trichloride produces products in which the boron atom has migrated in part from its original position.[25]

Unfortunately, the further formation into di-3-hexylbromoborane was very slow, even at still higher temperatures (85 °C), requiring 48 h for only 30% completion. We did not pursue this redistribution further since di-3-hexylbromoborane can be easily prepared by hydroboration of 3-hexene with $BH_2Br{\cdot}SMe_2$.

Thus the present procedure supplements the direct synthesis of alkyldibromo- and dialkylbromoboranes via hydroboration of alkenes with $BHBr_2{\cdot}SMe_2$ and $BH_2Br{\cdot}SMe_2$. Particularly, this method demonstrates its utility for the synthesis of ethyldibromoborane and cyclohexyldibromoborane, two derivatives which cannot be obtained easily from $BHBr_2{\cdot}SMe_2$. Internal alkenes such as 3-hexene work well for the synthesis of the alkyldibromoboranes but fail to provide the corresponding dialkylbromoboranes. Presently we are exploring the applications of these alkylbromoboranes for organic transformations.

Experimental Section

All glassware used for the experiments were dried in an oven at 140 °C for several hours, assembled hot, and cooled under a stream of nitrogen. The alkenes used for the study were obtained from Aldrich Chemical Co. or Chemical Samples Co. and were purified by distillation over a small quantity of $LiAlH_4$. Triethylborane was obtained from Callery Chemical Co. Reagent grade methanol was used after being stored over 3-Å molecular sieves and *n*-pentane was dried over molecular sieves, type 5 Å. The special experimental techniques used in handling air and moisture sensitive materials are described elsewhere.[26] ^1H NMR and ^{11}B NMR spectra were recorded on Varian T-60 and Varian FT-80A spectrometers, respectively. ^{11}B NMR chemical shifts are with reference to $BF_3{\cdot}OEt_2$ (δ 0), and the resonances upfield from the standard are assigned negative signs. GC analyses were carried out on a Varian 1200 FID gas chromatograph (column 12 ft × $^1/_8$ in. packed with 10% Carbowax 1540 on Chromosorb W 100/120).

Preparation of *n*-Hexyldibromoborane. Tri-*n*-hexylborane (20 mmol) was prepared from 1-hexene and $BH_3{\cdot}SMe_2$ in the usual way.[26] Solvent THF and SMe_2 were removed under reduced pressure. The residual tri-*n*-hexylborane was dissolved in 30 mL of *n*-pentane. Boron tribromide (40 mmol, 3.80 mL) was added, followed by a slow addition of 1.4 mmol of $BH_3{\cdot}SMe_2$ (BMS) in pentane (1.75 mL, 0.8 M) at 0 °C. The reaction mixture was stirred at room temperature for 4 h. ^{11}B NMR of the crude product showed a single peak at δ 64, which is indicative of *n*-hexyldibromoborane. Solvent *n*-pentane was removed, and distillation afforded 12.3 g (80%) of pure *n*-hexyldibromoborane: bp 69–71 °C (3 mm) [lit.[14] 56–58 °C (0.9 mm); ^{11}B NMR ($BF_3{\cdot}OEt_2$) δ 64 ((*n*-Hex)BBr_2). The methanolyzed product showed a single peak at δ 32 ((*n*-Hex)$B(OMe)_2$). Ethyl-, *n*-propyl-, 2-methyl-1-pentyl-, cyclopentyl-, and cyclohexyldibromoboranes were prepared in identical fashion to the above procedure.

Preparation of Di-*n*-hexylbromoborane. Tri-*n*-hexylborane (30 mmol) was treated with boron tribromide (15 mmol, 1.42 mL) under the same conditions as in the preparation of *n*-hexyldibromoborane to afford 9.52 g (81%) of di-*n*-hexylbromoborane: bp 102–103 °C (4 mm); ^{11}B NMR ($BF_3{\cdot}OEt_2$) δ 82 ((n-Hex)$_2$BBr). Diethyl-, bis(2-methyl-1-pentyl)-, dicyclopentyl-, and dicyclohexylbromoboranes were prepared in an identical manner.

Preparation of 3-Hexyldibromoborane. To 20 mmol of neat tri-3-hexylborane was added 40 mmol of BBr_3 (3.80 mL) at 0 °C, followed by a slow addition of 0.16 mL of neat $BH_3{\cdot}SMe_2$ (8.8 M). The reaction mixture was stirred at 70 °C for 20 h. Distillation furnished 12.20 g (79%) of 3-hexyldibromoborane: bp 60–62 °C (4.5 mm); ^{11}B NMR ($BF_3{\cdot}OEt_2$) δ 67 ((3-Hex)BBr_2). The methanolyzed product showed a single peak at δ 31, indicative of (3-Hex)$B(OMe)_2$. Oxidation of 3-hexyldibromoborane was carried out in the usual way[26] by using NaOH and H_2O_2. The alcohol obtained was found to be >99% pure 3-hexanol on GC analysis.

