Synthesis of *cis*-Olefins via Palladium-Catalyzed Coupling of Organic Halides, Norbornadiene, and Organotin Compounds

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Synopsis. Palladium-catalyzed cross-coupling of organic halides with organotin compounds in the presence of norbornadiene gave 5,6-disubstituted norbornene, which was treated by a retro Diels–Alder reaction yielding *cis*-ethene and cyclopentadiene.

A ternary coupling of organic halides, olefins, and organotin compounds catalyzed by palladium catalyst is an important methodology to construct complex molecules directly.[1] However, there was a restriction in the applicable olefins. Previously we reported the palladium-catalyzed cross-coupling of organic halides with organotin compounds involving insertion of norbornene.[2] As reported in the paper, the use of norbornadiene in place of norbornene gave rise to *exo*, *cis*-5,6-disubstituted norbornene, which was treated by a retro Diels–Alder reaction giving *cis*-olefin upon distilling for isolation. Then, the total process which involves the ternary coupling followed by thermolysis of the product is equivalent to *cis*-coupling of the halide and the tin compound with acetylene. From the viewpoint of the synthesis of *cis*-olefin, this report describes the utility of this method.

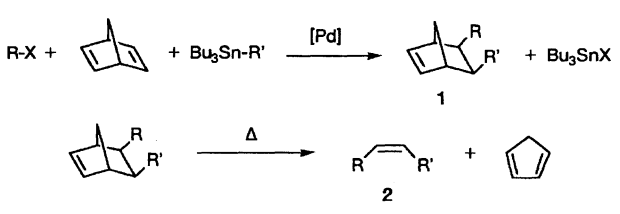
Table 1 shows the results. The structures of **1** were identified as the *exo cis* form from the observation of earlier reports by Chiusoli et al.[1] and ours.[2] Aryl and vinylic halides are potentially useful in this reaction. The presence of an electron-donating group in the aryl halide tends to increase the yield of 5,6-disubstituted norbornene **1**. A retro Diels–Alder reaction gave the *cis*-ethene **2** as a single product in good yield, although only the *cis* structure of 1,4-diphenyl-1-buten-3-yne was confirmed and the *cis* structure of others was elucidated (Scheme 1). The reactions showed some notable tendencies, the reasons for which are not yet clear. 2,3-Diphenylnorbornane was obtained from the reaction of bromobenzene with tributylphenyltin in the presence of norbornene in good yields,[2] but 5,6-diphenylnorbornene was not made by a similar reaction in the presence of norbornadiene. Furthermore, it is also noteworthy that although the reaction of tributyl(1-ethoxyvinyl)tin with iodobenzene in the presence of norbornadiene did not give the product, the reaction with bromobenzene gave moderate yields of the expected ketone to which the product was hydrolyzed under the usual work up.[3] The reaction of bromobenzene with tributylvinyltin in the presence of norbornadiene gave the 5-phenyl-6-vinylnobornene in 91% yield. This product was one of very few examples which can be distilled without the formation of (*Z*)-1-phenyl-1,3-butadiene, the retro Diels–Alder product. The use of dimethyl norbornadiene-2,3-dicarboxylate instead of norbornadiene, however, gave the (*Z*)-1-phenyl-1,3-butadiene in good yield as shown in the following equation (Scheme 2). This suggests that dimethyl norbornadiene-2,3-dicarboxylate may be an alternative "acetylene-donor," although it is less reactive toward the addition.

The reaction could be applied to dimethyl neither 7-oxanorbornadiene-2,3-dicarboxylate nor 1,4,5,6,7-pentamethylnorbornadiene-2,3-dicarboxylate.[4] Although this method has several restrictions, the following combinations of the halide and the tin compound

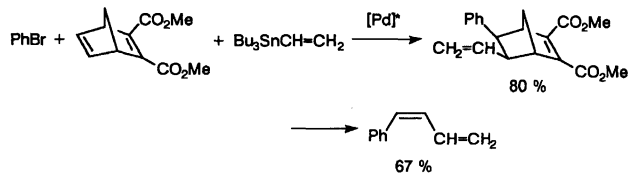
Table 1. Pd-Catalyzed Reaction of the Halides and Tin Compounds in the Presence of Norbornadiene[a]

