Hydroboration. 94. Rates of Hydroboration of 2-Organylapopinenes with 9-Borabicyclo[3.3.1]nonane, Providing *B*-(2-Organylapoisopinocampheyl)-9-borabicyclo[3.3.1]nonanes, Potentially Valuable for the Asymmetric Reduction of Prochiral Ketones

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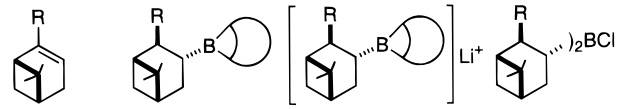
Five representative enantiomerically pure, hindered terpenes, derived from α-pinene, namely 2-organylapopinenes (2-R-apopinenes, R = Et, Pr, *i*-Bu, Ph, and *i*-Pr) have been treated with 9-borabicyclo[3.3.1]nonane (9-BBN) in a 1:1 molar ratio in THF at 24 °C and the rate of hydroboration followed. Increasing the bulk of the 2-R group from the 2-methyl of α-pinene (Ipc, 2-methylapopinene) to 2-ethyl- (Eap), to 2-propyl- (Prap), to 2-isobutyl- (*i*-Bap), to 2-phenyl- (Pap), and to 2-isopropyl- (*i*-Prap) significantly lowers the rate of hydroboration with 9-BBN. Thus, the rate of hydroboration of α-pinene with 9-BBN is faster than the rates for the 2-R-apopinenes studied. The sterically bulkier 2-isobutyl-, 2-phenyl-, and 2-isopropylapopinenes reveal a significantly slower rate of hydroboration with 9-BBN. At an elevated temperature, 65 °C, the reaction of 9-BBN (1.0 equiv) with a slight excess of optically pure 2-isobutyl- and 2-phenylapopinenes (1.10−1.20 equiv), under neat conditions, is facilitated to provide the desired *B*-(2-organylapoisopinocampheyl)-9-borabicyclo[3.3.1]nonanes (2-organyl = isobutyl- and phenyl) in quantitative yield. Unfortunately, this synthesis failed for 2-isopropylapopinene. Fortunately, an indirect synthesis proved satisfactory. Treatment of enantiomerically pure (2-isopropylapoisopinocampheyl)borane, *i*-PrapBH$_2$, conveniently synthesized from 2-isopropylapopinene, and 1,5-cyclooctadiene (1,5-COD), provided, after thermal isomerization, the desired 1:1 adduct [*B*-(2-Rap)-9-BBN; 2-Rap = 2-isopropylapoisopinyl skeleton] in quantitative yield. Consequently, five of the 2-R-apopinenes, R = Et, Pr, *i*-Bu, Ph, and *i*-Pr, have been successfully converted into the corresponding *B*-(2-Rap)-9-BBN derivatives.

Asymmetric synthesis has become an important branch of organic synthesis. Consequently, a number of reactions have been discovered to produce enantiomerically pure compounds using optically active reagents derived from various chiral auxiliaries.[2] In this endeavor, we have been exploring asymmetric synthesis based on α-pinene-derived borane reagents.[3] Shortly after the discovery of hydroboration,[4a] α-pinene [92% enantiomeric excess (ee)] was selected as an example of an easily rearranged olefin and subjected to hydroboration to see if rearrangement during hydroboration would be a problem. No rearrangement was observed. However, the product was a dialkylborane, Ipc$_2$BH, instead of the usual trialkylborane, R$_3$B. Consequently, the first asymmetric hydroborating agent had been prepared! The possibility of achieving asymmetric hydroboration was tested with an olefin of low steric requirements, *cis*-2-butene.[4b] The oxidation of the resulting trialkylborane gave 2-butanol in 87% ee, the first nonenzymatic synthesis in high ee!

Considerable success was achieved in studying asymmetric hydroboration with Ipc$_2$BH and isopinocampheylborane, IpcBH$_2$.[3] These studies provided convenient routes to chiral organoboranes, R*B<. It was then discovered that substitution of the R*B< groups proceeds predominantly with retention of configuration. Consequently, this approach provided a general synthesis of enantiomerically pure compounds.

