Directive Effect of the 2- and 3-Axial Hydroxy Groups That Appeared in the Complex Metal Hydride Reduction of Cyclohexanones

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A significant directive effect of the 2-axial hydroxy group appeared in the $LiAlH_4$, $NaBH_4$, and $Zn(BH_4)_2$ reduction of cyclohexanone, while the 3-axial hydroxy group exhibited a steric hindrance. The distance between the carbonyl carbon and the hydroxy group which interacts with the hydride reagent is mainly responsible for such a difference. In the reduction of $Na[B(OAc)_3H]$, both the 2- and 3-axial hydroxycyclohexanones exclusively gave the products which were obtained by the hydride approaching from the side of the hydroxy group. The key point of this stereoselectivity is the formation of $Na[B(OAc)_2(OR)H]$, which is far more reactive than the parent hydride, by exchanging the acetate ion with the alkoxide.

Stereochemistry in the complex metal hydride reduction of cyclohexanones has long been discussed, and many investigations have been reported. Stereoselectivity for the reduction of unhindered cyclohexanones has currently been discussed in terms of the concept of orbital overlap control,[1] while that of hindered cyclohexanones with the alkyl group is explained on the basis of the steric hindrance of the substituents. Recently, Tomoda and Senju have proposed a new idea: π facial stereoselectivity is based on the relative magnitudes of the exterior frontier orbital extensions of the LUMO above and below the carbonyl plane (EFOE Model).[2] When the polar substituent is introduced in the molecule, additional factors concerning the heteroatom of the substituent should be taken into consideration to explain the stereoselectivity.

Most of the popular complex metal hydride reagents react with active hydrogens to form a complex with the evolution of hydrogen. If both the reducible group and the substituent with active hydrogens are present in the molecule, the complex formation may occur prior to the hydride transfer to the reducible group. Such a complex formation will affect the stereochemistry of the reduction.

In order to investigate the effect of the axial hydroxy group in a cyclohexanone ring on the stereochemistry of the complex metal hydride reduction, 2-*r*-hydroxy-2,4-*t*-dimethylcyclohexanone (**1**) and 2-hydroxy-2-methylcyclohexanone (**2**), which include the 2-axial hydroxy group, and *trans*-9β-hydroxydecalin-2-one (**3**) and 3-hydroxy-3-methylcyclohexanone (**4**), which include the 3-axial hydroxy group, were reduced with $LiAlH_4$, $NaBH_4$, $Zn(BH_4)_2$, and $Na[B(OAc)_3H]$. The stereochemical outcome is compared with the corresponding unsubstituted or the methyl-substituted analogs, *cis*-2,4-dimethylcyclohexanone (**5**), 2,2,4-trimethylcyclohexanone (**6**), *trans*-decalin-2-one (**7**), and 3,3,5-trimethylcyclohexanone (**8**) (Fig. 1).

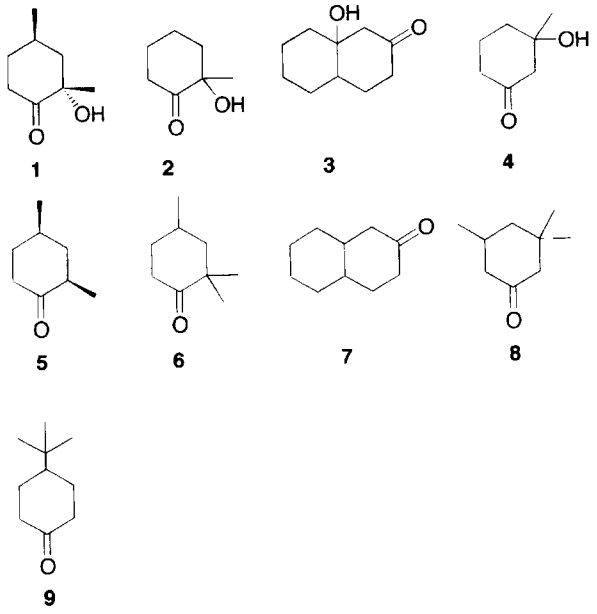

Fig. 1. Cyclohexanones.

