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TETRAHEDRON

Nickel-Catalyzed Coupling Reaction of Sterically Congested *cis* Bromides and Lithium Alkenylborates

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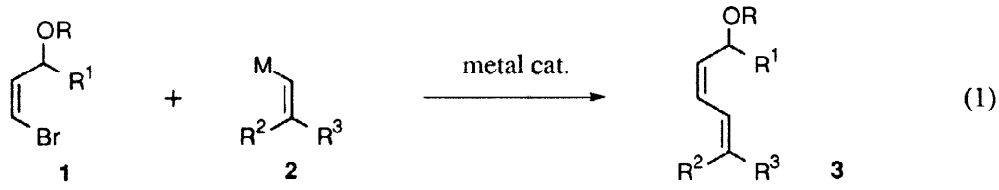
Abstract: Lithium alkenyl borates of general structure **5** (R_T = alkenyl) couple with *cis* bromides **1** at room temperature overnight in the presence of $NiCl_2(PPh_3)_2$ as a catalyst to furnish dienes of general structure **3** with retention of the olefin geometries present in both coupling partners. By using this reaction, *cis,trans* dienes **3** (R = TBDMS, TES, TBDPS; R^1 = *n*-C_5H_{11}, *c*-C_6H_{11}; R^2 = H; R^3 = *n*-C_5H_{11}, Ph) and *cis,cis* diene **3** (R = TBDMS; R^1 = R^2 = *n*-C_5H_{11}; R^3 = H) are synthesized in good yields.

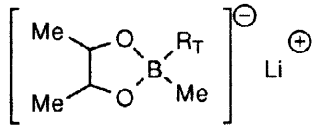
INTRODUCTION

The *cis,trans* conjugated olefin systems with the 1'-hydroxyalkyl (or 1'-alkoxyalkyl) group attached to the *cis* olefin end is frequently seen in biologically important compounds and synthetic intermediates such as leukotriene B_4,[1] the leukotriene B_4 metabolites,[1] fostriecin,[2] himbacine,[3] *etc.* For construction of this unit, one possible method is the coupling reaction of the *cis* bromides **1** with alkenyl organometallics **2** in the presence of a transition metal catalyst (eq 1).[4] The advantage of this approach is the ready availability of the *cis* bromides **1** with high stereoselectivity and high optical purity.[4c,5] However, *cis* bromides of type **1** are generally less reactive substrates in the coupling reaction because of the steric congestion. To circumvent such a difficulty, improved conditions and other methods have been developed.[3,6]



(1)

Recently, we have reported the highly reactive reagents **4** for the coupling reactions. The borates **4** deliver the aryl and alkenyl group R_T efficiently to secondary allylic carbonates[7] and arylmesylates[8] even at



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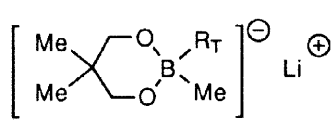

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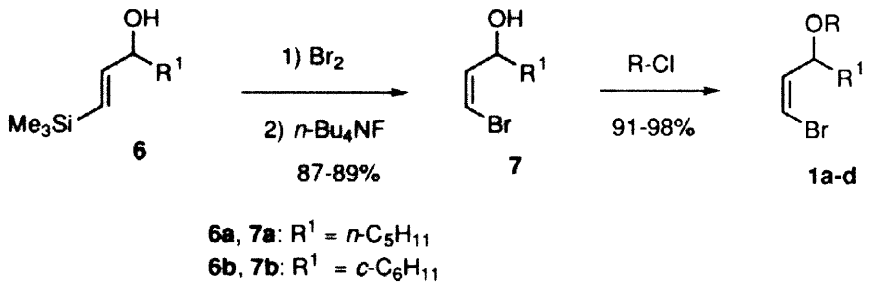


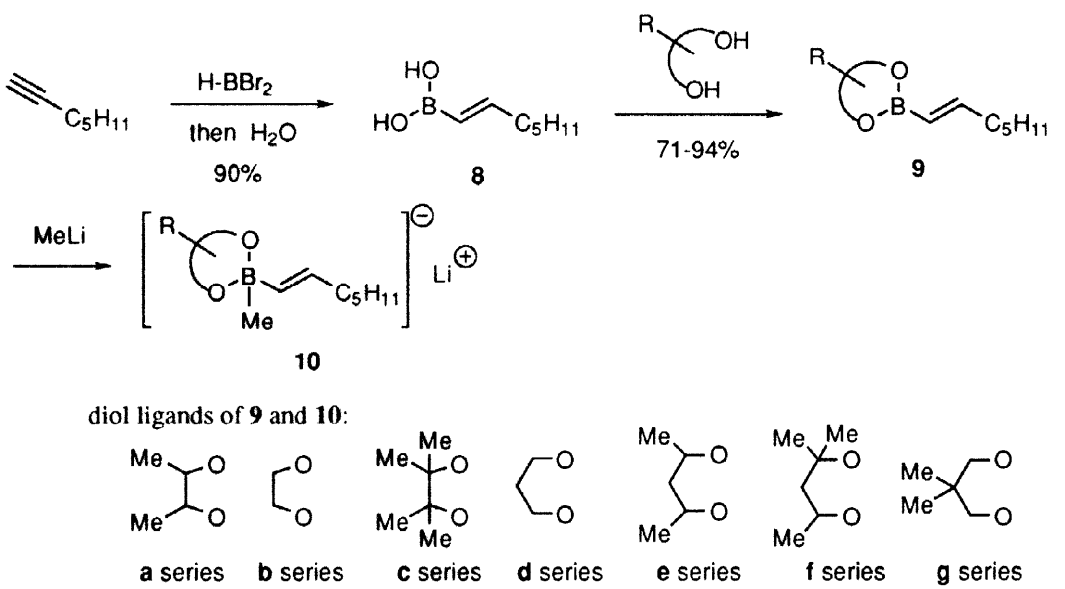
	R^1	R
a	n-C_5H_{11}	TBDMS
b	n-C_5H_{11}	TES
c	n-C_5H_{11}	TBDPS
d	c-C_6H_{11}	TBDMS

