Synthesis of 1,5-Enynes by Brønsted Acid Catalyzed Substitution of Propargylic Alcohols and One-Pot Synthesis of Bicyclo[3.1.0]hexenes

Roberto Sanz,*[a] Alberto Martínez,[a] Delia Miguel,[a] Julia M. Álvarez-Gutiérrez,[a] Félix Rodríguez*[b]

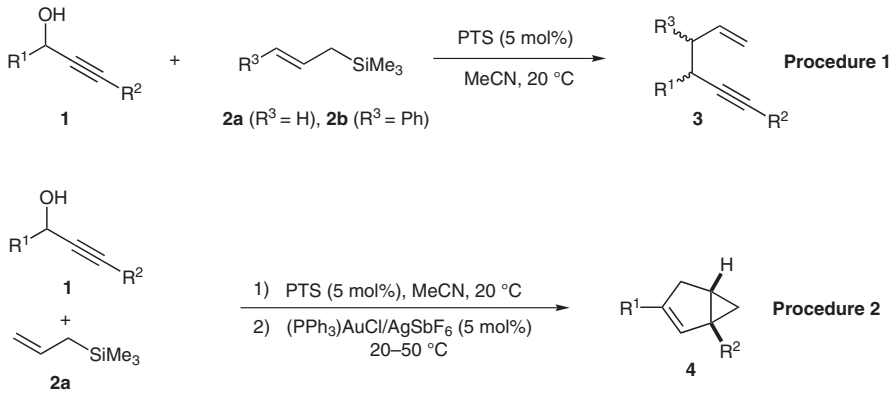
[a] Departamento de Química, Área de Química Orgánica, Facultad de Ciencias, Universidad de Burgos, Pza. Misael Bañuelos s/n, 09001-Burgos, Spain
Fax +34(947)258831; E-mail: rsd@ubu.es

[b] Instituto Universitario de Química Organometálica 'Enrique Moles', Universidad de Oviedo, C/ Julián Clavería 8, 33006-Oviedo, Spain
Fax +34(98)5103447; E-mail: frodriguez@uniovi.es

Received 12 March 2007

Abstract: A practical air and moisture tolerant procedure for the preparation of 1,5-enynes from propargylic alcohols by the Brønsted acid catalyzed direct propargylic substitution of the hydroxy group with allylsilanes is described. Also, a straightforward sequential catalytic protocol for the synthesis of bicyclo[3.1.0]hexane derivatives, from readily available starting materials, is presented.

Key words: catalysis, allylations, alcohols, enynes, tandem reactions



Scheme 1

The development of novel methods for the direct substitution of alcohols is one of the most challenging goals in organic chemistry. For the substitution of propargylic alcohols, reactions have been traditionally carried out using the Nicholas protocol with some limitations (several steps and a stoichiometric amount of $[Co_2(CO)_8]$).[1] Very recently, a few catalytic methodologies for the direct substitution of propargylic alcohols, including allylation reactions, have been reported in the presence of transition metal complexes of ruthenium,[2] rhenium,[3] or gold,[4] as well as other metal salts like $BiCl_3$.[5] Moreover, cations derived from propargylic alcohols can be generated from the corresponding alkoxides in the presence of BCl_3 and further allylated in situ.[6] However, all these strategies are limited by the syntheses and costs of the catalysts or by the need for anhydrous conditions. Thus, the development of efficient substitution reactions of propargylic alcohols using inexpensive reagents and mild conditions would be highly desirable. In this context, we have recently found that simple Brønsted acids like *p*-toluenesulfonic acid (PTSA) catalyze the direct nucleophilic substitution of propargylic,[7] as well as allylic and benzylic alcohols.[8]

On the other hand, 1,5-enynes are useful substrates for several cycloisomerization processes.[9] For example, the formation of interesting bicyclo[3.1.0]hexenes from 1,5-enynes has been reported using platinum and gold complexes.[10]

Herein, we describe a simple protocol for accessing 1,5-enynes through a Brønsted acid catalyzed substitution reaction of propargylic alcohols and allylsilanes (Procedure 1). Also, a straightforward procedure for the synthesis of bicyclo[3.1.0]hexenes through a one-pot tandem sequence involving both, Brønsted acid and gold-catalyzed reactions is reported (Procedure 2)[11](Scheme 1).