Results and Discussion

The reduction was generally carried out under a hydride deficient condition, namely, the hydride was added to the ketone solution. The isomer distribution of the products is shown in Table 1. The complex metal hydride reduction of **5**, in which the methyl groups are conformationally locked in the equatorial position, exhibited similar stereoselectivity to that of 4-*t*-butylcyclohexanone (**9**). The 2-axial methyl group in **6** showed a steric hindrance, which was also realized in 4-*t*-butyl-2,2-dimethylcyclohexanone, and the amount of the hydride attack from the side of the 2-axial methyl group to the carbonyl was generally reduced. The stereoselectivity of the reduction of **7** was similar to that of **9**, whereas the 3-

Table 1. Stereochemistry of the Complex Metal Hydride Reduction

Substrate Hydride (Solvent)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	Equatorial attack, % (Conversion, %)								
$LiAlH_4$ (THF)	100 (44)	74 (48)	38 (43)	49 (45)	18 (89)	5 (88)	10 (90)	58 (89)	11 (100)
$NaBH_4$ (THF)	100 (36)	59 (46)	23 (24)	18 (26)	13 (32)	8 (11)	7 (11)	66 (20)	7 (25)
$NaBH_4$ (EtOH)	100 (83)	57 (91)	37 (94)	38 (95)	17 (100)	6 (100)	16 (100)	74 (93)	17 (100)
$Zn(BH_4)_2$ (THF)	100 (48)	75 (45)	37 (57)	32 (42)	18 (98)	5 (81)	4 (90)	77 (88)	8 (89)
$NaB[(OAc)_3H]$ (AcOH)	100 (90)	97 (99)	0 (89)	4 (96)	38 (8)	27 (5)	32 (7)	66 (5)	28 (7)

axial methyl group in **8** exhibited significant steric hindrance and the hydride attack from the axial side was reduced.

1. Reduction of Conformationally Rigid System. Exclusive formation of the axial alcohol, which was obtained by the hydride transfer from the same side of the hydroxy group, was observed in the reduction of **1** with all the hydride reagents employed in this study. It is known that $LiAlH_4$ and $Zn(BH_4)_2$ react with active hydrogens in the molecule to form a complex with the evolution of hydrogen. Thus the reduction by these reagents is generally carried out in ether-type solvents. Cram and Leitereg reported that the stereoselectivity in the $LiAlH_4$ reduction of acyclic α-hydroxy ketones is controlled by the presence of the hydroxy group in the substrates.[3] It has also been reported that the $NaBH_4$ reduction of acyclic β-hydroxy ketone[4] and cyclic γ-hydroxy ketone[5] in alcoholic solvents exhibited a directive effect which is responsible for the hydroxy group. These results are explained by the complex formation of the hydroxy group with the hydride reagent.

Hydrogen evolution was observed in the addition of $LiAlH_4$, $NaBH_4$ and $Zn(BH_4)_2$ to **1** in THF. When the ketone/hydride ratio is unity, the amount of hydrogen evolved was nearly half an equivalent to the active hydrogen in the substrate, indicating that some of these hydride reagents react with the active hydrogen of the hydroxy group to form the complex. In the $Zn(BH_4)_2$ reduction of carbonyl compounds, which contain a heteroatom such as oxygen or sulfur other than the carbonyl oxygen in the molecule, the formation of a zinc-mediated cyclic intermediate has been suggested.[6] The formation of such a cyclic intermediate, therefore, should be taken into consideration in the reduction of **1**. Furthermore, the following reaction may have occurred, since hydrogen evolution was observed by mixing **1** and $Zn(BH_4)_2$:

$$Zn(BH_4)_2 + ROH \rightarrow Zn[(BH_4)B(OR)H_3] + H_2.$$

Hence, the complex formation of the hydroxy group with BH_4^-, like $NaBH_4$ as well as the chelate complex formation of heteroatoms in the molecule with Zn ion, are expected in the reduction of **1**. The reduction of **1** by these three types of hydride reagents proceeds with the prior formation of the complex and subsequent hydride transfer from the side of the hydroxy group to the carbonyl as an intramolecular fashion.