Scheme 1

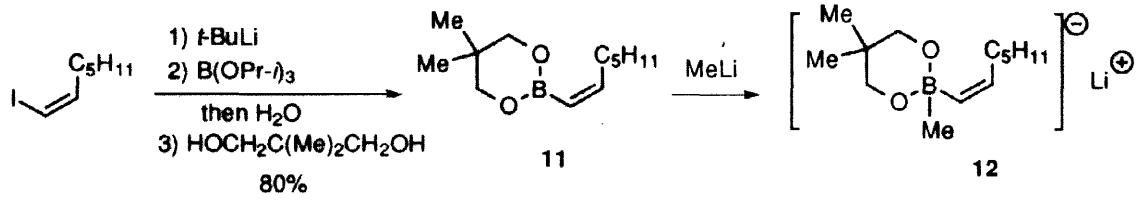
room temperature, while the borates are compatible with ester groups present in the substrates. Since these substrates were among the less reactive partners in the coupling reaction with the classical organometallics,[9] the success with the borates **4** prompted us to investigate the possibility of the borates of type **4** for the coupling with the *cis* bromides **1**. Although the borate **4** (R_T = (*E*)-1-heptenyl) indeed coupled with **1** (R^1 = n-C_5H_{11}, R = TBDMS) under the nickel catalyst, somewhat higher temperature (40-45 °C) was required. This result indicates the low reactivity of **1** in the coupling reaction. Nevertheless, to realize efficient coupling with the less reactive **1**, investigation has been continued and the borates of general structure **5** were elucidated, with which the coupling reaction went to completion at room temperature. Herein we report the results of these studies.

RESULTS AND DISCUSSION

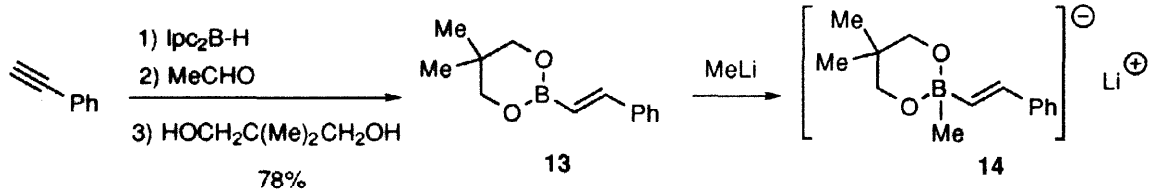
Four *cis* bromides **1a-d**, chosen for the study, were prepared from *trans* allylic alcohols **6a,b** stereoselectively (>98% *trans*) and in high yields according to the literature procedure[5] as delineated in Scheme 1. On the other hand, the boronate esters **9a-g**, which are precursors of the lithium borates **10a-g**,



Scheme 2. Preparation of the Borates **10a-g**.



Scheme 3. Preparation of the Borate **12**.



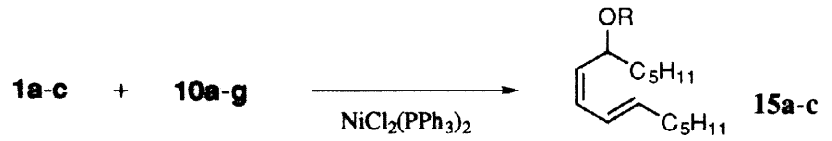
Scheme 4. Preparation of the Borate **14**.

respectively, were synthesized efficiently through hydroboration using $HBBr_2$ followed by esterification with the corresponding diols according to the procedure of Brown[10] (Scheme 2). Furthermore, to examine the potency of the most efficient diol-ligand (2,2-dimethyl-1,3-propanediol ligand) (*vide infra*), boronate esters **11** and **13** were prepared by the literature procedures[11,12] in good yields and transferred into the borates **12** and **14** with MeLi as shown in Scheme 3 and 4, respectively.

First, the coupling reaction was examined by using **1a** and the borate **10a**. Thus, boronate ester **9a** (1.5 equiv.) was converted into the borate **10a** with MeLi (1.5 equiv.) at 0-5 °C for 30 min and **10a** without isolation was submitted to the coupling with **1a** (1 equiv.) in the presence of 10 mol% of $NiCl_2(PPh_3)_2$ in THF. Unfortunately, several reactions at room temperature were capricious. However, slightly elevated temperature of ca 40-45 °C reproducibly led the reaction to completion, furnishing the *cis,trans* diene **15a** in 76% yield (Table 1, entry 1). Fortunately, the *cis,trans* conjugated diene system, which is in general somewhat unstable, was retained under the conditions examined. A related borate with a Bu ligand, which are pivotal in the coupling with aryl mesylates,[8] did not provide better results in this case.

The required temperature (40-45 °C) might be unacceptable in certain cases when applied the reaction to more complicated compounds. We then turned our attention to the possibility of changing the ligand on the borates because the reactivity of the borates in the nickel-catalyzed coupling reaction with the allylic carbonates is highly dependent on the diol-ligand.[7] We selected boronate esters **9b-g** and converted them into the borates **10b-g**, respectively (Scheme 2). Coupling reaction with **1a** was carried out at room temperature for 12 h in the presence of $NiCl_2(PPh_3)_2$ (10 mol%) and conversion of **1a** and the geometric purity of the product **15a** were analyzed by ^1H NMR spectroscopy. The results are also summarized in Table 1 (entries 2-7). The reaction was highly dependent on the diol-ligand and the order of reactivity was not at all parallel to that observed in the coupling with allylic carbonates: the best result was obtained with the borate **10g** to afford **15a** in 90% yield (entry 7), while with sterically less demanding borates **10b,d** and homologue of **10a** (ie., **10e**) resulted in unsatisfactory conversions. In every entry, the *cis* stereochemistry is maintained in the product **15a** (>95% purity). Attempted reaction of **1a** and **10g** with $PdCl_2(PPh_3)_2$ as a catalyst was marginal (data not shown).

