Palladium-Catalyzed Preparation of Propargylic or Allenylic Sulfides from Propargyl Halides or Mesylate and Thiols

Ken Tsutsumi,*[a] Kouji Fujimoto,[a] Tomomi Yabukami,[a] Tomohiro Kawase,[a] Tsumoru Morimoto,[a] and Kiyomi Kakiuchi*[a]

Keywords: Allenyl / Bidentate phosphane / Palladium / Propargyl / Sulfides

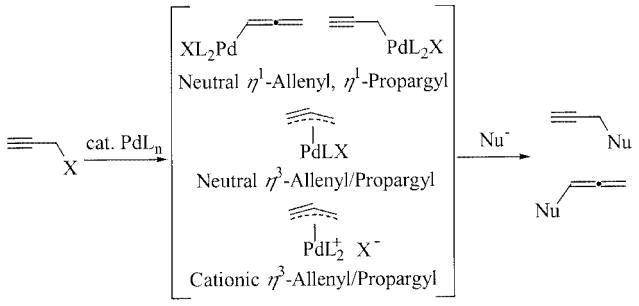
In the presence of a catalytic amount of Pd^0-dppe complex [dppe: 1,2-bis(diphenylphosphanyl)ethane], generated in situ from [$Pd_2(dba)_3$·$CHCl_3$] and dppe, propargylic bromide **1a** reacted with an equimolar amount of propanethiol at 60 °C in DMF to afford propargylic sulfide **2** in an excellent yield. The reaction occurs readily when carried out in the presence of the weak base triethylamine. The choice of both the phosphane, which is employed as the palladium atom's ligand, and the solvent have a remarkable effect on this reaction. We found that the optimum conditions for the reaction are those using a bidentate phosphane ligand (dppe) in a polar solvent (DMF). Compound **1a** reacted smoothly with both aromatic (PhSH) and secondary thiols (CySH) in high yields. The reactions with thiols bearing functional groups (OH or Cl) proceeded selectively in good to moderate yields. Primary chlorides **1b**–**e** were readily converted into their corresponding propargylic sulfides **7**–**10** in high yields. The Pd^0-dppe catalyst was ineffective in the reaction of the bromide **1g** bearing a *t*Bu group at the propargylic position, but the reaction of the corresponding mesylate **1h** using the Pd^0-DIOP catalyst [DIOP = *O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphenylphosphanyl)butane] at 100 °C afforded the product **11** in good yield. Allenylic sulfides were obtained from **1g**–**i**. We suggest that a cationic η^3-type complex may be a more reactive intermediate in this catalytic reaction than neutral η^1- or η^3-allenyl/propargylpalladium complexes.

Introduction

Propargylic sulfides, allenylic sulfides, and their oxidation products, sulfoxides and sulfones, are important reagents and/or quite useful intermediates in organic synthetic[1] and biological applications.[2] Propargylic sulfides have been prepared generally by Williamson-type reactions of propargylic bromides, iodides, or mesylates with thiols in the presence of inorganic bases.[3a] Varma reported that Ce-exchanged zeolite catalyzed the reaction of propargylic bromide with cyclohexanethiol and benzenethiol.[3b] Several synthetic methods for preparing allenylic sulfides have been reported, such as the alkylation of simple thioallenes or thioacetylenes,[4a,4b] the base-catalyzed isomerization of propargylic sulfides,[4b,4c] the *O*-sulfenylation of propargylic alcohols and their subsequent 2,3-sigmatropic rearrangement, followed by deoxygenation,[4a] the direct addition of phenylthiocopper trimethylphosphite complex to propargyl halides,[4d] and the Wittig-type reaction of phenylsulfanyl-acetyl chloride with carboxy phosphorane.[4e] Because research on these sulfur compounds is widely studied, highly selective and efficient methods are desired for preparing propargylic or allenylic sulfides catalyzed by transition metal complexes. Hidai, Uemura, and Mitsudo reported the ruthenium-catalyzed reaction of propargyl alcohols[5a,5b] or carbonates[5c] with thiols to afford propargylic sulfides. Miyaura reported the palladium-catalyzed reaction of propargylic carbonate with boron-sulfur reagents to yield allenylic sulfide.[6] In spite of the poisoning effects that sulfur-containing compounds have on catalysts,[7] there have been reports on transition metal-catalyzed reactions involving organosulfur compounds.[8] To the best of our knowledge, however, no examples of the preparation of propargylic and allenylic sulfides using palladium catalysts have been reported, other than those mentioned above, even though palladium is the most commonly and readily used transition metal catalyst in organic syntheses[9] and is capable of catalyzing a wide variety of reactions of propargylic compounds.[10] We have systematically investigated aspects of the preparation and reactions of some types of palladium complexes containing allenyl or propargyl ligands.[11] From these studies, we became interested in extending the palladium-catalyzed reactions of propargylic compounds to include thiols by considering the reactivity of the favorable allenyl/propargyl complexes toward them. Three types of palladium complexes — neutral η^1-allenyl and η^1-propargyl,[12a,12b] neutral η^3-allenyl/propargyl,[11b] and cationic η^3-allenyl/propargyl[11a,11c,12c] — are the key intermediates in palladium-catalyzed reactions of propargylic compounds (Scheme 1).[13] In view of their electronic properties, the cationic η^3-type complexes may show higher reactivities to-

[a] Graduate School of Materials Science, Nara Institute of Science and Technology (NAIST),
Takayama, Ikoma, Nara 630−0192, Japan
Fax: (internat.) +81-743-726089
E-mail: tsutsumi@ms.aist-nara.ac.jp

  DOI: 10.1002/ejoc.200300490



Scheme 1. Palladium-catalyzed reactions of propargylic compounds

ward nucleophiles than the neutral types. It is reasonable, therefore, to consider that the cationic complexes may play an important role in the nucleophilic substitution reactions of propargylic compounds.

