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Intramolecular allylboration of γ-(ω-formylalkoxy)allylboronates for syntheses of *trans*- or *cis*-2-(ethenyl)tetrahydropyran-3-ol and 2-(ethenyl)oxepan-3-ol

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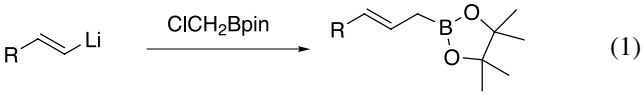
Abstract—3-Alkoxy-1-alkynes **4** were hydroborated with pinacolborane (HBpin) to give 3-alkoxy-1-alkenylboronates **5**. The latter gave (*E*)-3-alkoxyallylboronates (**8**: (*E*)-$(MeO)_2CHCH_2(CH_2)_nCH_2OCH{=}CHCH_2Bpin$, $n=1-3$) when they were subjected to iridium-catalyzed isomerization of the double bond. The corresponding (*Z*)-isomers **10** were synthesized by nickel-catalyzed isomerization of **5**. Both allylboronates underwent intramolecular allylboration leading to the formation of *trans*-2-(ethenyl)tetrahydropyran-3-ol or 2-(ethenyl)oxepan-3-ol from **8** and the corresponding *cis*-isomers from **10** in the presence of $Yb(OTf)_3$ (20 mol%) in aqueous acetonitrile at 90°C.

1. Introduction

Reactions of allylboron compounds with aldehydes or ketones[1] have proved to be very efficient for diastereoselective building of several adjacent chiral centers, intramolecular versions of which have recently developed to achieve five-, six-, seven-, or eight-membered cyclization with diastereoselectivity analogous to that of intermolecular reactions.[2–4] Although the protocol had been hampered by the lack of effective method for the synthesis of desired ω-acylallylboron compounds, several methods are now available. One-carbon homologation of isomerically pure 1-halo-1-alkenes to allylboronates via alkenyllithium intermediates stereoselectively provides both (*E*)- and (*Z*)-allylboronates (Eq. (1)).[5] Palladium-catalyzed coupling reaction of $pinBCH_2ZnI$ (pin=pinacolato) with 1-halo-1-alkenes is an alternative for direct homologation of 1-halo-1-alkenes (Eq. (2)).[2b,4a,6] One-carbon homologation of 1-alkenylboronates is convenient for the synthesis of (*E*)-allylboronates since (*E*)-1-alkenylboronates are easily accessible via hydroboration of terminal alkynes. The reaction of 1-alkenylboronates with $LiCH_2Cl$, in situ generated from ICH_2Cl and BuLi at −100°C, afforded the corresponding allylboronates with retention of *E*-configuration (Eq. (3)).[7] Two-methods are available for borylation of allyl nucleophiles or electrophiles. Palladium-catalyzed coupling reaction of diboron (pinBBpin) with allyl acetates or allyl chlorides stereospecifically yields (*E*)-allylboronates (Eq. (4)).[4b,8] Metalation of allyl ethers is used for the synthesis of (*Z*)-allyllithiums and their transmetalation to *i*-PrOBpin (Eq. (5)).[9] We recently demonstrated the synthesis of (*E*)-allylboronates from (*E*)-1-alkenylboronates via isomerization of the double bond. Various cationic iridium complexes converted 3-alkoxyl-1-alkenylboronates to the corresponding allylboronates at room temperature with high *E*-selectivities (Eq. (6)).[10] For the synthesis of ω-acylallylboron compounds from organolithiums, aldehyde and ketone carbonyls are protected as acetals and deprotected during allylboration. On the other hand, the catalytic coupling reactions shown in Eqs. (2) and (4) tolerate to carbonyl functionalities, thus allowing direct preparation from ω-acyl-1-halo-1-alkenes and their in situ cyclization. High stability of pinacol ester derivatives (Bpin) in the presence of water or air is advantageous for the synthesis and isolation of boron compounds.



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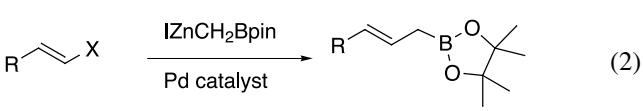

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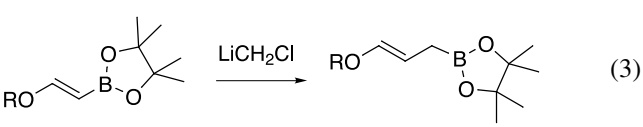

(3)

Keywords: allylboration; pinacolborane; iridium-catalyzed isomerization.

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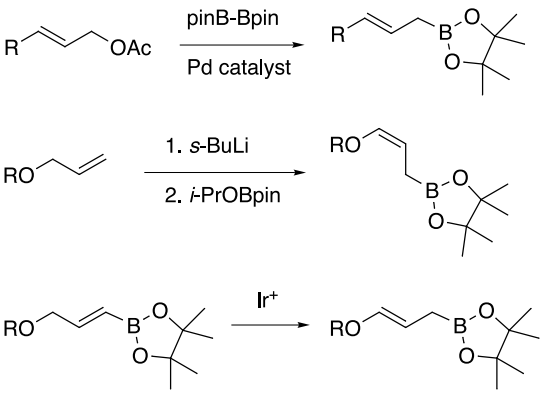
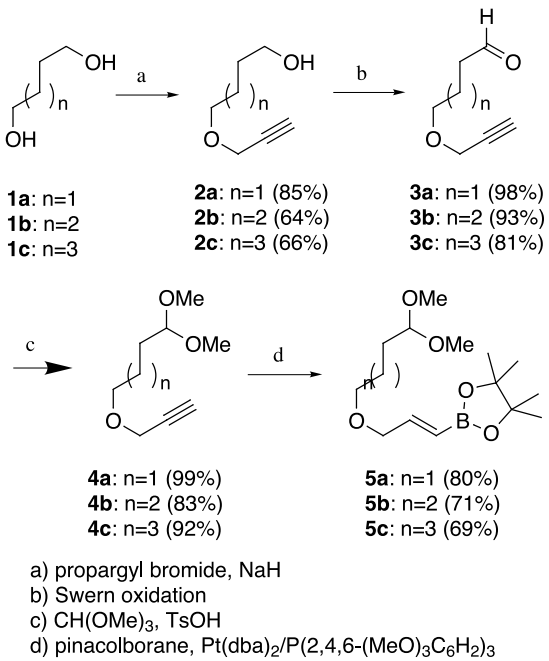
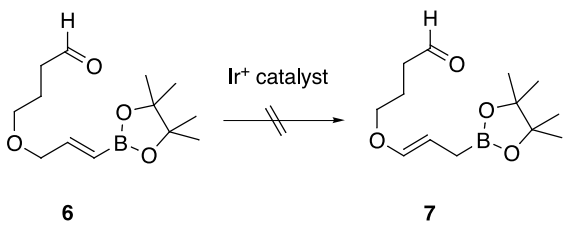