Table 1. Coupling of *cis* Bromides **1a-c** and Borates **10a-g** with $NiCl_2(PPh_3)_2$ (10 mol%).[a]

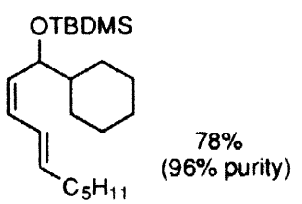


entry	bromide	borate[b]	temp. (°C)	product[a] No.	R	yield,%[c]		purity,%
1	**1a**	**10a**	40-45	**15a**	TBDMS	76		>95[d]
2	**1a**	**10b**	rt	**15a**	TBDMS		(56)	>95[d]
3	**1a**	**10c**	rt	**15a**	TBDMS		(0)	
4	**1a**	**10d**	rt	**15a**	TBDMS		(68)	>95[d]
5	**1a**	**10e**	rt	**15a**	TBDMS		(79)	>95[d]
6	**1a**	**10f**	rt	**15a**	TBDMS		(0)	
7	**1a**	**10g**	rt	**15a**	TBDMS	90	(100)	99[e]
8	**1b**	**10g**	rt	**15b**	TES	80		97[e]
9	**1c**	**10g**	rt	**15c**	TBDPS	84		93[e]

[a] Reactions were carried out with $NiCl_2(PPh_3)_2$ (10 mol%) for 10-16 h at the specified temperature in THF. [b] Borates were prepared from the corresponding 9 and MeLi at 0-5 °C for 15-30 min before use. [c] Numberes in the parentheses refer to conversion of the bromide **1a**. [d] NMR determination of the crude product. [e] NMR determination of the purified product.

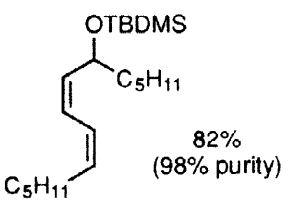
Then the power borate **10g** was applied to the coupling with other *cis* bromides **1b,c** possessing different hydroxyl protecting groups. The reactions proceeded smoothly and the corresponding products **15b,c** were obtained in high yields with retention of the olefin stereochemistries (entries 8 and 9 of Table 1). The high reactivity realized with the 2,2-dimethyl-1,3-propanediol-ligand was not obstructed by the steric hindrance near the reaction site.

To check the generality of the 2,2-dimethyl-1,3-propanediol-ligand for the borates, other entries of coupling reactions producing the following dienes **16-18** were carried out. As expected, these products were obtained in all cases without difficulty in high yields. The following comments are worth mentioning: (1) the sterically more crowded *cis* bromide **1d** could participate in the reaction; (2) although the dienes **17** and **18** are chemically more unstable than **15a** due to the additional *cis* double bond or conjugation with phenyl group, they were obtained with retention of the olefin geometries of the coupling partners.



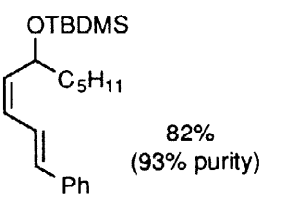
78% (96% purity)

16 from **1d** and **10g**



82% (98% purity)

17 from **1a** and **12**



82% (93% purity)

18 from **1a** and **14**

CONCLUSION

We have presented new alkenyl borates of general structure **5** (R_T = alkenyl) for coupling of the *cis* bromides **1** with steric congestion. The reaction proceeded efficiently at room temperature with a slight excess of **5**, which was prepared *in situ* from 1.5 equiv. of the boronate esters and 1.5 equiv. of MeLi. Moreover, the reaction proceeded with retention of the olefin geometries. Since boronate esters are air and moisture stable, and they can be synthesized by various methods using acetylenes, vinyl halides, and aldehydes, these synthetic advantages coupled with the powerful reactivity mentioned above should open new strategies for synthesis of the sterically hindered dienes. Synthesis of the LTB_4 metabolites using the present reaction is now under investigation.

EXPERIMENTAL

General: Infrared (IR) spectra are reported in wave numbers (cm^{-1}). ^1H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra were measured in $CDCl_3$ using $SiMe_4$ (δ = 0 ppm) and the center line of $CDCl_3$ triplet (δ = 77.1 ppm) as internal standards, respectively. Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl. (*E*)-1-Trimethylsilyl-1-octen-3-ol (**6a**) and (*E*)-1-cyclohexyl-3-trimethylsilyl-2-propen-1-ol (**6b**) were prepared according to the literatures,[5b,c] and $NiCl_2(PPh_3)_2$ according to the literature method.[13] All of the reactions were carried out under nitrogen atmosphere.

(*Z*)-1-Bromo-1-octenyl-3-ol (7a). To a solution of the alcohol **6a** (5.02 g, 25.1 mmol) in CH_2Cl_2 (50 mL) was added Br_2 (1.42 mL, 27.6 mmol) dropwise at -70 °C. After 10 min at -70 °C, the solution was poured into a mixture of $Na_2S_2O_7$ aq. solution and hexane with vigorous stirring. After separation of the layers, the aqueous layer was extracted with hexane. The combined hexane solutions were dried over $MgSO_4$ and concentrated to give the bromine adduct quantitatively.