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Registry No. $RBBr_2{\cdot}SMe2$ (R = ethyl), 83967-42-4; $R_2BBr{\cdot}SMe2$ (R = ethyl), 86646-22-2; $RBB_2{\cdot}SMe2$ (R = *n*-propyl), 86646-23-3; $RBBr_2$ (R = *n*-hexyl), 64770-03-2; R_2BBr (R = *n*-hexyl), 57476-26-3; $RBBr_2$ (R = 2-methyl-1-pentyl), 72205-96-0; R_2BBr (R = 2-methyl-1-pentyl), 86646-21-1; $RBBr_2$ (R = cyclopentyl), 64770-09-8; R_2BBr (R = cyclopentyl), 57476-09-2; $RBBr_2$ (R = cyclohexyl), 6783-09-1; R_2BBr (R = cyclohexyl), 22086-59-5; $RBBr_2$ (R = 3-hexyl), 64770-05-4; R_3B (R = ethyl), 97-94-9; R_3B (R = *n*-propyl), 1116-61-6; R_3B (R = *n*-hexyl), 1188-92-7; R_3B (R = 2-methyl-1-pentyl), 1188-50-7; R_3B (R = cyclopentyl), 23985-40-2; R_3B (R = cyclohexyl), 1088-01-3; R_3B (R = 3-hexyl), 1883-34-7; BBr_3, 10294-33-4.

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Organoboranes. 30. Convenient Procedures for the Synthesis of Alkyl- and Alkenylboronic Acids and Esters

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Alkyl- and alkenyldibromoborane–dimethyl sulfide complexes, readily obtained by the hydroboration of alkenes and alkynes with dibromoborane–dimethyl sulfide ($HBBr_2{\cdot}SMe_2$), react with water, giving the corresponding boronic acids, and with alcohols and glycols to give the corresponding esters. Various procedures have been developed for the preparation of boronic esters with primary and secondary alcohols, glycols, and tertiary alcohols. Boronic acids react with primary and secondary alcohols reversibly to form the corresponding esters. The equilibrium may be conveniently displaced in favor of ester by carrying out the reaction in pentane, from which the water component separates. This procedure does away with the necessity of azeotrope distillation of a ternary mixture, extensively used previously for the esterification of boronic acids.

Alkyl- and alkenylboronic acids and their esters have found extensive applications in organic synthesis in the last decade.[2-8] Recently, a number of chiral boronic esters have been utilized for the synthesis of optically active

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aldehydes and alcohols in high optical purity.[9] Apart from their use as intermediates in organic synthesis, they are also used as protecting groups in carbohydrate chemistry.[10,11] Further, these compounds have great synthetic potential in carbon–carbon bond forming reactions involving migration of organic groups from boron to carbon as the alkoxy groups serve two purposes: (i) they remain as the nonmigrating "blocking groups", thus giving exclusively the required product, and (ii) prevent the loss of precious "R" groups. The ease of conversion of these compounds into organomercurials[12] not only widens the scope of these compounds but also opens the gateway to a new area to work with through organoboron chemistry.

Although several methods are available for the preparation of boronic acids and esters, the yields are not always satisfactory.[13] Alkenylboronic acids and their esters, in particular, have received relatively less attention until recently.[14,15] In view of the growing importance and the availability of relatively few general methods of synthesis of these compounds, it was highly desirable to have available convenient and general methods, both of synthesizing these boronic acids and esters and interconverting them into each other.

Synthesis of simple alkylboronates dates back to 1862 when Frankland and Duppa[16] prepared diethyl ethylboronate by the oxidation of triethylborane (eq 1). However, ethyl diethylborinate and triethylborate were formed also.

$$B(C_2H_5)_3 + O_2 \rightarrow C_2H_5B(OC_2H_5)_2 \quad (1)$$

Until the discovery of the hydroboration reaction,[17] the most widely used method for the preparation of organoboron compounds, by far, was the reaction of the Grignard reagent with trihaloboranes and trialkoxyboranes. Thus, alkyl- or arylboronic acids were prepared according to eq 2 and 3.[18,19] This reaction fails to give the expected

$$B(OR')_3 + RMgX \rightarrow [RB(OR')_3]^-MgX^+ \xrightarrow{H_3O^+} RB(OH)_2 \quad (2)$$

$$BX_3 + RMgX \rightarrow [RBX_3]^-MgX^+ \xrightarrow{H_3O^+} RB(OH)_2 \quad (3)$$

Table I. Preparation of Alkyl- and Alkenylboronic Acids

R in $RB(OH)_2$	yield,[a] %	mp, °C	^{11}B chem shift, δ
n-hexyl	95	88	31.3
3-hexyl	93	79	30.9
cyclopentyl	96	108-109	27.4
(1*E*)-1-heptenyl	91	136	32.1
(1*E*)-3,3-dimethyl-1-butenyl	93	84	27.1

[a] Before crystallization.

products in a number of cases.[20,21] Organolithium reagents have been used in the synthesis of boronic acids that are prepared with difficulty or not at all via the Grignard reaction.[22,23]

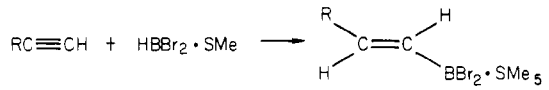
Various other methods such as the reaction of halogens with trialkylboranes, reaction of trihaloboranes with organomercury, organotin, and organoaluminum compounds, etc. have been reported in the literature.[24] A survey of the synthetic methods for the preparation of boronic acids reported in the literature indicates that most of the methods are centered around the preparation of phenyl- and other arylboronic acids.