Many different types of transition state structures of the hydride addition to the carbonyl group have been proposed, such as (1) acyclic,[7] (2) six-centered,[8] and (3) four-centered transition states.[9] Cieplak's proposal for the four-centered cyclic transition state has been supported by many experimental results.[9d] Since the 1970's, the studies of the transition state geometry by MO calculations were reported. The Dunitz group obtained the attack angle of the hydride to the carbonyl carbon to be 107±0.5° from the ab initio calculation of the formaldehyde–hydride system together with the survey of the crystal structure analysis.[10] Many other investigations by ab initio MO calculation elucidated that the nucleophilic reaction must involve an obtuse angle of approach of the nucleophile on the carbonyl group.[11] From results of these studies, we believe that the transition state of the hydride reduction is not four-centered with rectangular structure but is likely to be a deformed four-centered one.[9e,11c] The transition state is illustrated in light of Ashby's postulate including the four-centered cyclic structure with the carbonyl carbon, the carbonyl oxygen, the Al or B atom and the hydride being transferred to the carbonyl carbon (Fig. 2a).[9f]

At present, because we could not examine the transition state structure of the reaction using the semiempirical MO calculation (MNDO/AM1),[12] we tentatively calculated the structure for the product of the hydride transfer step in an intramolecular sense. There are two limitations on the geometry of this product: First, the two vicinal hydroxy groups are in *trans* and second, these two hydroxy groups should form the chelate ring with the Al or B atom. The obtained structure indicated that the cyclohexane skeleton is not the chair but the skew boat conformation (Fig. 3). This suggests that the actual structure of the transition state should be deformed from the illustrated chair transition state structure (Fig. 2a) to the skew boat conformation to a limited ($LiAlH_4$ reduction, early transition state) or appreciable ($NaBH_4$ reduction, late transition state) extent.

The reduction of **3**, which has the 3-axial hydroxy group, exhibited a lower amount of the equatorial alcohol, which is obtained by the hydride attack from the axial direction, com-

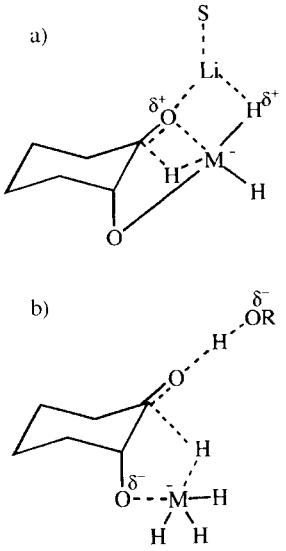

Fig. 2. Illustrated transition state of the reduction for 2-hydroxycyclohexanone. 2a; Complex formation mechanism. 2b; Push-pull mechanism.

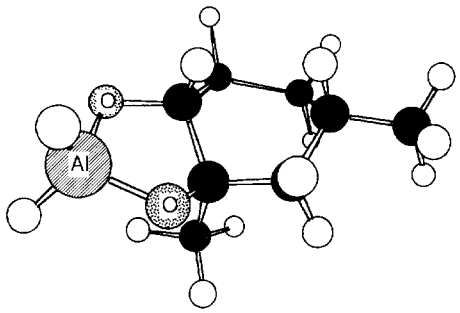

Fig. 3. Optimized structure of the product derived from **1** at the hydride transfer step.

pared to the case of the corresponding unsubstituted ketone, **7**. The observation that a hydrogen evolution by the mixing **3** and $LiAlH_4$ or $Zn(BH_4)_2$, also indicates the formation of the complex. The 2-axial hydroxy group plays a role of not blocking but accelerating the hydride approach to the carbonyl group, while the 3-axial hydroxy group operates as a steric hindrance. On the other hand, the fact that no hydrogen evolution was observed by mixing **3** and $NaBH_4$ in THF indicates that **3** does not form the complex.

As already mentioned, the complex metal hydride reduction of **1** proceeded via intramolecular hydride delivery under the hydride deficient condition. On the contrary, when the reduction was performed under an excess hydride condition, that is, the addition of **1** to the $LiAlH_4$ solution, the hydride did not exclusively approach the carbonyl group from the side of the 2-axial hydroxy group. The ratio of the axial to the equatorial attack became 41/59. The intramolecular and intermolecular hydride transfers competitively occurred under this condition.