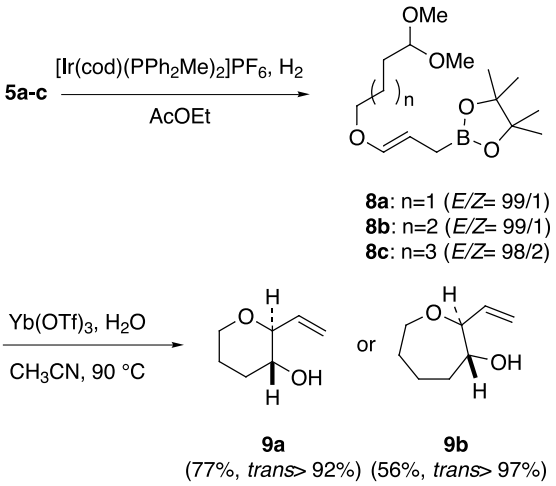
Herein, we report an alternative method for the synthesis of (*E*)- or (*Z*)-3-alkoxyallylboron compounds (**8**, **10**) via catalyzed isomerization of 1-alkenylboronates (**5**) and their cyclization to *cis*- or *trans*-2-(ethenyl)tetrahydropyran-3-ol (**9a**, **11a**) or 2-(ethenyl)oxepan-3-ol (**9b**, **11b**) (Schemes 1–4). For simplicity of the synthetic route, we used (*E*)-3-alkoxyalkenylboronates (**5a–c**) as common intermediates of both (*E*)- and (*Z*)-allylboronates. Iridium-catalyzed isomerization of the double bond of **5** stereoselectively gave (*E*)-allylboronates (**8a–c**, >99%), as was previously demonstrated in the intermolecular reaction.[10] Isomerization by a nickel catalyst gave (*Z*)-isomers (**10a–c**) with selectivities ranging from 90 to 93%.



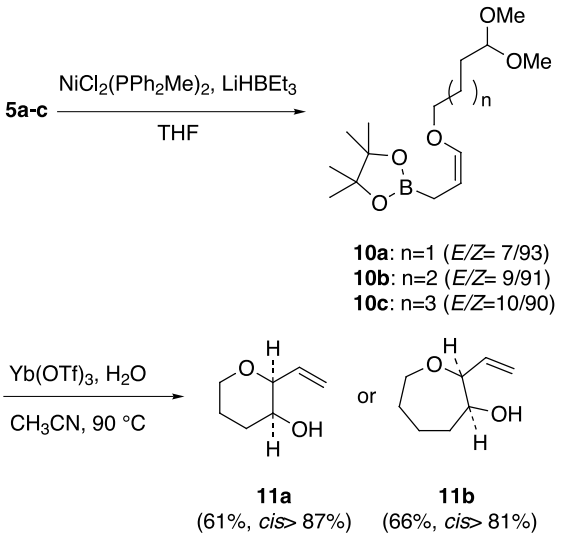
Scheme 1. Synthesis of pinacol 1-alkenylboronate (**5**).



Scheme 2.



Scheme 3.



Scheme 4.

2. Results and discussion

2.1. Synthesis of 1-alkenylboronates (5)

A difficulty in intramolecular allylmetalations is the necessity to synthesize an allylmetal moiety in the presence of a carbonyl group or to synthesize a carbonyl function in the presence of a labile allylmetal moiety. The former synthesis can be achieved by protection of the carbonyl group with a dimethyl acetal during the preparation of the allylboron moiety, as was amply demonstrated by Hoffman.[1] We adopted their protection–deprotection strategy for the synthesis of 3-alkoxyallylboronates (**8**, **10**) and their subsequent intramolecular allylboration. Monopropargylation of diols (**1a–c**) was followed by Swern oxidation and acetalization with $CH(OMe)_3/H^+$ to give protected propargyl ethers (**4a–c**) (Scheme 1). Although $RhCl(CO)(PPh_3)_2$[11a] failed the catalyzed hydroboration of **4** with pinacolborane (HBpin), a platinum(0) catalyst generated in situ from $Pt(dba)_2$ and TTMPP (4 equiv., TTMPP=tris(2,4,6-trimethoxyphenyl)phosphine)[11b]

Table 1. Isomerization of **5** to (*E*)- or (*Z*)-γ-alkoxyallylboronates (**8** or **10**)