R–X	–R′ in Bu_3Sn–R′	Isolated yield/%	
		1	**2**
p-$MeOC_6H_4$–I	–C≡CPh	89	88 (78)
p-MeC_6H_4–I		85	89 (75)
Ph–I		66	82 (54)
p-ClC_6H_4–I		63	73 (46)
p-NCC_6H_4–I		55	75 (41)
Ph–I or Ph–Br	–Ph	Trace	—
Ph–I	–C(OEt)=CH_2	0	
Ph–Br			(41)[c]
	–CH=CH_2	91	0
	–CH_2CH=CH_2	Trace	
(*E*) PhCH=CH–Br	–C≡CPh	54	70 (38)
	–Ph	48	83 (40)
	–CH=CH_2	71	69 (49)
	–C(OEt)=CH_2		(56)[c]
Me_2C=CH–Br	–C≡CPh	68	77 (52)
PhCO–Cl		0	
EtCO–Cl		0	
CH_2=$CHCH_2$–Cl		10	

a) $PdCl_2(PPh_3)_2$: 1 mol% at 80—100 °C, for 20 h, in PhH. b) In parenthesis, yield based on the halide. c) As ketone.



Scheme 1.



Scheme 2.

may give successful results; aryl halide and ethynyl or ethenyltin compound, and ethenyl halide and aryl, ethenyl, or ethynyltin compound.

Experimental

Instruments: ^{1}H and ^{13}C NMR spectra were recorded on a Varian Gemini 200 spectrometer. GC-MS spectra were measured on a Shimadzu QP2000A instrument. GC analyses were done on a Shimadzu GC-8A instrument using a 2 m column packed with 5% SE-30 on Celite 545. LC analyses were done on a LC-08 instrument of Japan Analytical Industry Co., Ltd. HRMS was recorded on a JEOL JMS-AX505W instrument of Tokyo Metropolitan University.

Materials: 1-Bromo-2-methylpropene and (*E*)-β-bromostyrene was prepared by the methods described in the literature.[6] Other halides and norbornadiene were purchased from Wako Pure Chemical Industries, Ltd. or Aldrich Chemical Co., Inc. Tributyl(phenylethynyl)tin,[7] tributylphenyltin,[8] tributyl(1-ethoxyvinyl)tin,[9] tributylvinyltin,[10] and allyltributyltin[11] were prepared by the standard method described. Dimethyl norbornadiene-2,3-dicarboxylate was prepared by the reaction of cyclopentadiene with dimethyl acetylenedicarboxylate.[12] Dichlorobis(triphenylphosphine)palladium was prepared by the standard method.[13]

Reactions: The reactions were done as follows: A tube containing a mixture of norbornadiene (6 mmol), halide (3 mmol), tin compound (3 mmol), and $PdCl_2(PPh_3)_2$ (0.03 mmol) in benzene (3 cm^3) as solvent was sealed in vacuo and immersed in a thermobath. Product **1** was obtained by silica gel chromatography, followed by distillation under reduced pressure. A retro Diels–Alder reaction was done by heating **1** at about 200 °C using a Kugelrohr apparatus. The structures of the norbornenes were elucidated by ^{1}H NMR and GC-MS spectra. They were used for the following pyrolysis without further identification.

Products: **[5-*exo*-Phenyl-6-*exo*-phenylethynyl-2-norbornene:]** ^{1}H NMR ($CDCl_3$) δ=7.4—7.1 (m, 8H), 6.9—6.8 (m, 2H), 6.5—6.2 (m, 2H), 3.1 (br s, 2H), 3.0—2.9 (m, 2H), 2.2 (br d, J=8 Hz, 1H), and 1.7 (br d, J=8 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ=143.4, 140.3, 137.0, 131.8, 129.1, 128.3, 127.6, 126.2, 124.3, 92.7, 84.5, 50.0, 48.5, 46.5, 46.2, and 37.4.

[(*Z*)-1,4-Diphenyl-1-buten-3-yne:] ^{1}H NMR ($CDCl_3$) δ=8.0—7.9 (m, 2H), 7.5—7.3 (m, 8H), 6.7 (d, J=12 Hz, 1H), and 5.9 (d, J=12 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ=139.1, 137.0, 131.9, 129.1, 128.9, 128.7, 128.6, 123.9, 107.8, 96.2, and 88.6. MS (70 eV) m/z 204 (M^+, base peak), 101, 76, 63, and 51. This compound was confirmed as (*Z*) structure by the coupling constant of ^{1}H NMR, while an authentic sample of (*E*) structure showed J=16 Hz. HRMS; Found: m/z 204.0920. Calcd for $C_{16}H_{12}$: M, 204.0939.

[6-Phenylethynyl-5-*p*-tolyl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.1 (br s, 7H), 6.9—6.8 (m, 2H), 6.4—6.1 (m, 2H), 3.1 (br s, 2H), 2.9 (q, J=9 Hz, 2H), 2.3 (s, 3H), 2.1 (br d, J=9 Hz, 1H), and 1.6 (br d, J=9 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ=140.4, 137.0, 135.6, 131.9, 129.0, 128.3, 127.6, 124.5, 93.1, 84.6, 50.0, 48.2, 46.7, 46.2, 37.5, and 21.2.

