

HYDROAMINATION OF ALKYNES CATALYZED BY PALLADIUM/BENZOIC ACID

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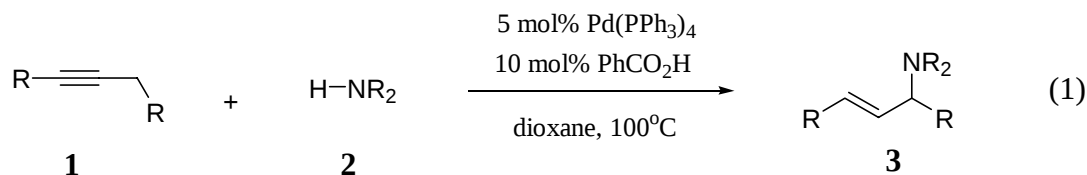
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Dedicated to Professor Albert I. Meyers on the occasion of his 70th birthday.

Abstract – The reaction of internal alkynes (**1**) with amines (**2**) in the presence of catalytic amount of Pd(PPh₃)₄ and benzoic acid in dioxane at 100°C gave the allylic amines (**3**) in good to excellent yields. The intramolecular reaction of alkynes with tethered amino groups (**4**) gave 2-vinylpyrrolidines and 2-vinylpiperidines (**5**) in good to excellent yields.

The carbon-nitrogen bond is frequently encountered in fragments of various biologically active natural products. Hence, the development of efficient synthetic approaches leading to nitrogen based compounds is a subject of considerable attraction. The organometallic reactions involving the formal addition of a N-H bond across a carbon-carbon multiple bond appear to offer the most attractive route to such

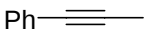
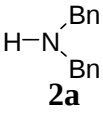
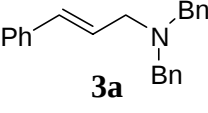
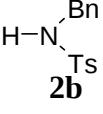
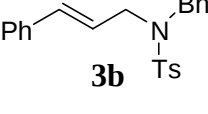
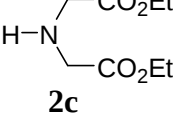
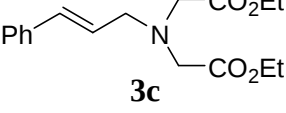
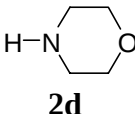
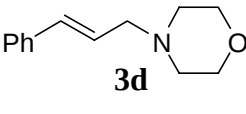
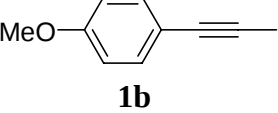
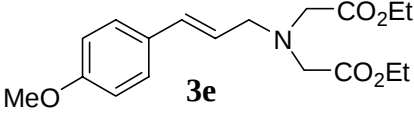
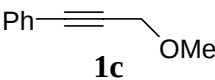
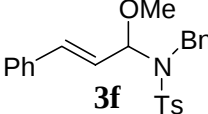
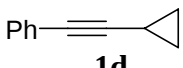
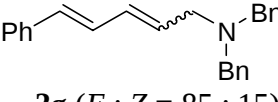
compounds, because this process does not generate byproducts generally observed in the metal-catalyzed substitution process.¹ The palladium-catalyzed intermolecular hydroaminations of 1,3-dienes,² allenes,³ enynes,⁴ and methylenecyclopropanes⁵ have been developed to realize the ideal carbon-nitrogen bond formation. On the other hand, we have previously reported that certain alkynes react with carbon pronucleophiles in the presence of palladium/acetic acid catalyst to give the corresponding allylation products.⁶ This hydrocarbonation is similar to the hydroacylation process reported by Trost *et al.* for the allylation of acetic acid with alkynes which gives allylic acetates.⁷ The utility of this methodology prompted us to extend the formal hydrocarbonation to the formal hydroamination to provide a new atom-economical procedure for the synthesis of amines from alkynes.⁸ In fact, the reaction of certain acetylene derivatives (**1**) with amines (**2**) in the presence of 5 mol% Pd(PPh₃)₄ and 10 mol% PhCO₂H in dioxane at 100°C gave the corresponding allylic amines (**3**) in very high to good yields (eq. 1). We describe herein an account of our results, part of which has been reported previously.⁹



