **13** to 5 mol % of **5** provided the desired product **18** in 93% yield (75 °C, 2.5 h, entry 3). Reaction of **14** with 5 mol % of **5** produced compound **19** in 96% NMR yield (75 °C, 11 h, entry 4). The reaction mixture was quenched with methanolic NaOH, producing the protodesilylated compound **20** in 90% yield. Under the optimum conditions, 6-aminoalkyne **15** was readily cyclized to afford **21** in 92% yield through 6-*exo-dig* intramolecular hydroamination (entry 6). Encouraged by these results regarding the preparation of five- and six-membered cyclic imines through hydroamination of 5- and 6-aminoalkyne, the intramolecular hydroamination of 7-aminoalkynes was subsequently examined. Exposure of 7-aminoalkyne **16** to catalyst **5** produced the seven-membered cyclic imine **22** in 93% yield (100 °C, 7 h) through 7-*exo-dig* intramolecular hydroamination (entry 7). Since the aminoalkynes **1** and **2**, which do not have substituents on carbon chain between amino and alkynyl group, gave the desired products **3** and **4** in excellent yields, the present method is not strongly reliant on the Thorpe–Ingold effect.

3. Conclusion

In conclusion, we have demonstrated that the neutral zirconium(IV) bis(thiophosphinic amidate) complex **5** generated in situ from the direct metalation of NPS ligand with Zr(NMe₂)₄ is a potent catalyst for intramolecular hydroamination of a variety of aminoalkynes. 5-*exo*-, 6-*exo*- and 7-*exo-dig* intramolecular hydroamination of aminoalkynes proceeded smoothly in all cases to produce the cyclic imines in excellent yields. No *endo*-cyclized products were formed in these reactions.

4. Experimental

4.1. General

Infrared spectra were recorded on a Perkin–Elmer model 1600 FT-IR. ¹H NMR spectra were recorded on a Bruker AVANCE DPX-300 (300 MHz) or AVANCE DPX-500 (500 MHz) spectrometer. Chemical shifts were reported in parts per million from TMS with the residual protic solvent resonance as the internal standard (chloroform: 7.27, benzene: 7.16). ¹³C NMR spectra were recorded on a Bruker AVANCE DPX-300 (75 MHz) or AVANCE DPX-500 (125 MHz) spectrometer. Chemical shifts were reported in parts per million from TMS with the solvent as an internal standard (CDCl₃: 77.23). High-resolution mass spectra were recorded on an Autospec M363 series (Micromass). All experiments were carried out under

an argon atmosphere. Organozirconium complexes were manipulated under an argon atmosphere in a glove box. Benzene was distilled from sodium. Zirconium(IV) bis(thiophosphinic amidate) complex (**5**) was prepared from the reaction of Zr(NMe₂)₄ with *N,N'*-bis(*p,p*-diisopropylthiophosphinyl)-2,2-dimethyl-1,3-propanediamine (NPS ligand).⁴

4.2. Typical procedure for intramolecular hydroaminations of aminoalkynes using catalyst **5**

In an argon-filled glove box, Zr(NMe₂)₄ (20 μl, 0.02 mmol, 1.0 M solution in benzene-*d*₆) and *N,N'*-bis(*p,p*-diisopropylthiophosphinyl)-2,2-dimethyl-1,3-propanediamine (7.97 mg, 0.02 mmol) in benzene-*d*₆ (0.4 mL) were introduced sequentially into a J. Young NMR tube.⁵ The reaction mixture was stirred at 25 °C for 10 min until ligand exchange was judged complete by the disappearance of the Zr(NMe₂)₄ resonance in the ¹H NMR spectrum with concomitant production of Me₂NH. The appropriate aminoalkyne (0.4 mmol) and *p*-xylene (10 μl, 0.08 mmol) as an internal standard were added to the resulting solution and the reaction mixture was subsequently heated at 75 or 100 °C in an oil bath to achieve hydroamination. The reaction mixture was treated with 10 drops of methanolic NaOH (5%), stirred for 0.5 h at room temperature, concentrated in vacuo, and filtered the crude compound through silica gel to afford pure imines.