We recently reported the synthesis of both alkyl- and alkenylboronic acids via hydroboration with catecholborane and subsequent hydrolysis of the catechol ester.[14] We are now reporting versatile methods for synthesizing alkyl- and alkenylboronic acids, their simple and cyclic esters, and for converting boronic acids to the esters. The methods are general and may be used wherever the corresponding alkene or alkyne is available.

Results and Discussion

Conversion of Alkyl- and Alkenyldibromoborane–Dimethyl Sulfide into the Corresponding Boronic Acids. Alkyl- and alkenyldibromoborane–dimethyl sulfide complexes may be easily prepared by the hydroboration of alkenes and alkynes, respectively, with dibromoborane–dimethyl sulfide (eq 4 and 5).[15] These complexes are decomposed by water into the corresponding boronic acids and HBr[25] (eq 6).

$$RCH{=}CH_2 + HBBr_2{\cdot}SMe_2 \rightarrow RCH_2CH_2BBr_2{\cdot}SMe_2 \quad (4)$$



(5)

$$RBBr_2{\cdot}SMe_2 + 2H_2O \rightarrow RB(OH)_2 + 2HBr \quad (6)$$

Thus, a solution of alkyldibromoborane–dimethyl sulfide in methylene chloride, when added to a mixture of water (excess) and ethyl ether, is converted rapidly and quantitatively into the corresponding boronic acid. The HBr liberated remains in the aqueous layer. Working up the organic layer affords reasonably pure boronic acid. Alkenylboronic acids may similarly be prepared without any significant addition of HBr to the double bond by carrying

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Table II. Preparation of Boronic Esters from Boronic Acids (with Alcohols and Glycols)

R in $RB(OH)_2$	alcohol or glycol	yield, %	bp, °C (mm)	^{11}B chem shifts, δ
n-hexyl	methanol	80	69-70 (16)	31.9
n-hexyl	ethanol	83	88-89 (16)	31.4
3-hexyl	methanol	83	61 (20)	32.3
(1*E*)-1-octenyl	methanol	90	62 (0.3)	27.8
(1*E*)-1-octenyl	2-propanol	88	73-74 (0.2)	27.4
n-hexyl	trimethylene glycol	88	95 (16)	31.1
3-hexyl	trimethylene glycol	84	85 (17)	31.2
cyclopentyl	pinacol	85	97-98 (16)	34.8
(1*E*)-1-octenyl	ethylene glycol	83	72 (0.1)	26.9
(1*E*)-3,3-dimethyl-1-butenyl	trimethylene glycol	81	61-62 (0.35)	27.8

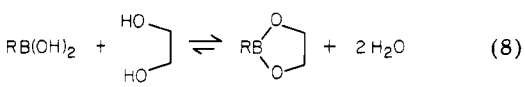
out the reaction at ~0 °C. The results are summarized in Table I.

Esterification of Boronic Acids. The most widely used method for the esterification of boronic acids with simple alcohols (primary and secondary) and glycols is to reflux the acid with an excess of alcohol and remove the water of esterification azeotropically with a solvent such as benzene or toluene as a ternary mixture.[21,26] Anhydrous copper sulfate in a Soxhlet apparatus has been used also.[26] More recently, an esterification method limited to methyl esters was reported.[27] This consists in heating the boronic acid with an excess of 2,2-dimethoxypropane and removing the methanol and acetone formed in the reaction. The fact that no catalyst such as a proton is necessary indicates a rapid equilibrium between the acid and ester (eq 7).

$$RB(OH)_2 + 2R'OH \rightleftharpoons RB(OR')_2 + 2H_2O \quad (7)$$

Consequently, any method which preferentially removes water should force the equilibrium to favor the formation of ester. Further, the reaction should be essentially instantaneous. Carrying out the reaction in pentane (*n*-pentane) offers such a unique situation. While the product ester and the reacting alcohol are soluble, water and the boronic acid are not. Thus, shaking the boronic acid with pentane containing 2 equiv of the alcohol in a separatory funnel (for convenience) for a few seconds results in an instantaneous separation of water. In a quantitative experiment, it was found, however, that the aqueous layer accounted for more than the stoichiometric amount due to the presence of some dissolved alcohol. This difficulty could be readily overcome by using an additional 2 equiv[28] of the alcohol, followed by removal of additional water of esterification (with some unreacted alcohol). The pentane layer provides an essentially quantitative yield of the ester. This procedure works smoothly for both alkyl- and alkenylboronic acids with primary and secondary alcohols. Tertiary esters cannot be prepared in this way. The details are given in the Experimental Section, and the results are presented in Table II.

Glycols differ in their reactivity with boronic acids from that of alcohols in two ways. First, the reaction of glycols with boronic acids appears to be slower than that of alcohols. This may be due to the low solubility of diols in pentane. Second, and more significant, the equilibrium is in favor of the cyclic ester (eq 8). Thus, the cyclic esters



(8)

are relatively more stable to hydrolysis than to their acyclic analogues. These differences make unnecessary the addition of 100% excess of the glycol, as well as the immediate removal of water of esterification. Consequently, cyclic esters of boronic acids may be conveniently prepared by stirring equimolar quantities of the boronic acid and the glycol in pentane for 15–30 min and then working up the pentane layer.[29] Table II illustrates the utility of this method.