$NaBH_4$ is stable in popular alcoholic solvents such as ethanol and 2-propanol, though it is decomposed by exchanging its hydrides by methoxide ion to form trihydromethoxyborate with the evolution of hydrogen in methanol.[13] Wigfield has proposed a push-pull mechanism involving isopropoxide and 2-propanol in the reduction of cyclohexanone in 2-propanol based on the kinetic measurements.[14] The proposed transition state is shown as follows;

$$\text{Pr-}i\text{–O}^{\delta-}\cdots{}^{-}\text{BH}_3\cdots\text{H}\cdots\text{C(R)}_2\cdots\text{O}\cdots\text{H}\cdots{}^{\delta-}\text{OP-}i.$$

The $NaBH_4$ reduction of **1** in ethanol also exclusively gave the *trans*-diol in which the hydride attacks from the same side of the 2-axial hydroxy group. In this case a very slow evolution of hydrogen, the amount of which corresponded to less than 10% of the theoretical by the reaction of the hydroxy group, was observed during the addition of $NaBH_4$ under the reaction condition employed here. The reaction seems to mainly proceed by the push–pull mechanism (Fig. 2b), in which the 2-axial hydroxy group in the substrate presumably participates, along with the complex formation mechanism to a small extent. In any event, the 2-axial hydroxy group is responsible for the direction of the hydride transfer. Compound **3** showed no hydrogen evolution with the addition of $NaBH_4$ in ethanol, and less hydride approach from the side of the 3-axial hydroxy group than in the case of **7**, which has no substituent at the 3-axial position. The 3-axial hydroxy group is considered to behave as a steric hindrance.

Why does $NaBH_4$ react with the active hydrogen of some hydroxy groups but not with others? We believe that hydrogen evolution, in other words, a complex formation, is related to the acidity of the active hydrogen. The hydroxy group of 2-hydroxy ketones is considered to be more acidic than that of 3-hydroxy ketones due to the electron withdrawing nature of the carbonyl group. For comparison, the electron densities of the active hydrogens for **1**, **3**, 1,3-dimethylcyclohexanol, and *trans*-decalin-9β-ol were calculated by the semiempirical MO calculation. There are three possible conformers depending on the orientation of the alcoholic hydrogens of the axial hydroxy groups for **1**, **3**, and 1,3-dimethylcyclohexanol, and two possible conformers for *trans*-decalin-9-ol. From the optimized structures of these conformers, the weighted average of the electron density for each compound was obtained (Table 2). The 2-axial hydroxy group is more acidic than the 3-axial hydroxyl group.

In order to obtain further information about the effect of the hydroxy group on the reactivity of the carbonyl group, binary mixtures prepared from equimolar amounts of **1** and **5** or **6**, and **3** and **7** were reduced with $LiAlH_4$ and $NaBH_4$ in THF. The relative reactivities were determined during the early stages of the reduction. The conversion of the competitive reduction was controlled so as to be less than 10%. The relative reactivities for the formation of 2-*t*,4-*t*-

Table 2. Electron Density of the Alcoholic Hydrogen Obtained by MO Calculation

	V_{ac}	in THF	in EtOH
cis-1,3-Dimethylcyclohexanol	0.8050	0.7739	0.7686
1	0.7946	0.7563	0.7488
trans-Decalin-9β-ol	0.8020	0.7780	0.7740
3	0.7998	0.7723	0.7675

dimethyl-1-*r*-cyclohexanol and *trans*-decalin-2α-ol from the corresponding ketones are arbitrarily set at 100. These results are tabulated in Table 3. The relative reactivities from the equatorial side of **6**, which carries the 2-axial methyl group, were about 1/3, while those of **1**, which carries the 2-axial hydroxy group, became more than 4 times larger with $LiAlH_4$ and $NaBH_4$ than those of the unhindered ketone, **5** in THF. This also supports the fact that the hydride transfer is accelerated from the side of the 2-axial hydroxy group by the complex formation. On the other hand, the relative reactivities from the axial side of **5** and **6** were similar in magnitude, while that of **1** became 0, though the steric environment of these three compounds is considered to be almost the same. Since the amount of the used hydride was very small compared to that of the carbonyl compound, all the hydride reagents initially react to form the complex and the subsequent intramolecular hydride shift to the carbonyl, so that the hydride attack did not intermolecularly occur from the axial side. The relative reactivity from the axial direction of **3**, which carries the 3-axial hydroxy group in the reduction of $LiAlH_4$ and $NaBH_4$ in THF, became about 1/3 compared to that of **7**, indicating that the 3-axial hydroxy group behaved as a steric hindrance even if it formed the complex.