In an initial experiment, 1-phenyl-1-propyne (**1a**) was treated with 1 equiv of dibenzylamine (**2a**), Pd(PPh₃)₄ (5 mol%), and benzoic acid (10 mol%) in dioxane at 100°C to give the allylic amine (**3a**) as a sole product in 98% yield (Table 1, entry 1). Similarly, the reactions of **1a** with secondary amines (**2b-d**) gave the allylic amines (**3b-d**), respectively, in good to high yields (entries 2-4). In all cases, no regio- or stereoisomers were obtained. The addition of carboxylic acid was essential, as no reaction took place in its absence. Several acids such as acetic, tartaric and benzoic were effective, with the latter giving slightly better yields. Other examples with various alkynes are summarized in Table 1. While *p*-methoxyphenylalkyne (**1b**) also readily reacted, attempts for hydroamination of substrates possessing electron-withdrawing group on the phenyl ring only led to complex mixtures of products. A novel *N,O*-acetal (**3f**) was synthesized in good yield from the propargylic ether (**1c**) (entry 6). Treatment of

cyclopropylphenylacetylene (**1d**) with **2a** produced an 85 : 15 mixture of the *E* and *Z* linear adducts (**3g**)

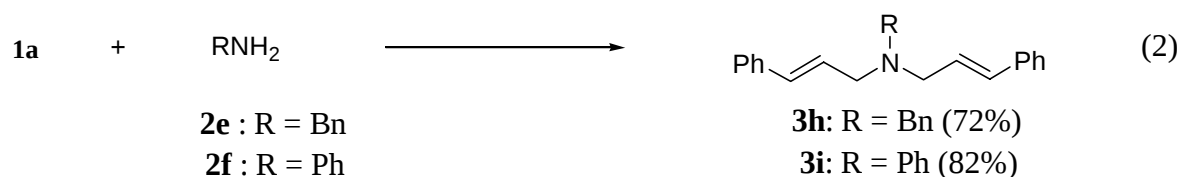
Table1. Pd/PhCO₂H Catalyzed Intermolecular Hydroamination of Alkynes^a

entry	alkyne	amine	product	yield(%) ^b
1	 1a	 2a	 3a	98
2	1a	 2b	 3b	98
3	1a	 2c	 3c	77
4	1a	 2d	 3d	94
5	 1b	2c	 3e	82
6	 1c	2b	 3f	61
7	 1d	2a	 3g (<i>E</i> : <i>Z</i> = 85 : 15)	72 ^c

^aAll reactions were conducted in dioxane using 5 mol% of Pd(PPh₃)₄ and 10 mol% of PhCO₂H overnight.

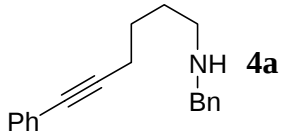
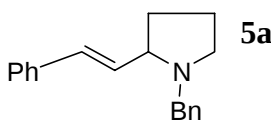
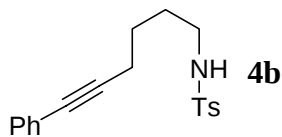
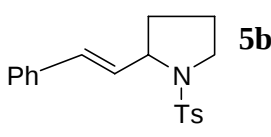
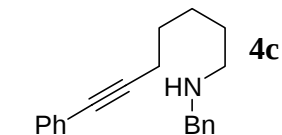
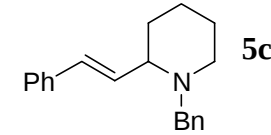
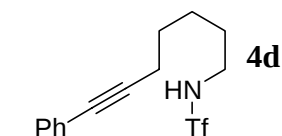
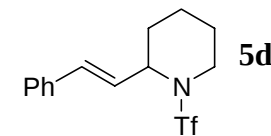
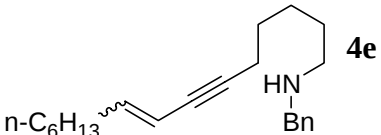
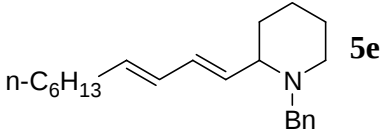
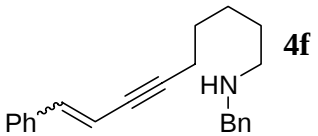
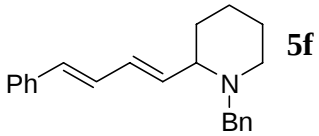
^bIsolated yield. ^cInseparable mixture of the stereoisomers. The ratio was determined by ¹H NMR spectral analysis.

in 72% yield (entry 7). Aliphatic acetylenes such as 3-hexyne and 1-octyne did not react with amines under the conditions mentioned above. The reaction of primary amines (**2e**) and (**2f**) with **1a** afforded the 2 : 1 adducts (**3h**) and (**3i**), respectively, in good yields (eq. 2).