Formation of Alkyl- and Alkenylboronic Esters by the Alcoholysis of the Corresponding Dibromides. Alkyl- and alkenyldichloroborane–dimethyl sulfide complexes react with methanol giving the corresponding boronates (eq 9) in essentially quantitative yields.[15] In the same study,[14] it was observed that the corresponding dibromides methanolyzed easily but the isolation of boronates was apparently complicated by the formation of Me_2S·HBr. Yields of boronates were low due to the formation of significant amounts of the corresponding boronic acids.

$$RBCl_2{\cdot}SMe_2 + 2MeOH \rightarrow RB(OMe)_2 + 2HCl + Me_2S \quad (9)$$

Originally we hoped that we could treat the hydroboration product $RBBr_2{\cdot}SMe_2$ with 2 mol of alcohol to form the desired ester. We anticipated that 1 mol of hydrogen bromide would form an adduct with dimethyl sulfide and the second mole would dissolve in the reaction mixture (largely methylene chloride) (eq 10).

$$RBBr_2{\cdot}SMe_2 + 2R'OH \rightarrow RB(OR')_2 + Me_2S\text{-}HBr + HBr \quad (10)$$

This worked quite satisfactorily for ethyl and isopropyl alcohol as well as phenol, but not for methanol or *tert*-butyl alcohol. In the case of methanol, the hydrogen bromide formed evidently induced a reaction of methanol with dimethyl sulfide to form trimethylsulfonium bromide (eq 11). The water formed in this reaction hydrolyzes the ester. Consequently, the yields are decreased (~40%).

$$MeOH + Me_2S + HBr \rightarrow Me_3S^+Br^- + H_2O \quad (11)$$

In the case of ethanol and 2-propanol, this reaction is evidently much slower so that the reaction takes the desired course (eq 10). In the case of phenol, this reaction is not a problem.

It was possible to circumvent this difficulty by utilizing 4 mol of methanol/mol of $RBBr_2{\cdot}SMe_2$. In this case, the hydrogen bromide formed dissolves in the excess methanol to give a concentrated methanol–hydrogen bromide solution (eq 12).

$$RBBr_2{\cdot}SMe_2 + 4MeOH \rightarrow RB(OMe)_2 + 2HBr{\cdot}2MeOH + Me_2S \quad (12)$$

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(28) Addition of any more than the recommended amount of alcohol is disadvantageous as it solubilizes water in pentane, thus causing the partial hydrolysis of the ester, resulting in the decrease in yield of pure ester.
(29) The facile reaction of ethylene glycol and pinacol hydrate with boronic acids has already been reported: see footnote 11 of ref 7.

Table III. Preparation of Alkyl- and Alkenylboronates from $RBBr_2 \cdot SMe_2$

R in $RBBr_2 \cdot SMe_2$	alcohol used	procedure	yield,[a] %	bp, °C (mm)	^{11}B chem shift, δ
n-hexyl	methanol	A-C	85	69-70 (16)	31.9
n-hexyl	ethanol	A	80	88-90 (16)	31.4
n-hexyl	2-propanol	A, B	85	94-95 (16)	30.7
cyclopentyl	methanol	A	80	79-80 (46)	32.4
cyclopentyl	ethanol	A	81	72-74 (16)	31.5
cyclopentyl	2-propanol	A	83	78-80 (16)	30.9
cyclohexyl	ethanol	A	76	91-92 (16)	31.3
(1*E*)-1-octenyl	methanol	A-C	90	62-63 (0.3)	27.8
(1*E*)-1-octenyl	2-propanol	A	87	73-74 (0.2)	27.4
cis-4-octenyl	methanol	A	83	61-62 (0.6)	29.4
(1*E*)-3,3-dimethyl-1-butenyl	methanol	A	86	40-41 (0.35)	27.5
(1*E*)-1-hexenyl	phenol	D	83	154-155 (0.15)	27.6
cis-1-bromo-1-octenyl	methanol	C	80	78 (0.2)	25.5
(1*E*)-1-hexenyl	*tert*-butyl alcohol	E	63	78 (0.3)	25.2
n-hexyl	*tert*-butyl alcohol	E	58	94 (6.5)	
n-hexyl	*tert*-butyl alcohol	F	81	94 (6.5)	

Table IV. Preparation of Cyclic Esters from Alkyl- and Alkenyldibromoborane-Dimethyl Sulfide

R in $RBBr_2 \cdot SMe_2$	glycol	procedure	yield, %	bp, °C (mm)	^{11}B chem shift, δ
n-hexyl	ethylene glycol	D	85	84-86 (17)	34.7
n-hexyl	pinacol	D	83	98-100 (8)	34.4
cyclopentyl	pinacol	D	83	97-98 (17)	34.8
(1*E*)-1-octenyl	ethylene glycol	D	88	72-73 (0.1)	26.9
(1*E*)-1-octenyl	trimethylene glycol	D	80	80-81 (0.2)	27.1
cis-4-octenyl	ethylene glycol	D	89	74 (0.3)	30.8
(1*E*)-3,3-dimethyl-1-butenyl	trimethylene glycol	D	93	56 (0.2)	27.8

Even under these conditions, some trimethylsulfonium bromide and water are formed. However, in the presence of excess methanol, the water formed has little deleterious effect. The yields isolated are in the range of 80–90% (Table III).