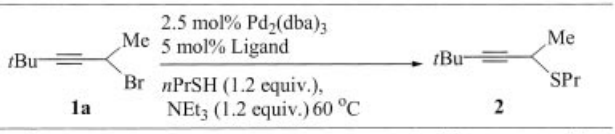
We report here that palladium catalysts accelerate the nucleophilic substitution reactions of propargylic halides or mesylates with various thiols in the presence of the weak base, triethylamine. This reaction affords a facile and selective procedure for the preparation of various propargylic or allenylic sulfides under mild conditions. We also discuss the scope and limitations of this reaction, and mechanistic aspects that account for the effects of the reaction variables, particularly the necessity for a dppe or DIOP, on the C−S bond formation reaction via the cationic η^3-allenyl/propargylpalladium intermediate. This mechanistic study and some other aspects of this reaction have been presented in an earlier report.[14]

Results and Discussion

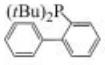
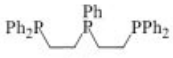
Influence of the Phosphane Ligands and Solvents

Cationic η^3-type complexes can be generated in solution through the spontaneous dissociation of the halide ion from neutral η^1-type complexes, in which both η^1- and η^3-types of complexes may coexist in an equilibrium state. In fact, we have observed such equilibrium directly and have found that, by using a bidentate ligand (dppe > PPh_3) in a more-polar solvent (DMF > chloroform > benzene), the equilibrium lies in favor of the cationic species.[11c] Based on the above results, we initiated our investigations on the palladium-catalyzed thiolation using propargylic bromide **1a** and *n*PrSH in the presence of the weak organic base, triethylamine (Table 1). Complex formation of triethylamine and thiols might activate the nucleophilicity of the thiols and prevent poisoning of the catalyst. At first, the reaction was carried out in the presence of [$Pd_2(dba)_3$·$CHCl_3$] (dba = 1,5-diphenyl-1,4-pentadiene-3-one) and dppe in [D_7]DMF at 60 °C to afford the corresponding propargylic sulfide **2** in 99% yield (Table 1, entry 1). In the absence of the palladium catalyst, the reaction resulted in a low yield after a longer reaction time (Table 1, entry 2), which indicates that the catalyst does promote C−S bond formation. The propargylic structure of **2** was assigned unambiguously from the ^{13}C NMR spectrum, which exhibits two signals of sp-hybridized carbon atoms (δ = 91.9 and 79.1 ppm). When using a monodentate phosphane (PPh_3) instead of a bidentate phosphane (dppe), the reaction time was prolonged and the yield decreased (Table 1, entry 3). Bulky and electron-rich monophosphanes, P(*t*Bu)$_3$ and P(biphenyl)(*t*Bu)$_2$, were inferior to dppe (Table 1, entries 4 and 5). In some cases, Migita−Stille coupling of propargylic halides proceeds more rapidly and cleanly when using a catalyst having a PPh_3/Pd ratio of 1:1 rather than 4:1.[15] In that coupling reaction, the neutral η^3-allenyl/propargylpalladium monophosphane complex, rather than the η^1-allenyl or η^1-propargylpalladium[bis(phosphane)] complex, was proposed as a new effective intermediate. The present reaction, however, was less sensitive to the PPh_3/Pd ratio (Table 1, entry 6). Moreover, the reaction proceeded in moderate yield when using the tridentate phosphane, bis(2-diphenylphosphinoethyl)phenylphosphane (Table 1, entry 7). Other bidentate phosphanes having larger bite angles — dppp [dppp = 1,3-bis(diphenylphosphanyl)propane], dppb [dppb = 1,3-bis(diphenylphosphanyl)butane], and dppf [dppf = 1,1′-bis(diphenylphosphanyl)ferrocene] — were less effective than dppe (Table 1, entries 8, 9, and 10). In less-polar solvents ($CDCl_3$ and [D_6]benzene), the reaction resulted in good yields, but longer reaction times were required (Table 1, entries 11 and 12). These results suggest the intervention of a polar species, such as a cationic η^3-allenyl/propargylpalladium complex, at the rate-determining step.

Table 1. Ligand and solvent effects in C−S bond formation between **1a** and *n*PrSH

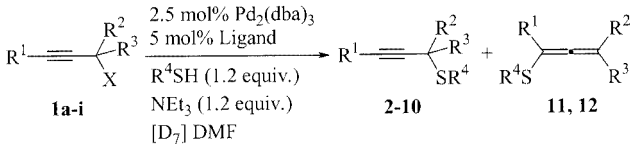


1a **2**

Entry[a]	Ligand	Solvent	Time [h][b]	Yield [%][c]
1	dppe	[D_7]DMF	2 (3)	99 (95)
2[d]	–	[D_7]DMF	10	20[e]
3[f]	2PPh_3	[D_7]DMF	12	55
4[f]	2P(*t*Bu)$_3$	[D_7]DMF	13	61
5[f]	2 	[D_7]DMF	13	51
6	PPh_3	[D_7]DMF	12	59
7		[D_7]DMF	13	64
8	dppp	[D_7]DMF	3	83
9	dppb	[D_7]DMF	3	complex mixture
10	dppf	[D_7]DMF	3	45
11	dppe	$CDCl_3$	5	89
12	dppe	[D_6]Benzene	12	84

[a] Reactions were carried out under a nitrogen atmosphere. [b] Value in parenthesis is the reaction time of a 1-mM scale reaction. [c] Determined by ^1H NMR spectroscopy. Isolated yield is shown in parenthesis. [d] In the absence of [$Pd_2(dba)_3$·$CHCl_3$] and ligand. [e] At 93% conversion. [f] [$Pd_2(dba)_3$·$CHCl_3$] (2.5 mol %) and ligand (10 mol %) were used.