An early attempt was made to use this approach to achieve the asymmetric reduction of ketones. The hydroboration of α-pinene with 9-BBN provided *B*-isopinocampheyl-9-borabicyclo[3.3.1]nonane (*B*-Ipc-9-BBN, Alpine-Borane, **2a**). This was converted to the borohydride, lithium *B*-3-pinanyl-9-borabicyclo[3.3.1]nonyl hydride (Alpine-Hydride, **3a**).[5] Asymmetric reduction of certain class of prochiral ketones with this borohydride **3a** provided disappointingly low optical yield for the product alcohols.



1a R = Me **1d** R = *i*-Bu **2** **3** **4a** R = Me
1b R = Et **1e** R = Ph **b** R = Et
1c R = Pr **1f** R = *i*-Pr

Midland and his co-workers established that the *B*-Ipc-9-BBN (**2a**) was an excellent reagent for the reduction of α-deuterioaldehydes, RCDO, giving the primary alco-

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hols, RCHDOH, in optical purities approaching 100%.[6] This reagent **2a** was also excellent for the reduction of more active ketones, such as acetylenic ketones and keto esters, but less suitable for the majority of less active ketones.

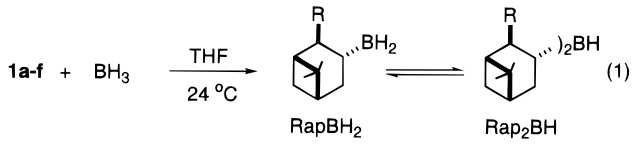
We then introduced *B*-chlorodiisopinocampheylborane (Ipc_2BCl, DIP-chloride, **4a**) and achieved the reduction of aralkyl ketones, such as acetophenone in an optical yield of ~98%. Fluorinated ketones gave satisfying optical yields.[3b] Unfortunately, aliphatic ketones, such as 3-methyl-2-butanone, underwent reduction in only 34% ee. In such reductions the 2-methyl group of the α-pinene moiety appears to play a very important role. Indeed, simply by replacing the methyl group by an ethyl, the resulting reagent, Eap_2BCl (**4b**),[7] reduced 3-methyl-2-butanone in 95% ee.

Encouraged by these results, we synthesized the asymmetric hydroborating agents, 2-organylapoisopinocampheylboranes ($RapBH_2$; R = Et, $EapBH_2$;[8] R = *i*-Pr, *i*-$PraBH_2$[9]), readily obtained from the sterically-demanding chiral auxiliaries (**1b** and **1f**), which achieve improved enantioselection for the asymmetric hydroboration of prochiral alkenes in comparison with that of the less sterically-demanding $IpcBH_2$.[10]

These observations persuaded us of the desirability of making a systematic study of the rate of hydroboration of sterically-varied 2-R-apopinenes **1a**−**f** with 9-BBN. Recently, we made a quantitative rate study of the chiral auxiliaries **1a**−**f** with borane reagents, namely borane dimethyl sulfide (BH_3·SMe_2, BMS) and BH_3·THF.[11] This study was performed in order to understand the properties of these sterically-varied α-pinene-derived chiral auxiliaries **1a**−**f** toward relatively less hindered borane reagents to establish conditions for developing practical procedures for the synthesis of optically pure $RapBH_2$[12] or Rap_2BH. In this paper, we wish to report a quantitative study of the rate of hydroboration of the structurally-varied 2-organylapopinenes with the bulkier hydroborating agent, 9-BBN in THF at 24 °C, and the synthesis of optically pure *B*-(2-organylapoisopinocampheyl)-9-borabicyclo[3.3.1]nonanes [*B*-(2-Rap)-9-BBN, **2d**−**f**], by direct and indirect methods to be discussed, potentially useful for the selective asymmetric reduction of prochiral ketones.