As shown in Procedure 1, treatment of secondary propargylic alcohols **1** with a slight excess (1.1 equiv) of the allylsilanes **2**[12] and 5 mol% of *p*-toluenesulfonic acid (PTSA) in analytical grade acetonitrile (1 mL $mmol^{-1}$) at room temperature led to the formation of 1,5-enynes **3** in

SYNTHESIS 2007, No. 20, pp 3252–3256
Advanced online publication: 30.07.2007
DOI: 10.1055/s-2007-983831; Art ID: Z06107SS

high yields.[13] Regarding the structure of the starting alkynol **1**, it is important to note that secondary benzylic substrates are needed in order to achieve high conversions. Thus, aryl (**1a**,**b**), functionalized aryl (**1c**–**e**), or heteroaryl alkynols (**1f**) gave the expected substitution compounds **3** in generally short reaction times (Table 1). Moreover, the R^2 substituent of the starting alkyne can be an aromatic (**1a**,**e**,**f**) or an aliphatic (**1b**–**d**) group. Regarding the starting allylsilane, both **2a** (R^3 = H) and **2b** (R^3 = Ph) gave similar results.

Table 1 PTSA-Catalyzed Allylation of Alkynols **1** with Allylsilanes **2**

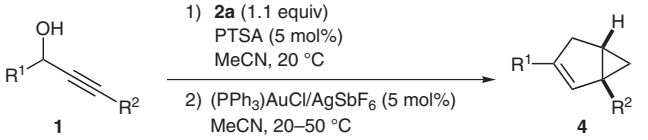
Alkynol	R^1	R^2	Allylsilane	Product	Yield (%)[a]
1a	Ph	Ph	**2a**	**3aa**	73
1b	Ph	*n*-Bu	**2a**	**3ba**	85
1c	4-ClC_6H_4	*n*-Bu	**2a**	**3ca**	62[b]
1d	3-BrC_6H_4	*n*-Bu	**2a**	**3da**	60[b]
1e	3-$MeOC_6H_4$	Ph	**2a**	**3ea**	74
1f	3-thienyl	Ph	**2a**	**3fa**	80
1b	Ph	*n*-Bu	**2b**	**3bb**	81[c]
1c	4-ClC_6H_4	*n*-Bu	**2b**	**3cb**	86[c]

[a] Isolated yields based on starting alkynol **1**.
[b] Carried out at reflux; ca. 20% of the symmetric ethers derived from the corresponding alkynol **1** were also isolated.
[c] Carried out at reflux. Obtained as a ca. 1:1 mixture of diastereoisomers.

These results prompted us to develop a catalytic sequential reaction to synthesize complex organic molecules from simple and readily available alkynols and allylsilanes. Our attention was focused on the reported gold-catalyzed cycloisomerization of enyne systems.[10c]

Thus, as shown in Procedure 2, the consecutive reaction of propargylic alcohols **1** and the allyltrimethylsilane **2a** with PTSA (5 mol%) and an in situ formed cationic gold(I) complex (5 mol%) led to the formation of bicyclo[3.1.0]hexene derivatives **4** in moderate to high yields. It should be remarked that this one-pot process does not require any solvent change or the removal of the PTSA prior to the addition of the gold catalyst.[14] These reactions were easily followed by GC-MS. When the PTSA-catalyzed reaction of alkynols **1** with **2a**, to give the intermediate enynes **3**, was completed, the resulting mixture was added to a preformed suspension of chloro(triphenylphosphine)gold and silver hexafluoroantimonate (5 mol%) in MeCN. The cycloisomerization reaction is slow even at refluxing acetonitrile. Surprisingly, we have observed that the reactions are always completed when the solvent is removed under reduced pressure using a water bath at ca. 50 °C. In this way, bicyclo[3.1.0]hexene derivatives **4** were easily isolated after silica gel column chromatography with hexanes (Table 2).

Table 2 One-Pot Synthesis of Bicyclo[3.1.0]hexenes **4** from Alkynols **1**



Alkynol	R^1	R^2	Product	Yield (%)[a]
1a	Ph	Ph	**4a**	64
1b	Ph	*n*-Bu	**4b**	82
1c	4-ClC_6H_4	*n*-Bu	**4c**	52[b]
1d	3-BrC_6H_4	*n*-Bu	**4d**	50[b]
1e	3-$MeOC_6H_4$	Ph	**4e**	61

[a] Isolated yields based on starting alkynol **1**.
[b] The first step was carried out at reflux; ca. 20% of the symmetric ethers derived from the corresponding **1** were also generated.

In conclusion, we have developed a practical method for the preparation of 1,5-enynes from propargylic alcohols by the Brønsted acid catalyzed direct propargylic substitution of the hydroxy group with allylsilanes. The reaction is tolerant to air and moisture. This metal-free strategy represents a clean, environmentally friendly, and synthetically competitive alternative to the already established use of metal complexes. Moreover, we have also developed a practical sequential catalytic protocol for the synthesis of bicyclo[3.1.0]hexenes from easily available starting materials. This procedure provides a clear example of concurrent tandem catalysis with potential application in diversity-oriented synthesis.