Table 2. C−S bond formation of **1a**−**i** with thiols



Entry[a]	Substrate [R^1, R^2, R^3, X]	R^4SH	Ligand	Temp. [°C]	Time[b] [h]	Product Yield [%][c]
	1a [*t*Bu, Me, H, Br]	PhSH	dppe	60	1 (6)	**3** 99 (77)
2	**1a** [*t*Bu, Me, H, Br]	CySH	dppe	60	3 (6)	**4** 96 (91)
3	**1a** [*t*Bu, Me, H, Br]	$HO(CH_2)_3SH$	dppe	60	1 (6)	**5** 95 (87)
4	**1a** [*t*Bu, Me, H, Br]	$Cl(CH_2)_3SH$	dppe	60	(6)	**6** (64)
5	**1b** [*t*Bu, H, H, Cl]	*n*PrSH	dppe	60	2 (6)	**7** 90 (74)
6	**1c** [Ph, H, H, Cl]	*n*PrSH	dppe	60	(3)	**8** (87)
7	**1d** [TMS, H, H, Cl]	*n*PrSH	dppe	60	3 (6)	**9** 97 (87)
8	**1e** [H, H, H, Cl]	*n*PrSH	dppe	60	2 (6)	**10** 97 (59)
9	**1f** [[*t*Bu, H, Me, Cl]	*n*PrSH	dppe	60	19	**2** 10
10	**1g** [*t*Bu, *t*Bu, H, Br]	*n*PrSH	dppe	60	24	**11** 7
11	**1h** [*t*Bu, *t*Bu, H, OMs]	*n*PrSH	DIOP	100	1 (6)	**11** 80 (88)
12	**1i** [H, Me, Me, Cl]	*n*PrSH	DIOP	60	1 (1)	**12** 81 (78)

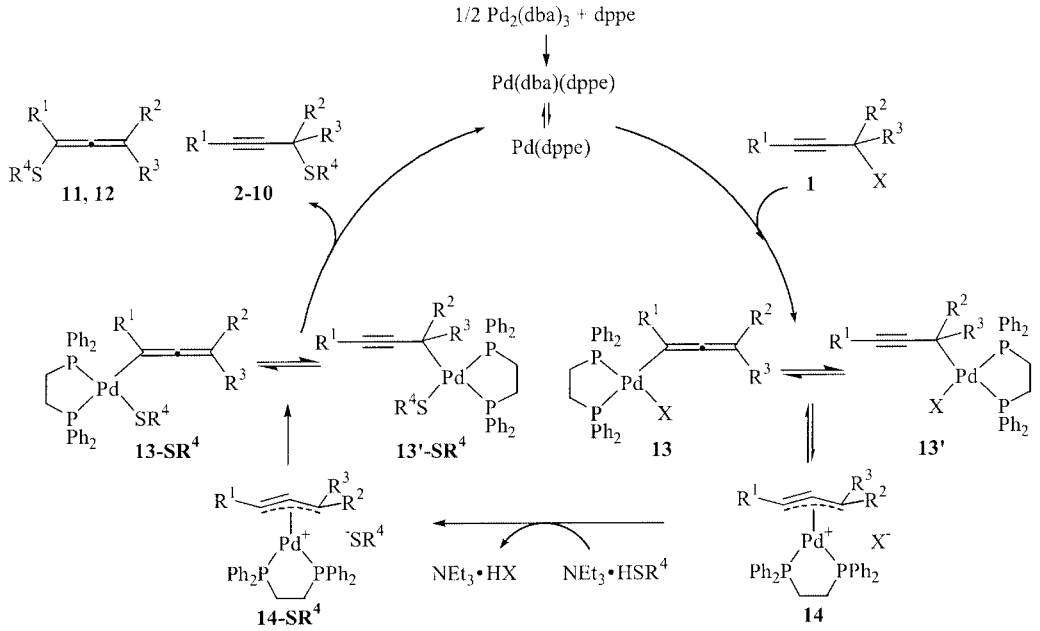
[a] Reactions were carried out under a nitrogen atmosphere. [b] Values in parentheses are reaction times of 1-mM scale reactions. [c] Determined by ^1H NMR spectroscopy. Isolated yields are shown in parentheses.

Scope and Limitations

Next, we extended our studies on the scope of these palladium-catalyzed nucleophilic substitution reactions (Table 2). Our experiments showed that reactions between **1a** and an aromatic thiol (PhSH) or a secondary thiol (CySH) [Cy = cyclohexyl] were complete within 1−3 h to afford sulfides **3** and **4** in excellent yields, respectively (Table 2, entries 1 and 2). In the reaction with $HO(CH_2)_3SH$, the SH group reacted selectivity to give the OH-containing sulfide **5** in good yield (Table 2, entry 3). The Pd-catalyzed reaction with $Cl(CH_2)_3SH$ gave the Cl-substituted sulfide **6** in moderate yield (Table 2, entry 4). Primary chlorides **1b**−**e** were readily converted into the corresponding propargylic sulfides **7**−**10** in higher yields than the secondary chloride **1f** (Table 2, entries 5−9). Although the addition of thiols to terminal alkynes in the presence of palladium catalysts is well known,[16] vinyl sulfides were not produced in this case (Table 2, entry 8). The Pd-dppe catalyst may be more efficient for the reaction of chlorides relative to the Williamson-type reaction of bromides or iodides.[3] When a bulky substituent (*t*Bu group) was present at the propargylic position of **1g**, however, a low yield of the coupling product **11** was obtained (Table 2, entry 10). By using the mesylate **1h** instead of bromide **1g**, however, and conducting the reaction in the presence of Pd-DIOP at 100 °C, the sulfide **11** was obtained in 80% isolated yield (Table 2, entry 11). The difference in reactivities might be explained by the following factors: 1) the oxidative addition to Pd-DIOP proceeds more smoothly[17] and 2) the mesylate anion leaves from the metal center to generate the cationic η^3-allenyl/propargylpalladium complex as a reactive intermediate more readily than does the bromide ion. Structural analysis of product **11** was conducted using its ^{13}C NMR spectrum, which exhibits a signal for an allenylic sp-hybridized carbon atom at $\delta = 192.3$ ppm, suggesting that the well-known propargylic-to-allenylic rearrangement took place in this reaction. The tertiary chloride bearing a terminal acetylene **1i** reacted smoothly to afford the allenylic sulfide **12** in good yield.