Results and Discussion

Recently, we have examined the effect of the steric requirements of the groups R (Me, Et,[8] Pr,[7b] *i*-Bu,[11] Ph,[13] and *i*-Pr[11]) of the 2-R-apopinenes **1a**−**f** on the rates of hydroboration with BMS and BH_3·THF, to provide the corresponding mono- ($RapBH_2$) and bis(2-R-apoisopinocampheyl)boranes (Rap_2BH) (eq 1).[11]



(1)

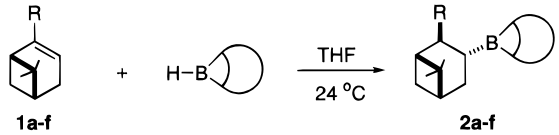
Table 1. Data for the Rate of Hydroboration of 2-Organylapopinenes with 9-BBN in a 1:1 Molar Ratio (0.50 M Each) in THF at 24 °C[a]

	formation of trialkylborane[a,b] (%)					
time (h)	**2a**	**2b**	**2c**	**2d**	**2e**	**2f**
2	22	11	10	10	6	0
6	63	37	33	15	11	
10	84	65	44	17	16	2
24	98	85	59	20	18	7
48		98	81	25	20	11
72			93	28	22	13

[a] Determined by GC analysis (see Experimental Section). [b] Percentage of the reaction is based on the amount of alcohol formed after oxidation ($NaOH/H_2O_2$) of trialkylborane.

It is observed that with the increasing steric requirements of R, there is an increasing tendency for the reaction to stop short of the Rap_2BH stage, tending to proceed cleanly to $RapBH_2$ in the cases of R = Ph (**1e**) and *i*-Pr (**1f**). Thus, the hydroboration of these 2-R-apopinenes (**1e** and **1f**) with borane reagents, BMS or BH_3·THF, provide essentially pure $RapBH_2$ for R = Ph (**1e**) and *i*-Pr (**1f**).[11] Therefore, in this context it was interesting to observe the effect of the R groups of the 2-R-apopinenes (**1a**−**f**) in their hydroboration with a bulkier hydroborating reagent, 9-BBN, to provide a new class of sterically-demanding *B*-(2-Rap)-9-BBN, potentially important for the asymmetric reduction of certain classes of prochiral ketones.

Rate of Hydroboration of 2-R-apopinenes 1a−f with 9-BBN. We have previously reported the synthesis of 2-R-apopinenes **1a**−**f**.[7b,8,11,13] These 2-R-apopinenes **1a**−**f** were subjected to hydroboration with 9-BBN in a 1:1 molar ratio in THF at 24 °C (0.50 M) (eq 2).



(2)

The rate of hydroboration was determined by two methods:[11] (i) aliquots of the solution were removed at appropriate periods of time, hydrolyzed with excess methanol, oxidized with alkaline peroxide, and analyzed by GC for the residual 2-R-apopinenes and/or the silyl ether of the alcohol, produced by hydroboration−oxidation, using a suitable internal standard; (ii) by ^{11}B NMR spectrum of aliquots taken at appropriate intervals of time for the formation of trialkylborane **2a**−**f**. These analytical procedures gave concurrent results. The results are summarized in Table 1 and depicted graphically in Figure 1.

It is apparent from the experimental data that the less sterically-demanding α-pinene reacts with 9-BBN at a faster rate, compared with the more hindered 2-R-apopinenes **1b**−**f**, to provide the desired 1:1 adduct with 9-BBN in nearly quantitative yield in 24 h. In the case of 2-ethyl- (**1b**) and 2-propylapopinenes (**1c**), 50% hydroboration with 9-BBN proceeds in nearly 10 h but then proceeds to almost completion at a much slower rate, with >90% reaction achieved in 48 and 72 h for **2b** and **2c**,