We found that the 2-axial hydroxy group accelerates the hydride transfer from the equatorial side of the cyclohexanone ring in the reduction with all the hydride reagents employed, while the 3-axial hydroxy group restricted the hydride approach from the axial side except in the case of $Na[B(OAc)_3H]$. Since it is impossible to examine the transition state of the reaction by semiempirical MO calculations, we tentatively examined the optimized structure of **1** and **3** and obtained the distance between the hydroxy oxygen, and the carbonyl carbon and oxygen of **1** to be 2.40 and 3.30 Å and for **3** to be 2.97 and 3.75 Å respectively (Table 4). The longer distance increases the difficulty of the hydride transfer from the complexed Al or B atom to the carbonyl group in an intramolecular fashion.

In the $Na[B(OAc)_3H]$ reduction the hydride attack from the side of the hydroxy group exclusively occurred in both 2-axial and 3-axial hydroxycyclohexanones. It is known that $Na[B(OAc)_3H]$ may be exchanged to give an alkoxy species such as $Na[B(OAc)_2(OR)H]$ in the presence of an alcohol and that the latter might act as an improved H^- donor compared to the former species.[15] Exchanging the acetate ion with the alkoxide will primarily occur by the addition of the hydride reagent to the hydroxy ketone, then the hydride transfers to the carbonyl group via an intramolecular sense. Even in the case of 3-hydroxycyclohexanone, the intramolecular hydride transfer from the complexed Al or B atom in the molecule occurred in preference to the intermolecular sense.

Table 3. Relative Reactivity in the $LiAlH_4$ and $NaBH_4$ Reductions in THF

Hydride	Conversion (%)	Relative ractivity (Axial attack/Equatorial attack)		
		Substrate		
		1	**5**	**6**
$LiAlH_4$	8.2	0.0/97	100/18	87/4.6
$NaBH_4$	6.3	0.0/63	100/15	81/4.9
		3	**7**	
$LiAlH_4$	7.9	41/25	100/15	
$NaBH_4$	8.1	27/8.0	100/10	

Table 4. The Distance between Hydroxy Oxygen and Carbonyl Group in the Optimized Structure of Complexed **1** and **3**

	Distance (Å)	
	–O····C=O	–O····O=C
1	2.40	3.30
3	2.97	3.75

Although the cyclic four-centered transition state is suggested for the $NaBH_4$ reduction in aprotic solvent, the reaction in protic solvent is considered to occur by transfer of a hydride ion to the carbonyl carbon atom with prior or concurrent protonation of the carbonyl oxygen atom. The linear transition state is reasonable in this case, as reported by Wigfield. Similarly, the $Na[B(OAc)_3H]$ reduction in acetic acid most likely occurs through the linear transition state as the $NaBH_4$ reduction in protic solvents.

The conversion of hydroxycyclohexanones was more than 90%, while that of the alkylcyclohexanones was relatively low. The reactivity of alkylcyclohexanones was checked for **6** and **9** (Table 5). The reduction of these alkylcyclohexanones was found to be very slow. The conversion of **9** was 29% and that of **6** was only 15% after 48 h when the ketone/hydride ratio was 1. In addition, the competitive reduction of the mixtures of **2** and **6**, and **3** and **7** gave only the reduction products from **2** and **3**, respectively. These facts also support the high reactivity of $Na[B(OAc)_2(OR)H]$ compared to the parent hydride.