Entry	5	Catalyst	Temperature ((C)/Time (h)	Solvent	Convn (%)[a]	Selectivity (%)[a]
1	**5a**	$[Ir(cod)(PPh_2Me)_2]PF_6/H_2$	20/0.5	AcOEt	99	*E*>99
2	**5b**	$[Ir(cod)(PPh_2Me)_2]PF_6/H_2$	20/0.5	AcOEt	97	*E*>99
3	**5c**	$[Ir(cod)(PPh_2Me)_2]PF_6/H_2$	20/0.5	AcOEt	98	*E*>98
4	**5a**	$NiCl_2$(dppb)/$LiBHEt_3$	20/18	THF	92	*Z*>86
5	**5a**	$NiCl_2$(dppf)/$LiBHEt_3$	20/18	THF	87	*Z*>93
6	**5a**	$NiCl_2(PPh_3)_2/LiBHEt_3$	20/18	THF	33	*Z*>94
7	**5a**	$NiCl_2(PPh_2Me)_2/LiBHEt_3$	20/18	THF	89	*Z*>93
8	**5b**	$NiCl_2(PPh_2Me)_2/LiBHEt_3$	20/18	THF	92	*Z*>91
9	**5c**	$NiCl_2(PPh_2Me)_2/LiBHEt_3$	20/18	THF	93	*Z*>90

All reactions were carried out at 20°C for in the presence of **5** (1 mmol) and catalyst (Ir cat: 3 mol%, Ni cat: 4 mol%).
[a] Determined by ^{1}H NMR of crude products.

furnished three alkenylboronates (**5a–c**) required for six-, seven- and eight-membered cyclization.

2.2. Isomerization of 1-alkenylboronates to allylboronates

Since 1-alkenylboronates are much less sensitive to acidic water than allylboronates during deprotection of the carbonyl group, we first examined the isomerization of **6** to **7**, which would in situ undergo intramolecular allylboration. However, all attempts at catalyzed isomerization of **6** failed completely. Alkenylboronate (**6**) remained intact, presumably due to a chelation to a carbonyl group.

The effect of catalysts on positional isomerization of **5** is shown in Table 1. Felkin's cationic iridium(I) complex isomerizes the double bond via a π-allyl mechanism in predominating (*E*)-alkenes.[10,12] Thus, *E*-selective isomerization of the double bond in **5** to the γ-position giving **8** was carried out in ethyl acetate at room temperature in the presence of 3 mol% of $[IrH_2(solv)_2(PPh_2Me)_2]PF_6$, which was generated in situ by passing a stream of H_2 into a solution of $[Ir(cod)(PPh_2Me)_2]PF_6$.[10] High *E*-selectivities exceeding 99% and high conversions in a range of 97–99% were easily achieved for **5a–c** (entries 1–3). On the other hand, we followed the nickel-catalyzed procedure[13] in preparing (*Z*)-isomers since *t*-BuOK in DMSO[14] was hampered by the sensitivity of the allylboron moiety to the base. The conversions and selectivities of the nickel-catalyzed isomerization[13] were found to be very sensitive to the phosphine ligands (entries 4–7). Among the complexes used, PPh_2Me was recognized to be the best ligand to achieve both high conversions and *Z*-selectivities for **5a–c** (entries 7–9).

2.3. Cyclization via intramolecular allylboration

A sequence of *E*-selective isomerization of **5** and their six- or seven-membered cyclization is shown in Scheme 3. Because of the high sensitivity of allylboronates (**8**) to chromatography on silica gel, the synthesis of **8** was directly followed by cyclization to **9**. Yields of **9** were highly dependent on the catalysts and solvents used for hydrolysis of acetal.[2,15,16] The use of protic acids such as HCl and TfOH resulted in significantly low yields, presumably due to a competitive, hydrolytic B–C bond cleavage of the allylboron intermediate. Ytterbium(III) triflate (20 mol%) afforded the best yield for the six-membered cyclization (**9a**), among the metal salts that facilitate the hydrolysis of acetal in aqueous acetonitrile at 90°C; e.g. $LiBF_4$ (56%), CuOTf (44%), AgOTf (42%), $Sm(OTf)_3$ (55%), $Er(OTf)_3$ (58%), $Yb(OTf)_3$ (77%). Allylboration is faster in less-polar solvents than that of donating to the boron atom, but acetonitrile was recognized to be the best solvent; e.g. acetonitrile (77%), 1,2-dichloroethane (58%), THF (28%), and DMF (18%). Analogously, the cyclization of **5b** gave **9b** in 56% yield, but the protocol completely failed the eight-membered cyclization of **8c**, presumably due to an intermolecular reaction giving polymeric materials. Such eight-membered cyclization has been limitedly reported in the corresponding allylboronates possessing a *Z*-double bond in a main chain because it fixes a conformation favorable for cyclization.[2f]

Analogously, *Z*-selective isomerization of **5** to **10** was directly followed by intramolecular allylboration to give **11a** or **11b** (Scheme 4). Since the cyclization proceeds through a chair-like, six-membered transition state as was demonstrated in the intramolecular allylboration of carbonyl compounds,[1] *cis*-isomers (**11a**,**b**) were selectively given from (*Z*)-allylboronates (**10a**,**b**). The reactions resulted in slightly lower *cis*-selectivities than that of *Z*-selectivities of **10**, thus suggesting *E–Z* isomerization of **10** before allylboration. Again, the protocol failed the eight-membered cyclization of **10c**.

In conclusion, we have found a reliable route to the syntheses of (*E*)- and (*Z*)-3-alkoxyallylboronates starting from the corresponding 1-alkenylboronates, which are easily accessible by hydroboration of terminal alkynes. Six- and seven-membered *trans*- or *cis*-2-ethenyl-3-oxacycloalkanols were diastereoselectively obtained by cyclization via the intramolecular allylboration of 3-alkoxyallylboronates.