[4-Phenyl-1-*p*-tolyl-1-buten-3-yne:] ^{1}H NMR ($CDCl_3$) δ=7.9—7.1 (m, 9H), 6.7 (d, J=12 Hz, 1H), 5.8 (d, J=12 Hz, 1H), and 2.4 (s, 3H). ^{13}C NMR ($CDCl_3$) δ=131.9, 131.8, 129.4, 129.2, 128.8, 128.7, 124.0, 106.7, 96.0, 88.8, and 21.5. MS (70 eV) m/z 218 (M^+, base peak), 202, 189, 108, and 101. HRMS; Found: m/z 218.1096. Calcd for $C_{17}H_{14}$: M, 218.1096.

[5-*p*-Methoxyphenyl-6-phenylethynyl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.2—7.1 (m, 5H), 6.9—6.8 (m, 4H), 6.4—6.1 (m, 2H), 3.8 (s, 3H), 3.1 (d, J=9 Hz, 2H), 2.9 (q, J=9 Hz, 2H), 2.1 (br d, J=8 Hz, 1H), and 1.5 (br d, J=8 Hz, 1H).

[1-*p*-Methoxyphenyl-4-phenyl-1-buten-3-yne:] ^{1}H NMR ($CDCl_3$) δ=7.9—6.9 (m, 9H), 6.6 (d, J=12 Hz, 1H), 5.8 (d, J=12 Hz, 1H), and 3.8 (s, 3H). MS (70 eV) m/z 234 (M^+, base peak), 201, 191, 189, and 165. HRMS; Found: m/z 234.1068. Calcd for $C_{17}H_{14}O$: M, 234.1044.

[5-*p*-Chlorophenyl-6-phenylethynyl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.3—7.1 (m, 7H), 6.9—6.8 (m, 2H), 6.4—6.1 (m, 2H), 3.1 (d, J=10 Hz, 2H), 2.9 (dq, J=2 and 6 Hz, 2H), 2.1 (br d, J=9 Hz, 1H), and 1.6 (br d, J=9 Hz, 1H).

[1-*p*-Chlorophenyl-4-phenyl-1-buten-3-yne:] ^{1}H NMR ($CDCl_3$) δ=7.8 (d, 2H), 7.5—7.3 (m, 7H), 6.6 (d, J=12 Hz, 1H), 5.9 (d, J=12 Hz, 1H). HRMS; Found: m/z 238.0549. Calcd for $C_{16}H_{11}Cl$: M, 238.0549.

[5-*p*-Cyanophenyl-6-phenylethynyl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.7—7.6 (m, 2H), 7.2—6.8 (m, 7H), 6.4—6.1 (m, 2H), 3.1 (d, J=11 Hz, 2H), 3.0—2.9 (m, 2H), 2.0 (br d, J=8 Hz, 1H), and 1.6 (br d, J=8 Hz, 1H).

[1-*p*-Cyanophenyl-4-phenyl-1-buten-3-yne:] ^{1}H NMR ($CDCl_3$) δ=7.7—7.3 (m, 9H), 6.6 (d, J=10 Hz, 1H), and 5.9 (d, J=10 Hz, 1H). MS (70 eV) m/z 229 (M^+), 202 (base peak), and 101. HRMS; Found: m/z 230.0973. Calcd for $C_{17}H_{12}N$: M+1, 230.0970.

[5-Phenyl-6-vinyl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.3—7.1 (m, 5H), 6.4—6.2 (m, 2H), 5.2—4.6 (m, 3H), 3.1 (s, 1H), 2.9—2.8 (br s, 1H), 2.7 (s, 1H), 2.6—2.4 (m, 1H), 1.9 (br d, J=8 Hz, 1H), and 1.6 (br s, 1H). MS (70 eV) m/z 196 (M^+), 129 (base peak), 115, 91, and 77.

[Dimethyl 5-phenyl-6-vinyl-2-norbornene-2,3-dicarboxylate:] ^{1}H NMR ($CDCl_3$) δ=7.3—7.0 (m, 5H), 5.1—4.7 (m, 3H), 3.77 (s, 3H), 3.83 (s, 3H), 3.5—2.8 (m, 4H), 2.0 (br d, J=9 Hz, 1H), and 1.9 (br d, J=9 Hz, 1H).