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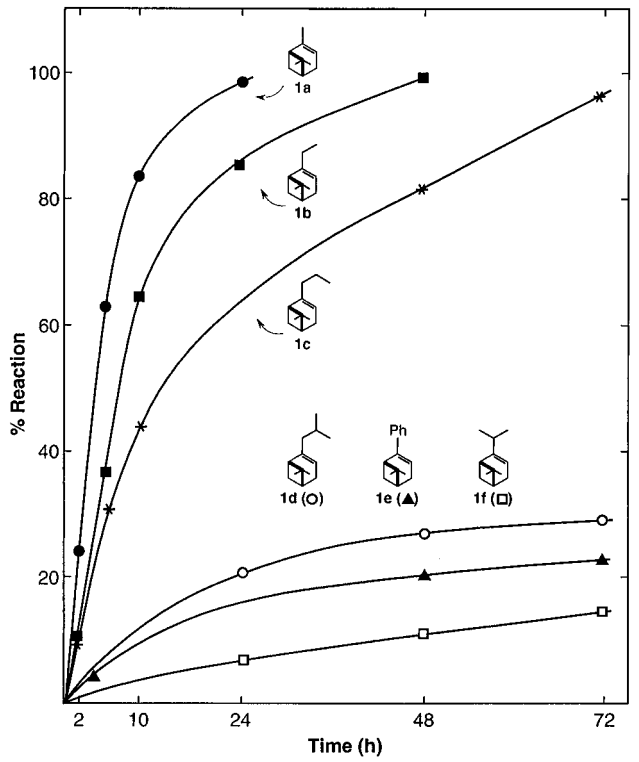


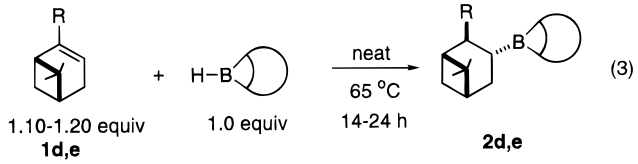
Figure 1. Rate of hydroboration of 2-R-apopinenes (0.50 M) with 9-BBN (0.50 M) in THF at 24 °C. Molar ratio 1:1.

respectively. Compared with the simpler 2-R-apopinene derivatives **1a**,**c**, alkenes **1d**−**f** show an even slower rate of hydroboration with 9-BBN, with only 13−28% reaction in 72 h.

On the contrary, the hydroboration of the more hindered 2-R-apopinenes (**1d**−**f**) with BMS, a sterically less demanding borane reagent, in 1:1 molar ratio (0.50 M) is over in 24 h to the extent of 97−100%, producing >90% of the desired 1:1 adduct as $RapBH_2$ (R = *i*-Bu, Ph, and *i*-Pr).[11] Under similar conditions, the hydroboration of 2-R-apopinenes **1d**−**f** with the more loosely complexed borane reagent, BH_3·THF, in a 1:1 molar ratio (0.50 M), provides almost the same distribution of the products in 1 h for **1d**, 2 h for **1e**, and 4 h for **1f**.[11]

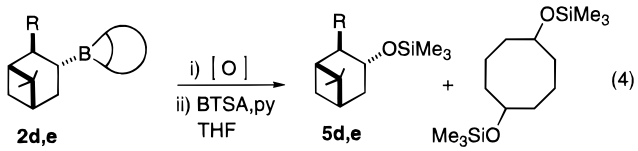
These results clearly demonstrate the effect of the nature of the reagents on the rates of hydroboration of the sterically-different 2-R-apopinenes. Bulkier reagents, such as 9-BBN, hydroborate less hindered terpenes such as α-pinene (**1a**), 2-ethyl- (**1b**), and 2-propylapopinenes (**2c**) smoothly to provide the desired 1:1 adducts, i.e., *B*-(2-Rap)-9-BBN reagents **2a**−**c**. However, as the bulk on the 2-position of apopinene is increased to isobutyl- (**1d**), to phenyl- (**1e**), and to isopropyl- (**1f**), the rate of hydroboration with 9-BBN, although it is relatively insensitive to the steric factor,[14] is extremely slow in providing the required *B*-(2-Rap)-9-BBN reagents **2d**−**f** in adequate amounts. Consequently, this experimental observation led us to consider the synthesis of *B*-(2-Rap)-9-BBN reagents **2d**−**f** under the conditions reported for the synthesis of **2a**−**c**,[7b,15] which is described in the following section.