Mechanistic Aspects

As shown in Scheme 1, some allenyl/propargylpalladium complexes are considered to be key intermediates in catalytic reactions. These complexes can be generated selectively, however, by adjusting the reaction conditions: the neutral η^1-type complexes are obtained by the reaction of propargyl halides with Pd^0 and two or more equiv. of monophosphane ligands;[11b,12a,12b] the neutral η^3-type complexes are prepared in this case by using one equiv. of PPh_3.[11b] In the presented reactions, the fact that the presence of a monophosphane decreased the reaction rate and yield suggests that the neutral η^1- and η^3-type complexes are lowly reactive intermediates in this catalytic reaction (Table 1, entries 3−6). The best result was obtained when dppe was used in the polar solvent, DMF, under conditions in which cationic η^3-type complexes are generated favorably.[11c] By considering the relationship between the catalytic reactivity and the stability of the cationic η^3-allenyl/propargyl species, we propose an alternative catalytic cycle that involves cation-type complexes (Scheme 2). The oxidative addition of propargylic compound **1** using Pd(dppe), or Pd(dba)(dppe) generated in situ from a mixture of $Pd_2(dba)_3$ and dppe,[17] can afford an equilibrium mixture of neutral η^1-type complexes **13** and **13′** and cationic η^3-type complex **14**. The subsequent exchange of the anion (X^-) with the thiolate anion ($^-SR^4$) can yield the thiolate complex **14-SR⁴**, where the exchange may be more feasible for **14** than for **13** because the X^- ligand has already been



Scheme 2. Suggested catalytic cycle

liberated from the metal. We noticed that [η^1-(PhC≡CCH$_2$)Pt(PPh$_3$)$_2$Cl], which hardly isomerizes to the cationic η^3-allenyl/propargyl complex,[11a][11c] did not react with *n*PrSH and NEt_3 in [D_7]DMF at 60 °C for 1 h. Similar anion exchange processes have been reported for the palladium-catalyzed reactions of allyl compounds with nucleophiles.[18] There are two pathways available from the complex **14-SR^4**. One is the direct attack of the thiolate anion at the terminal carbon atom of the η^3-allenyl/propargyl ligand, which leads to the coupling products **2**−**12**. The other is the addition of the thiolate anion to the palladium atom to form the η^1-allenyl- and η^1-propargylpalladium thiolate complexes **13-SR^4** and **13′-SR^4**, from which reductive eliminations proceed to give **2**−**12**. Although cationic η^3-allenyl/propargyl transition metal complexes tend to undergo regioselective additions of soft nucleophiles at the central carbon atom,[12c,19] we did not observe the corresponding adduct in our reactions. Using ^{1}H NMR spectroscopy, we monitored the stoichiometric reaction of the equilibrium mixture of **13**, **13′**, and **14**, which was generated by the reaction of **1a** and Pd(dppe) in [D_7]DMF, with *n*PrSH at room temperature. No intermediates, however, such as **13-SR^4**, **13′-SR^4**, and **14-SR^4**, were observed in this reaction. The precise mechanism for the nucleophilic attack of the $^-SR^4$ anion is not clear, but the latter pathway might be more reasonable considering the regioselectivity of the C−S bond formation. When the R^2 and R^3 groups are relatively small, propargylic products arise from **13′-SR^4** by avoiding steric hindrance. In contrast, in the case when **13′-SR^4** contains a bulky substituent, such as *t*Bu, or is disubstituted at the propargylic position, reductive elimination may occur after the conversion of propargylic **13′-SR^4** to allenylic **13-SR^4**. Such isomerization between η^1-allenyl and η^1-propargyl transition metal complexes has been investigated in detail.[20] Reductive elimination is generally accelerated when using a bidentate phosphane having the larger bite angle (dppf, dppb, dppp),[21] but these ligands decreased the rate of the C−S coupling reactions (Table 1, entries 8−10). These results suggest that reductive elimination is not the rate-determining step. The generation of cation-type complexes **14** may, therefore, be the important step in the two reaction pathways: the direct attack of the thiolate anion on the propargyl ligand of intermediate **14** or the addition of the thiolate anion to the palladium atom to form **13-SR^4** and **13′-SR^4**. To the best of our knowledge, however, very few catalytic reactions actually proceed with η^3-allenyl/propargylpalladium complexes as key intermediates,[11c,15,22] relative to those featuring neutral η^1-allenyl and η^1-propargylpalladium complexes.[9,10]

Conclusion

Propargylic and allenylic sulfides were prepared readily in high yields through palladium-catalyzed reactions between propargylic compounds and thiols. The yields of the coupling products are dependent on the nature of both the phosphorus ligand (bidentate > monodentate) and the solvent ([D_7]DMF > $CDCl_3$ > [D_6]benzene), which, thus, indicates that the cationic η^3-propargyl/allenylpalladium complex may be an important intermediate in this reaction. This reaction offers an excellent method for not only C−S bond formation of propargylic substrates, but also for other nucleophilic substitution reactions of various compounds. Further investigations, including asymmetric reactions and other carbon−heteroatom bond formations, are currently in progress.