3. Experimental

3.1. Reagents

All phosphine ligands were commercially available and purified by distillation if necessary. $Yb(OTf)_3$, Cu(OTf), Ag(OTf), $Nb(OTf)_3$, $Sm(OTf)_3$, $Er(OTf)_3$ and $LiBHEt_3$ in THF were purchased from Sigma-Aldrich. $Pt(dba)_2$,[17] $[Ir(cod)(PPh_2Me)_2]PF_6$,[18] $NiCl_2(PPh_3)_2$,[19] $NiCl_2(PPh_2Me)_2$,[20] $NiCl_2$(dppb),[21] and $NiCl_2$(dppf)[22] were synthesized by the reported procedures. Pinacolborane was prepared from borane–methylsulfide complex and pinacol.[23]

3.2. Syntheses of 2a–c (Scheme 1)

3.2.1. 4-(Prop-2-ynyloxy)butan-1-ol (2a). A solution of 1,4-butanediol (54.1 g, 0.6 mol) in DMF (50 ml) was dropwise added into a suspension of sodium hydride (13.2 g, 0.55 mol) in DMF (100 ml) at 0°C. After being stirred for 0.5 h at 0°C, a solution of propargyl bromide (17.8 g, 0.15 mol) in DMF (50 ml) was added. The mixture was then stirred for 24 h at room temperature. The product was extracted with ether, washed with water, dried over $MgSO_4$, and finally concentrated in vacuo. Distillation afforded **2a** (16.3 g, 85%); bp 65–70°C/0.05 mm Hg; IR (neat): 3375, 3291, 2111 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.63–1.75 (m, 4H), 1.91 (s, 1H), 2.44 (t, *J*=2.4 Hz, 1H), 3.57 (t, *J*=5.9 Hz, 2H), 3.67 (t, *J*=6.0 Hz, 2H), 4.16 (d, *J*=2.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 26.2, 29.8, 58.1, 62.6, 70.0, 74.4, 79.6; MS (EI): *m/z* 39 (66), 69 (56), 71 (100), 81 (15), 89 (14), 127 (2); exact mass calcd for $C_7H_{12}O_2$: 127.0759 (M^+-1), found: 127.0763.

3.2.2. 5-(Prop-2-ynyloxy)pentan-1-ol (2b). Yield: 64%; bp 61°C/0.15 mm Hg; IR (neat): 3386, 3291, 2125 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.43–1.50 (m, 3H), 1.57–1.68 (m, 4H), 2.42 (t, *J*=2.3 Hz, 1H), 3.53 (t, *J*=6.5 Hz, 2H), 3.66 (t, *J*=6.5 Hz, 2H), 4.14 (t, *J*=2.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.3, 29.2, 32.4, 58.0, 62.8, 70.0, 74.2, 79.9; MS (EI): *m/z* 39 (100), 55 (59), 69 (76), 84 (61), 101 (21), 141 (2); exact mass calcd for $C_8H_{14}O_2$: 141.0916 (M^+-1), found: 141.0923.

3.2.3. 6-(Prop-2-ynyloxy)hexan-1-ol (2c). Yield: 66%; bp 71–76°C/0.03 mm Hg; IR (neat): 3362, 3292, 2114 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.34–1.44 (m, 4H), 1.55–1.65 (m, 4H), 1.92 (s, 1H), 3.43 (t, *J*=2.4 Hz, 1H), 3.52 (t, *J*=6.6 Hz, 2H), 3.64 (t, *J*=6.6 Hz, 2H), 4.14 (d, *J*=2.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.5, 25.8, 29.4, 32.6, 58.0, 62.8, 70.1, 74.1, 79.9; MS (FAB): *m/z* 55 (35), 83 (41), 107 (21), 137 (80), 157 (78); exact mass calcd for $C_9H_{16}O_2$: 157.1229 (M^++1), found: 157.1224.

3.3. Syntheses of 3a–c (Scheme 1)

3.3.1. 4-(Prop-2-ynyloxy)butanal (3a). Dimethyl sulfoxide (11 ml, 156 mmol) was dropwise added into a solution of oxalyl chloride (7.6 ml, 87 mmol) in dichloromethane (100 ml) at −78°C. After being stirred for 15 min, a solution of **2a** (9.3 g, 72 mmol) in dichloromethane (10 ml) was added. The resulting mixture was stirred for 15 min at −78°C. Triethylamine (49 ml, 351 mmol) was then added. The mixture was allowed to reach 0°C slowly before addition of water (200 ml). The product was extracted with dichloromethane. Distillation gave **3a** (10.1 g, 99%); bp 56°C/0.4 mm Hg; IR (neat): 3280, 2128, 1719 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.91 (tt, *J*=6.1, 7.1 Hz, 2H), 2.40 (t, *J*=2.5 Hz, 1H), 2.53 (dt, *J*=1.4, 7.1 Hz, 2H), 3.53 (t, *J*=6.0 Hz, 2H), 4.10 (d, *J*=2.5 Hz, 2H), 9.76 (t, *J*=1.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.2, 40.7, 58.1, 68.8, 74.3, 76.6, 202.1; MS (EI): *m/z* 71 (42), 77 (20), 89 (24), 107 (27), 125 (40), 127 (32); exact mass calcd for $C_7H_{10}O_2$: 127.0759 (M^++1), found: 127.0767.

3.3.2. 5-(Prop-2-ynyloxy)pentanal (3b). Yield: 93 %; bp 49°C/0.23 mm Hg; IR (neat): 3282, 2121, 1720 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.61–1.78 (m, 4H), 2.43 (t, *J*=2.4 Hz, 1H), 2.48 (dt, *J*=1.7, 7.3 Hz, 2H), 3.54 (t, *J*=6.6 Hz, 2H), 4.14 (d, *J*=2.4 Hz, 2H), 9.78 (t, *J*=1.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 18.8, 22.8, 43.5, 58.0, 69.5, 74.2, 79.8, 202.4; MS (FAB): *m/z* 39 (67), 41 (71), 68 (44), 69 (73), 85 (100), 95 (10), 141 (5); exact mass calcd for $C_8H_{12}O_2$: 141.0916 (M^++1), found: 141.0920.