***B*-(2-Organylapoisopinocampheyl)-9-borabicyclo-[3.3.1]nonane 2d,e.** It is observed from the above rate data that the synthesis of **3d**−**f** is extremely slow in the reaction of 9-BBN with the 2-R-apopinenes **1d**−**f** in THF at 24 °C. Previous work has shown that 9-BBN is less sensitive to steric effects of substrate alkenes than other bulky dialkylboranes, such as disiamylborane.[14] This observation has been attributed to the increased electrophilic nature of the boron atom as a result of the steric strain inherent in the 9-borabicyclo[3.3.1]nonane structure. Therefore, we explored the possibility of carrying out the hydroboration of a slight excess (10−20%) of the 2-R-apopinenes **1d**−**f** with 9-BBN, under neat reaction conditions, at a higher temperature, such as at 65 °C, as reported for **2a**.[15] Hopefully, this would provide a simple route to the desired *B*-(2-Rap)-9-BBN reagents **2d**−**f** (eq 3).



(3)

Indeed, the reaction of optically pure **1d** (1.1 equiv) with 9-BBN (1.0 equiv) under neat favorable conditions at 65 °C provided the desired **2d** in 14 h in quantitative yield. The chemical and optical purities of this 1:1 adduct were confirmed by oxidizing **2d** with alkaline peroxide in the presence of an internal standard and analyzing the products *viz.* 2-isobutylapopinene (**1d**), 2-isobutylapoisopinocampheol, and *cis*-1,5-cyclooctanediol as their silyl ethers on GC. The analysis of the reaction mixture indicated the quantitative formation of the desired **2d**. The silyl ethers were prepared from the reaction of alcohols with bis(trimethylsilyl)acetamide (BTSA)[16] (eq 4).



(4)

Similarly, the alcohol was isolated and compared with an authentic sample[17] by its $^1H/^{13}C$ NMR spectra, mixed melting point, and optical rotation. The optical rotation of 2-isobutylapoisopinocampheol in comparison with the authentic sample of ≥99% ee suggested the optical purity of ≥99% for the desired 1:1 adduct **2d**.

In another approach, the chemical and optical purity of the trialkylborane **2d** was confirmed by liberating and analyzing the optically pure 2-isobutylapopinene (**1d**) from **2d** in comparison with the authentic sample as described above. Thus, the treatment of the trialkylborane **2d** with aldehyde, followed by stirring at 24 °C for 2 h, provided a nearly quantitative formation of the borinate ester (^{11}B NMR, δ 54) and an 81% isolated yield of optically pure (+)-2-isobutylapopinene (**1d**),[17] eliminated in the reaction with aldehyde.

Under the same conditions as described for the synthesis of **2d**, 2-phenylapopinene (1.20 equiv) was hydroborated with 9-BBN (1.0 equiv) to provide the desired trialkylborane **2e** in 24 h in nearly quantitative yield. The chemical and optical purity of the **2e** was determined

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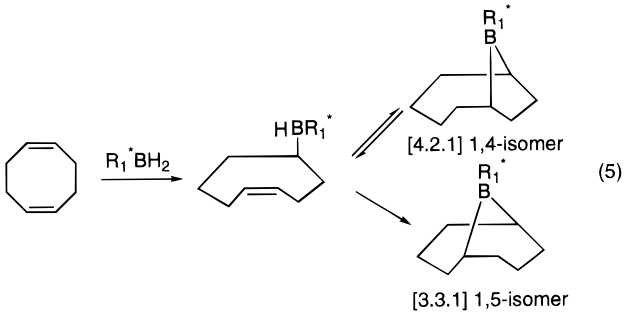
as described for **2d**. However, under these conditions, the hydroboration of **1f** (1.20 equiv) with 9-BBN (1 equiv) was complicated by the formation of undesired species (20−25%) along with the required trialkylborane **2f**. Consequently, an indirect method for the synthesis of trialkylborane **2f** was developed.

Synthesis of *B*-(2-Isopropylapoisopinocampheyl)-9-borabicyclo[3.3.1]nonane (2f). An alternative synthesis of *B*-(2-isopropylapoisopinocampheyl)-9-borabicyclo-[3.3.1]-nonane (**2f**) was developed. It has been demonstrated in previous work from this laboratory that the cyclic hydroboration of 1,5-COD with thexylborane (Thx-BH_2) gives two regioisomeric products, arising from the 1,4- and 1,5-cycloaddition in a 4:1 ratio, respectively.[18] It has also been reported that the chiral monoalkylboranes (R_1*BH_2) react with 1,5-COD to give a 70:30 mixture of the 1,4- and 1,5-cyclic adducts.[19] Apparently, the hydroboration proceeds in two stages. The first step is the hydroboration of one of the double bonds. The second stage is the intramolecular cyclic hydroboration, which favors formation of the five-membered boracyclane over the six-membered ring (eq 5). The less stable 1,4-regioisomer is readily isomerized to the 1,5-isomer at 65 °C.[19]