4.2.1. Spectral data

4.2.1.1. 5-Phenyl-4-pentynyl-1-amine (**1**). ¹H NMR (CDCl₃, 500 MHz) δ 7.38–7.37 (m, 2H, Ph), 7.27–7.26 (m, 3H, Ph), 2.87 (t, *J*=6.8 Hz, 2H, CH₂NH₂), 2.48 (t, *J*=7.0 Hz, 2H, CH₂≡C), 1.74 (q, *J*=6.9 Hz, 2H, CH₂CH₂CH₂), 1.32 (br, 2H, NH₂). ¹³C NMR (CDCl₃, 125 MHz) δ 131.7, 128.4, 127.8, 124.1, 89.8, 81.1, 41.5, 32.7, 17.1. IR (film) 3298, 3056, 2938, 2866, 2228, 1598, 1570, 1560, 1490, 1442, 756, 692 cm⁻¹. HRMS (EI): calcd for C₁₁H₁₃N (M⁺), 159.1048; found, 159.1043.

4.2.1.2. 5-Decynyl-1-amine (**2**). ¹H NMR (CDCl₃, 500 MHz) δ 2.67 (t, 2H, *J*=6.5 Hz, CH₂NH₂), 2.15–2.10 (m, 4H, CH₂C≡CCH₂), 1.51–1.45 (m, 4H, NH₂CH₂CH₂CH₂), 1.45–1.32 (m, 4H, C≡CCH₂CH₂CH₂), 1.08 (br, 2H, NH₂), 0.87 (t, *J*=7.0 Hz, 3H, CH₂CH₃). ¹³C NMR (CDCl₃, 125 MHz) δ 80.6, 79.9, 42.0, 33.2, 31.4, 26.6, 22.1, 18.8, 18.6, 13.8. IR (film) 3338, 2958, 2934, 2862, 2158, 1570, 1488, 1466, 1434, 1382, 1328 cm⁻¹. HRMS (EI): calcd for C₁₀H₁₉N (M⁺), 153.1517; found, 153.1516.

4.2.1.3. 1-Methyl-4-nonyl-1-amine (**12**). ¹H NMR (CDCl₃, 500 MHz) δ 3.02 (sex, 1H, *J*=6.3 Hz, CHNH₂), 2.24–2.21 (m, 2H, CH₂C≡C), 2.16–2.12 (m, 2H, C≡CCH₂), 1.56–1.45 (m, 4H, C≡CCH₂CH₂CH₂), 1.43–1.35 (m, 4H, CHCH₂, NH₂), 1.08 (d, *J*=6.5 Hz, 3H, NH₂CHCH₃), 0.90 (t, *J*=7.5 Hz, 3H, CH₂CH₃). ¹³C NMR (CDCl₃, 125 MHz) δ 80.8, 79.7, 46.3, 39.2, 31.4, 23.9, 22.2, 18.6, 16.1, 13.8. IR (film) 3300, 2950–2850, 1590, 1460, 1370, 825 cm⁻¹. HRMS (EI): calcd for C₁₀H₁₉N (M⁺), 153.1517; found, 153.1519.