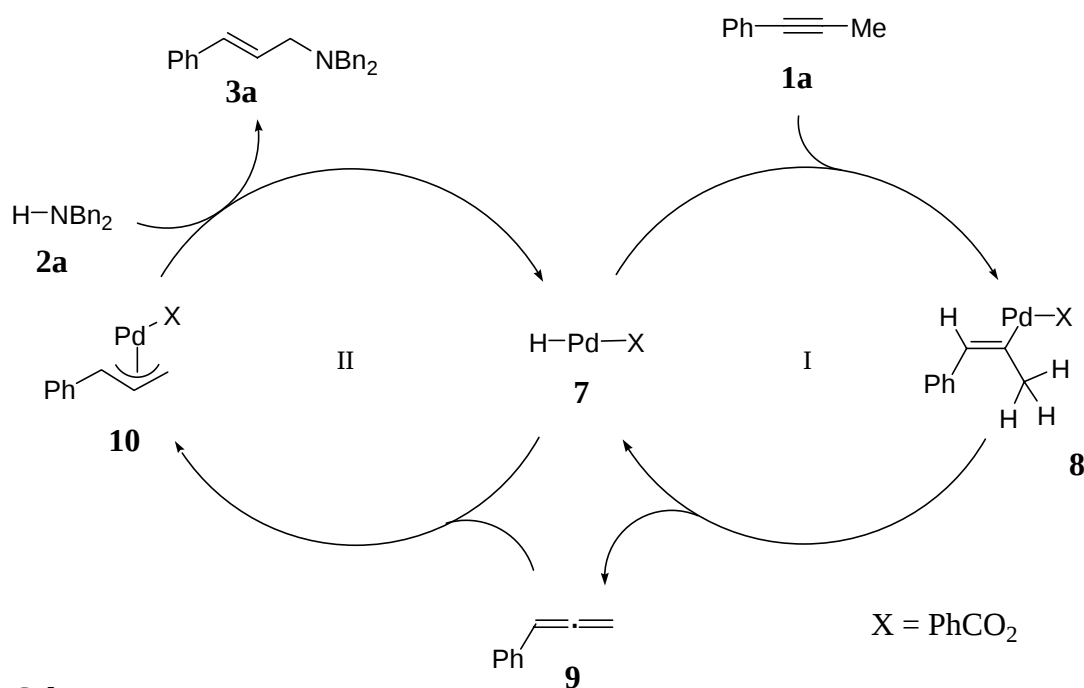
The usefulness of this transformation is further demonstrated by the intramolecular version as outlined in Table 2. The reaction of the alkynes (**4a**) and (**4b**) having a monoprotected amino group at the terminus of the carbon chain, under the standard conditions mentioned above gave the pyrrolidines (**5a**) and (**5b**),

Table 2. Pd/PhCO₂H Catalyzed Intramolecular Hydroamination of Alkynes^a

entry	substrate	product	yield(%) ^b
1	 4a	 5a	70
2	 4b	 5b	82
3	 4c	 5c	91
4	 4d	 5d	98
5	 4e	 5e	52
6	 4f	 5f	55

^aAll reactions were conducted in dioxane using 5 mol% of Pd(PPh₃)₄ and 10 mol% of PhCO₂H overnight. ^bIsolated yield

respectively, in good yields (entries 1 and 2). Similarly, the benzylamine derivative (**4c**) and the trifluoromethanesulfonylamide (**4d**) cyclized to produce piperidines (**5c**) and (**5d**) in 91 and 98% yields,



Scheme 1

In conclusion, we have developed a simple and efficient method for the synthesis of various acyclic and cyclic allylic amines using palladium/benzoic acid catalyst. The use of readily available starting materials and the cleanness of the process make it an interesting alternative to the existing approaches to these types of compounds.