Thus, the hydroboration of 1,5-COD with an ethereal solution of (2-isopropylapoisopinocampheyl)borane (*i*-PraBH_2) at 0 °C for 1 h achieved the quantitative formation of the 1:1 mixed trialkylboranes as determined by ^{11}B NMR (δ 81, 86), and the GC analysis of the products resulted after alkaline peroxide oxidation.[17] The thermal isomerization of the less stable 1,4-isomer to the more stable desired trialkylborane **2f** (^{11}B NMR: δ 83) was complete in 24 h in refluxing THF. The reaction was monitored periodically by ^{11}B NMR of aliquots and also by GC analysis of the silyl ethers of the alcohols, produced by alkaline peroxide oxidation of the boron components. Optical and chemical purity of the trialkylborane **2f**, obtained after the isomerization reaction, was determined as described previously.

Conclusions

This paper describes a detailed study of the behavior of six representative sterically different 2-organylapopinenes (2-R-apopinenes; R = Me, Et, Pr, *i*-Bu, Ph and *i*-Pr) in the hydroboration with the bulkier 9-BBN in THF at 24 °C. We have demonstrated that as the R group in the 2-R-apopinenes become bulkier, the rate of hydroboration slows, becoming so slow with the latter three 2-R-apopinenes as to be impractical. However, for sterically-demanding terpenes, such as 2-isobutyl- and 2-phenyl-apopinenes (1.10−1.20 equiv), hydroboration with 9-BBN (1.0 equiv) is readily achieved under neat conditions at 65 °C in 14−24 h. Unfortunately, hydroboration of the more sterically-demanding, 2-isopropylapopinene (**1f**), with 9-BBN, did not proceed satisfactorily to furnish the desired *B*-(2-Rap)-9-BBN (2-Rap = 2-isopropylapopinyl skeleton). Fortunately, an indirect method, the reaction of (2-isopropylapoisopinocampheyl)borane (*i*-PraBH_2) with 1,5-COD, achieves the synthesis of the desired trialkylborane **2f**, following thermal isomerization, in nearly quantitative yield. Consequently, this indirect approach provides an independent route to the sterically bulkier *B*-2-organylapopinyl-9-BBN compounds, difficult to obtain *via* direct hydroboration. Thus, the syntheses of these *B*-2-organylapopinyl-9-BBN compounds **2c**−**f** provide easy access to them to study the effect of the 2-organyl group on the selective asymmetric reduction of acetylenic ketones and α-keto esters. Also, the corresponding optically pure lithium trialkylborohydrides **3c**−**f** should provide sterically bulkier analogues of lithium *B*-isopinocampheyl-9-borabicyclo[3.3.1]nonyl hydride (Alpine-Hydride),[5] possibly more effective for the asymmetric reduction of prochiral ketones.

Experimental Section

All glassware was dried at 140 °C overnight, assembled hot, and cooled to ambient temperature in a stream of nitrogen.[20] All reactions involving air- or moisture-sensitive compounds were performed under a static pressure of dry nitrogen.[20] Reported melting points are uncorrected. ^{11}B NMR spectra were recorded at 96 MHz and were referenced relative to BF_3·EE. ^{1}H and ^{13}C NMR spectra were recorded at 200 and 50 MHz, respectively, relative to internal tetramethylsilane (TMS). Chemical shifts in the ^{1}H and ^{13}C NMR spectra are reported as parts per million (ppm) downfield from TMS. All materials for which optical rotation information is provided were purified by preparative GC on a 6 ft × 0.5 in. column packed with 20%-SE 30 on Chromosorb W (60−80 mesh). Optical rotations were measured on a digital polarimeter in a 1-dm cell. GC analyses for chemical purity and rate data were performed using columns packed either with 10%-SE 30 on Chromosorb W (100−120 mesh) or 10% Carbowax on Chromosorb W (80−100 mesh). Capillary GC analyses were performed using the SPB-5 column (30 m).