4.2.1.4. 3-Methyl-4-nonynyl-1-amine (13). ^1H NMR (CDCl_3 , 500 MHz) δ 2.83–2.76 (m, CH_2NH_2), 2.49–2.45 (m, 1H, $\text{CHC}\equiv\text{C}$), 2.15 (td, $J=6.87$, 2.07 Hz, 2H, $\text{C}\equiv\text{CCH}_2$), 1.53–1.46 (m, 4H, $\text{NH}_2\text{CH}_2\text{CH}_2$, NH_2), 1.45–1.33 (m, 4H, $\text{C}\equiv\text{CCH}_2\text{CH}_2\text{CH}_2$), 1.15 (d, $J=6.89$ Hz, 3H, CHCH_3), 0.90 (t, $J=7.11$ Hz, 3H, CH_2CH_3). ^{13}C NMR (CDCl_3 , 125 MHz) δ 84.1, 80.8, 41.2, 40.4, 31.3, 23.6, 21.9, 21.7, 18.4, 13.6. IR (film) 3353, 2958, 2934, 2859, 2158, 1488, 1382 cm^{-1} . HRMS (EI): calcd for $\text{C}_{10}\text{H}_{19}\text{N}$ (M^+), 153.1517; found, 153.1515.

4.2.1.5. 3-Benzoyloxy-2,2-dimethyl-5-trimethylsilyl-4-pentynyl-1-amine (14). ^1H NMR (CDCl_3 , 500 MHz) δ 7.35 (d, $J=4.5$ Hz, 4H, Ph), 7.31–7.28 (m, 1H, Ph), 4.83 (d, $J=12.0$ Hz, 1H, CH_2Ph), 4.47 (d, $J=12.0$ Hz, 1H, CH_2Ph), 3.87 (s, 1H, CHOCH_2), 2.89 (d, $J=13.0$ Hz, 1H, CHHNH_2), 2.67 (d, $J=13.0$ Hz, 1H, CHHNH_2), 1.63 (br, 1H, NH_2), 1.03 (s, 3H, $(\text{CH}_3)_2\text{C}$), 1.01 (s, 3H, $(\text{CH}_3)_2\text{C}$), 0.21 (s, 9H, $\text{Si}(\text{CH}_3)_3$). ^{13}C NMR (CDCl_3 , 125 MHz) δ 138.3, 128.5, 128.2, 127.8, 103.4, 92.5, 75.6, 71.0, 50.1, 39.6, 22.2, 21.5, 0.2. IR (film) 3396, 3064, 2957, 2887, 2167, 1652, 1608, 1496, 1454, 1386, 1249, 1069, 840, 759, 697 cm^{-1} . HRMS (EI): calcd for $\text{C}_{17}\text{H}_{27}\text{NOSi}$ (M^+), 289.1862; found, 289.1864.

4.2.1.6. 4-Methyl-5-decynyl-1-amine (15). ^1H NMR (CDCl_3 , 500 MHz) δ 2.67–2.60 (m, 2H, CH_2NH_2), 2.34–2.31 (m, 1H, $\text{C}\equiv\text{CCHCH}_3$), 2.09 (td, $J=6.5$, 2.0 Hz, 2H, $\text{CHC}\equiv\text{CCH}_2$), 1.57–1.48 (m, 1H, CH_2CHCH_3), 1.48–1.46 (m, 1H, CH_2CHCH_3), 1.44–1.29 (m, 6H, $\text{NH}_2\text{CH}_2\text{CH}_2$, $\text{C}\equiv\text{CCH}_2\text{CH}_2\text{CH}_2$), 1.24 (br, 1H, NH_2), 1.08 (d, $J=7.0$ Hz, $\text{CH}_3\text{CHC}\equiv\text{C}$), 0.84 (t, $J=7.0$ Hz, 3H, $\text{CH}_2\text{CH}_2\text{CH}_3$). ^{13}C NMR (CDCl_3 , 125 MHz) δ 84.6, 80.6, 42.2, 34.7, 31.8, 31.4, 26.0, 22.0, 21.7, 18.5, 13.7. IR (film) 3366, 3296, 2933, 2862, 2152, 1608, 1587, 1455, 1388, 1095, 845, 784 cm^{-1} . HRMS (EI): calcd for $\text{C}_{11}\text{H}_{21}\text{N}$ (M^+), 167.1674; found, 167.1675.