2. Reduction of Conformationally Mobile System. In the complex metal hydride reduction of **2**, an appreciable amount of the *cis* diol, which was derived by the hydride attack from the opposite side of the hydroxy group, was also found except in the case of the $Na[B(OAc)_3H]$ reduction. This is because the 2-hydroxy group may not be fixed in the axial position by flipping of the cyclohexanone ring. When the complexed hydroxy group is in the equatorial position, the hydrides attached to the Al or B atom are difficult to place on a trajectory to attack the carbonyl carbon, so that the

Table 5. The Conversion of the $Na[B(OAc)_3H]$ Reduction of Alkylcyclohexanone

Time (min)	Conversion (%)	
	6	**9**
10	1.3	2.1
90	5.7	6.7
150	6.6	8.8
240	11	16
1440	14	28
2880	15	29

hydride is supplied to the carbonyl group in an intermolecular fashion. The stereoselectivity of **2** will be less than that of **1**. The same has been true for the push–pull mechanism. On the other hand, the reduction of **4** showed similar stereoselectivity to the case of **3**. The hydroxy group and the methyl group, which are placed at the axial position by the interconversion of the cyclohexanone ring, appear to be the steric hindrances. Different from the other hydride reagents, a high stereoselectivity was observed, similar to the rigid system, in the reduction with $Na[B(OAc)_3H]$. This indicates that the alkoxy species, which is highly reactive, exclusively supplies the hydride to the carbonyl carbons from the B atom at the axially situated hydroxy group in the intramolecular sense prior to transfer of the less reactive hydride from the parent hydride in an intermolecular sense.

3. Conversion Efficiency and the Mechanism. Although the reduction was performed under the condition that the hydride/substrate ratio was 1 in this study, the conversion of the hydroxy ketone to an alcohol were less than half for the $LiAlH_4$, $NaBH_4$ and $Zn(BH_4)_2$ reductions in THF. This may be because more than half of the hydride was consumed by prior formation of the complex; thus only the remaining hydride is used for the reduction. On the contrary, the conversions in the $NaBH_4$ reduction in ethanol were more than 90%. This supports our claim that the major contribution comes from the push–pull mechanism in this case. It is not clear why the same mechanism does not operate in THF. The high conversions in the $Na[B(OAc)_3H]$ reduction can be rationalized by assuming the intervention of the alkoxy species $Na[B(OAc)_2(OR)H]$.[15]

Summary

A significant directive effect of the 2-axial hydroxy group appears in the reduction of cyclohexanone with representative complex metal hydrides, while the 3-axial hydroxy group exhibits a steric hindrance. The distance between the carbonyl carbon and the hydroxy group which interacts with the hydride reagent is mainly responsible for such a difference. Both the 2- and 3-axial hydroxycyclohexanones exclusively give the products which are obtained by the hydride approach from the side of the hydroxy group in the reduction of $Na[B(OAc)_3H]$. The key point of this reduction is the formation of $Na[B(OAc)_2(OR)H]$, which is far more reactive than the parent hydride, by exchanging the acetate ion with the alkoxide.

Experimental

Materials. 1,5-*t*-Dimethylcyclohexane-1-*r*,2-*t*- and 1,5-*t*-Dimethylcyclohexane-1-*r*,2-*c*-diol: A mixture of $Hg(OAc)_2$ (17.26 g, 54.2 mmol) and 2,4-dimethyl-2-cyclohexenol (6.5 g, 51.2 mmol) was stirred for 90 min at room temperature. Sodium hydroxide (3.0 M, 30 cm^3, 1 M = 1 mol dm^{-3}) and $NaBH_4$ (1.67 g, 44.1 mmol) in aqueous NaOH (3.0 M, 40 cm^3) were added at 0 °C. The precipitated Hg was removed by filtration. The product was isolated by diethyl ether extraction. After drying over Na_2SO_4 and evaporation, 1,5-dimethylcyclohexane-1,2-diol (4.12 g, 28.6 mmol, 55.6%) was obtained; bp 117—127 °C (25 mmHg, 1 mmHg = 133.322 Pa). The mixture of the stereoisomer was separated by the column chromatography {SiO_2, hexane–ether (10 : 1)}.