Materials. Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl and used as required. Anhydrous diethyl ether was used without purification. The 2-R-apopinenes **1b**−**f** were synthesized by the known procedures.[7b,8,11,13] The 2-R-apopinenes **1b**−**d**,**f** were derived from (+)-α-pinene, while (+)-phenylapopinene (**1e**) was synthesized from (+)-β-pinene.[13]

General Procedure for the Determination of the Rate of the Hydroboration of 2-R-apopinenes 1a−f with 9-BBN. The reactions were carried out in THF at 24 °C. In all these experiments, 10−12 mmol of 2-R-apopinenes **1a**−**f** were used for the reaction with 9-BBN. The concentration of 2-R-apopinenes with 9-BBN was maintained at 0.50 M each. The progress of the reaction was monitored at appropriate time intervals by the following analytical techniques: (i) ^{11}B NMR spectral analysis, for trialkylborane and dialkylborane (9-BBN),[21] of an aliquot taken after definite time intervals; (ii) GC analysis of either residual 2-R-apopinenes or silyl ether (**5a**−**f**) (silylation was done with bis(trimethylsilyl)acetamide using a catalytic amount of pyridine in THF)[16] of the product 2-organylapoisopinocampheol, resulting from the hydrobora-

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Table 2. Rate of Hydroboration of 2-Ethylapopinene (1b) with 9-BBN in a 1:1 Molar Ratio (0.50 M Each)[a] in THF at 24 °C

time (h)	residual olefin[b] (mmol)	alcohol[c] formed (mmol)	% reaction[d]
2	10.49	1.31	11
6	7.53	4.31	37
10	4.30	7.54	65
24	1.75	9.95	85
48	0.23	11.52	≥98

[a] 2-Ethylapopinene (**1b**) (11.7 mmol), 9-BBN (11.7 mmol), and *n*-dodecane (5.037 mmol) in THF (20.0 mL). [b] Mmol of residural olefin corresponds to mmol of 1,5-cyclooctanediol. [c] 2-Ethylapoisopinocampheol. [d] Based on the mmol of alcohol formed.

tion−oxidation, using a suitable internal standard whose response factor had been calculated. In the experiments involving 2-R-apopinenes **1a**,**b**, *n*-dodecane was used as an internal standard, while for the 2-R-apopinenes **1c**−**f**, *n*-tridecane was so used.

The following procedure is representative. One equiv of solid 9-BBN (11.7 mmol) was dissolved in THF (15.0 mL) and maintained at 24 °C. The 2-ethylapopinene (**1b**) (1.76 g, 11.7 mmol) was dissolved in THF (5.0 mL) and added dropwise. The molarity of the solution was maintained at 0.50 M with respect to the reactants. At appropriate time intervals, the ^{11}B NMR spectrum was recorded, and also a 2.0 mL aliquot was removed, dissolved in 3−4 mL of THF, and oxidized ($NaOH/H_2O_2$). The usual workup procedure[20] provided a mixture of products, i.e., 2-ethylapopinene (**1b**), 2-ethylapoisopinocampheol, and 1,5-cyclootanediol. The resultant mixture was subjected to silylation [py/THF/bis(trimethylsilylacetamide)].[16] GC analysis of the unreacted 2-ethylapopinene (**1b**), alcohol, and diol was measured against the internal standard as described above. These results are presented in the Table 2 and graphically depicted in Figure 1. The rates of hydroboration of 2-R-apopinenes **1a**,**c**−**f** with 9-BBN, under similar conditions, are summarized in Tables 3−6 provided as Supporting Information.

Preparation of *B*-(2-Organylapoisopinocampheyl)-9-borabicyclo[3.3.1]nonanes 2d,e. The reaction was performed on a 5−10 mmol scale. Solid 9-BBN (5 mmol) was transferred under nitrogen to 50-mL round-bottom flask. Optically pure 2-R-apopinene (R = *i*-Bu **1d**, Ph, **1e**) was added to the flask *via* a double-ended needle. The flask was heated in an oil bath at 65 °C (14 h for **2d** preparation and 24 h for **2e** preparation) to complete the hydroboration (^{11}B NMR: δ 80−83).