4.2.1.7. 2,2-Dimethyl-7-phenyl-6-heptynyl-1-amine (16). ^1H NMR (CDCl_3 , 500 MHz) δ 7.41 (dd, $J=7.75$, 2.0 Hz, 2H, Ph), 7.30–7.25 (m, 3H, Ph), 2.46 (s, 2H, CH_2NH_2), 2.39 (t, $J=7.0$ Hz, 2H, $\text{CH}_2\equiv\text{C}$), 1.59–1.53 (m, 2H, CH_2CH_2), 1.37–1.33 (m, 2H, CH_2CH_2), 1.18 (br, 2H, NH_2), 0.87 (s, 6H, $(\text{CH}_3)_2\text{C}$). ^{13}C NMR (CDCl_3 , 125 MHz) δ 131.5, 128.1, 127.4, 124.0, 90.2, 80.7, 52.7, 38.7, 34.3, 24.7, 23.6, 20.2. IR (film) 3346, 3067, 2936, 2864, 2232, 1560, 1542, 1490, 756 cm^{-1} . HRMS (EI): calcd for $\text{C}_{15}\text{H}_{21}\text{N}$ (M^+), 215.1674; found, 215.1671.

4.2.1.8. 6-Pentyl-2,3,4,5-tetrahydropyridine (4). Subjecting 5-decynyl-1-amine (61.3 mg, 0.4 mmol) to 5 mol % **5** under the general procedure provided the cyclic imine **4** (58.2 mg, 95%). ^1H NMR (CDCl_3 , 500 MHz) δ 3.48 (t, $J=6.5$ Hz, 2H, CH_2N), 2.08–2.03 (m, 4H, $\text{CH}_2\text{C}=\text{N}$, $\text{N}=\text{CCH}_2$), 1.62–1.57 (m, 2H, $\text{CH}_2\text{CH}_2\text{C}=\text{N}$), 1.51–1.43 (m, 4H, $\text{CH}_2\text{CH}_2\text{N}$, CCH_2CH_2), 1.28–1.21 (m, 4H, $\text{CH}_2\text{CH}_2\text{CH}_3$), 0.87 (t, $J=6.75$ Hz, 3H, CH_2CH_3). ^{13}C NMR (CDCl_3 , 125 MHz) δ 171.3, 49.2, 41.2, 31.8, 29.1, 26.3, 22.6, 22.0, 19.7, 14.1. IR (film) 2958, 2934, 2860, 1660 cm^{-1} . HRMS (EI): calcd for $\text{C}_{10}\text{H}_{19}\text{N}$ (M^+), 153.1517; found, 153.1519.

4.2.1.9. 2-Methyl-5-pentyl-3,4-dihydro-2H-pyrrole (17). ^1H NMR (CDCl_3 , 500 MHz) δ 4.04–3.99 (m, 1H, CHN), 2.57–2.50 (m, 1H, $\text{CH}_2\text{C}=\text{N}$), 2.45–2.40 (m, 1H, $\text{CH}_2\text{C}=\text{N}$), 2.30 (t, $J=7.75$ Hz, $\text{N}=\text{CCH}_2$), 2.10–2.03 (m, 1H, NCHCH_2), 1.60–1.54 (m, 2H, $\text{CCH}_2\text{CH}_2\text{CH}_2$), 1.39–1.28 (m, 5H, $\text{CCH}_2\text{CH}_2\text{CH}_2\text{CH}_2$, NCHCH_2), 1.27 (d, $J=7.0$ Hz, 3H, CHCH_3), 0.89 (t, $J=7.0$ Hz, 3H, CH_2CH_3). ^{13}C NMR (CDCl_3 , 125 MHz) δ 177.4, 67.8, 37.5, 34.1, 31.9, 30.9, 26.5, 22.7, 22.3, 14.2. IR (film) 2950, 2920, 2860, 1620, 1425, 1410, 1360 cm^{-1} . HRMS (EI): calcd for $\text{C}_{10}\text{H}_{19}\text{N}$ (M^+), 153.1517; found, 153.1516.