To the above adduct dissolved in THF (25 mL) was added *n*-Bu_4NF (27.5 mL, 1 M in THF, 27.5 mmol) dropwise at -70 °C. After 15 min at -70 °C, the solution was poured into brine and the product was extracted with Et_2O repeatedly. The combined extracts were dried over $MgSO_4$ and concentrated in vacuo to leave an oil, which was distilled under reduced pressure to give *cis* bromide **7a** (4.52 g, 87%): bp ca 110 °C/ 2 mmHg; ^1H NMR δ 0.88 (t, J = 7 Hz, 3 H), 1.24-1.68 (m, 8 H), 2.05 (br s, 1 H), 4.58 (q, J = 7 Hz, 1 H), 6.13 (t, J = 7 Hz, 1 H), 6.23 (d, J = 7 Hz, 1 H); ^{13}C NMR δ 137.8, 108.4, 70.0, 36.0, 31.6, 24.6, 22.5, 14.0; IR (neat) 3338, 3080, 1624 cm^{-1}.

(*Z*)-1-Bromo-3-((*tert*-butyldimethylsilyl)oxy)-1-octene (1a). To a solution of the alcohol **7a** (1.80 g, 8.70 mmol) and imidazole (0.90 g, 13 mmol) in DMF (20 mL) was added TBDMSCl (1.60 g, 10.6 mmol). The solution was stirred overnight at room temperature and poured into a mixture of hexane and sat. $NaHCO_3$ aq. solution with vigorous stirring. The resulting layers were separated and aqueous layer was extracted with hexane twice. The combined extracts were dried over $MgSO_4$ and concentrated in vacuo to leave an oil, which was purified by chromatography on silica gel to afford the TBDMS ether **1a** (2.75 g, 98%): bp 120 °C/ 2 mmHg; ^1H NMR δ 0.04 (s, 3 H), 0.08 (s, 3 H), 0.86-0.91 (m, 12 H), 1.22-1.57 (m, 8 H), 4.54 (q, J = 7 Hz, 1 H), 6.08 (t, J = 7 Hz, 1 H), 6.11 (d, J = 7 Hz, 1 H); ^{13}C NMR δ 139.2, 106.0, 71.0, 37.0,

31.7, 25.8, 24.6, 22.6, 18.1, 14.0, -4.5, -5.0; IR (neat) 3080, 1622 cm^{-1}.

(Z)-1-Bromo-3-((triethylsilyl)oxy)-1-octene (1b). A mixture of the alcohol **7a** (1.00 g, 4.83 mmol), imidazole (0.66 g, 9.7 mmol), and TESCl (0.99 mL, 5.8 mmol) in DMF (10 mL) was stirred overnight to give the TES ether **1b**, which was isolated as described above (1.40 g, 91%): bp 150 °C/ 2 mmHg; ^1H NMR δ 0.60 (q, J = 8 Hz, 6 H), 0.88 (t, J = 7 Hz, 3 H), 0.95 (t, J = 8 Hz, 9 H), 1.22-1.60 (m, 8 H), 4.54 (q, J = 7 Hz, 1 H), 6.09 (t, J = 7 Hz, 1 H), 6.12 (d, J = 7 Hz, 1 H); ^{13}C NMR δ 139.0, 106.1, 70.7, 37.2, 31.8, 24.6, 22.6, 14.0, 6.7, 4.7; IR (neat) 3080, 1622 cm^{-1}.

(Z)-1-Bromo-3-((*tert*-butyldiphenylsilyl)oxy)-1-octene (1c). A mixture of the alcohol **7a** (1.00 g, 4.83 mmol), imidazole (0.50 g,7.2 mmol), and TBDPSCl (1.5 mL, 5.8 mmol) in DMF (10 mL) was stirred overnight to give the TBDPS ether **1c**, which was isolated as described above (2.04 g, 95%): ^1H NMR δ 0.82 (t, J = 7 Hz, 3 H), 1.05 (s, 9 H), 1.09-1.62 (m, 8 H), 4.57-4.66 (m, 1 H), 5.98 (dd, J = 1.2, 7 Hz, 1 H), 6.14 (t, J = 7 Hz, 1 H), 7.30-7.46 (m, 6 H), 7.60-7.71 (m, 4 H); ^{13}C NMR δ 138.3, 136.10, 136.08, 134.3, 129.74, 129.68, 127.7, 127.6, 106.5, 71.8, 37.1, 31.7, 27.0, 24.1, 22.5, 19.3, 14.0; IR (neat) 3070, 3043, 1622, 1093 cm^{-1}.

(Z)-3-Bromo-1-cyclohexyl-2-propen-1-ol (7b). According to the procedure for the preparation of the *cis* bromide **7a**, the alcohol **6b** (2.75 g, 13 mmol) was converted first with Br_2 (0.74 mL, 14 mmol) in CH_2Cl_2 (15 mL) to the bromine adduct, which was then treated with n-Bu_4NF (14.3 mL, 1 M in THF, 14.3 mmol) in THF (15 mL) to furnish the title compound **7b** (2.52 g, 89%): bp 100-130 °C/ 2 mmHg; ^1H NMR δ 0.94-1.30 (m, 5 H), 1.39-1.55 (m, 1 H), 1.58-1.81 (m, 4 H), 1.84-1.95 (m, 1 H), 2.26 (br peak, 1 H), 4.33 (t, J = 7 Hz, 1 H), 6.12 (t, J = 7 Hz, 1 H), 6.27 (d, J = 7 Hz, 1 H); ^{13}C NMR δ 136.3, 109.2, 73.9, 43.2, 28.4, 28.2, 26.4, 26.0, 25.8; IR (neat) 3342, 3078, 1622 cm^{-1}.