In the case of *tert*-butyl alcohol, the reaction of hydrogen bromide with the alcohol is so rapid that very little ester is formed. In this case, the difficulty could be overcome by utilizing 2 mol of pyridine. The hydrogen bromide formed reacts with pyridine forming pyridine hydrobromide as an insoluble solid (eq 13).

$$RBBr_2 \cdot SMe_2 + 2t\text{-BuOH} + 2py \rightarrow RB(O\text{-}t\text{-Bu})_2 + 2py \cdot HBr + Me_2S \quad (13)$$

Alternatively, *tert*-butyl esters can also be prepared by using 2 mol of lithium *tert*-butoxide/mol of $RBBr_2 \cdot SMe_2$ (eq 14).[30]

$$RBBr_2 \cdot SMe_2 + 2t\text{-BuOLi} \rightarrow RB(O\text{-}t\text{-Bu})_2 + 2LiBr + Me_2S \quad (14)$$

Reaction of glycols with $RBBr_2 \cdot SMe_2$ proceeds essentially as in the case of alcohols. However, owing to the relative stability of the cyclic esters toward hydrolysis and due to the relative difficulty in the formation of trialkylsulfonium bromide, stoichiometric quantities of glycols give satisfactory results. The hydrogen bromide formed is evidently retained as the adduct $Me_2S \cdot HBr$. Addition of 2 mol of methanol to the reaction mixture dissolves this adduct and makes it easier to dispose of the hydrogen bromide–dimethyl sulfide byproducts.

The same procedure is applicable to phenols. In general, this procedure is applicable to any higher (more expensive) alcohol, provided enough time is allowed for the alcohol to react before the addition of methanol. Ester exchanges do not take place under these conditions (eq 15). The results are given in Table IV.

$$RBBr \cdot SMe_2 + \xrightarrow[\text{(ii) 2MeOH}]{\text{(i) 2R'OH}} RB(OR')_2 + Me_2S \cdot 2HBr \cdot 2MeOH \quad (15)$$

We have developed four different procedures (A–D) for the esterification with primary and secondary alcohols, glycols and phenols and two procedures (E, F) for the esterification with tertiary alcohols. Procedure A is a one-pot reaction that is simple and applicable to most ordinary preparations while procedure B involves the preparation of $RBBr_2 \cdot SMe_2$ free of dichloromethane. This should be advantageous if one wants to use the pentane solution as such for further reactions involving a strong base. Procedure C involves an inverse addition ($RBBr_2$ to alcohol–pentane). Finally, Procedure D, a modification of C, is particularly useful for the preparation of cyclic esters, phenyl esters, and any other higher alkyl esters including those cases where the alcohol is a solid. Procedure E makes use of pyridine to trap the hydrogen bromide formed, while procedure F employs lithium *tert*-butoxide.

All of these procedures are equally efficient, and it depends on the user's need and convenience to choose a particular procedure. Various esters have been prepared by these methods and are summarized in Table III. As can be seen, many have been prepared by more than one method.

Experimental Section

All manipulations of air- and moisture-sensitive compounds were carried out under a purified nitrogen atmosphere. All glassware used were dried in an oven at 140 °C, assembled hot, and cooled with a stream of nitrogen. The alkenes and alkynes used were commercial products of high purity and were further purified wherever necessary. Spectrophotometric grade methanol and dichloromethane, stored over molecular sieves, type 3 Å, and *n*-pentane, stored over molecular sieves, type 5 Å, were used in all preparations. Dibromoborane–dimethyl sulfide complex was

(30) *tert*-Butyl esters have been prepared by refluxing boronic acid anhydride–pyridine complex with *tert*-butyl alcohol, but the reaction is very slow (~9 days): Matteson, D. S. *J. Org. Chem.* **1962**, *27*, 3712.

prepared according to the procedure developed in this laboratory.[31] Further special experimental techniques are described elsewhere.[32]

All of the compounds prepared have been fully characterized by ^1H, ^{11}B, and ^{13}C NMR spectra. The yields reported in all cases are of pure compounds unless otherwise mentioned. Melting points and boiling points reported here are uncorrected. ^1H NMR spectra were recorded on a Varian T-60 instrument. ^{11}B and ^{13}C NMR spectra were recorded on a Varian FT-80A spectrometer. ^{11}B NMR chemical shifts are with reference to $BF_3{\cdot}OEt_2$ (δ 0), and the resonances downfield from the reference are assigned positive sign.

Alkyldibromoborane–Dimethyl Sulfide Complexes. Alkyldibromoborane–dimethyl sulfide complexes were prepared according to the procedure developed in this laboratory.[15] Preparation of *n*-hexyldibromoborane–dimethyl sulfide is representative. In a 100-mL reaction flask fitted with a reflux condenser was placed 1-hexene (6.25 mL, 50 mmol) dissolved in dichloromethane (23.75 mL). $HBBr_2{\cdot}SMe_2$ solution (20 mL, 2.5 M, 50 mmol) was then added to this flask, slowly, and the mixture was heated under reflux for 3 h.