Experimental Section

NMR spectra were recorded on a JNM-ECP-500 spectrometer (^{1}H at 500 MHz, ^{13}C at 126 MHz). ^{1}H NMR spectra are reported as chemical shifts in parts-per-million (ppm) relative to the $SiMe_4$ signal (δ = 0.00 ppm). The following abbreviations are used to describe spin multiplicities: s = singlet; d = doublet; t = triplet; q = quadruplet; m = multiplet; and b = broad. Coupling constants (J) are reported in Hertz (Hz). ^{13}C NMR spectra are reported as chemical shifts in ppm based on the middle peak of [D]chloroform (77.0 ppm). High-resolution mass spectra (HRMS) were obtained on a JEOL JMS-700 mass spectrometer. Analytical GLC was carried out on a Hitachi G-3500 gas chromatograph with a TC-1 capillary column (0.25 mm × 10 m) using helium as the carrier gas. Flash column chromatography was performed using Merck silica gel 60N. Oxygen- and moisture-sensitive reactions were conduced using glassware that had been dried under nitrogen. Commercially available reagents were used without further purification. All anhydrous solvents were purified by standard procedures. RC≡CCH(R′)OH (R = *t*Bu, R′ = Me; R = *t*Bu, R′ = H; R = TMS, R′ = H; R = *t*Bu, R′ = *t*Bu),[23] [$Pd_2(dba)_3$·$CHCl_3$] (dba = 1,5-diphenyl-1,4-pentadiene-3-one),[24] and *trans*-[η^1-(PhC≡CCH_2)$Pt(PPh_3)_2Cl$][20b] were prepared according to published methods. Bromination,[25] chlorination,[26] and mesylation[27] of RC≡CCH(R′)OH (R = *t*Bu, R′ = Me; R = *t*Bu, R′ = H; R = Ph, R′ = H; R = TMS, R′ = H; R = *t*Bu, R′ = *t*Bu) were conducted according to literature procedures.

Pd(dppe)-Catalyzed Reaction of 1a with *n*PrSH: [$Pd_2(dba)_3$·$CHCl_3$] (2.6 mg, 0.0025 mmol) and dppe (2.0 mg, 0.0050 mmol) were added under a nitrogen atmosphere to a [D_7]DMF solution (0.5 mL) of **1a** (18.9 mg, 0.10 mmol) and 1,3,5-trioxane (4.5 mg, 0.050 mmol; internal standard) in an NMR tube. After 5 min, *n*PrSH (9.1 mg, 0.12 mmol) and NEt_3 (12.1 mg, 0.12 mmol) were added to the NMR tube and the mixture was heated to 60 °C. The reaction was monitored by ^{1}H NMR spectroscopy. Other NMR experiments were carried out in a similar manner.

Isolation of *t*BuC≡CCH(Me)SPr (2): [$Pd_2(dba)_3$·$CHCl_3$] (25.9 mg, 0.025 mmol) and dppe (19.9 mg, 0.050 mmol) were added to a solution of **1a** (189.1 mg, 1.00 mmol) in dry DMF (5.0 mL) under a nitrogen atmosphere. After 5 min, *n*PrSH (91.4 mg, 1.20 mmol) and NEt_3 (121.4 mg, 1.20 mmol) were added and the mixture was heated to 60 °C. After 3 h, the reaction mixture was purified by column chromatography (pentane), and the eluent was concentrated carefully in vacuo to provide **2** (174.7 mg, 0.948 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.00 (t, $^3J_{H,H}$ = 7.5 Hz, 3 H, Pr), 1.21 (s, 9 H, *t*Bu), 1.44 (d, $^3J_{H,H}$ = 7.0 Hz, 3 H, Me), 1.65 (m, 2 H, Pr), 2.59 (m, 1 H, Pr), 2.72 (m, 1 H, Pr), 3.63 (q, $^3J_{H,H}$ = 7.0 Hz, 1 H, CH) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 13.63, 22.27, 22.96, 27.42, 29.27, 31.21, 33.32, 79.08, 91.85 ppm. HRMS calcd for $C_{11}H_{20}S$: 184.1286, found 184.1282.

***t*BuC≡CCH(Me)SPh (3):** The reaction of **1a** (189.1 mg, 1.00 mmol) with PhSH (132.2 mg, 1.20 mmol) was carried out as described above to give **3** (168.8 mg, 0.77 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.14 (s, 9 H, *t*Bu), 1.48 (d, $^3J_{H,H}$ = 7.3 Hz, 3 H, Me), 3.91 (q, $^3J_{H,H}$ = 7.3 Hz, 1 H, CH), 7.27−7.30 (m, 3 H, Ph), 7.52 (d, $^3J_{H,H}$ = 6.7 Hz, 2 H, Ph) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 14.14, 22.31, 31.07, 33.82, 79.18, 92.66, 127.63, 128.65, 133.42, 134.32 ppm. HRMS calcd for $C_{14}H_{18}S$: 218.1129, found 218.1132.

***t*BuC≡CCH(Me)SCy (4):** The reaction of **1a** (189.1 mg, 1.00 mmol) with CySH (139.5 mg, 1.20 mmol) was carried out as described above to give **4** (204.4 mg, 0.910 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.20 (s, 9 H, *t*Bu), 1.22−1.39 (m, 5 H, Cy), 1.41 (d, $^3J_{H,H}$ = 7.0 Hz, 3 H, Me), 1.57−1.64 (b, 1 H, Cy), 1.72−1.81 (b, 2 H, Cy), 1.94−2.06 (b, 2 H, Cy), 2.87−2.96 (b, 1 H, Cy), 3.70 (q, $^3J_{H,H}$ = 7.0 Hz, 1 H, CH) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 22.20, 25.84, 27.40, 28.06, 31.17, 33.49, 33.96, 43.59, 79.35, 91.62 ppm. HRMS calcd for $C_{14}H_{24}S$: 224.1599, found 224.1597.

***t*BuC≡CCH(Me)S$(CH_2)_3$OH (5):** The reaction of **1a** (189.1 mg, 1.00 mmol) with HS$(CH_2)_3$OH (110.6 mg, 1.20 mmol) was carried out as described above to give **5** (173.8 mg, 0.868 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.21 (s, 9 H, *t*Bu), 1.44 (d, $^3J_{H,H}$ = 7.0 Hz, 3 H, Me), 1.88 (m, 2 H, CH_2), 2.43 (b, 1 H, OH), 2.79 (m, 2 H, CH_2), 3.64 (q, $^3J_{H,H}$ = 7.0 Hz, 1 H, CH), 3.75 (t, $^3J_{H,H}$ = 6.5 Hz, 2 H, CH_2) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 22.17, 27.41, 27.88, 29.40, 31.18, 31.95, 61.61, 78.88, 92.08 ppm. HRMS calcd for $C_{11}H_{20}OS$: 200.1235, found 200.1235.