(Z)-1-Bromo-3-((*tert*-butyldimethylsilyl)oxy)-3-cyclohexyl-1-propene (1d). A mixture of the alcohol **7b** (150 mg, 0.68 mmol), imidazole (70 mg, 1.0 mmol), and TBDMSCl (123 mg, 0.82 mmol) in DMF (1.5 mL) was stirred overnight to give the silyl ether **1d**, which was isolated as described above (220 mg, 97%): bp 140 °C/ 2 mmHg; ^1H NMR δ 0.03 (s, 3 H), 0.07 (s, 3 H), 0.88 (s, 9 H), 0.96-1.28 (m, 5 H), 1.34-1.47 (m, 1 H), 1.58-1.79 (m, 4 H), 1.80-1.91 (m, 1 H), 4.26-4.31 (m, 1 H), 6.06 (dd, J = 7, 8 Hz, 1 H), 6.18 (dd, J = 1, 7 Hz, 1 H); ^{13}C NMR δ 137.8, 107.0, 74.8, 44.2, 28.5, 28.4, 26.6, 26.2, 26.1, 25.8, 18.1, -4.4, -5.0; IR (neat) 3080, 1622 cm^{-1}.

(*E*)-Heptenylboronic Acid (8). 1-Heptyne (6.60 mL, 4.84 g, 50 mmol) was placed in a flask and a CH_2Cl_2 solution of $HBBr_2$ (50 mL, 1.0 M, 50 mmol) was added to it over 30 min, during which time the flask was occasionally immersed to an ice-water bath to prevent a temperature rise. The solution was stirred at room temperature for 6 h and then cold water (10 mL) and Et_2O (25 mL) were added slowly to it with vigorous stirring. After 15 min, the organic layer was separated, washed with brine, dried over $MgSO_4$, and concentrated in vacuo to give the boronic acid **8** (6.41 g, 90%): ^1H NMR (selected peaks) δ 5.40 and 5.52 (2d, J = 18 and 18 Hz, 0.3 H and 0.7 H), 6.51 and 6.96 (2dt, J = 18, 6 and 18, 6 Hz, 0.3 H and 0.7 H); IR (nujol) 3211, 1633, 1163, 997 cm^{-1}.

(*E*)-2-(1-Heptenyl)-4,5-dimethyl-1,3,2-dioxaborolane (9a): A mixture of the boronic acid **8** (500 mg, 3.52 mmol), 2,3-butanediol (0.33 mL, 3.6 mmol), and granular $MgSO_4$ (1.5 g) in benzene (15 mL) was stirred at room temperature overnight and filtered through a pad of Celite. The remaining white solid on the Celite was washed with benzene. The filtrates were concentrated in vacuo to give an oil, which was

purified by chromatography on silica gel to give the boronate ester **9a** (610 mg, 88%) as a diastereomeric mixture of *meso* : *dl* = 72 : 28, which was distilled under reduced pressure for the coupling reaction before use: bp 80-90 °C/ 1 mmHg; ^{1}H NMR δ 0.87 (t, *J* = 7 Hz, 3 H), 1.17-1.35 (m, 10 H), 1.35-1.47 (m, 2 H), 2.15 (dq, *J* = 1.5, 7 Hz, 2 H), 3.96-4.06 and 4.48-4.58 (2m, total 2 H), 5.43 (d, *J* = 18 Hz, 1 H), 6.65 (dt, *J* = 18, 7 Hz, 1 H); IR (neat) 1639, 1074, 999, 920 cm^{-1}. Anal. calcd for $C_{11}H_{21}BO_2$: C, 67.38; H, 10.79. Found: C, 67.00; H, 10.92.

(*E*)-2-(1-Heptenyl)-1,3,2-dioxaborolane (9b). According to the procedure for **9a**, boronic acid **8** (500 mg, 3.52 mmol) was transformed into the title compound **9b** (420 mg, 71%) with ethylene glycol (0.20 mL, 3.6 mmol) and granular $MgSO_4$ (1.5 g) in benzene (1.5 mL): bp ca 70 °C/ 1 mmHg; ^{1}H NMR δ 0.87 (t, *J* = 7 Hz, 3 H), 1.22-1.35 (m, 4H), 1.35-1.47 (m, 2 H), 2.16 (dq, *J* = 1.5, 7 Hz, 2 H), 4.22 (s, 4 H), 5.46 (dt, *J* = 18, 1.5 Hz, 1 H), 6.66 (dt, *J* = 18, 7 Hz, 1 H); IR (neat) 1637, 1028, 1001, 947 cm^{-1}. Anal. calcd for $C_9H_{17}BO_2$: C, 64.33; H, 10.20. Found: C, 63.46; H, 10.05.

(*E*)-2-(1-Heptenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (9c). According to the procedure for **9a**, boronic acid **8** (500 mg, 3.52 mmol) was transformed into the title compound **9c** (650 mg, 82%) with pinacol (0.43 g, 3.6 mmol) and granular $MgSO_4$ (1.5 g) in benzene (15 mL): bp 100-140 °C/ 2 mmHg; ^{1}H NMR δ 0.87 (t, *J* = 7 Hz, 3 H), 1.22-1.34 (m, 16 H), 1.35-1.47 (m, 2 H), 2.14 (dq, *J* = 7 Hz, 2 H), 5.42 (dt, *J* = 18, 1.5 Hz, 1 H), 6.63 (dt, *J* = 18, 7 Hz, 1 H); IR (neat) 1637, 1147, 999 cm^{-1}. Anal. calcd for $C_{13}H_{25}BO_2$: C, 69.66; H, 11.24. Found: C, 69.96; H, 11.25.

(*E*)-2-(1-Heptenyl)-1,3,2-dioxaborinane (9d). According to the procedure for **9a**, boronic acid **8** (500 mg, 3.52 mmol) was transformed into the title compound **9d** (540 mg, 84%) with 1,3-propanediol (0.26 mL, 3.6 mmol) and granular $MgSO_4$ (1.5 g) in benzene (15 mL): bp 80 °C/ 1 mmHg; ^{1}H NMR δ 0.86 (t, *J* = 7 Hz, 3 H), 1.21-1.33 (m, 4 H), 1.33-1.44 (m, 2 H), 1.91-1.99 (m, 2 H), 2.10 (dq, *J* = 1.5, 7 Hz, 2 H), 4.02 (t, *J* = 5.5 Hz, 4 H), 5.30 (dt, *J* = 18, 1.5 Hz, 1 H), 6.50 (dt, *J* = 18, 7 Hz, 1 H); IR (neat) 1639, 1101, 999 cm^{-1}. Anal. calcd for $C_{10}H_{19}BO_2$: C, 65.97; H, 10.52. Found: C, 65.95; H, 10.52.