All reactions were carried out under air in oven-dried glassware with magnetic stirring. NMR spectra were recorded in $CDCl_3$ at 300 or 400 MHz for ^{1}H NMR and 75.4 or 100.6 MHz for ^{13}C NMR (Varian Mercury-Plus 300 and Varian Inova 400). Chemical shifts are reported in ppm relative to TMS. IR spectra were recorded on a Nicolet Impact 410 (Software Omnic for Windows) spectrometer. Low-resolution MS were recorded using a GC/MS combination of the type HP 6890 and MSD 5973 with a HP-5MS column. HRMS were recorded on a Micromass Autospec spectrometer (EI, 70 eV). Flash column chromatographic purifications were carried out using Merck Kieselgel 60 (230–400 mesh ASTM). Solvents used were analytical grade (SDS). *p*-Toluenesulfonic acid monohydrate (PTSA) reagent grade (98%) was purchased from Aldrich. Other commercially available starting materials were purchased form Acros, Fluka and Aldrich and used without further purification. The starting propargylic alcohols **1** were synthesized as previously described,[7a] by addition of the corresponding lithium acetylide to the carbonyl derivative.

PTSA-Catalyzed Allylation of Propargylic Alcohols; 1,5-Enynes 3 (Procedure 1)

The corresponding propargylic alcohol **1** (3 mmol) was dissolved in MeCN (3 mL). Then, silane **2** (3.3 mmol) and PTSA (28.5 mg, 0.15 mmol) were added. The mixture was stirred at r.t. or at reflux until all the starting material was consumed (determined by TLC and GC/MS analysis). The solvent was removed under reduced pressure

and the residue was purified by column chromatography (eluent: hexane) affording the corresponding 1,5-enynes **3**.

1,3-Diphenyl-5-hexen-1-yne (3aa)
Obtained from alkynol **1a** (0.62 g, 3 mmol) and silane **2a** (0.38 g, 3.3 mmol), according to Procedure 1 at r.t. for 1 h, as a colorless oil (0.51 g, 73%) after column chromatography (hexane); R_f = 0.28 (hexane).

IR (film): 3422, 3061, 3027, 2198, 1721, 1683, 1596, 1450, 915, 757, 694 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.60–7.20 (m, 10 H), 6.04–5.88 (m, 1 H), 5.20–5.08 (m, 2 H), 3.95 (t, *J* = 7.2 Hz, 1 H), 2.68–2.58 (m, 2 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 141.5, 135.6, 131.8 (2 C), 128.6 (2 C), 128.3 (2 C), 127.9, 127.7, 127.0, 123.8, 117.2, 91.0, 83.9, 42.9, 38.7.

MS (EI, 70 eV): *m*/*z* (%) = 232 (1, $[M^+]$), 191 (100).

HRMS (EI): *m*/*z* $[M^+]$ calcd for $C_{18}H_{16}$: 232.1252; found: 232.1261.

(1-Allylhept-2-ynyl)benzene (3ba)
Obtained from alkynol **1b** (0.56 g, 3 mmol) and silane **2a** (0.38 g, 3.3 mmol), according to Procedure 1 at r.t. for 1 h, as a colorless oil (0.54 g, 85%) after column chromatography (hexane); R_f = 0.48 (hexane).

IR (film): 2956, 2929, 2867, 2353, 1641, 1554, 917 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.47–7.25 (m, 5 H), 6.03–5.88 (m, 1 H), 5.19–5.09 (m, 2 H), 3.77 (tt, *J* = 7.1, 2.2 Hz, 1 H), 2.57 (t, *J* = 7.2 Hz, 2 H), 2.36–2.28 (m, 2 H), 1.66–1.45 (m, 4 H), 1.01 (t, *J* = 7.1 Hz, 3 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 142.2, 135.9, 128.4 (2 C), 127.6 (2 C), 126.6, 116.7, 83.8, 81.2, 43.2, 38.1, 31.3, 22.0, 18.6, 13.7.

MS (EI, 70 eV): *m*/*z* (%) = 212 (2, $[M^+]$), 197 (2), 183 (2), 171 (100), 141 (11), 129 (45), 115 (27), 91 (37).

HRMS (EI): *m*/*z* $[M^+ - C_3H_5]$ calcd for $C_{13}H_{15}$: 171.1174; found: 171.1160.