A sample of the reagent was treated with 1 equiv of acetaldehyde, as described in the reported procedure,[17] to liberate 2-R-apopinenes **1d**,**e**. Treatment with aqueous NaOH removed the boron components, and the 2-R-apopinene **1d**,**e** was extracted into ethyl ether, dried with $MgSO_4$, concentrated, distilled, and purified by preparative GC. Gas chromatographic analysis was identical with that of an authentic sample, thus indicating no isomerization had occurred during the preparation of the reagent. (+)-2-Isobutylapopinene: $[\alpha]^{24}_D$ +15.25 (neat) [lit.[17] $[\alpha]^{20}_D$ +15.29 (neat)]. (+)-Phenylapopinene: $[\alpha]^{24}_D$ +19.86° (neat) [lit.[17] $[\alpha]^{20}_D$ −19.89° (neat)].

Similarly, this reaction was run in the presence of an internal standard, *n*-tridecane, the resultant trialkylboranes, **2d**,**e**, were subjected to alkaline peroxide oxidation, and the products of the reaction were analyzed as described above. The 2-organylapoisopinocampheols (2-organyl = isobutyl and phenyl) were isolated and purified by the preparative GC for their optical rotation measurements, which showed ≥99% ee with respect to their authentic samples. (−)-2-Isobutylapoisopinocampheol: mp 91 °C; $[\alpha]^{24}_D$ −33.7° (*c* 1, MeOH) [lit.[12] $[\alpha]^{24}_D$ −33.9° (*c* 1, MeOH)]. (−)-2-Phenylapoisopinocampheol: mp 107 °C; $[\alpha]^{24}_D$ −24.7° (*c* 1, MeOH) [lit.[12] $[\alpha]^{20}_D$ +24.8° (*c* 1, MeOH)].

Similarly, these alcohols were derivatized as the menthyl carbonate[22] (for 2-isobutylapoisopinocampheol) and the MTPA ester[23] (for 2-phenylapoisopinocampheol) and analyzed on capillary GC (on an SPB-5, 30 m column) with respect to their 1:1 diastereomeric mixtures.[12] These results in turn indicated ≥99% chemical and optical purity for the desired trialkylboranes **2d** and **2e**.

Indirect Route for the Synthesis of *B*-(2-Isopropylapoisopinocampheyl)-9-borabicyclo[3.3.1]nonane (2f). An ether solution of *i*-$PraBH_2$ (12 mL of a 0.62 M solution, 7.43 mmol) prepared as described in the literature[12] was cooled to 0 °C, followed by the dropwise addition of 1,5-cyclooctadiene (0.8 g, 7.43 mmol). The reaction was allowed to warm to 24 °C. The ^{11}B NMR showed a quantitative consumption of *i*-$PraBH_2$ as evidenced by almost 1:1 peaks at δ 86 and 81. The ether was evaporated from the reaction flask (10 mmHg, 1 h, rt), 15 mL of dry THF was introduced into the flask, and the solution was heated under reflux for 24 h. Aliquots were removed after appropriate time intervals and oxidized as described above. The resultant alcohols were silylated and analyzed as described previously. The results of this experiment showed the quantitative formation of 1,5-cyclooctanediol, formed after complete thermal isomerization of 1,4-cyclic adduct, after 24 h. The chemical and optical purity of ≥99% of the resultant trialkylborane **2f** was determined as described in the preceding experiment. (+)-2-Isopropylapopinene (**1e**): $[\alpha]^{24}_D$ +38.9° (*c* 1, MeOH) [lit.[12] $[\alpha]^{20}_D$ +39.0° (*c* 1, MeOH)]. (−)-2-Isopropylapoisopinocampheol: mp 75 °C; $[\alpha]^{24}_D$ −16.5° (*c* 1, MeOH) [lit.[12] $[\alpha]^{20}_D$ −16.4° (*c* 1, MeOH)].

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Supporting Information Available: Tables 3−7 summarizing the results of the rate of hydroboration of **1a**,**c**−**f** with 9-BBN (5 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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