(*E*)-2-(1-Heptenyl)-4,6-dimethyl-1,3,2-dioxaborinane (9e). According to the procedure for **9a**, boronic acid **8** (1.0 g, 7.0 mmol) was transformed into the title compound **9e** (1.38 g, 94%) as a diastereomeric mixture of *meso* : *dl* = 41 : 59 with 2,4-pentanediol (0.77 mL, 7.0 mmol) and granular $MgSO_4$ (3.0 g) in benzene (30 mL): bp ca 100 °C/ 1 mmHg; ^{1}H NMR δ 0.86 (t, *J* = 7 Hz, 3 H), 1.22-1.34 (m, 10 H), 1.33-1.45 (m, 2 H), 1.73 and 1.88 (t, *J* = 5 Hz and dt, *J* = 14, 3 Hz, total 2 H), 2.10 (m, 2 H), 4.06-4.17 and 4.21-4.31 (2m, total 2 H), 5.29-5.37 (m, 1 H), 6.46-6.59 (m, 1 H); IR (neat) 1637, 1128, 999, 904 cm^{-1}. Anal. calcd for $C_{12}H_{23}BO_2$: C, 68.59; H, 11.03. Found: C, 68.63; H, 11.01.

(*E*)-2-(1-Heptenyl)-4,4,6-trimethyl-1,3,2-dioxaborinane (9f). According to the procedure for **9a**, boronic acid **8** (1.0 g, 7.0 mmol) was transformed into the title compound **9f** (1.20 g, 77%) with 2-methyl-2,4-pentanediol (0.72 mL, 5.64 mmol) and granular $MgSO_4$ (3.0 g) in benzene (30 mL): bp ca 110 °C/ 1 mmHg; ^{1}H NMR δ 0.87 (t, *J* = 7 Hz, 3 H), 1.23-1.32 (m, 13 H), 1.34-1.43 (m, 2 H), 1.49 (dd, *J* = 11, 14 Hz, 1 H), 1.76 (dd, *J* = 3, 14 Hz, 1 H), 2.10 (dq, *J* = 1.5, 7 Hz, 2 H), 4.15-4.26 (m, 1 H), 5.33 (dt, *J* = 18, 1.5 Hz, 1 H), 6.53 (t, *J* = 18, 7 Hz, 1 H); IR (neat) 1637, 1165, 999 cm^{-1}. Anal. calcd for $C_{13}H_{25}BO_2$: C, 69.66; H, 11.24. Found: C, 69.64; H, 11.20.

(*E*)-2-(1-Heptenyl)-5,5-dimethyl-1,3,2-dioxaborinane (9g). According to the procedure for **9a**, boronic acid **8** (1.0 g, 7.0 mmol) was transformed into the title compound **9g** (1.30 g, 88%) with 2,2-

dimethyl-1,3-propanediol (0.73 g, 7.0 mmol) and granular $MgSO_4$ (3.0 g) in benzene (30 mL): bp 120-130 °C/ 2 mmHg; ^{1}H NMR δ 0.86 (t, J = 7 Hz, 3 H), 0.96 (s, 6 H), 1.22-1.34 (m, 4 H), 1.34-1.45 (m, 2 H), 2.11 (dq, J = 1.5, 7 Hz, 2 H), 3.62 (s, 4 H), 5.33 (dt, J = 18, 1.5 Hz, 1 H), 6.53 (dt, J = 18, 7 Hz, 1 H); IR (neat) 1637, 1092, 999 cm^{-1}. Anal. calcd for $C_{12}H_{23}BO_2$: C, 68.59; H, 11.03. Found: C, 68.43; H, 11.17.

(*Z*)-2-(1-Heptenyl)-5,5-dimethyl-1,3,2-dioxaborinane (11). To a solution of (*Z*)-1-iodoheptene (1.0 g, 45 mmol) in Et_2O (5 mL) was added *t*-BuLi (6.1 mL, 1.64 M in pentane, 10 mmol) slowly at -78 °C. The solution was stirred for 1 h at -78 °C and B(O-*i*-Pr)$_3$ (1.2 mL, 5.0 mmol) was added dropwise to it. After the addition, the solution was allowed to warm to room temperature over 3 h and poured into brine. To the mixture was added aqueous 1 N HCl and the product was extracted with AcOEt three times. The combined extracts were dried over $MgSO_4$ and the volatile materials were removed by evaporation to furnish the corresponding boronic acid, which was used for the next reaction without further purification.

To the above boronic acid dissolved in Et_2O (20 mL) was added 2,2-dimethyl-1,3-propanediol (0.52 g, 5.0 mmol) and $MgSO_4$ (2.0 g). The resulting mixture was stirred at room temperature overnight and filtered through a pad of Celite with Et_2O. The remaining solid was washed with Et_2O twice. The combined filtrates were concentrated in vacuo and the residual oil thus obtained was purified by silica gel chromatography to afford the title boronate ester **11** (0.76 g, 80%), which was distilled under reduced pressure for the coupling reaction before use: bp 80 °C/ 1 mmHg; ^{1}H NMR δ 0.88 (t, J = 7 Hz, 3 H), 0.97 (s, 6 H), 1.24-1.43 (m, 6 H) 2.36 (dq, J = 1.5, 7 Hz, 2 H), 3.64 (s, 4 H), 5.23 (dt, J = 14, 1.5 Hz, 1 H), 6.32 (dt, J = 14, 7 Hz, 1 H); IR (neat) 1626, 1080 cm^{-1}. Anal. calcd for $C_{12}H_{23}BO_2$: C, 68.59; H, 11.03. Found: C, 68.34; H, 11.00.