1-(1-Allylhept-2-ynyl)-4-chlorobenzene (3ca)
Obtained from alkynol **1c** (0.67 g, 3 mmol) and silane **2a** (0.68 g, 6 mmol), according to Procedure 1 at reflux for 12 h, as a colorless oil (0.46 g, 62%) after column chromatography (hexane); R_f = 0.41 (hexane).

IR (film): 3090, 2937, 2861, 2235, 1723, 1489, 1086 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.30–7.28 (m, 4 H), 5.91–5.75 (m, 1 H), 5.07–4.99 (m, 2 H), 3.65 (tt, *J* = 7.0, 2.2 Hz, 1 H), 2.44 (tt, *J* = 7.0, 1.2 Hz, 2 H), 2.24 (td, *J* = 6.9, 2.2 Hz, 2 H), 1.58–1.36 (m, 4 H), 0.93 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 140.7, 135.4, 132.4, 129.0 (2 C), 128.5 (2 C), 117.1, 84.2, 80.7, 43.1, 37.5, 31.2, 22.1, 18.6, 13.8.

MS (EI, 70 eV): *m*/*z* (%) = 246 (2, $[M^+]$), 205 (100), 189 (6), 163 (20), 149 (17), 125 (51), 115 (8).

HRMS (EI): *m*/*z* $[M^+ - C_3H_5]$ calcd for $C_{13}H_{14}Cl$: 205.0784; found: 205.0774.

1-(1-Allylhept-2-ynyl)-3-bromobenzene (3da)
Obtained from alkynol **1d** (0.86 g, 3 mmol) and silane **2a** (0.68 g, 6 mmol), according to Procedure 1 at reflux for 1 h, as a colorless oil (0.52 g, 60%) after column chromatography (hexane); R_f = 0.36 (hexane).

IR (film): 3078, 2955, 2929, 2873, 2238, 2202, 1710, 1470, 1419, 1070 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.52 (s, 1 H), 7.37–7.33 (m, 1 H), 7.30–7.25 (m, 1 H), 7.18 (t, *J* = 7.7 Hz, 1 H), 5.90–5.75 (m, 1 H), 5.09–5.00 (m, 2 H), 3.67–3.60 (m, 1 H), 2.48–2.41 (m, 2 H), 2.24 (td, *J* = 6.8, 2.0 Hz, 2 H), 1.58–1.36 (m, 4 H), 0.93 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 144.6, 135.4, 130.7, 130.0, 129.8, 126.3, 122.5, 117.2, 84.5, 80.4, 43.0, 37.8, 31.2, 22.1, 18.6, 13.8.

MS (EI, 70 eV): *m*/*z* (%) = 292 (2, $[M^+ + 2]$), 290 (2, $[M^+]$), 251 (100), 249 (100), 169 (60), 155 (64), 141 (45), 128 (73), 115 (22).

HRMS (EI): *m*/*z* $[M^+ - C_3H_5]$ calcd for $C_{13}H_{14}Br$: 249.0279; found: 249.0268.

1-Methoxy-3-(1-phenylethynylbut-3-enyl)benzene (3ea)
Obtained from alkynol **1e** (0.71 g, 3 mmol) and silane **2a** (0.38 g, 3.3 mmol), according to Procedure 1 at r.t. for 1 h, as a pale yellow oil (0.58 g, 74%) after column chromatography (hexane); R_f = 0.40 (hexane–EtOAc, 20:1).

^1H NMR (300 MHz, $CDCl_3$): δ = 7.49–7.46 (m, 2 H), 7.33–7.29 (m, 4 H), 7.05–7.03 (m, 2 H), 6.85–6.81 (m, 1 H), 6.02–5.89 (m, 1 H), 5.18–5.10 (m, 2 H), 3.93 (t, *J* = 7.1 Hz, 1 H), 3.84 (s, 3 H), 2.63 (t, *J* = 7.1 Hz, 2 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 160.0, 143.3, 135.8, 132.0 (2 C), 129.8, 128.5 (2 C), 128.1, 124.0, 120.3, 117.4, 113.8, 112.4, 91.1, 84.2, 55.5, 43.0, 38.9.

MS (EI, 70 eV): *m*/*z* (%) = 262 (9, $[M^+]$), 221 (100), 189 (6), 178 (11), 152 (5).

HRMS (EI): *m*/*z* $[M^+]$ calcd for $C_{19}H_{18}O$: 262.1358; found: 262.1368.