A slightly longer time was required for cyclopentene (5 h).[15] Cyclohexyldibromoborane was prepared by the redistribution reaction of tricyclohexylborane with boron tribromide.[33]

Alkenyldibromoborane–Dimethyl Sulfide Complexes. Alkenyldibromoborane–dimethyl sulfide complexes were prepared by the hydroboration of alkynes with $BHBr_2{\cdot}SMe_2$.[34] Preparation of (1*E*)-1-octenyldibromoborane–dimethyl sulfide is representative. To a solution of 1-octyne (7.4 mL, 50 mmol) in dichloromethane (22.6 mL) contained in a 100-mL flask fitted with a reflux condenser was added $BHBr_2{\cdot}SMe_2$ solution (20 mL), 2.5 M, 50 mmol) slowly. The reaction was exothermic. After the addition, the mixture was stirred for 4 h.

1-Bromo-1-octyne required a longer reaction time (~24 h), whereas the reaction with 4-octyne was over in less than 2 h.

Preparation of Alkyl- and Alkenylboronic Acids. The general method used was to add a cooled (0 °C) solution of alkyl-/alkenyldibromoborane–dimethyl sulfide in dichloromethane to an excess of water in ether. Preparation of *n*-hexylboronic acid is typical.

n-Hexyldibromoborane–dimethyl sulfide (50 mL of 1 M solution), cooled to 0 °C, was added to a stirred mixture of water (9 mL, 500 mmol) and ether (25 mL) at 0 °C (ice bath) through a double-ended needle. The mixture was stirred for about 10 min after the addition and water (lower) layer was separated. The organic layer was washed with cold water (2 × 15 mL) and brine (1 × 25 mL) and dried with anhydrous $MgSO_4$. On evaporation of the solvent under reduced pressure, *n*-hexylboronic acid (6.2 g, 95%) was obtained in reasonably pure form; a small sample, recrystallized from benzene, mp 88 °C.

Esterification of Boronic Acids with Primary and Secondary Alcohols. Preparation of dimethyl (1*E*)-1-octenylboronate is representative. (1*E*)-1-Octenylboronic acid (7.8 g, 50 mmol) was suspended in pentane (40 mL) in a separatory funnel, methanol (4.05 mL, 100 mmol) was added to it, and the mixture was shaken for a few seconds. Water separated immediately and was removed (3.2 mL, 1.4 mL in excess 100 mmol). Another 100-mmol portion of methanol was added to the mixture, the mixture shaken for a few seconds, and the water separated was removed. When the pentane layer was dried with anhydrous $MgSO_4$ and the solvent was removed, essentially pure dimethyl ester (8.95 g, 97%) was obtained. On distillation, this gave 8.19 g (89%) of pure ester, bp 62–63 °C (0.3 mm).

Esterification with Glycols. The above procedure was slightly modified to account for the fact that glycols react with the boronic acids at a slower rate compared to the alcohols. preparation of trimethylene *n*-hexylboronare illustrates this modification. *n*-Hexylboronic acid (6.5 g, 50 mmol) was stirred with pentane (40 mL) and trimethylene glycol (3.8 g, 50 mmol) for 0.5 h. Water separated was removed, the pentane layer was dried, and on removal of solvent, almost pure ester (8.16 g, 95%) was obtained.

Conversion of Alkyl- and Alkenyldibromoborane–Dimethyl Sulfide Complexes to the Corresponding Esters. Procedure A. Preparation of dimethyl (1*E*)-1-octenylboronate is representative. (1*E*)-1-Octenyldibromoborane–dimethyl sulfide (50 mmol) in dichloromethane was prepared as described earlier. Pentane (25 mL) was added to the reaction flask, and it was cooled to ~−10 °C (ice–salt bath).[35] Methanol (8.1 mL, 200 mmol) was slowly added to the flask. Stirring was continued for an additional 15 min. The pentane–dichloromethane layer containing the boronate formed the upper layer, which was separated from the lower acidic layer. The latter was extracted with cold (0 °C) pentane (3 × 10 mL), and the combined pentane extract, on removal of solvent under reduced pressure, gave 8.9 g (97%) of the crude product. On distillation, 8.25 g (90%) of pure dimethyl (1*E*)-1-octenylboronate, bp 62–63 °C (0.3 mm), was obtained.

Procedure B. Preparation of dimethyl *n*-hexylboronate is illustrative. *n*-Hexyldibromoborane–dimethyl sulfide (50 mmol) in dichloromethane was prepared as usual. The solvent was completely pumped off, and the complex was dissolved in pentane (40 mL). The solution was cooled to 0 °C (~−10 °C in the case of alkenyldibromoboranes), followed by the addition of methanol (8.1 mL, 200 mmol). Stirring was continued for another 15 min, and the pentane layer was separated. Subsequent workup as in Procedure A gave dimethyl *n*-hexylboronate (6.48 g, 82%), bp 68–70 °C (16 mm).