(*E*)-2-(2-Phenyl-1-ethenyl)-5,5-dimethyl-1,3,2-dioxaborinane (13). To an ice-cold solution of $BH_3 \cdot SMe_2$ (1.0 mL, 10 mmol) in THF (5 mL) was added (-)-α-pinene (3.5 mL, 22 mmol). The solution was stirred for 1 h at 0 °C and then 2 h at room temperature and cooled down to -35 °C. Phenylacetylene (1.0 mL, 9.1 mmol) was added to it and stirring was continued for 1 h at -35 °C and then 3 h at room temperature. Acetaldehyde (7.7 mL, 140 mmol) was added to the solution and the solution was refluxed for 12 h. Evaporation of low-boiling materials afforded the corresponding ethyl boronate ester.

To a solution of the above product dissolved in THF (10 mL) was added 2,2-dimethyl-1,3-propanediol (0.94 g, 9.1 mmol). After 3 h at room temperature, the solution was concentrated in vacuo and the residue was purified by chromatography on silica gel to afford the title compound **13** (1.53 g, 78%) as the white solid, which was distilled under reduced pressure for the coupling reaction: bp 150 °C/ 1 mmHg; ^{1}H NMR δ 1.01 (s, 6 H), 3.71 (s, 4 H), 6.11 (d, J = 18 Hz, 1 H), 7.27-7.52 (m, 6 H); IR (nujol) 3088, 3026, 1624, 1080, 997 cm^{-1}. Anal. calcd for $C_{13}H_{17}BO_2$: C, 72.26; H, 7.93. Found: C, 72.43; H, 8.12.

(7*Z*,9*E*)-6-((*tert*-Butyldimethylsilyl)oxy)-7,9-pentadecadiene (15a). To an ice-cold suspension of the boronate ester **9g** (100 mg, 0.48 mmol) and $NiCl_2(PPh_3)_2$ (20 mg, 0.031 mmol) in THF (1 mL) was added a ethereal solution of MeLi (0.20 mL, 2.35 M, 0.47 mmol) to generate **10g**. After 30 min at 0 °C, *cis* bromide **1a** (100 mg, 0.311 mmol) was added to the solution and the cooling bath was removed. The solution was stirred overnight at room temperature and then sat. NH_4Cl aq. solution was added to it. The mixture was extracted with hexane three times. The combined extracts were dried over $MgSO_4$ and concentrated in vacuo to leave an oil, which was purified by chromatography on silica gel to give the diene **15a** (94 mg, 90%): ^{1}H NMR δ 0.02 (s, 3 H), 0.05 (s, 3 H), 0.85-0.91 (m, 15 H), 1.20-1.60 (m, 14 H), 2.10 (q,

J = 7 Hz, 2 H), 4.47-4.55 (m, 1 H), 5.24 (t, J = 11 Hz, 1 H), 5.67 (dt, J = 15, 7 Hz, 1 H), 5.89 (t, J = 11 Hz 1 H), 6.23 (ddd, J = 1, 11, 15 Hz, 1 H); ^{13}C NMR δ 136.3, 133.5, 127.9, 125.7, 69.1, 38.5, 32.8, 31.8, 31.4, 28.9, 25.9, 25.0, 22.7, 22.5, 18.2, 14.0, -4.3, -4.8; IR (neat) 3025, 1254, 835, 775 cm^{-1}. Anal. calcd for $C_{21}H_{42}OSi$: C, 74.48; H, 12.50. Found: C, 74.41; H, 12.42.

(7*Z*,9*E*)-6-((Triethylsilyl)oxy)-7,9-pentadecadiene (15b). According to the procedure for **15a**, coupling of bromide **1b** (100 mg, 0.31 mmol) and borate **10g**, prepared from the boronate ester **9g** (95 mg, 0.45 mmol) and MeLi (0.25 mL, 1.80 M in Et_2O, 0.45 mmol) in THF (1.2 mL), using $NiCl_2(PPh_3)_2$ (20 mg, 0.031 mmol) was carried out at room temperature overnight to afford the title compound **15b** (84 mg, 80%): ^{1}H NMR δ 0.58 (q, J = 8 Hz, 6 H), 0.83-0.99 (m, 15 H), 1.18-1.60 (m, 14 H), 2.10 (q, J = 7 Hz, 2 H), 4.46-4.55 (m, 1 H), 5.25 (t, J = 11 Hz, 1 H), 5.68 (dt, J = 15, 7 Hz, 1 H), 5.90 (t, J = 11 Hz, 1 H), 6.23 (ddd, J = 1, 11, 15 Hz, 1 H); ^{13}C NMR δ 136.3, 133.2, 128.1, 125.6, 68.8, 38.6, 32.8, 31.8, 31.3, 28.9, 25.0, 22.6, 22.5, 14.0, 6.8, 4.9; IR (neat) 3025, 1238, 744, 725 cm^{-1}; Anal. calcd for $C_{21}H_{42}OSi$: C, 74.48; H, 12.50. Found: C, 74.46; H, 12.40.

