A Study of the Lithium Aluminum Hydride Reduction of a Series of Nonenolizable Ketones[1]

John J. Cawley* and David V. Petrocine[2]

Department of Chemistry, Villanova University, Villanova, Pennsylvania 19085

Received December 15, 1975

The lithium aluminum hydride and lithium aluminum tri(*tert*-butoxy)hydride reductions of 2,2-dimethylindandione and a series of related monoketones were examined. The range of the isomer distribution was determined to be a function of the reducing agent, temperature of the reaction, and equivalent ratio of the reactants. The possible mechanisms for the stereochemical results of such reductions are discussed.

In a recent communication[3] we reported that no intramolecular hydride transfer need be invoked for the lithium aluminum hydride ($LiAlH_4$) reduction of 2,2-dimethylindandione even though such transfers have been suggested in many $LiAlH_4$ reductions of nonenolizable β-diketones.[4,5] This type of transfer has also been invoked for related compounds, such as hydroxy ketones, in which the complexed hydroxy group is proposed to exhert a synergistic effect on the reduction of a neighboring carbonyl function.[6-11]

A specific example, by Martin et al.,[7] will illustrate this concept. The reduction of 1,5-dimethylbicyclo[3.3.1]nonane-2,9-dione with lithium aluminum tri(*tert*-butoxy)hydride [$LiA(O\text{-}t\text{-}Bu)_3H$] yielded the exo 2-hydroxy ketone. This compound was then treated with $LiAlH_4$ to yield the corresponding diols. The authors suggested that the trans diol is a result of an intramolecular hydride transfer from the aluminate to the remaining carbonyl function.

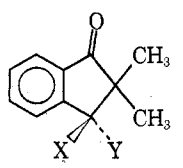
Alder and Fremery[12] had previously reported the $LiAlH_4$ reduction of a nonenolizable β-diketone, 2,2-dimethylindandione (**1a**). In this work, no mention was made of the stereochemistry of the resulting diols. This system serves as the basis for our study.

The sequence of events in $LiAlH_4$ reductions has been investigated by Eliel and Haubenstock.[13] In the $LiAlH_4$ reduction of 3,3,5-trimethylcyclohexanone, changes in the product distribution were observed when methanol, ethanol, or *tert*-butyl alcohol was added to the $LiAlH_4$ medium prior to reaction with the cyclohexanone. It was found that 2-propanol, acetone, and cyclohexanone yielded approximately the same distribution of products as did the reduction using $LiAlH_4$ alone.

A disproportionation mechanism which continuously regenerates the tetrahydrido species was proposed to explain these results. If this proposed mechanism is operative, the entire reduction is accomplished by the $LiAlH_4$ species.[13]

It has been shown that a trialkoxy lithium aluminum hydride reducing agent, like $LiAl(O\text{-}t\text{-}Bu)_3$, is a more stereospecific reducing agent, in the reduction of ketones, than is $LiAlH_4$.[13] Since it contains only one available hydride, any disproportionation or intramolecular hydride transfer mechanism can be assumed to be inoperative.

Using 2,2-dimethylindandione (**1a**) and a series of related monoketones (**1b–e**) as probes, the $LiAlH_4$ and $LiAl(O\text{-}t\text{-}Bu)_3H$ reductions were investigated. To ensure a homogeneous reaction medium, the reductions were carried out at high dilution, with the hydride solution added to a solution of the substrate in diethyl ether.



	X	Y
1a	=O	
b	H	OH
c	H	OCH_3
d	CH_3	OH
e	CH_3	OCH_3

In order to clearly delineate the relationship between the amounts of reagents used in any given experiment, the equivalent reduction ratio (ERR) must be known. The equivalent reduction ratio is defined as the number of available carbonyl functions to be reduced divided by the number of hydrides truly available for the reduction.

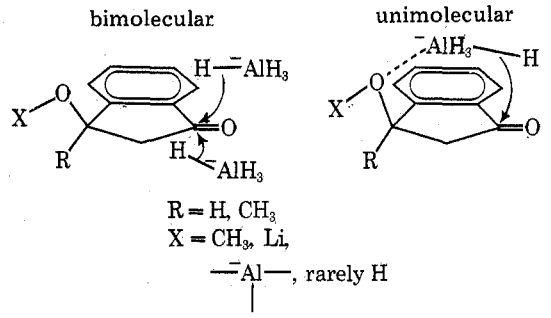
All product ratios were determined at several different times during the reaction. The unchanging ratios found in any given run assure that *all* results represent kinetic control of product formation.

Results

The results of the $LiAlH_4$ and $LiAl(O\text{-}t\text{-}Bu)_3H$ reductions for compounds **1a–e** are given in Tables I and II. The results are accurate to 3%. Therefore relative percent trans of 56 may be read as 56 ± 3. Two trends are evident from the examination of these tables. Generally as the ERR value was varied from excess hydride (0.5) to a deficient amount of hydride (2.0), the amount of trans product increased; it never decreased. At identical ERR values, the more stereospecific reducing agent, $LiAl(O\text{-}t\text{-}Bu)_3H$, for the most part, yielded more of the trans compound than did $LiAlH_4$. As one might expect this pattern was more pronounced in the low-temperature runs.