ACKNOWLEDGEMENTS

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EXPERIMENTAL

The NMR experiments were performed with a JEOL JNM-LA 300 or JEOL GSX-270 spectrometer, and chemical shifts are expressed in ppm (δ) with TMS as an internal reference. IR spectra were measured on a Shimadzu FTIR-8200A or Hitachi M260-10 spectrophotometer. HRMS were recorded on a Hitachi M2500S, JMSDX303 or JMSAX500 spectrometer. All reactions were carried out under an argon atmosphere in a closed vial. The synthesis of unknown alkynylamines (**4**) will be published elsewhere.

General procedure for the intermolecular hydroamination of alkynes:

A mixture of alkyne (**1**) (0.6 mmol), amine (**2**) (0.5 mmol), Pd(PPh₃)₄ (29 mg, 0.025 mmol), and PhCO₂H (6.1 mg, 0.05 mmol) in dry dioxane (2 mL) was stirred overnight at 100°C. The reaction mixture was then filtered through a short silica gel column using ether as an eluent, and the filtrate was concentrated. The residue was purified by silica gel column chromatography (hexane/AcOEt mixtures) to give **3**.

General procedure for the intramolecular hydroamination of alkynes:

A mixture of alkynylamine (**4**) (0.5 mmol), Pd(PPh₃)₄ (29 mg, 0.025 mmol), and PhCO₂H (6.1 mg, 0.05 mmol) in dry dioxane (2 mL) was stirred overnight at 100°C. The resulting mixture was treated as above to give **5**.

(E)-N,N-Dibenzyl-3-phenyl-2-propenylamine (3a): IR (neat) 3026, 2922, 1495, 1121, 966 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 7.44-7.17 (m, 15 H), 6.53 (d, *J* = 15.9 Hz, 1H), 6.30 (dt, *J* = 15.9, 6.4 Hz, 1H), 3.63 (s, 4H), 3.22 (d, *J* = 6.4 Hz, 2H); Anal. Calcd for C₂₃H₂₃N: C, 88.13; H, 7.40; N, 4.47. Found: C, 88.18; H, 7.56; N, 4.27.

N-Benzyl-N-[(E)-3-phenyl-2-propenyl]tosylamide (3b): IR (neat) 3059, 3026, 1337, 1153 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 7.77 (d, *J* = 8.1 Hz, 2 H), 7.36-7.21 (m, 10H), 7.12 (d, *J* = 8.1 Hz, 2H), 6.24 (d, *J* = 15.8 Hz, 1H), 5.75 (dt, *J* = 15.8, 7.0 Hz, 1H), 4.38 (s, 2H), 3.90 (d, *J* = 7.0 Hz, 2H), 2.45 (s, 3H); ¹³C NMR (CDCl₃) δ 143.3, 137.5, 136.1, 136.0, 134.2, 133.3, 129.7, 128.55, 128.47, 127.8, 127.7, 127.3, 126.3, 123.3, 50.4, 49.0, 21.5; HRMS (EI) Calcd for C₂₃H₂₃NO₂S (M⁺) 377.1448, found 377.1452.

(E)-N,N-Bis(ethoxycarbonylmethyl)-3-phenyl-2-propenylamine (3c): IR (neat) 2982, 2936, 1744, 1512, 1190 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 7.30 (d, *J* = 8.7 Hz, 2H), 6.85 (d, *J* = 8.7 Hz, 1H), 6.48 (d, *J* = 15.8 Hz, 1H), 6.16 (dt, *J* = 15.8, 6.9 Hz, 1H), 4.16 (q, *J* = 7.2 Hz, 4H), 3.81 (s, 3H), 3.59 (s, 4H), 3.51 (d, *J* = 6.9 Hz, 2H), 1.25 (t, *J* = 7.2 Hz, 6H); Anal. Calcd for C₁₈H₂₅NO₅: C, 64.46; H, 7.51; N, 4.18. Found: C, 64.34; H, 7.55; N, 4.18.

(E)-N-(3-Phenyl-2-propenyl)morpholine (3d): IR (neat) 3026, 2959, 2806, 1452, 1119 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.40-7.20 (m, 5H), 6.54 (d, J = 15.8 Hz, 1H), 6.26 (dt, J = 15.8, 6.8 Hz, 1H), 3.74 (m, 4H), 3.16 (m, 2H), 2.51 (m, 4H); ^{13}C NMR (CDCl_3) δ 136.7, 133.3, 128.5, 127.5, 126.3, 126.0, 66.9, 61.4, 53.6; HRMS (EI) Calcd for $\text{C}_{13}\text{H}_{17}\text{NO}$ (M^+) 203.1309, found 203.1313.