Procedure C. Synthesis of dimethyl *B*-(*cis*-1-bromo-1-octenyl)boronate is representative of this inverse addition procedure. 1-Bromo-1-octyne (50 mmol) was hydroborated with $HBBr_2{\cdot}SMe_2$ as described earlier. The reaction product, cooled to ~−10 °C,[35] was slowly transferred to a cooled (−10 °C) mixture of methanol (200 mmol) and pentane (30 mL), through a double-ended needle. Subsequent procedure was as in procedure A. Dimethyl *B*-(*cis*-1-bromo-1-octenyl)boronate, bp 78 °C (0.2 mm), was obtained in 80% yield (10.5 g).

Procedure D. This is a modification of procedure C, especially suited for the preparation of cyclic esters (with glycols) and aryl esters (with phenols). Preparation of trimethylene *B*-(*cis*-4-octenyl)boronate is typical of this procedure. 4-Octyne (50 mmol) was hydroborated with $HBBr_2{\cdot}SMe_2$. The reaction mixture was cooled to ~−10 °C[35] (ice–salt bath) and was added to a mixture of trimethylene glycol (3.89 g, 50 mmol) and pentane (30 mL) at −10 °C, through a double-ended needle. The mixture was stirred for 0.5 h at −10 °C, and methanol (4.05 mL, 100 mmol) was added. Stirring was continued for another 10 min. Subsequent procedure was as in A. Distillation gave pure trimethylene *B*-(*cis*-4-octenyl)boronate (8.62 g, 88%), bp 78 °C (0.25 mm).

Aryl esters were prepared in the same way using 2 mol of phenol and 2 mol of methanol/mol of $RBBr_2{\cdot}SMe_2$.

Preparation of *tert*-Butyl Esters. Procedure E. Synthesis of di-*tert*-butyl (1*E*)-1-hexenylboronate illustrates the use of pyridine to react with the hydrogen bromide liberated. 1-Hexyne (50 mmol) was hydroborated with $HBBr_2{\cdot}SMe_2$ as described earlier. The product was slowly transferred to a cooled (0 °C) mixture of *tert*-butyl alcohol (8.14 g, 110 mmol) and pyridine (8.8 g, 110 mmol) in pentane (30 mL). Pyridine hydrobromide precipitated as a white crystalline solid. The mixture was warmed to room temperature, and stirring was continued for an additional 0.5 h. The pentane layer was separated from the solid, and the latter was repeatedly (3 × 20 mL) extracted with warm pentane. The combined pentane extract, on workup and subsequent distillation, gave 7.5 g (63%) of di-*tert*-butyl (1*E*)-1-hexenylboronate, bp 78 °C (0.3 mm).

Procedure F. Di-*tert*-butyl *n*-hexylboronate was prepared by this procedure. To a solution of *tert*-butyl alcohol (7.4 g, 100 mmol) in pentane (20 mL) was added dropwise a solution of *n*-butyllithium (100 mmol) in hexane. The formation of lithium *tert*-butoxide was instantaneous with the evolution of *n*-butane. Concomitantly, a solution of *n*-hexyldibromoborane–dimethyl sulfide in pentane was prepared (50 mmol, cf. procedure B) and cooled to 0 °C. The latter was slowly added to the base solution

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(35) An ice bath is satisfactory for alkyldibromoboranes.

and stirred for 0.5 h at room temperature. Lithium bromide precipitated and was removed by centrifuging. The solid was extracted repeatedly (3 × 10 mL) with pentane. The combined pentane extract, on distillation, gave 9.80 g (81% of pure di-*tert*-butyl *n*-hexylboronate, bp 94–96 °C (6.5 mm).