3.3.3. 6-(Prop-2-ynyloxy)hexanal (3c). Yield: 81%; bp 60°C/0.25 mm Hg; IR (neat): 3278, 2127, 1720 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.38–1.46 (m, 2H), 1.59–1.70 (m, 4H), 2.42 (t, *J*=2.4 Hz, 1H), 2.45 (dt, *J*=1.7, 7.3 Hz, 2H), 3.52 (t, *J*=6.5 Hz, 2H), 4.13 (d, *J*=2.4 Hz, 2H), 9.77 (t, *J*=1.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.8, 25.7, 29.2, 43.7, 58.0, 69.8, 74.1, 79.9, 202.6; MS (FAB): *m/z* 55 (42), 69 (57), 93 (100), 97 (49), 115 (45), 153 (40), 155 (20); exact mass calcd for $C_9H_{14}O_2$: 155.1072 (M^++1), found: 155.1072.

3.4. Syntheses of 4a–c (Scheme 1)

3.4.1. 3-[4,4-(Dimethoxy)butoxy]propyne (4a). To a solution of **3a** (3.78 g, 30 mmol) in anhydrous methanol (37 ml) were added *p*-toluenesulfonic acid (2 g) and (trimethoxy)methane (40 ml, 366 mmol). After being stirred for 1 day at room temperature, the product was extracted with diethyl ether, washed in saturated aqueous Na_2SO_4 and brine, and then dried over $MgSO_4$. Distillation gave **4a** (5.1 g, 99%); bp 46°C/0.06 mm Hg; IR (neat): 3260, 2135 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.62–1.72 (m, 4H), 2.42 (t, *J*=2.4 Hz, 1H), 3.32 (s, 6H), 3.54, (t, *J*=6.1 Hz, 2H), 4.14 (d, *J*=2.4 Hz, 2H), 4.39 (t, *J*=5.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.6, 29.1, 52.7, 58.0, 69.7, 74.2, 79.9, 104.3; MS (EI): *m/z* 39 (58), 47 (74), 55 (74), 75 (100), 85 (89), 101 (30), 109 (25), 141 (82), 171 (4); exact mass calcd for $C_9H_{16}O_3$: 171.1021 (M^+-1), found: 171.1011.

3.4.2. 3-[5,5-(Dimethoxy)pentyloxy]propyne (4b). Yield: 83%; bp 60–67°C/0.37 mm Hg; IR (neat): 3260, 2112 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.36–1.43 (m, 2H), 1.57–1.63 (m, 4H), 2.39 (t, *J*=2.5 Hz, 1H), 3.28 (s, 6H), 3.49 (t, *J*=6.5 Hz, 2H), 4.10 (d, *J*=2.5 Hz, 2H), 4.33 (t, *J*=5.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.1, 29.2, 32.2, 52.6, 58.0, 69.9, 74.1, 79.9, 104.4; MS (EI): *m/z* 39 (10), 41 (10), 47 (11), 67 (12), 71 (22), 75 (100), 101 (7), 155 (23), 185 (1); exact mass calcd for $C_{10}H_{18}O_3$: 185.1178 (M^+-1), found: 185.1190.

3.4.3. 3-[6,6-(Dimethoxy)hexyloxy]propyne (4c). Yield: 92%; bp 68–74°C/0.25 mm Hg; IR (neat): 3260, 2135 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.29–1.41 (m, 4H), 1.55–1.65 (m, 4H), 2.39 (t, *J*=2.2 Hz, 1H), 3.28 (s, 6H), 3.48 (t, *J*=6.5 Hz, 2H), 4.10 (d, *J*=2.2 Hz, 2H), 4.33 (t, *J*=5.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.4, 25.9, 29.4, 32.4, 52.6, 58.0, 70.1, 74.1, 80.0, 104.4; MS (EI): *m/z* 39 (24), 41 (30), 47 (35), 71 (70), 75 (100), 81 (57), 97 (11), 113 (15), 143 (6), 169 (75), 199 (2); exact mass calcd for $C_{11}H_{20}O_3$: 199.1334 (M^+-1), found: 199.1335.

3.5. Syntheses of 5a–c (Scheme 1)

3.5.1. 2-{(*E*)-3-[4,4-(Dimethoxy)butoxy]propen-1-yl}-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5a). Pinacolborane

(8.5 g, 67 mmol), $Pt(dba)_2$ (1.0 g, 1.64 mmol), and tris(2,4,6-trimethoxyphenyl)phosphine (3.5 g, 6.6 mmol) were added into a solution of **4a** (9.0 g, 52.2 mmol) in toluene (150 ml) at 0°C. After being stirred for 1 day, the mixture was treated with methanol (20 ml) and poured into a buffer solution (pH 7). The product was extracted with ether, dried over $MgSO_4$. Chromatography on silica gel with hexane/ethyl acetate (10/1) afforded **5a** (12.6 g, 80%). IR (neat): 1644 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.24 (s, 12H), 1.57–1.69 (m, 4H), 3.29 (s, 6H), 3.42 (t, J=6.1 Hz, 2H), 3.54 (t, J=5.4 Hz, 1H), 4.01 (dd, J=1.7, 4.6 Hz, 2H), 5.67 (dt, J=1.7, 18.3 Hz, 1H), 6.61 (dt, J=4.6, 18.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.7, 24.8, 29.2, 52.7, 70.2, 77.3, 83.2, 104.3, 149.5; MS (EI): m/z 71 (100), 75 (31), 85 (93), 101 (20), 117 (13), 197 (15), 269 (62), 299 (10); exact mass calcd for $C_{15}H_{29}BO_5$: 299.2030 (M^+-1), found: 299.2029.