(E)-N,N-Bis(ethoxycarbonylmethyl)-3-(4-methoxyphenyl)-2-propenylamine (3e): IR (neat) 2982, 2936, 1744, 1512, 1190 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.30 (d, J = 8.7 Hz, 2H), 6.85 (d, J = 8.7 Hz, 1H), 6.48 (d, J = 15.8 Hz, 1H), 6.16 (dt, J = 15.8, 6.9 Hz, 1H), 4.16 (q, J = 7.2 Hz, 4H), 3.81 (s, 3H), 3.59 (s, 4H), 3.51 (d, J = 6.9 Hz, 2H), 1.25 (t, J = 7.2 Hz, 6H); Anal. Calcd for $\text{C}_{18}\text{H}_{25}\text{NO}_5$: C, 64.46; H, 7.51; N, 4.18. Found: C, 64.34; H, 7.55; N, 4.18.

N-Benzyl-N-[(E)-1-methoxy-3-phenyl-2-propenyl]tosylamide (3f): IR (neat) 3028, 2932, 1339, 1161 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.67 (d, J = 8.2 Hz, 2 H), 7.32-7.08 (m, 12 H), 6.57 (d, J = 15.8 Hz, 1 H), 5.75 (dd, J = 15.8, 5.0 Hz, 1 H), 5.63 (d, J = 5.0 Hz, 1 H), 4.46-4.30 (m, 2 H), 3.22 (s, 3 H), 2.40 (s, 3 H); Anal. Calcd for $\text{C}_{24}\text{H}_{25}\text{NO}_3\text{S}$: C, 70.73; H, 6.18; N, 3.44. Found: C, 70.54; H, 6.35; N, 3.40.

(2E,4E and 2Z,4E)-N,N-Dibenzyl-5-phenyl-2,4-pentadienylamines (3g): IR (neat) 3024, 2795, 1495, 1452, 1366 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) **(2E,4E)** δ 7.42-7.18 (m, 15H), 6.78 (dd, J = 15.6, 10.5 Hz, 1H), 6.49 (d, J = 15.6 Hz, 1H), 6.35 (dd, J = 15.3, 10.5 Hz, 1H), 5.91 (ddd, J = 15.3, 6.6, 6.6 Hz, 1H), 3.15 (d, J = 6.6 Hz, 2H); **(2E,4Z)** δ 7.42-7.18 (m, 15H), 6.92 (dd, J = 15.6, 10.5 Hz, 1H), 6.51 (d, J = 15.6 Hz, 1H), 6.31 (dd, J = 15.3, 10.5 Hz, 1H), 5.69 (ddd, J = 15.3, 6.6, 6.6 Hz, 1H), 3.62 (s, 4H), 3.28 (d, J = 7.1 Hz, 2H); Anal. Calcd for $\text{C}_{25}\text{H}_{25}\text{N}$: C, 88.45; H, 7.42; N, 4.13. Found: C, 88.10; H, 7.42; N, 3.89.

N,N-Bis[(E)-3-phenyl-2-propenyl]benzylamine (3h): IR (neat) 3026, 2795, 1495, 1121, 966 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.40-7.18 (m, 15H), 6.55 (d, J = 15.7 Hz, 2H), 6.31 (dt, J = 15.7, 6.6 Hz, 2H), 3.68 (s, 2H), 3.30 (d, J = 6.6 Hz, 4H); ^{13}C NMR (CDCl_3) δ 139.3, 137.1, 132.6, 129.0, 128.5, 128.2, 127.6, 127.3, 126.9, 126.3, 58.0, 56.0; HRMS (EI) Calcd for $\text{C}_{25}\text{H}_{25}\text{N}$ (M^+) 339.1986, found 339.1997.