Registry No. $RB(OH)_2$ (R = *n*-hexyl), 16343-08-1; $RB(OH)_2$ (R = 3-hexyl), 86595-36-0; $RB(OH)_2$ (R = cyclopentyl), 63076-51-7; $RB(OH)_2$ (R = (1*E*)-1-octenyl), 42599-16-6; $RB(OH)_2$ (R = (1*E*)-3,3-dimethyl-1-butenyl), 86595-37-1; $RB(OR')_2$ (R = *n*-hexyl, R′ = methyl), 2344-23-2; $RB(OR')_2$ (R = *n*-hexyl, R′ = ethyl), 86595-38-2; $RB(OR')_2$ (R = 3-hexyl, R′ = methyl), 37981-92-3; $RB(OR')_2$ (R = (1*E*)-1-octenyl, R′ = methyl), 86595-39-3; $RB(OR')_2$ (R = (1*E*)-1-octenyl, R′ = isopropyl), 86595-40-6; $RB(OR')_2$ (R = *n*-hexyl, R′ = $(CH_2)_3$), 86290-24-6; $RB(OR')_2$ (R = 3-hexyl, R′ = $(CH_2)_3$), 86290-28-0; $RB(OR')_2$ (R = cyclopentyl, R′ = $C(CH_3)_2C(CH_3)_2$), 66217-55-8; $RB(OR')_2$ (R = (1*E*)-1-octenyl, R′ = $(CH_2)_2$), 86595-41-7; $RB(OR')_2$ (R = (1*E*)-3,3-dimethyl-1-butenyl, R′ = $(CH_2)_3$), 86595-42-8; $RB(OR')_2$ (R = *n*-hexyl, R′ = isopropyl), 86290-26-8; $RB(OR')_2$ (R = cyclopentyl, R′ = methyl), 41156-60-9; $RB(OR')_2$ (R = cyclopentyl, R′ = ethyl), 86595-43-9; $RB(OR')_2$ (R = cyclopentyl, R′ = isopropyl), 86595-44-0; $RB(OR')_2$ (R = cyclohexyl, R′ = ethyl), 86595-45-1; $RB(OR')_2$ (R = *cis*-4-octenyl, R′ = methyl), 86595-46-2; $RB(OR')_2$ (R = (1*E*)-3,3-dimethyl-1-butenyl, R′ = methyl), 86595-47-3; $RB(OR')_2$ (R = (1*E*)-1-hexenyl, R′ = phenyl), 86595-48-4; $RB(OR')_2$ (R = *cis*-1-bromo-1-octenyl, R′ = methyl), 86595-49-5; $RB(OR')_2$ (R = (1*E*)-1-hexenyl, R′ = *tert*-butyl), 86595-50-8; $RB(OR')_2$ (R = *n*-hexyl, R′ = *tert*-butyl), 86595-51-9; $RB(OR')_2$ (R = *n*-hexyl, R′ = $(CH_2)_2$), 86290-25-7; $RB(OR')_2$ (R = *n*-hexyl, R′ = $C(CH_3)_2C(CH_3)_2$), 86308-26-1; $RB(OR')_2$ (R = (1*E*)-1-octenyl, R′ = $(CH_2)_3$), 86595-52-0; $RB(OR')_2$ (R = *cis*-4-octenyl, R′ = $(CH_2)_2$), 86595-53-1; $RB(OR')_2$ (R = *cis*-4-octenyl, R′ = $(CH_2)_3$), 86595-54-2; $RBBr_2{\cdot}SMe_2$ (R = *n*-hexyl), 64770-04-3; $RBBr_2{\cdot}SMe_2$ (R = 3-hexyl), 64770-06-5; $RBBr_2{\cdot}SMe_2$ (R = cyclopentyl), 64770-10-1; $RBBr_2{\cdot}SMe_2$ (R = (1*E*)-1-octenyl), 86687-40-3; $RBBr_2{\cdot}SMe_2$ (R = (1*E*)-3,3-dimethyl-1-butenyl), 72228-60-5; $RBBr_2{\cdot}SMe_2$ (R = *cis*-1-bromo-1-octenyl), 86610-17-5; $RBBr_2{\cdot}SMe_2$ (R = *cis*-4-octenyl), 86610-18-6; $RBBr_2{\cdot}SMe_2$ (R = (1*E*)-1-hexenyl), 72228-56-9; $RBBr_2{\cdot}SMe_2$ (R = cyclohexyl), 86610-19-7; methanol, 67-56-1; trimethylene glycol, 504-63-2; *tert*-butyl alcohol, 75-65-0; ethanol, 64-17-5; 2-propanol, 67-63-0; pinacol, 76-09-5; ethylene glycol, 107-21-1; phenol, 108-95-2.

Organoboranes. 31. A Simple Preparation of Boronic Esters from Organolithium Reagents and Selected Trialkoxyboranes

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The reaction of methyllithium with trimethoxyborane at −78 °C in ethyl ether yields a mixture of methylated boranes and their corresponding "ate" complexes. We have found that under the same conditions triisopropoxyborane reacts cleanly with methyllithium to form the lithium methyltriisopropoxyborate complex. Protonation of this complex with anhydrous hydrogen chloride quantitatively yields methyl diisopropoxyborane. This reaction of organolithium reagent with triisopropoxyborane appears to provide a general, valuable route to boronic esters. Other alkoxyboranes were examined for their selectivity for monomethylation by methyllithium. In addition to triisopropoxyborane, triisobutoxyborane and tri-*sec*-butoxyborane also give the methylboronic esters quantitatively. This development provides the first general preparation of boronic esters from organolithium reagents.

The utility of boronic esters and acids has largely been limited in the past to protecting groups in carbohydrate chemistry[1] and as derivatizing agents for difunctional compounds for GC and GC–MS analysis.[2] Recently the homologation of boronic esters has been demonstrated, and this promises to become an important application of boronic esters.[3-5] A variety of methods have been used to prepare boronic esters. The addition of Grignard reagents to trialkoxyboranes at low temperatures followed by an aqueous hydrolysis yields the boronic acids.[6-9] However, low yields are realized for the smaller alkyl groups, and subsequent esterification is necessary to obtain the ester. The redistribution of triorganylboranes with trialkoxyborane[10] and trihaloboranes[11,12] has been employed. Other less direct routes utilizing haloboranes,[13] catecholborane,[14] and thexylborane[15,16] have been described. However, the alkyl groups employed are limited to those obtained via hydroboration. While alkyllithiums have been used, they tend to form the borinic ester preferentially.[17] Having overcome these difficulties and limitations, we describe here a simple and direct route for preparing boronic esters from organolithium reagents and selected trialkoxyboranes.

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