3.5.2. 2-{(*E*)-3-[5,5-(Dimethoxy)pentyloxy]propen-1-yl}-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5b). Yield: 71%; IR (neat): 1643 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.24 (s, 12H), 1.35–1.43 (m, 2H), 1.54–1.61 (m, 4H), 3.29 (s, 6H), 3.41 (t, J=6.6 Hz, 2H), 4.01 (dd, J=1.8, 4.6 Hz, 2H), 4.33 (t, J=5.8 Hz, 1H), 5.67 (dt, J=1.8, 18.1 Hz, 1H), 6.61 (dt, J=4.6, 18.1 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.3, 24.7, 29.5, 32.3, 52.6, 70.5, 72.4, 76.7, 83.2, 104.4, 149.5; MS (EI): m/z 57 (25), 75 (41), 85 (100), 99 (33), 115 (31), 167 (30), 197 (20), 283 (66), 313 (5); exact mass calcd for $C_{16}H_{31}BO_5$: 313.2186 (M^+-1), found: 313.2171

3.5.3. 2-{(*E*)-3-[6,6-(Dimethoxy)hexyloxy]propen-1-yl}-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5c). Yield: 69%; IR (neat): 1644 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.27 (s, 12H), 1.33–1.43 (m, 4H), 1.56–1.63 (m, 4H), 3.31 (s, 6H), 3.43 (t, J=6.6 Hz, 2H), 4.04 (dd, J=1.7, 4.6 Hz, 2H), 4.36 (t, J=5.7 Hz, 1H), 5.69 (dt, J=1.7, 18.1 Hz, 1H), 6.64 (dt, J=4.6, 18.1 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.5, 24.8, 26.1, 29.7, 32.4, 52.6, 70.6, 72.4, 83.2, 104.5, 149.6; MS (EI): m/z 71 (83), 81 (88), 99 (73), 113 (75), 129 (51), 167 (42), 197 (47), 297 (100), 327 (10); exact mass calcd for $C_{17}H_{33}O_5B_1$: 327.2343 (M^+-1), found: 327.2340.

3.6. Iridium-catalyzed isomerization (Table 1 and Scheme 3)

A dry 25 ml two-neck flask, equipped with a magnetic bar and a rubber septum, was charged with $[Ir(cod)(PPh_2Me)_2]$-PF_6 (0.023 g, 0.03 mmol) and flushed with argon. AcOEt (5 ml) was then added. Hydrogen gas was bubbled for 3 min into the solution through a needle to give a light yellow solution. The excess hydrogen was thoroughly replaced with argon by passing into the solution for 3 min. To the catalyst solution thus obtained was added **5a** (1.0 mmol) and the mixture was then stirred at room temperature for 3 h. The reaction was quenched with a pH 7 buffer solution. The product was extracted with ether, dried ($MgSO_4$), and concentrated. ^1H NMR analysis of the residue gave the conversions and the *trans*/*cis*-selectivities shown in Table 1 and Scheme 3.

Compound **8a**. ^1H NMR (400 MHz, $CDCl_3$) δ 1.24 (s, 12H), 1.50 (d, J=7.6 Hz, 2H), 1.66–1.70 (m, 4H), 3.31 (s, 6H), 3.63 (brs, 2H), 4.38 (brs, 1H), 4.78 (dt, J=7.6, 12.5 Hz, 1H), 6.22 (d, J=12.5 Hz, 1H).

Compound **8b**. ^1H NMR (400 MHz, $CDCl_3$): δ 1.22 (s, 12H), 1.36–1.43 (m, 2H), 1.51–1.62 (m, 6H), 3.29 (s, 6H), 3.60 (t, J=6.6 Hz, 2H), 4.33 (t, J=5.8 Hz, 1H), 4.75 (dt, J=7.6, 12.5 Hz, 1H), 6.18 (dt, J=1.5, 12.5 Hz, 1H).

Compound **8c**. ^1H NMR (400 MHz, $CDCl_3$): δ 1.25 (s, 12H), 1.30–1.45 (m, 4H), 1.50–1.68 (m, 6H), 3.33 (s, 6H), 3.51 (t, J=6.6 Hz, 2H), 4.35 (t, J=5.0 Hz, 1H), 4.78 (dt, J=6.6, 12.5 Hz), 6.23 (d, J=12.5 Hz, 1H).

3.7. Nickel-catalyzed isomerization (Table 1 and Scheme 4)

$NiCl_2(PPh_2Me)_2$ (0.021 g, 0.04 mmol) was added to a solution of **5a** (1.0 mmol) in anhydrous THF (3 ml) at 0°C. $LiBHEt_3$ in THF (1 M, 0.04 ml, 0.04 mmol) was then added and the mixture was stirred for 1 day at 30°C. The reaction was quenched with a pH 7 buffer solution. The product was extracted with ether, dried over $MgSO_4$, and concentrated. The residue was then analyzed by ^1H NMR to estimate the conversions and the selectivities shown in Table 1 and Scheme 4.

Compound **10a**. ^1H NMR (400 MHz, $CDCl_3$): δ 1.24 (s, 12H), 1.66–1.71 (m, 6H), 3.31 (s, 6H), 3.71–3.74 (broad t, 2H), 4.38 (brs, 1H), 4.44 (dt, J=6.1, 7.4 Hz, 1H), 5.95 (d, J=6.1 Hz, 1H).

Compound **10b**. ^1H NMR (400 MHz, $CDCl_3$): δ 1.25 (s, 12H), 1.35–1.45 (m, 2H), 1.59–1.66 (m, 6H), 3.32 (s, 6H), 4.42 (dt, J=6.2, 7.6 Hz, 1H), 5.95 (d, J=6.2 Hz, 1H).

Compound **10c**. ^1H NMR (400 MHz, $CDCl_3$): δ 1.25 (s, 12H), 1.32–1.43 (m, 4H), 1.52–1.70 (m, 6H), 3.31 (s, 6H), 3.70 (t, J=6.6 Hz, 2H), 4.36 (t, J=5.8 Hz, 1H), 4.44 (dt, J=6.1, 7.7 Hz), 5.95 (dt, J=1.7, 6.1 Hz, 1H).

3.8. Procedures for cyclization via intramolecular allylboration (Schemes 3 and 4)

The residue obtained by the procedure in Section 3.6. Compound (**8a**) was dissolved in acetonitrile (10 ml). Water (1.1 ml) and ytterbium triflate (0.124 g, 0.2 mmol) were then added. After being stirred for 2 h at 90°C, ether and 1 M hydrochloric acid were added. The product was extracted with ether and dried over $MgSO_4$. Chromatography on silica gel with pentane/diethyl ether (1/1) gave **9a** (98 mg, 77%).