***t*BuC≡CCH(Me)S$(CH_2)_3$Cl (6):** The reaction of **1a** (189.1 mg, 1.00 mmol) with HS$(CH_2)_3$Cl (132.7 mg, 1.20 mmol) was carried out as described above to give **6** (140.4 mg, 0.642 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.21 (s, 9 H, *t*Bu), 1.44 (d, $^3J_{H,H}$ = 7.0 Hz, 3 H, Me), 2.10 (m, 2 H, CH_2), 2.84 (m, 2 H, CH_2), 3.63 (q, $^3J_{H,H}$ = 7.0 Hz, 1 H, CH), 3.66 (t, $^3J_{H,H}$ = 6.5 Hz, 2 H, CH_2) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 22.25, 27.48, 28.39, 29.49, 31.21, 32.27, 43.69, 78.81, 92.25 ppm. HRMS calcd for $C_{11}H_{19}ClS$: 218.0896, found 218.0896.

***t*BuC≡CCH_2SPr (7):** The reaction of **1b** (130.1 mg, 1.00 mmol) was carried out as described above to give **7** (126.4 mg, 0.742 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.00 (t, $^3J_{H,H}$ = 7.5 Hz, 3 H, Pr), 1.22 (s, 9 H, *t*Bu), 1.65 (tq, $^3J_{H,H}$ = 7.5, 7.5 Hz, 2 H, Pr), 2.63 (t, $^3J_{H,H}$ = 7.5 Hz, 2 H, Pr), 3.24 (s, 2 H, CH_2) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 13.46, 19.65, 22.48, 27.49, 31.10, 33.44, 74.15, 91.90 ppm. HRMS calcd for $C_{10}H_{18}S$: 170.1129, found 170.1127.

PhC≡CCH_2SPr (8): The reaction of **1c** (150.6 mg, 1.00 mmol) was carried out as described above to give **8** (165.8 mg, 0.871 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.03 (t, $^3J_{H,H}$ = 7.5 Hz, 3 H, Pr), 1.70 (tq, $^3J_{H,H}$ = 7.5, 7.5 Hz, 2 H, Pr), 2.73 (t, $^3J_{H,H}$ = 7.5 Hz, 2 H, Pr), 3.49 (s, 2 H, CH_2), 7.29−7.31 (m, 3 H, Ph), 7.41−7.44 (m, 2 H, Ph) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 13.46, 20.16, 22.46, 33.80, 82.85, 85.58, 123.18, 128.07, 128.23, 131.70 ppm. HRMS calcd for $C_{12}H_{14}S$: 190.0816, found 190.0813.

TMSC≡CCH_2SPr (9): The reaction of **1d** (146.7 mg, 1.00 mmol) was carried out as described above to give **9** (162.0 mg, 0.869 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.16 (s, 9 H, TMS), 1.00 (t, $^3J_{H,H}$ = 7.3 Hz, 3 H, Pr), 1.64 (tq, $^3J_{H,H}$ = 7.3, 7.3 Hz, 2 H, Pr), 2.65 (t, $^3J_{H,H}$ = 7.3 Hz, 2 H, Pr), 3.27 (s, 2 H, CH_2) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 0.03, 13.49, 20.27, 22.47, 33.68, 87.70, 101.93 ppm. HRMS calcd for $C_9H_{18}SSi$: 186.0898, found 186.0899.

HC≡CCH_2SPr (10): The reaction of **1e** (74.5 mg, 1.00 mmol) was carried out as described above to give **10** (67.8 mg, 0.594 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.98 (t, $^3J_{H,H}$ = 7.3 Hz, 3 H, Pr), 1.62 (tq, $^3J_{H,H}$ = 7.3, 7.3 Hz, 2 H, Pr), 2.21 (t, $^3J_{H,H}$ = 2.4 Hz, 1 H, CH), 2.63 (t, $^3J_{H,H}$ = 7.3 Hz, 2 H, Pr), 3.21 (d, $^3J_{H,H}$ = 2.4 Hz, 2 H, CH_2) ppm. ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$): δ = 13.46, 19.10, 22.33, 33.65, 70.79, 80.22 ppm. HRMS calcd for $C_6H_{10}S$: 114.0503, found 114.0504.

(*t*Bu)HC=C=C(*t*Bu)SPr (11): [$Pd_2(dba)_3$·$CHCl_3$] (25.9 mg, 0.025 mmol) and DIOP (24.9 mg, 0.050 mmol) were added to a

solution of **1h** (246.4 mg, 1.00 mmol) in dry DMF (5.0 mL) under a nitrogen atmosphere. After 5 min, *n*PrSH (91.4 mg, 1.20 mmol) and NEt_3 (121.4 mg, 1.20 mmol) were added and the mixture was heated to 100 °C. After 6 h, the reaction mixture was purified by column chromatography (pentane). The eluent was concentrated carefully in vacuo to provide **11** (199.4 mg, 0.880 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.97 (t, $^3J_{H,H}$ = 7.3 Hz, 3 H, Pr), 1.04 (s, 9 H, *t*Bu), 1.14 (s, 9 H, *t*Bu), 1.63 (tq, $^3J_{H,H}$ = 7.3, 7.3 Hz, 2 H, Pr), 2.51 (t, $^3J_{H,H}$ = 7.3 Hz, 2 H, Pr), 5.37 (s, 1 H, CH) ppm. $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$): δ = 13.65, 22.59, 29.88, 30.14, 32.74, 34.86, 35.35, 109.40, 115.49, 192.31 ppm. HRMS calcd for $C_{14}H_{26}S$: 226.1755, found 226.1753.