3-(1-Phenylethynylbut-3-enyl)thiophene (3fa)
Obtained from alkynol **1f** (0.64 g, 3 mmol) and silane **2a** (0.38 g, 3.3 mmol), according to Procedure 1 at r.t. for 1 h, as a pale yellow oil (0.57 g, 80%) after column chromatography (hexane); R_f = 0.22 (hexane).

IR (film): 3100, 2933, 2906, 2229, 1489, 1435, 917, 688 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$): δ = 7.56–7.50 (m, 2 H), 7.40–7.28 (m, 5 H), 7.21–7.17 (m, 1 H), 6.09–5.94 (m, 1 H), 5.27–5.15 (m, 2 H), 4.09 (t, *J* = 6.9 Hz, 1 H), 2.74–2.65 (m, 2 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 141.8, 135.4, 131.7 (2 C), 128.3 (2 C), 127.9, 127.1, 125.9, 123.6, 121.2, 117.3, 90.8, 83.3, 41.6, 33.8.

MS (EI, 70 eV): *m*/*z* (%) = 238 (4, $[M^+]$), 197 (100), 152 (6).

HRMS (EI): *m*/*z* $[M^+]$ calcd for $C_{16}H_{14}S$: 238.0816; found: 238.0819.

[1-(1-Phenylallyl)hept-2-ynyl]benzene (3bb)
Obtained as a ca. 1:1 mixture of diastereoisomers from alkynol **1b** (0.56 g, 3 mmol) and silane **2b** (0.63 g, 3.3 mmol), according to Procedure 1 at reflux for 30 min, as a pale yellow oil (0.70 g, 81%) after column chromatography (hexane); R_f = 0.35 (hexane).

IR (film): 3073, 3019, 2956, 2925, 2236, 1493, 1454, 921, 695 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.34–7.22 (m, 18 H), 7.19–7.15 (m, 2 H), 6.43–6.33 (m, 1 H), 6.23–6.13 (m, 1 H), 5.20–4.95 (m, 4 H), 4.09–4.02 (m, 2 H), 3.68–3.60 (m, 2 H), 2.35–2.30 (m, 2 H), 2.24–2.19 (m, 2 H), 1.65–1.33 (m, 8 H), 1.01 (t, *J* = 7.2 Hz, 3 H), 0.94 (t, *J* = 7.3 Hz, 3 H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 142.4, 141.3, 140.9, 140.5, 139.4, 138.3, 128.9 (2 C), 128.6 (2 C), 128.4 (2 C), 128.3 (2 C), 128.2 (2 C), 128.1 (2 C), 128.0 (2 C), 127.8 (2 C), 126.8, 126.6, 126.5, 126.4, 116.9, 116.2, 85.6, 85.2, 80.2, 79.8, 57.2, 57.1, 44.6, 44.4, 31.2, 31.0, 22.0, 21.9, 18.7, 18.6, 13.8, 13.7.

MS (EI, 70 eV): *m/z* (%) = 288 (24, [M$^+$]), 259 (4), 245 (7), 231 (100), 184 (27), 129 (59), 115 (75), 91 (76).

HRMS (EI): *m/z* [M$^+$] calcd for $C_{22}H_{24}$: 288.1878; found: 288.1877.

[1-(1-(4-Chlorophenyl)allyl)hept-2-ynyl]benzene (3cb)
Obtained as a ca. 1:1 mixture of diastereoisomers from alkynol **1c** (0.67g, 3 mmol) and silane **2b** (0.63 g, 3.3 mmol), according to Procedure 1 at reflux for 12 h, as a pale yellow oil (0.83 g, 86%) after column chromatography (hexane); R_f = 0.20 (hexane).

IR (film): 3074, 2954, 1647, 1483, 1102, 1015 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.44–7.08 (m, 18 H), 6.41–6.26 (m, 1 H), 6.13–6.09 (m, 1 H), 5.20–4.95 (m, 4 H), 4.07–3.96 (m, 2 H), 3.65–3.51 (m, 2 H), 2.31 (td, *J* = 6.7, 1.9 Hz, 2 H), 2.21 (td, *J* = 6.7, 1.8 Hz, 2 H), 1.64–1.30 (m, 8 H), 0.99 (t, *J* = 7.2 Hz, 3 H), 0.94 (t, *J* = 7.1 Hz, 3 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 141.9, 140.9, 139.5, 139.1, 139.0, 138.1, 138.0, 132.4, 132.3, 129.9 (2 C), 129.7 (2 C), 128.8 (2 C), 128.3 (2 C), 128.1 (2 C), 128.0 (2 C), 127.9 (2 C), 126.7 (2 C), 117.2, 116.5, 85.9, 85.6, 79.6, 79.4, 57.1, 57.0, 44.0, 43.8, 31.1, 31.0, 22.1, 21.9, 18.6, 18.5, 13.8 (2 C).