3.9. Syntheses of 9a,b and 11a,b (Schemes 3 and 4)

The iridium-catalyzed isomerization of **5** (procedure in Section 3.6) was directly followed by cyclization without isolation of **8** (procedure in Section 3.8) to synthesize **9**. A sequence of nickel-catalyzed isomerization (procedure in Section 3.7) and cyclization (procedure in Section 3.8) gave **11**.

3.9.1. *trans*-2-(Ethenyl)tetrahydropyran-3-ol (9a).[24] Yield: 77%; IR (neat): 3409 cm^{-1}; ^1H NMR (400 MHz,

$CDCl_3$): δ 1.40–1.51 (m, 1H), 1.69–1.79 (m, 3H), 2.14–2.18 (m, 1H), 3.30–3.51 (m, 3H), 3.90–3.96 (m, 1H), 5.33 (dd, *J*=0.8, 10.5 Hz, 1H), 5.44 (dd, *J*=0.9, 17.5 Hz, 1H), 5.88 (ddd, *J*=7.1, 10.5, 17.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.3, 31.5, 67.4, 69.5, 84.0, 118.9, 136.1; MS (FAB): *m/z* 41 (97), 55 (100), 71 (61), 77 (53), 83 (62), 91 (61), 95 (40), 101 (37), 129 (39); exact mass calcd for $C_7H_{12}O_2$: 129.0916 (M^++1), found: 129.0903.

3.9.2. *trans*-2-(Ethenyl)oxepan-3-ol (9b).[24] Yield: 56%; IR (neat): 3425 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.56–1.81 (m, 6H), 2.04 (m, 1H), 3.57 (ddd, *J*=4.1, 8.0, 12.0 Hz, 1H), 3.63–3.69 (m, 2H), 3.96 (ddd, *J*=5.6, 6.0, 11.7 Hz, 1H), 5.26 (d, *J*=10.5 Hz, 1H), 5.35 (d, *J*=17.3 Hz, 1H), 5.93 (ddd, *J*=6.3, 10.5, 17.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.6, 30.2, 35.1, 70.0, 74.4, 85.6, 117.0, 137.6; MS (ESI): *m/z* 41 (38), 55 (38), 85 (63), 101 (45), 136 (100), 154 (86), 165 (20); exact mass calcd for $C_8H_{14}O_2$: 165.0891 (M^++23), found: 165.0880.

3.9.3. *cis*-2-(Ethenyl)tetrahydropyran-3-ol (11a).[24] Yield: 61%; IR (neat): 3427 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.39–1.48 (m, 1H), 1.66–1.75 (m, 1H), 1.85 (s, 1H), 1.92–2.00 (m, 2H), 3.47–3.60 (m, 1H), 3.74 (s, 1H), 3.94–3.95 (m, 1H), 4.06 (dd, *J*=4.4, 10.6 Hz, 1H), 5.29 (ddd, *J*=1.4, 1.5, 10.7 Hz, 1H), 5.38 (ddd, *J*=1.5, 1.7, 17.5 Hz, 1H), 5.88 (ddd, *J*=4.4, 10.7, 17.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.1, 31.5, 66.6, 68.2, 79.9, 116.7, 135.8; MS (FAB): *m/z* 41 (50), 55 (41), 71 (100), 83 (54), 101 (51), 111 (60), 129 (42); exact mass calcd for $C_7H_{12}O_2$: 129.0916 (M^++1), found: 129.0916.

3.9.4. *cis*-2-(Ethenyl)oxepan-3-ol (11b).[24] Yield: 66%; IR (neat): 3434 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.56–1.81 (m, 4H), 1.87–2.18 (m, 3H), 3.73–3.78 (m, 1H), 3.83–3.87 (m, 2H), 3.93–3.99 (m, 1H), 5.21 (dd, *J*=0.8, 10.7 Hz, 1H), 5.36 (dd, *J*=0.8, 17.3 Hz, 1H), 5.94 (ddd, *J*=5.1, 10.7, 17.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.5, 30.0, 36.4, 69.0, 71.9, 78.8, 115.8, 137.1; MS (ESI): *m/z* 135 (3), 139 (1), 143 (4), 157 (34), 165 (100); exact mass calcd for $C_8H_{14}O_2$: 165.0891 (M^++23), found: 165.0878.