4.2.1.10. 4-Methyl-5-pentyl-3,4-dihydro-2H-pyrrole (18). ^1H NMR (CDCl_3 , 400 MHz) δ 3.82–3.76 (m, 1H, CH_2N), 3.66–3.59 (m, 1H, CH_2N), 2.78–2.68 (m, 1H, $\text{CHC}=\text{N}$), 2.35–2.18 (m, 2H, $\text{N}=\text{CCH}_2$), 2.15–2.07 (m, 1H, NCH_2CH_2), 1.67–1.56 (m, 2H, NCHCH_2), 1.48–1.41 (m, 1H, NCH_2CH_2), 1.32 (br m, 2H, $\text{CCH}_2\text{CH}_2\text{CH}_2\text{CH}_2$), 1.22 (td, $J=5.02$, 1.09 Hz, 2H, $\text{CCH}_2\text{CH}_2\text{CH}_2\text{CH}_2$), 1.17 (td, $J=5.58$, 1.03 Hz, 2H, $\text{CCH}_2\text{CH}_2\text{CH}_2\text{CH}_2$), 1.11 (dd, $J=7.13$, 1.34 Hz, 3H, CHCH_3), 0.89 (t, $J=6.10$ Hz, 3H, CH_2CH_3). ^{13}C NMR (CDCl_3 , 100 MHz) δ 182.3, 58.8, 44.4, 32.2, 32.1, 31.69, 26.3, 22.9, 17.8, 14.4. IR (film) 2950, 2928, 2860, 1622 cm^{-1} . HRMS (EI): calcd for $\text{C}_{10}\text{H}_{19}\text{N}$ (M^+), 153.1517; found, 153.1515.

4.2.1.11. 4-Benzoyloxy-3,3,5-trimethyl-3,4-dihydro-2H-pyrrole (20). ^1H NMR (CDCl_3 , 500 MHz) δ 7.38 (d, 2H, $J=4.0$ Hz, Ph), 7.34–7.31 (m, 1H, Ph), 4.75 (d, $J=12.0$ Hz, 1H, CH_2Ph), 4.60 (d, $J=12.0$ Hz, 1H, CH_2Ph), 3.98 (s, 1H, CHOBN), 3.55 (d, $J=14.5$ Hz, 1H, CH_2N), 3.37 (d, $J=14.5$ Hz, 1H, CH_2N), 2.03 (s, 3H, CCH_3), 1.17 (s, 3H, $\text{C}(\text{CH}_3)_2$), 1.03 (s, 3H, $\text{C}(\text{CH}_3)_2$). ^{13}C NMR (CDCl_3 , 125 MHz) δ 176.2, 138.3, 128.7, 128.1, 128.1, 92.8, 73.8, 71.9, 42.8, 26.7, 21.6, 18.0. IR (film) 3334, 2981, 2361, 1626, 1481, 1377, 1309, 754, 730 cm^{-1} . HRMS (CI): calcd for $\text{C}_{14}\text{H}_{20}\text{NO}$ ($\text{M}+1$), 218.1544; found, 218.1534.

4.2.1.12. 5-Methyl-6-pentyl-2,3,4,5-tetrahydropyridine (21). ^1H NMR (CDCl_3 , 500 MHz) δ 3.58–3.50 (m, 2H, CH_2N), 2.26–2.16 (m, 3H, $\text{CH}_2\text{C}=\text{N}$, $\text{N}=\text{CCHCH}_3$), 1.80–1.74 (m, 1H, $\text{CH}_2\text{CHC}=\text{N}$), 1.66–1.59 (m, 1H, $\text{CH}_2\text{CH}-\text{C}=\text{N}$), 1.56–1.46 (m, 3H, $\text{CH}_2\text{CH}_2\text{C}=\text{N}$, NCH_2CH_2), 1.45–1.40 (m, 1H, NCH_2CH_2), 1.35–1.25 (m, 4H, $\text{CH}_2\text{CH}_2\text{CH}_3$), 1.13 (d, $J=7.5$ Hz, CHCH_3), 0.89 (t, $J=7.0$ Hz, 3H, CH_2CH_3). ^{13}C NMR (CDCl_3 , 125 MHz) δ 49.6, 38.4, 32.9, 32.0, 28.3, 26.6, 22.7, 20.0, 18.8, 14.1. IR (film) 2955, 2930, 2864, 1663 cm^{-1} . HRMS (EI): calcd for $\text{C}_{11}\text{H}_{21}\text{N}$ (M^+), 167.1674; found, 167.1676.