***N,N*-Bis[(*E*)-3-phenyl-2-propenyl]aniline (3i):** IR (neat) 3059, 3024, 1599, 1504, 1356 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.38-7.18 (m, 12H), 6.82 (d, J = 7.9 Hz, 2H), 6.72 (t, J = 7.4 Hz, 1H), 6.54 (d, J = 15.7 Hz, 2H), 6.28 (ddd, J = 15.7, 5.1, 5.1 Hz, 2H), 4.14 (d, J = 5.1 Hz, 4H); Anal. Calcd for $\text{C}_{24}\text{H}_{23}\text{N}$: C, 88.57; H, 7.12; N, 4.30. Found: C, 88.90; H, 7.00; N, 4.06.

***N*-Benzyl-2-[(*E*)-2-phenylethenyl]pyrrolidine (5a):** IR (neat) 3026, 2964, 1601, 1495, 1452 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.42-7.18 (m, 10H), 6.55 (d, J = 15.9 Hz, 1H), 6.19 (dd, J = 15.9, 8.5 Hz, 1H), 4.06 (d, J = 12.8 Hz, 1H), 3.13 (d, J = 12.8 Hz, 1H), 3.02-2.92 (m, 2H), 2.22-1.94 (m, 2H), 1.90-1.66 (m, 3H); ^{13}C NMR (CDCl_3) δ 139.3, 137.1, 132.5, 131.6, 128.9, 128.5, 128.1, 127.3, 126.7, 126.2, 67.8, 58.3, 53.3, 31.7, 22.1; Anal. Calcd for $\text{C}_{19}\text{H}_{21}\text{N}$: C, 86.55; H, 8.25; N, 5.22. Found: C, 86.64; H, 8.04; N, 5.32.

***N*-Tosyl-2-[(*E*)-2-phenylethenyl]pyrrolidine (5b):** The ^1H and ^{13}C NMR spectral data of **5b** were identical with the literature data.¹³

***N*-Benzyl-2-[(*E*)-2-phenylethenyl]piperidine (5c):** IR (neat) 3026, 2932, 1495, 1450 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.48-7.18 (m, 10H), 6.54 (d, J = 15.9 Hz, 1H), 6.28 (dd, J = 8.4, 15.9 Hz, 1H), 4.09 (d, J = 13.6 Hz, 1H), 3.11 (d, J = 13.6 Hz, 1H), 2.90-2.78 (m, 2H), 1.93 (ddd, J = 11.1, 11.1, 3.3 Hz, 1H), 1.80-1.35 (m, 6H); Anal. Calcd for $\text{C}_{20}\text{H}_{23}\text{N}$: C, 86.59; H, 8.36; N, 5.05. Found: C, 86.34; H, 8.19; N, 4.99.

***N*-Triflyl-2-[(*E*)-2-phenylethenyl]piperidine (5d):** IR (neat) 3028, 2949, 1497, 1448 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.36-7.19 (m, 5H), 6.54 (dd, J = 16.1, 1.7 Hz, 1H), 6.17 (dd, J = 16.1, 5.1 Hz, 1H), 4.77 (br s, 1H), 3.78 (br d, J = 13.6 Hz, 1H), 3.25 (m, 1H), 1.89 (m, 2H), 1.67-1.52 (m, 4H); ^{13}C NMR (CDCl_3) δ 136.0, 133.3, 128.6, 128.1, 126.5, 125.5, 117.8, 56.2, 43.2, 29.6, 25.3, 18.6; HRMS (EI) Calcd for $\text{C}_{14}\text{H}_{16}\text{NO}_2\text{F}_3\text{S}$ (M^+) 319.0853, found 319.0834.

***N*-Benzyl-2-[(*E,E*)-1,3-decadienyl]piperidine (5e):** IR (neat) 3022, 2928, 1495, 1452 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.30-7.20 (m, 5H), 6.15 (dd, J = 14.8, 10.3 Hz, 1H), 6.04 (dd, J = 14.8, 10.4 Hz, 1H), 5.64 (dt, J = 14.5, 7.1 Hz, 1H), 5.61 (dd, J = 14.8, 8.7 Hz, 1H), 4.05 (d, J = 13.5 Hz, 1H), 3.01 (d, J

= 13.6 Hz, 1H), 2.79 (m, 1H), 2.6 (m, 1H), 2.06 (m, 2H), 1.90-1.28 (m, 15H), 0.88 (m, 3H); ^{13}C NMR (CDCl_3) δ 139.5, 135.1, 134.1, 131.4, 129.9, 129.0, 128.0, 126.5, 65.7, 60.0, 52.2, 33.8, 32.6, 31.7, 29.3, 29.0, 25.8, 24.0, 22.6, 14.1; HRMS (EI) Calcd for $\text{C}_{22}\text{H}_{33}\text{N}$ (M^+) 311.2611, found 311.2572.