(7*Z*,9*E*)-6-((*tert*-Butyldiphenylsilyl)oxy)-7,9-pentadecadiene (15c). According to the procedure for **15a**, coupling of bromide **1c** (100 mg, 0.22 mmol) and borate **10g**, prepared from boronate ester **9g** (70 mg, 0.33 mmol) and MeLi (0.18 mL, 1.80 M in Et_2O, 0.32 mmol) in THF (0.9 mL), using $NiCl_2(PPh_3)_2$ (13 mg, 0.020 mmol) was carried out at room temperature overnight to afford the title compound **15c** (86 mg, 84%): ^{1}H NMR δ 0.82 (t, J = 7 Hz, 3 H), 0.88 (t, J = 7 Hz, 3 H), 1.04 (s, 9 H), 1.08-1.64 (m, 14 H), 1.91 (q, J = 7 Hz, 2 H), 4.47-4.55 (m, 1 H), 5.30 (t, J = 10 Hz, 1 H), 5.51 (dt, J = 15, 7 Hz, 1 H), 5.69 (dd, J = 10, 15 Hz, 1 H), 5.79 (t, J = 10 Hz, 1 H), 7.29-7.45 (m, 6 H), 7.62-7.72 (m, 4 H): ^{13}C NMR δ 136.2, 136.1, 135.8, 134.8, 134.6, 132.3, 129.6, 129.5, 128.5, 128.4, 127.6, 127.5, 125.7, 69.9, 38.3, 32.6, 31.8, 31.4, 28.8, 27.0, 24.5, 22.5, 19.3, 14.01, 13.98; IR (neat) 3070, 1110, 1066, 822, 734 cm^{-1}. Anal. calcd for $C_{31}H_{46}OSi$: C, 80.46; H, 10.02. Found: C, 80.62; H, 9.98.

(2*Z*,4*E*)-((*tert*-Butyldimethylsilyl)oxy)-1-cyclohexyl-2,4-decadiene (16). According to the procedure for **15a**, coupling of bromide **1d** (100 mg, 0.30 mmol) and borate **10g**, prepared from boronate ester **9g** (88 mg, 0.42 mmol) and MeLi (0.23 mL, 1.8 M in Et_2O, 0.41 mmol) in THF (1.1 mL), using $NiCl_2(PPh_3)_2$ (20 mg, 0.031 mmol) was carried out at room temperature overnight to afford the title compound **16** (77 mg, 73%): ^{1}H NMR δ 0.01 (s, 3 H), 0.02 (s, 3 H), 0.80-0.94 (m, 12 H), 1.04-1.94 (m, 17 H), 2.09 (q, J = 7 Hz, 2 H), 4.17-4.23 (m, 1 H), 5.21 (t, J = 11 Hz, 1 H), 5.66 (dt, J = 15, 7 Hz, 1 H), 5.94 (t, J = 11 Hz, 1 H), 6.21 (ddd, J = 1, 11, 15 Hz, 1 H); ^{13}C NMR δ 136.2, 132.2, 128.8, 126.0, 73.3, 44.9, 32.7, 31.3, 28.91, 28.88, 28.85, 26.7, 26.3, 26.2, 25.9, 22.5, 18.2, 14.0, -4.2, -4.9; IR (neat) 3025, 1254, 837, 775 cm^{-1}. Anal. calcd for $C_{22}H_{42}OSi$: C, 75.36; H, 12.07. Found: C, 75.17; H, 11.82.

(7*Z*,9*Z*)-6-((*tert*-Butyldimethylsilyl)oxy)-7,9-pentadecadiene (17). According to the procedure for **15a**, coupling of bromide **1a** (100 mg, 0.31 mmol) and borate **12**, prepared from boronate ester **11** (95 mg, 0.45 mmol) and MeLi (0.25 mL, 1.80 M in Et_2O, 0.45 mmol) in THF (1.2 mL), using $NiCl_2(PPh_3)_2$ (20 mg, 0.031 mmol) was carried out at room temperature overnight to afford the title compound **17** (86 mg, 82%): ^{1}H NMR δ 0.01 (s, 3 H), 0.04 (s, 3 H), 0.84-0.94 (m, 15 H), 1.16-1.64 (m, 14 H), 2.16 (q, J = 7 Hz, 2 H), 4.49-4.58 (m, 1 H), 5.32-5.40 (m, 1 H), 5.42-5.53 (m, 1 H), 6.12-6.26 (m, 2 H); ^{13}C NMR δ 135.5, 133.6, 123.5, 122.5, 68.8, 38.4, 31.8, 31.4, 29.2, 27.3, 25.9, 25.0, 22.6, 22.5, 18.2, 14.0, -4.3, -4.9; IR (neat) 3040, 3005, 1254, 1078, 835, 775 cm^{-1}. Anal. calcd for $C_{21}H_{42}OSi$: C, 74.48; H,

12.50. Found: C, 74.21; H, 12.31.

(1*E*,3*Z*)-5-((*tert*-Butyldimethylsilyl)oxy)-1,3-decadiene (18). According to the procedure for **15a**, coupling of bromide **1a** (100 mg, 0.31 mmol) and borate **14**, prepared from boronate ester **13** (97 mg, 0.45 mmol) and MeLi (0.25 mL, 1.8 M in Et_2O, 0.45 mmol) in THF (1.2 mL), using $NiCl_2(PPh_3)_2$ (20 mg, 0.031 mmol) was carried out at room temperature overnight to afford the title compound **18** (86 mg, 82%): ^1H NMR δ 0.05 (s, 3 H), 0.08 (s, 3 H), 0.86-0.91 (m, 12 H), 1.20-1.69 (m, 8 H), 4.59-4.67 (m, 1 H) 5.47 (t, *J* = 11 Hz, 1 H), 6.10 (t, *J* = 11 Hz, 1 H), 6.55 (d, *J* = 16 Hz, 1 H), 7.01 (ddd, *J* = 1, 11, 16 Hz, 1 H), 7.21-7.44 (m, 5 H); ^{13}C NMR δ 137.5, 136.5, 133.4, 128.8, 127.8, 126.5, 124.3, 69.3, 38.6, 31.8, 25.9, 25.0, 22.6, 18.2, 14.0, -4.2, -4.8; IR (neat) 3028, 1254, 835, 775 cm^{-1}. Anal. calcd for $C_{22}H_{37}OSi$: C, 76.90; H, 10.27. Found: C, 76.87; H, 10.42.

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