4.2.1.13. 7-Benzyl-3,3-dimethyl-3,4,5,6-tetrahydro-2H-azepine (22). ^1H NMR (CDCl_3 , 500 MHz) δ 7.30–7.25 (m, 4H, Ph), 7.22–7.20 (m, 1H, Ph), 3.55 (s, 2H, CH_2Ph), 3.40 (s, 2H, CH_2N), 2.24 (t, $J=5.75$ Hz, 2H, $\text{CH}_2\text{C}=\text{N}$), 1.40 (t, $J=6.0$ Hz, 2H, $(\text{CH}_3)_2\text{CCH}_2$), 1.20–1.14 (m, 2H, $\text{CH}_2\text{CH}_2\text{CH}_2$), 0.88 (s, 6H, $(\text{CH}_3)_2\text{C}$). ^{13}C NMR (CDCl_3 , 125 MHz) δ 176.8, 137.1, 129.4, 128.6, 126.9, 61.9, 49.7, 44.4, 32.1, 27.3, 19.5, 16.3. IR (film) 3100–2860, 1680, 1485 cm^{-1} . HRMS (EI): calcd for $\text{C}_{15}\text{H}_{21}\text{N}$ (M^+), 215.1674; found, 215.1668.

4.3. Preparative synthesis of 3,4-dihydro-5-benzyl-2H-pyrrole (3)

Zr(NMe₂)₄ (150.0 µl, 0.15 mmol, 1.0 M solution in benzene-*d*₆) was added to a solution of *N,N'*-bis(*p,p*-diisopropylthiophosphinyl)-2,2-dimethyl-1,3-propanediamine (59.79 mg, 0.15 mmol) in benzene (3 mL) under an argon atmosphere. The homogeneous reaction mixture was stirred at 25 °C for 10 min. After 5-phenyl-4-pentynyl-1-amine (**1**) (477.7 mg, 3.0 mmol) was added to the reaction mixture, it was heated to 75 °C for 1.5 h to complete hydroamination. The reaction mixture was cooled and treated with 10 drops of methanolic NaOH (5%), and then stirred for 0.5 h at room temperature and concentrated in vacuo. The residue was subjected to flash chromatography on silica gel using MeOH/CH₂Cl₂=1:15 to furnish the title compound (406.0 mg, 85%) as a colorless oil. ¹H NMR (CDCl₃, 500 MHz) δ 7.33–7.30 (m, 2H, Ph), 7.25–7.22 (m, 3H, Ph), 3.84 (t, *J*=6.0 Hz, 2H, CH₂NH₂), 3.69 (s, 2H, CH₂Ph), 2.40 (t, *J*=8.0 Hz, 2H, CH₂CH₂CH₂), 1.84 (quintet, *J*=8.0 Hz, 2H, CH₂CH₂CH₂). ¹³C NMR (CDCl₃, 125 MHz) δ 177.1, 137.2, 129.2, 128.8, 126.8, 61.1, 40.9, 36.7, 22.8. IR (film) 3100–2850, 1604, 1496 cm^{−1}. HRMS (EI): calcd for C₁₁H₁₃N (M⁺), 159.1048; found, 159.1046.

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- J. Young NMR tubes purchased from Aldrich or J. Young Ltd were used under refluxing conditions (75 °C or 100 °C) without any special precautions.