[1-Phenyl-1,3-butadiene:] ^{1}H NMR ($CDCl_3$) δ= 7.4—7.2 (m, 5H) and 6.6—5.1 (m, 5H). MS (70 eV) m/z 130 (M^+), 129 (base peak), 115, 64, and 51.

[5-Phenylethynyl-6-styryl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.5—7.1 (m, 10H), 6.5—6.4 (m, 2H), 6.3—6.1 (m, 2H), 3.1 (s, 1H), 2.8—2.7 (m, 2H), 2.6—2.4 (m, 1H), 2.0 (br d, J=8 Hz, 1H), and 1.5 (br d, J=8 Hz, 1H).

[1,6-Diphenyl-1,3-hexadien-5-yne:] ^{1}H NMR ($CDCl_3$) δ=7.5—7.2 (m, 10H) and 6.9—5.8 (m, 4H). MS (70 eV) m/z 230 (M^+), 229 (base peak), 215, 202, and 115. HRMS; Found: m/z 230.1066. Calcd for $C_{18}H_{14}$: M, 230.1096.

[5-Phenyl-6-styryl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.3—6.9 (m, 10H), 6.4—6.1 (m, 3H), 5.5—5.3 (m, 1H),

3.2—2.6 (m, 4H), 2.0 (br d, J=8 Hz, 1H), 1.6 (br d, J=8 Hz, 1H).

[1,4-Diphenyl-1,3-butadiene:] ^{1}H NMR ($CDCl_3$) δ= 7.5—7.2 (m, 10H), 6.8—6.3 (m, 4H). MS (70 eV) m/z 206 (M^+), 191, 128, 115, 91 (base peak). HRMS; Found: 206.1103. Calcd for $C_{16}H_{14}$: M, 206.1095.

[5-Stytyl-6-vinyl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.4—7.1 (m, 5H), 6.4—5.7 (m, 5H), 5.1—4.9 (m, 2H), 2.8—2.7 (m, 2H), 2.5—2.2 (m, 2H), 1.8 (br d, J=9 Hz, 1H), and 1.4 (br d, J=9 Hz, 1H).

[1-Phenyl-1,3,5-hexatriene:] ^{1}H NMR ($CDCl_3$) δ= 7.5—7.1 (m, 5H), and 6.5—5.1 (m, 7H). MS (70 eV) m/z 156 (M^+, base peak), 141, 115, 91, and 78. HRMS; Found: m/z 156.0959. Calcd for $C_{12}H_{12}$: M, 156.0939.

[5-(2-Methyl-1-propenyl)-6-phenylethynyl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.4—7.2 (m, 5H), 6.3—6.1 (m, 2H), 5.4—5.3 (m, 1H), 3.0 (s, 1H), 2.7—2.4 (m, 3H), 1.8 (br d, J=8 Hz, 1H), 1.7 (s, 3H), 1.6 (s, 3H), and 1.4 (br d, J=8 Hz, 1H).

[6-Methyl-1-phenyl-3,5-heptadien-1-yne:] ^{1}H NMR ($CDCl_3$) δ=7.5—7.2 (m, 5H), 6.7—6.4 (m, 2H), 5.6—5.5 (m, 1H), 1.9 (s, 3H), and 1.8 (s, 3H). MS (70 eV) m/z 182 (M^+), 167 (base peak), 165, 143, and 115. HRMS; Found: m/z 182.1109. Calcd for $C_{14}H_{14}$: M, 182.1096.

[5-Allyl-6-phenylethynyl-2-norbornene:] ^{1}H NMR ($CDCl_3$) δ=7.6—7.1 (m, 5H), 6.4—5.9 (m, 3H), 5.2—4.9 (m, 2H), 3.4—2.5 (m, 6H), 1.8 (br d, J=8 Hz, 1H), and 1.6 (br d, J=8 Hz, 1H). MS (70 eV) m/z 234 (M^+), 193, 178, 115, and 79 (base peak).

[4-Phenyl-3-buten-2-one:] ^{1}H NMR ($CDCl_3$) δ= 7.5—7.4 (m, 5H), 6.8 (s, 1H), 6.7 (s, 1H), and 2.4 (s, 3H). HRMS; Found: m/z 146.0689. Calcd for $C_{10}H_{10}O$: M, 146.0732.

[6-Phenyl-3,5-hexadien-2-one:] ^{1}H NMR ($CDCl_3$) δ=7.5—7.2 (m, 6H), 7.0—6.8 (m, 2H), 6.3—6.2 (m, 1H), and 2.3 (s, 3H). MS (70 eV) m/z 172 (M^+), 157, 128 (base peak), 95, and 43. HRMS; Found: m/z 172.0840. Calcd for $C_{12}H_{12}O$: M, 172.0888.

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