MS (EI, 70 eV): *m/z* (%) = 324 (8, [M$^+$ + 2]), 322 (24, [M$^+$]), 265 (100), 230 (23), 155 (28), 125 (68), 117 (91), 91 (45).

HRMS (EI): *m/z* [M] calcd for $C_{22}H_{23}Cl$: 322.1488; found: 322.1517.

Tandem PTSA- and Gold-Catalyzed Reaction of Propargylic Alcohols 1 and Allylsilane 2a; One-Pot Synthesis of Bicyclo[3.1.0]hexenes 4 (Procedure 2)
To a mixture of the corresponding propargylic alcohol **1** (2 mmol) and PTSA (19 mg, 0.1 mmol) in MeCN (2 mL), was added allyltrimethylsilane **2a** (0.25 g, 2.2 mmol or 0.46 g, 4 mmol for the reactions carried out at reflux). The mixture was stirred at r.t. or at reflux until all the starting material was consumed (determined by TLC and GC/MS analysis). The resulting solution was transferred via a pipette – assisted with MeCN (0.5 mL) – to a flask containing a preformed mixture of $(PPh_3)AuCl$ (49.5 mg, 0.1 mmol) and $AgSbF_6$ (34.3 mg, 0.1 mmol). After stirring for 30 min at r.t., the solvent was removed under reduced pressure (20 mmHg) at 50 °C (water bath) until dryness. The residue was purified by column chromatography (eluent: hexane), affording the corresponding bicyclo[3.1.0]hexenes **4**.

1,3-Diphenylbicyclo[3.1.0]hex-2-ene (4a)
Obtained from alkynol **1a** (0.42 g, 2 mmol) and silane **2a** (0.25 g, 2.2 mmol), according to Procedure 2, as a white solid (0.30 g, 64%) after column chromatography (hexane); mp 46–48 °C; R_f = 0.28 (hexane).

IR (KBr): 3054, 3027, 2910, 2826, 1602, 1505, 750 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.50–7.45 (m, 2 H), 7.39–7.20 (m, 8 H), 6.66–6.64 (m, 1 H), 3.26 (ddd, *J* = 16.9, 7.0, 1.9 Hz, 1 H), 2.86 (d, *J* = 16.9 Hz, 1 H), 2.02–1.95 (m, 1 H), 1.66 (dd, *J* = 8.2, 4.1 Hz, 1 H), 0.81 (t, *J* = 4.4 Hz, 1 H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 142.6, 139.9, 136.4, 131.0, 128.5 (2 C), 128.4 (2 C), 127.2, 126.5 (2 C), 125.8, 125.4 (2 C), 39.9, 37.1, 26.9, 25.3.

MS (EI, 70 eV): *m/z* (%) = 232 (100, [M$^+$]), 217 (33), 202 (21), 189 (8), 153 (14), 141 (14), 115 (12), 91 (12).

HRMS (EI): *m/z* [M$^+$] calcd for $C_{18}H_{16}$: 232.1252; found: 232.1258.

1-Butyl-3-phenylbicyclo[3.1.0]hex-2-ene (4b)
Obtained from alkynol **1b** (0.38 g, 2 mmol) and silane **2a** (0.25 g, 2.2 mmol), according to Procedure 2, as a colorless oil (0.35 g, 82%) after column chromatography (hexane); R_f = 0.42 (hexane).

IR (film): 3054, 3027, 2956, 2921, 2855, 1606, 1489, 1446, 1026, 750, 688 cm^{-1}.

H NMR (400 MHz, $CDCl_3$): δ = 7.42–7.37 (m, 2 H), 7.33–7.28 (m, 2 H), 7.23–7.18 (m, 1 H), 6.34 (t, *J* = 1.8 Hz, 1 H), 3.06 (ddd, *J* = 16.9, 7.0, 1.8 Hz, 1 H), 2.71 (d, *J* = 16.9 Hz, 1 H), 1.77–1.68 (m, 1 H), 1.59–1.31 (m, 6 H), 0.94 (t, *J* = 7.0 Hz, 3 H), 0.83 (dd, *J* = 7.9, 3.6 Hz, 1 H), 0.28 (t, *J* = 3.8 Hz, 1 H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 138.7, 136.8, 132.4, 128.4 (2 C), 126.8, 125.2 (2 C), 37.0, 36.6, 33.2, 30.9, 23.3, 23.0, 21.4, 14.3.