N-Benzyl-2-[(E,E)-4-phenyl-1,3-butadienyl]piperidine (5f): IR (neat) 3024, 2932, 1495, 1448 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.44-7.17 (m, 10H), 6.79 (dd, J = 15.7, 10.5 Hz, 1H), 6.50 (d, J = 15.6 Hz, 1H), 6.35 (dd, J = 15.2, 10.5 Hz, 1H), 5.88 (dd, J = 15.3, 8.7 Hz, 1H), 4.06 (d, J = 13.6 Hz, 1H), 3.03 (d, J = 13.5 Hz, 1H), 2.79 (m, 2 H), 1.91 (dt, J = 11.1, 3.4 Hz, 1H), 1.76-1.65 (m, 2H), 1.57-1.42 (m, 3H), 1.38-1.23 (m, 1H); ^{13}C NMR (CDCl_3) δ 137.3, 131.3, 129.0, 128.9, 128.5, 128.0, 127.3, 126.6, 126.2, 65.7, 60.2, 52.2, 33.7, 25.7, 23.9; HRMS (EI) Calcd for $\text{C}_{22}\text{H}_{25}\text{N}$ (M^+) 303.1986, found 303.2001.

REFERENCES AND NOTES

1. For reviews of palladium-catalyzed pronucleophile addition to C-C multiple bonds, see: (a) B. M. Trost, *Science*, 1991, **254**, 1471; (b) B. M. Trost, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 259; (c) Y. Yamamoto, *Pure Appl. Chem.*, 1996, **68**, 9; (d) Y. Yamamoto and U. Radhakrishnan, *Chem. Soc. Rev.*, 1999, **28**, 199.
2. R. W. Armbruster, M. M. Morgan, J. L. Schmidt, C. M. Lau, R. M. Riley, D. L. Zabrowski, and H. A. Dieck, *Organometallics*, 1986, **5**, 234.
3. L. Besson, J. Goré, and B. Cazes, *Tetrahedron Lett.*, 1995, **36**, 3857; M. Al-Masum, M. Meguro, and Y. Yamamoto, *Tetrahedron Lett.*, 1997, **38**, 6071.
4. U. Radhakrishnan, M. Al-Masum, and Y. Yamamoto, *Tetrahedron Lett.*, 1998, **39**, 1037.
5. I. Nakamura, H. Itagaki, and Y. Yamamoto, *J. Org. Chem.*, 1998, **63**, 6458.
6. I. Kadota, A. Shibuya, Y.-S. Gyoung, and Y. Yamamoto, *J. Am. Chem. Soc.*, 1998, **120**, 10262.
7. B. M. Trost, W. Brieden, and K. H. Baringhaus, *Angew. Chem., Int. Ed Engl.*, 1992, **31**, 1335.
8. For lanthanoid-catalyzed intramolecular hydroamination of alkynes, see: Y. Li and T. Marks, *J. Am. Chem. Soc.*, 1996, **118**, 9295 and references therein.

9. I. Kadota, A. Shibuya, L. M. Lutete, and Y. Yamamoto, *J. Org. Chem.*, 1999, **64**, 4570.
10. B. M. Trost and F. Rise, *J. Am. Chem. Soc.*, 1987, **109**, 3161.
11. For palladium-catalyzed isomerization of alkynes to allenes, see: (a) H. Sheng, S. Lin, and Y. Huang, *Tetrahedron Lett.*, 1986, **27**, 4893; (b) B. M. Trost and T. Schmidt, *J. Am. Chem. Soc.*, 1988, **110**, 2301; (c) X. Lu, J. Ji, D. Ma, and W. Shen, *J. Org. Chem.*, 1991, **56**, 5774.
12. For the allylation of acetic acid with alkynes via a π -allylpalladium intermediate, see ref. 7 and M. Al-Masum and Y. Yamamoto, *J. Am. Chem. Soc.*, 1998, **120**, 3809.
13. R. C. Larock, H. Yang, S. M. Weinreb, and R. J. Herr, *J. Org. Chem.*, 1994, **59**, 4172.