1,5-*t*-dimethylcyclohexane-1-*r*,2-*t*-diol; mp 119—121 °C; (Found: C, 66.65; H, 11.17%. Calcd for $C_8H_{16}O_2$: C, 66.63; H, 11.18%). ^{1}H NMR (400 MHz; $CDCl_3$), δ_H = 0.90 (3H, d, J = 6.8 Hz, 4-CH_3), 1.10—1.23 (1H, m), 1.25 (3H, s, 1-CH_3), 1.31—1.47 (3H, m), 1.41 (1H, s, 2-OH), 1.62 (1H, s, 1-OH), 1.65—1.81 (2H, m), 1.96 (1H, m, 4-H), 3.52 (1H, d, J = 1.2 Hz, 2-H) ; ^{13}C NMR (100 MHz; $CDCl_3$) δ_C = 22.2 (5-CH_3), 27.2 (C4), 27.4 (C5), 27.7 (1-CH_3), 28.8 (C6), 42.1 (C3), 72.1 (C1), 72.9 (C2).

1,5-*t*-Dimethylcyclohexane-1-*r*,2-*c*-diol; mp 84—86 °C, (Found: C, 66.66; H, 11.17%. Calcd for $C_8H_{16}O_2$: C, 66.63; H, 11.18%). ^{1}H NMR (400 MHz; $CDCl_3$), δ_H = 0.86 (3H, d, J = 6.4 Hz, 5-CH_3), 0.89—1.04 (3H, m), 1.24 (3H, s, 1-CH_3), 1.52—1.78 (4H, m), 1.98 (1H, s, 1-OH), 2.01 (1H, d, J = 6.58 Hz, 2-OH), 3.32 (1H, m, 2-H); ^{13}C NMR (100 MHz; $CDCl_3$), δ_C = 21.6 (5-CH_3), 27.1 (C4), 27.4 (C5), 30.5 (1-CH_3), 33.1 (C6), 46.3 (C3), 71.6 (C1), 75.1 (C2).

2-*r*-Hydroxy-2,4-*t*-dimethylcyclohexanone (1): The diol mixture (3.09 g, 21.4 mmol) was oxidized by PCC (9.30 g, 43.1 mmol) in CH_2Cl_2 (100 cm^3) to give **1** including a small amount of 2-*r*-hydroxy-2,4-*c*-dimethylcyclohexanone (1.99 g, 14.1 mmol, 65.6%). The compound, **1**, was purified as semicarbazone;

semicarbazone; mp 196—197 °C, (Found: C, 54.28; H, 8.58; N, 21.07%. Calcd for $C_9H_{17}N_3O_2$: C, 54.25; H, 8.60; N, 21.09%), **1**; bp 80 °C (27 mmHg) ^{1}H NMR (400 MHz; $CDCl_3$), δ_H = 0.85 (3H, d, J = 6.8 Hz, 4-CH_3), 1.28 (3H, s, 2-CH_3), 1.32—1.51 (2H, m), 1.95—2.07 (2H, m), 2.14 (1H, s, 2-OH), 2.16—2.48 (3H, m); ^{13}C NMR (100 MHz; $CDCl_3$), δ_C = 20.9 (4-CH_3), 24.5 (C5), 26.9 (2-CH_3), 34.9 (C4), 36.6 (C3), 48.9 (C6), 74.9 (C2), 213.1 (C1).

Other hydroxy ketones were prepared by the oxymercuration-demercuration of the corresponding allylic alcohols, followed by PCC oxidation, similar to the preparation of 2-*r*-Hydroxy-2,4-*t*-dimethylcyclohexanone.

2-Hydroxy-2-methylcyclohexanone;[16] bp 80—83 °C (19 mmHg). ^{1}H NMR (400 MHz; $CDCl_3$), δ_H = 1.42 (3H, s, 2-CH_3), 1.58—1.86 (5H, m), 2.08 (1H, s, OH), 2.12—2.33 (1H, m), 2.49—2.56 (2H, m); ^{13}C NMR (100 MHz; $CDCl_3$), δ_C = 23.0 (C4), 25.1 (C5), 27.9 (CH_3), 37.7 (C3), 42.0 (C6), 76.4 (C2), 214.4 (C1).