Me_2C=C=CHSPr (12): The reaction of **1i** (102.6 mg, 1.00 mmol) was carried out as described above to give **12** (110.6 mg, 0.777 mmol). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.98 (t, $^3J_{H,H}$ = 7.0 Hz, 3 H, Pr), 1.64 (tq, $^3J_{H,H}$ = 7.0, 7.0 Hz, 2 H, Pr), 1.75 (d, $^3J_{H,H}$ = 3.0 Hz, 6 H, Me), 2.54 (t, $^3J_{H,H}$ = 7.0 Hz, 2 H, Pr), 5.60 (qq, $^3J_{H,H}$ = 3.0, 3.0 Hz, 1 H, CH) ppm. $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$): δ = 13.62, 20.90, 22.83, 34.20, 85.60, 102.07, 198.86 ppm. HRMS calcd for $C_8H_{14}S$: 142.0816, found 142.0815.

Acknowledgments

We thank Assoc. Prof. Dr. S. Ogoshi and Prof. Dr. H. Kurosawa, Faculty of Engineering, Osaka University, for their valuable discussions and suggestions. Thanks are also due to Ms. Y. Nishikawa for her assistance in obtaining HRMS measurements. This work was supported by a Grant-in-Aid for Scientific Research on Priority Areas (No. 15036247, "Reaction Control of Dynamic Complexes") from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, and by a Sasagawa Scientific Research Grant from the Japan Science Society.

[1] [1a] P. Metzner, A. Thuillier, *Sulfur Reagents in Organic Synthesis*, Academic Press, London, **1994**. [1b] J. T. Kim, A. V. Kel'in, V. Gevorgyan, *Angew. Chem. Int. Ed.* **2003**, *42*, 98−101. [1c] T. M. Mitzel, C. Palomo, K. Jendza, *J. Org. Chem.* **2002**, *67*, 136−145. [1d] T. Takada, S. Kuroi, K. Yanai, A. Tsubouchi, *Tetrahedron Lett.* **2002**, *43*, 5641−5644. [1e] R. Prabharasuth, D. L. V. Vranken, *J. Org. Chem.* **2001**, *66*, 5256−5258. [1f] N. G. Kundu, B. Nandi, *Tetrahedron* **2001**, *57*, 5885−5895. [1g] S. Braverman, Y. Zafrani, H. E. Gottlieb, *Tetrahedron Lett.* **2000**, *41*, 2675−2678. [1h] J. P. Bacci, K. L. Greenman, D. L. V. Vranken, *J. Org. Chem.* **2003**, *68*, 4955−4958.

[2] [2a] S. Braverman, Y. Zafrani, H. E. Gottlieb, *Tetrahedron* **2001**, *57*, 9177−9185. [2b] K. C. Nicolaou, W.-M. Dai, *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 1387−1416.

[3] [3a] S. E. Denmark, M. A. Harmata, K. S. White, *J. Org. Chem.* **1987**, *52*, 4031−4042. [3b] T. I. Reddy, R. S. Varma, *Chem. Commun.* **1997**, 621−622.

[4] [4a] R. C. Cookson, P. J. Parsons, *J. Chem. Soc., Chem. Commun.* **1978**, 822−825. [4b] L. Brandsma, H. E. Wijers, J. F. Arens, *Recl. Trav. Chim. Pays-Bas* **1963**, *82*, 1040−1046. [4c] G. Pourcelot, P. Cadiot, A. Willemant, *Comptes Rendus* **1961**, *252*, 1630−1632. [4d] A. J. Bridges, *Tetrahedron Lett.* **1980**, *21*, 4401−4404. [4e] C. C. Silveira, P. Boeck, A. L. Braga, *Tetrahedron Lett.* **2000**, *41*, 1867−1869.

[5] [5a] Y. Nishibayashi, I. Wakiji, M. Hidai, *J. Am. Chem. Soc.* **2000**, *122*, 11019−11020. [5b] Y. Inada, Y. Nishibayashi, M. Hidai, S. Uemura, *J. Am. Chem. Soc.* **2002**, *124*, 15172−15173. [5c] T. Kondo, Y. Kanda, A. Baba, K. Fukuda, A. Nakamura, K. Wada, Y. Morisaki, T.-A. Mitsudo, *J. Am. Chem. Soc.* **2002**, *124*, 12960−12961.

[6] T. Ishiyama, M. Mori, A. Suzuki, N. Miyaura, *J. Organomet. Chem.* **1996**, *525*, 225−231.

[7] [7a] L. S. Hegedus, R. W. McCabe, *Catalyst Poisoning*, Marcel Dekker, New York, **1984**. [7b] A. T. Hutton, in: *Comprehensive Coordination Chemistry* (Eds.: G. Wilkinson, R. D. Gillard, J. A. McCleverty), Pergamon, Oxford, **1984**; Vol. 5, p. 1131.

[8] For recent review on metal-catalyzed carbon−sulfur bond formation, see: [8a] T. Kondo, T.-A. Mitsudo, *Chem. Rev.* **2000**, *100*, 3205−3220. [8b] H. Kuniyasu, *Catalytic Heterofunctionalization* (Eds: A. Tobni, H. Grützmacher), Wiley & Sons, Weinheim, **2001**, p. 217.

[9] General references on palladium-catalyzed reactions: [9a] R. F. Heck, *Palladium Reagents in Organic Synthesis*, Academic, London, **1985**. [9b] J. L. Malleron, J. C. Fiand, J. Y. Legos, *Handbook of Palladium-Catalyzed Organic Reactions*, Academic, London, **1997**.

[10] [10a] J. Tsuji, T. Mandai, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2589−2612. [10b] J. Tsuji, *Palladium Reagents and Catalysts*, Wiley, Chichester, **1995**, pp. 453−471. [10c] I. Minami, M. Yuhara, H. Watanabe, J. Tsuji, *J. Organomet. Chem.* **1987**, *334*, 225−242, and references cited therein.