MS (EI, 70 eV): *m/z* (%) = 212 (23, [M$^+$]), 170 (50), 155 (100), 141 (17), 115 (16), 91 (16).

HRMS (EI): *m/z* [M$^+$] calcd for $C_{16}H_{20}$: 212.1565; found: 212.1570.

1-Butyl-3-(4-chlorophenyl)bicyclo[3.1.0]hex-2-ene (4c)
Obtained from alkynol **1c** (0.45 g, 2 mmol) and silane **2a** (0.46 g, 4 mmol), according to Procedure 2, as a colorless oil (0.26 g, 52%) after column chromatography (hexane); R_f = 0.41 (hexane).

IR (film): 3036, 2921, 1609, 1483, 1091, 819 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.30–7.21 (m, 4 H), 6.31 (t, *J* = 1.7 Hz, 1 H), 3.00 (ddd, *J* = 16.8, 7.0, 1.7 Hz, 1 H), 2.65 (d, *J* = 16.8 Hz, 1 H), 1.74–1.63 (m, 1 H), 1.54–1.30 (m, 6 H), 0.92 (t, *J* = 7.1 Hz, 3 H), 0.83 (dd, *J* = 7.9, 3.7 Hz, 1 H), 0.25 (t, *J* = 3.9 Hz, 1 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 137.6, 135.3, 133.1, 132.3, 128.4 (2 C), 126.4 (2 C), 37.0, 36.8, 33.1, 30.9, 23.4, 23.0, 21.5, 14.3.

MS (EI, 70 eV): *m/z* (%) = 246 (1, [M$^+$]), 205 (100), 163 (19), 149 (17), 141 (10), 125 (45), 115 (9).

HRMS (EI): *m/z* [M$^+$] calcd for $C_{16}H_{19}Cl$: 246.1175; found: 246.1185.

3-(3-Bromophenyl)-1-butylbicyclo[3.1.0]hex-2-ene (4d)
Obtained from alkynol **1d** (0.57 g, 2 mmol) and silane **2a** (0.46 g, 4 mmol), according to Procedure 2, as a colorless oil (0.29 g, 50%) after column chromatography (hexane); R_f = 0.59 (hexane).

IR (film): 3057, 2950, 2924, 1588, 1552, 1475 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.49 (t, *J* = 1.8 Hz, 1 H), 7.32–7.24 (m, 2 H), 7.13 (t, *J* = 7.8 Hz, 1 H), 6.34 (t, *J* = 1.7 Hz, 1 H), 2.99 (ddd, *J* = 16.8, 7.0, 1.7 Hz, 1 H), 2.64 (d, *J* = 16.8 Hz, 1 H), 1.76–1.64 (m, 1 H), 1.52–1.29 (m, 6 H), 0.91 (t, *J* = 7.1 Hz, 3 H), 0.82 (dd, *J* = 7.9, 3.7 Hz, 1 H), 0.24 (t, *J* = 3.9 Hz, 1 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 139.0, 137.4, 134.1, 129.9, 129.5, 128.2, 123.8, 122.7, 36.9, 36.8, 33.0, 30.9, 23.4, 23.0, 21.5, 14.3.

MS (EI, 70 eV): *m/z* (%) = 292 (17, [M + 2]), 290 (17, [M$^+$]), 250 (35), 248 (35), 235 (20), 233 (20), 168 (36), 154 (100), 128 (10).

HRMS (EI): *m/z* [M$^+$] calcd for $C_{16}H_{19}Br$: 290.0670; found: 290.0679.

3-(3-Methoxyphenyl)-1-phenylbicyclo[3.1.0]hex-2-ene (4e)
Obtained from alkynol **1e** (0.48 g, 2 mmol) and silane **2a** (0.25 g, 2.2 mmol), according to Procedure 2, as a colorless oil (0.32 g, 61%) after column chromatography (hexane); R_f = 0.21 (hexane).

IR (film): 3057, 2910, 2839, 1598, 1576, 1494, 1293, 1048, 852 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.42–7.21 (m, 6 H), 7.10 (d, *J* = 7.7 Hz, 1 H), 7.30 (s, 1 H), 6.85 (d, *J* = 8.2 Hz, 1 H), 6.68 (s, 1 H), 3.87 (s, 3 H), 3.27 (dd, *J* = 16.9, 7.0 Hz, 1 H), 2.87 (d, *J* = 16.9 Hz, 1 H), 2.05–1.95 (m, 1 H), 1.71–1.65 (m, 1 H), 0.83 (td, *J* = 4.3, 2.2 Hz, 1 H).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 159.7, 142.5, 139.7, 137.9, 131.4, 129.4, 128.4 (2 C), 126.4 (2 C), 125.8, 118.0, 112.5, 111.1, 55.3, 39.8, 37.1, 26.9, 25.2.