3-Hydroxy-3-methylcyclohexanone;[17] bp 86—87 °C (0.5 mmHg); ^{1}H NMR (400 MHz; $CDCl_3$), δ_H = 1.33 (3H, s, 3-CH_3), 1.72—1.83 (3H, m), 1.85—2.13 (1H, m), 2.22—2.37 (3H, m), 2.43 (1H, s, OH), 2.59 (1H, s) ; ^{13}C NMR (100 MHz; $CDCl_3$), δ_C = 21.3 (C5), 29.9 (CH_3), 37.4 (C4), 40.4 (C6), 54.9 (C2), 73.8 (C3), 211.0 (C1).

trans-9-Hydroxydecalin-2-one;[18] mp 146—147 °C; ^{1}H NMR (400 MHz; $CDCl_3$), δ_H = 1.28—1.40 (2H, m), 1.47—1.83 (9H, m), 1.96 (1H, s, 9-OH), 2.32—2.42 (4H, m, 1-H and 3-H); ^{13}C NMR (100 MHz; $CDCl_3$), δ_C = 20.6 (C7), 25.7 (C5), 27.6 (C6), 28.6 (C8), 39.6 (C4), 41.4 (C3), 42.7 (C1), 55.3 (C10), 73.9 (C9), 211.2 (C2).

Alkylcyclohexanones are known in the literature; *cis*-2,4-dimethylcyclohexanone,[19] 2,2,4-trimethylcyclohexanone.[20] *trans*-Decalin-2-one is commercially available.

Reduction with Complex Metal Hydride. $LiAlH_4$ and $NaBH_4$ Reduction: The solution of $LiAlH_4$ or $NaBH_4$ (0.02 M, 5 cm^3) in dried solvent was added dropwise to 0.4 mmol of the substrate in 5 cm^3 of the same solvent over a period of 10—15 min at 0 °C and the mixture was stirred for 30 min. Water and crushed ice were added and the organic layer was separated, dried over Na_2SO_4, and analyzed by GLC.

$Zn(BH_4)_2$ Reduction: The solution of $Zn(BH_4)_2$ (0.01 M, 2.5 cm^3) in THF was added dropwise to 0.4 mmol of the substrate in 5 cm^3 of the same solvent over a period of 10—15 min at 0 °C and the

mixture was stirred for 60 min. Water and crushed ice were added and extracted with diethyl ether. The organic layer was separated, dried over Na_2SO_4, and analyzed by GLC.

Na[B(OAc)$_3$H] Reduction: The solution of $NaB(OAc)_3H$ (0.08 M, 5 cm^3) in AcOH was added dropwise to 0.4 mmol of the substrate in 5 cm^3 of the same solvent over a period of 10—15 min at 0 °C and then the mixture was stirred for 240 min. Water and crushed ice were added and the mixture was extracted with diethyl ether. The organic layer was washed with aqueous $NaHCO_3$ followed by brine, dried over Na_2SO_4, and analyzed by GLC.

Competitive Reduction with LiAlH$_4$.[21] The calculated amount (0.025 molar amount) of a hydride solution in diethyl ether (0.01 M) was added to a mixture of two ketones (**6** with **2**, **5**, **7**, **8**, or **9** and **2** with **5**, **7**, or **8**, 0.5 mmol of each) in 3 cm^3 of diethyl ether over a period of 10—15 min at 0 °C. The reaction mixture was stirred for 30 min. Water and crushed ice were added and the organic layer was separated, dried over Na_2SO_4, and analyzed by GLC.

NMR and Gas Chromatographic Analyses. ^{13}C NMR and ^{1}H NMR spectra were obtained with a JEOL JNM α-400 instrument in the pulse Fourier mode. Gas chromatographic analyses were performed on a Shimadzu model GC-8AIF with carbowax 20M chemical bonded silica capillary column (0.25 mm × 25 m) at a column temperature of 120 °C.

The reduction products were known in the literature except for 2,4-dimethylcyclohexane-1,2-diols, whose physical constants have appeared in the synthetic section: 1-methylcyclohexane-1,2-diol,[22] 1-methylcyclohexane-1,3-diol,[23] *trans*-decalin-2,9-diol,[18] and *trans*-decalin-2-ol.[24] The isomeric ratios were determined by the comparison of NMR spectra and gas chromatographic analyses with authentic samples.

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