[11] [11a] S. Ogoshi, K. Tsutsumi, H. Kurosawa, *J. Organomet. Chem.* **1995**, *493*, C19−C21. [11b] K. Tsutsumi, S. Ogoshi, S. Nishiguchi, H. Kurosawa, *J. Am. Chem. Soc.* **1998**, *120*, 1938−1939. [11c] K. Tsutsumi, T. Kawase, K. Kakiuchi, S. Ogoshi, Y. Okada, H. Kurosawa, *Bull. Chem. Soc. Jpn.* **1999**, *72*, 2687−2692.

[12] [12a] C. J. Elsevier, H. Kleijin, K. Ruitenberg, P. Vermeer, *J. Chem. Soc., Chem. Commun.* **1983**, 1529−1530. [12b] C. J. Elsevier, H. Kleijin, J. Boersma, P. Vermeer, *Organometallics* **1986**, *5*, 716−720. [12c] M. W. Baize, P. W. Blosser, V. Plantevin, D. G. Schimpff, J. C. Gallucci, A. Wojcicki, *Organometallics* **1996**, *15*, 164−173.

[13] Reviews and recent report for the chemistry of allenyl/propargyl transition-metal complexes: [13a] S. Doherty, J. F. Corrigan, A. J. Carty, E. Sappa, *Adv. Organomet. Chem.* **1995**, *37*, 39−129. [13b] A. Wojcicki, *New. J. Chem.* **1994**, *18*, 61−68. [13c] H. Kurosawa, S. Ogoshi, *Bull. Chem. Soc. Jpn.* **1998**, *71*, 973−984. [13d] A. Wojcicki, C. E. Shuchart, *Coord. Chem. Rev.* **1990**, 35−60. [13e] J.-T. Chen, *Coord. Chem. Rev.* **1999**, 1143−1168. [13f] P. W. Blosser, M. Calligaris, D. G. Schimpff, A. Wojcicki, *Inorg. Chim. Acta* **2001**, *320*, 110−116. [13g] A. Wojcicki, *Inorg. Chem. Commun.* **2002**, *5*, 82−97. [13h] C. P. Casey, T. M. Boller, S. Kraft, I. A. Guzei, *J. Am. Chem. Soc.* **2002**, *124*, 13215−13221.

[14] K. Tsutsumi, T. Yabukami, K. Fujimoto, T. Kawase, T. Morimoto, K. Kakiuchi, *Organometallics* **2003**, *22*, 2996−2999.

[15] K. Tsutsumi, S. Ogoshi, K. Kakiuchi, S. Nishiguchi, H. Kurosawa, *Inorg. Chim. Acta* **1999**, *296*, 37−44.

[16] [16a] H. Kuniyasu, A. Ogawa, K.-I. Sato, I. Ryu, N. Kambe, N. Sonoda, *J. Am. Chem. Soc.* **1992**, *114*, 5902−5903. [16b] A. Ogawa, T. Ikeda, K. Kimura, T. Hirao, *J. Am. Chem. Soc.* **1999**, *121*, 5108−5114.

[17] Amotore and Jutand reported the rates and mechanism of the oxidative addition of some palladium(0) complexes, containing various bidentate ligands, to phenyl iodide. The $Pd(dba)_2$/DIOP (1:1) mixture is the effective system for this oxidative addition. See: C. Amatore, G. Broeker, A. Jutand, F. Khalil, *J. Am. Chem. Soc.* **1997**, *119*, 5176−5185.

[18] For examples, see: [18a] R. Lakhmiri, P. Lhoste, D. Sinou, *Tetrahedron Lett.* **1989**, *30*, 4669−4672. [18b] C. Goux, P. Lhoste, D. Sinou, *Tetrahedron Lett.* **1992**, *33*, 8099−8102.

[19] [19a] T.-M. Huang, J.-T. Chen, G.-H. Lee, Y. Wang, *J. Am. Chem. Soc.* **1993**, *115*, 1170−1171. [19b] P. W. Blosser, D. G. Schimpff, J. C. Gallucci, A. Wojcicki, *Organometallics* **1993**, *12*, 1993−1995.

[20] Mutual isomerizations, including mechanistic studies, have been reported. See: [20a] S. Ogoshi, Y. Fukunishi, K. Tsutsumi, H. Kurosawa, *J. Chem. Soc., Chem. Commun.* **1995**, 2485−2986. [20b] S. Ogoshi, Y. Fukunishi, K. Tsutsumi, H. Kurosawa, *Inorg. Chim. Acta* **1997**, *265*, 9−15.

[21] T. Hayashi, M. Konishi, Y. Kobori, M. Kumada, T. Higuchi, K. Hirotsu, *J. Am. Chem. Soc.* **1984**, *106*, 158−163.

[22] C. P. Casey, J. R. Nash, C. S. Yi, A. D. Selmeczy, S. Chung, D. R. Powell, R. K. Hayashi, *J. Am. Chem. Soc.* **1998**, *120*, 722−733.
[23] I. Maclnnes, J. C. Walton, *J. Chem. Soc., Perkin Trans. 2* **1987**, 1077−1087.
[24] T. Ukai, H. Kawazura, Y. Ishii, J. J. Bonnett, J. A. Ibers, *J. Organomet. Chem.* **1974**, *65*, 253−266.
[25] M. C. Marson, U. Grabowska, T. Walsgrove, S. D. Eggleston, W. P. Baures, *J. Org. Chem.* **1994**, *59*, 284−290.
[26] J. G. Calzada, J. Hooz, *Org. Synth.* **1988**, Coll. Vol. VI, p. 634.
[27] R. K. Crossland, K. L. Servis, *J. Org. Chem.* **1970**, *35*, 3195−3196.

Received August 2, 2003