MS (EI, 70 eV): *m*/*z* (%) = 262 (100, [M$^+$]), 247 (20), 231 (18), 215 (21), 202 (16), 171 (11), 153 (11), 121 (13), 115 (14).

HRMS (EI): *m*/*z* [M$^+$] calcd for $C_{19}H_{18}O$: 262.1358; found: 262.1351.

Acknowledgment

We gratefully thank Junta de Castilla y León (BU012A06) and Ministerio de Educación y Ciencia and FEDER (CTQ2004-08077-C02-02/BQU) for financial support. A.M. and D.M. are grateful to MEC for FPU predoctoral fellowships. J.M.A.-G. and F.R. are grateful to MEC and Fondo Social Europeo ('Ramón y Cajal' contracts).

References

(1) (a) Nicholas, K. M. *Acc. Chem. Res.* **1987**, *20*, 207. (b) Teobald, B. J. *Tetrahedron* **2002**, *58*, 4133.
(2) Nishibayashi, Y.; Inada, Y.; Hidai, M.; Uemura, S. *J. Am. Chem. Soc.* **2003**, *125*, 6060.
(3) Luzung, M. R.; Toste, F. D. *J. Am. Chem. Soc.* **2003**, *125*, 15760.
(4) Georgy, M.; Boucard, V.; Campagne, J.-M. *J. Am. Chem. Soc.* **2005**, *127*, 14180.
(5) Zhan, Z.-P.; Yang, W.-Z.; Yang, R.-F.; Yu, J.-L.; Li, J.-P.; Liu, H.-J. *Chem. Commun.* **2006**, 3352.
(6) Kabalka, G. W.; Yao, M.-L.; Borella, S. *J. Am. Chem. Soc.* **2006**, *128*, 11320.
(7) (a) Sanz, R.; Martínez, A.; Álvarez-Gutiérrez, J.-M.; Rodríguez, F. *Eur. J. Org. Chem.* **2006**, 1383. (b) Sanz, R.; Martínez, A.; Miguel, D.; Álvarez-Gutiérrez, J.-M.; Rodríguez, F. *Org. Lett.* **2007**, *9*, 727.
(8) Sanz, R.; Martínez, A.; Miguel, D.; Álvarez-Gutiérrez, J.-M.; Rodríguez, F. *Adv. Synth. Catal.* **2006**, *348*, 1841.
(9) Zhang, L.; Sun, J.; Kozmin, S. A. *Adv. Synth. Catal.* **2006**, *348*, 2271.
(10) (a) Mamane, V.; Gress, T.; Krause, H.; Fürstner, A. *J. Am. Chem. Soc.* **2004**, *126*, 8654. (b) Harrak, Y.; Blaszykowski, C.; Bernard, M.; Cariou, K.; Mainetti, E.; Mouries, V.; Dhimane, A. L.; Fensterbank, L.; Malacria, M. *J. Am. Chem. Soc.* **2004**, *126*, 8656. (c) Luzung, M. R.; Markham, J. P.; Toste, F. D. *J. Am. Chem. Soc.* **2004**, *126*, 10858. (d) Nishibayashi, Y.; Yoshikawa, M.; Inada, Y.; Hidai, M.; Uemura, S. *J. Am. Chem. Soc.* **2004**, *126*, 16066.
(11) Concurrent tandem catalysis constitutes a significant challenge for synthetic chemists and presents a number of opportunities to improve chemical transformations, see: Wasilke, J.-C.; Obrey, S. J.; Baker, R. T.; Bazan, G. C. *Chem. Rev.* **2005**, *105*, 1001.
(12) For the preparation of **2b**, see: Hayashi, T.; Kabeta, K.; Hamachi, I.; Kumada, M. *Tetrahedron Lett.* **1983**, *24*, 2865.
(13) In some cases, and when refluxing conditions are required, competitive formation of the corresponding symmetric ether is observed (ca. 20% isolated yield).
(14) Some interesting processes in which different transition-metal catalysts work in the same medium have been reported. However, in most cases, the reaction conditions have to be changed. See, for instance: (a) Jeong, N.; Seo, S. D.; Shin, J. Y. *J. Am. Chem. Soc.* **2000**, *122*, 10220. (b) Son, S. U.; Park, K. H.; Chung, Y. K. *J. Am. Chem. Soc.* **2002**, *124*, 6838.