References

1. (a) Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 555. (b) Roush, W. R. *Comprephensive Organic Synthesis*; Heathcock, C. H., Ed.; Pergamon: Oxford, 1991; Vol. 2, pp 1–54. (c) Matteson, D. S. *Stereodirected Synthesis with Organoboranes*; Springer: Berlin, 1995.
2. (a) Hoffmann, R. W.; Niel, G. *Liebigs Ann. Chem.* **1991**, 1195. (b) Hoffmann, R. W.; Sander, T.; Hense, A. *Liebigs Ann. Chem.* **1993**, 771. (c) Hoffmann, R. W.; Sander, T. *Liebigs Ann. Chem.* **1993**, 1185. (d) Sander, T.; Hoffmann, R. W. *Liebigs Ann. Chem.* **1993**, 1193. (e) Hoffmann, R. W.; Hense, A. *Liebigs Ann. Chem.* **1996**, 1283. (f) Krüger, J.; Hoffmann, R. W. *J. Am. Chem. Soc.* **1997**, *119*, 7499. (g) Hoffman, R. W.; Münster, I. *Liebigs Ann. Chem./Recueil* **1997**, 1143. (h) Hoffmann, R. W.; Brückner, D.; Gerusz, V. J. *Heterocycles* **2000**, *52*, 121. (i) Hoffmann, R. W.; Krüger, J.; Brückner, D. *New J. Chem.* **2001**, *25*, 102. (j) Hoffmann, R. W.; Brückner, D. *New J. Chem.* **2001**, *25*, 369.
3. (a) Yamada, J.; Asano, T.; Kadota, I.; Yamamoto, Y. *J. Org. Chem.* **1990**, *55*, 6066. (b) Yamamoto, Y.; Yamada, J.; Kadota, I. *Tetrahedron Lett.* **1991**, *32*, 7069. (c) Kadota, I.; Yamamoto, Y. *J. Synth. Org. Chem. Jpn* **1997**, *55*, 619. (d) Park, J.-Y.; Kadota, I.; Yamamoto, Y. *J. Org. Chem.* **1999**, *64*, 4901.
4. (a) Watanabe, T.; Sakai, M.; Miyaura, N.; Suzuki, A. *J. Chem. Soc., Chem. Commun.* **1994**, 467. (b) Ahiko, T.-A.; Ishiyama, T.; Miyaura, N. *Chem. Lett.* **1997**, 811.
5. (a) Brown, H. C.; De Lue, N. R.; Yamamoto, Y.; Maruyama, K.; Kasahara, T.; Murahashi, S.-I.; Sonoda, A. *J. Org. Chem.* **1977**, *42*, 4088. (b) Wuts, P. G. M.; Bigelow, S. S. *J. Org. Chem.* **1982**, *47*, 2498. (c) Wuts, P. G. M.; Thompson, P. A.; Callen, G. R. *J. Org. Chem.* **1983**, *48*, 5398. (d) Roush, W. R.; Adam, M. A.; Walts, A. E.; Harris, D. J. *J. Am. Chem. Soc.* **1986**, *108*, 3422. (e) Nyzam, V.; Belaud, C.; Villiéras, J. *Tetrahedron Lett.* **1993**, *34*, 6899.
6. Watanabe, T.; Miyaura, N.; Suzuki, A. *J. Organomet. Chem.* **1993**, *444*, C1.
7. (a) Matteson, D. S.; Majumdar, D. *Organometallics* **1983**, *2*, 1195. (b) Sadhu, K. M.; Matteson, D. S. *Organometallics* **1985**, *4*, 1687. (c) Brown, H. C.; Singh, S. M.; Rangaishenvi, M. V. *J. Org. Chem.* **1986**, *51*, 3150. (d) Sato, M.; Yamamoto, Y.; Hara, S.; Suzuki, A. *Tetrahedron Lett.* **1993**, *34*, 7071.
8. Ishiyama, T.; Ahiko, T.-A.; Miyaura, N. *Tetrahedron Lett.* **1996**, *37*, 6889.
9. (a) Rauchschwalbe, G.; Schlosser, M. *Helv. Chim. Acta* **1975**, *58*, 1094. (b) Hoffmann, R. W.; Zeiß, H.-J. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 306. (c) Hoffmann, R. W.; Zeiß, H.-J. *J. Org. Chem.* **1981**, *46*, 1309. (d) Hoffmann, R. W.; Kemper, B. *Tetrahedron Lett.* **1981**, *52*, 5263. (e) Hoffmann, R. W.; Kemper, B.; Metternich, R.; Lehmeier, T. *Liebigs Ann. Chem.* **1985**, 2246.
10. (a) Moriya, T.; Suzuki, A.; Miyaura, N. *Tetrahedron Lett.* **1995**, *36*, 1887. (b) Yamamoto, Y.; Miyairi, T.; Ohmura, T.; Miyaura, N. *J. Org. Chem.* **1999**, *64*, 296.
11. (a) Pereira, S.; Srebnik, M. *Tetrahedron Lett.* **1996**, *37*, 3283. (b) Yamamoto, Y.; Fujikawa, R.; Yamada, A.; Miyaura, N. *Chem. Lett.* **1999**, 1069.
12. (a) Baudry, D.; Ephritikhine, M.; Felkin, H. *J. Chem. Soc., Chem. Commun.* **1978**, 694. (b) Ohmura, T.; Shirai, Y.; Yamamoto, Y.; Miyaura, N. *Chem. Commun.* **1998**, 1337. (c) Ohmura, T.; Yamamoto, Y.; Miyaura, N. *Organometallics* **1999**, *18*, 413. (d) Yamamoto, Y.; Fujikawa, R.; Miyaura, N. *Synth. Commun.* **2000**, *30*, 2383.
13. Wille, A.; Tomm, S.; Frauenrath, H. *Synthesis* **1998**, 305.
14. Price, C. C.; Snyder, W. H. *J. Am. Chem. Soc.* **1961**, *83*, 1773.
15. Inanaga, J.; Yokoyama, Y.; Hanamoto, T. *Tetrahedron Lett.* **1993**, *34*, 2791.
16. Lipshutz, B. H.; Harvey, D. F. *Synth. Commun.* **1982**, *12*, 267.
17. Cherwinski, W. J.; Johnson, B. F. G.; Lewis, J. *J. Chem. Soc., Dalton Trans.* **1974**, 1405.
18. Fordyce, W. A.; Crosby, G. A. *Inorg. Chem.* **1982**, *21*, 1455.
19. Venanzi, L. M. *J. Chem. Soc.* **1958**, 719.
20. Hayter, R. G.; Humiec, F. S. *Inorg. Chem.* **1965**, *4*, 1701.
21. (a) Booth, G.; Chatt, J. *J. Chem. Soc.* **1965**, 3239. (b) Van Hecke, G. R.; Horrocks, Jr. W. D. *Inorg. Chem.* **1966**, *5*, 1968.
22. Hayashi, T.; Konishi, M.; Yokota, K.; Kumada, M. *Chem. Lett.* **1980**, 767.
23. Tucker, C. E.; Davidson, J.; Knochel, P. *J. Org. Chem.* **1992**, *57*, 3482.
24. Nicolaou, K. C.; Prasad, C. V. C.; Somers, P. K.; Hwang, C.-K. *J. Am. Chem. Soc.* **1989**, *111*, 5330.