Discussion and Conclusions

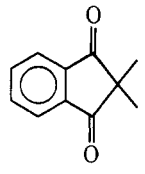
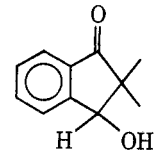
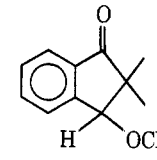
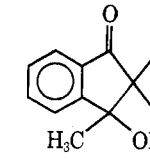
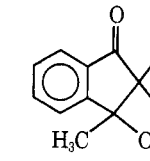
In the $LiAlH_4$ reductions, since kinetic control is operative, the changes in the product distribution with the variation in the ERR value may be viewed in terms of either a bimolecular or unimolecular interaction.



At an ERR value of 0.5 (excess hydride), the hydride species may attack the carbonyl function from either side. This bimolecular attack may be quite competitive with any unimolecular process because excess hydride is present. Such a mode of reaction can lead to a nonspecificity of products, i.e., both cis and trans product.

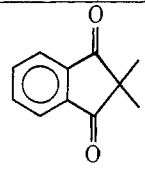
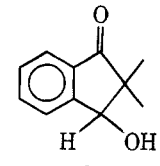
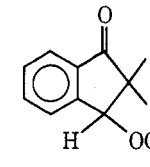
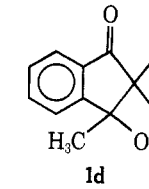
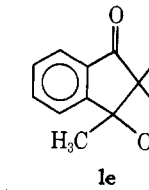
At an ERR value of 2.0 (deficient hydride), any hydride species associated with the ethereal oxygen may be transferred unimolecularly in preference to the with the ethereal oxygen may be transferred unimolecularly in preference to bimolecular pathways. This preferential attack leads to more of the trans compound.

Table I. $LiAlH_4$ Reductions

Ratio[a] of substrate to hydride	Relative percent trans									
	 1a		 1b		 1c		 1d		 1e	
	34 °C	−78 °C	34 °C	−78 °C	34 °C	−78 °C	34 °C	−78 °C	34 °C	−78 °C
0.5	46	44	29	3	100	100	61	20	27	19
1.0	64	87	48	12	100	100	65	22	32	52
2.0	71	93	53	56	100	100	62	31	32	83

[a] Equivalent reduction ratio.

Table II. $LiAl(O\text{-}t\text{-}Bu)_3H$ Reductions

Ratio[a] of substrate to hydride	Relative percent trans									
	 1a		 1b		 1c		 1d		 1e	
	34 °C	−78 °C	34 °C	−78 °C	34 °C	0 °C	34 °C	0 °C	34 °C	0 °C
0.5	88	100	26	94	100	100	48	44	54	54
1.0	100	100	77	94	100	100	46	40	63	51
2.0	100	100	86	96	100	100	47	42	90	90

[a] Equivalent reduction ratio.

The same general response is found in the $LiAl(O\text{-}t\text{-}Bu)_3H$ reductions with analogous changes in the ERR values. These changes may be similarly interpreted if the same associative mechanism is invoked, which allows the reducing species to complex with the ethereal oxygen before reduction occurs. The amount of trans product generally increases as the unimolecular process predominates.

One of the earliest attempts to unify the many different stereochemical results from $LiAlH_4$ reductions of cyclohexanones was undertaken by Dauben et al.[14] Dauben proposed that when the less stable isomer is formed preferentially in the competitive attack on a carbonyl function, from a hindered or an unhindered side, the rationale should be termed "steric approach control". Conversely, when the more stable isomer is formed preferentially an energy consideration involving the relative stability of the possible products should be invoked, and termed "product development control".[14]

The unifying rationales of Dauben have been further investigated by Eliel and Senda.[15] These workers examined the competitive rates of hydride reductions of pairs of ketones in the presence of a deficient amount of hydride. They concluded that, in general, steric approach control plays the major role and that product development control plays only a minor role in these reductions.

Our results may be interpreted to mean that a minimum of three possible pathways must be operative since the product ratios vary from >1.0 to <1.0 in a given series. The two "bimolecular" pathways must be discussed in terms of "steric approach control" vs. "product development control". At higher temperatures, where the "bimolecular" pathways should be increasingly more important, a trend to more of the cis product is apparent. This is certainly true as long as the benzylic hydrogen is not replaced by a methyl group. This trend indicates that steric approach control is the more important factor governing these "bimolecular" pathways.

The "unimolecular", associative pathway should not be discussed in the same terms. A comparison between the "unimolecular" pathway of two different substrates should be made on the basis of a preequilibrium (association), followed by rate-determining ("unimolecular") reorganization.

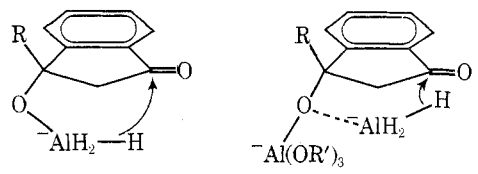
This proposed internal solvent interaction is not without precedent.[16] Most $LiAlH_4$ and/or lithium alkoxyaluminum hydride reductions are effected in ether or similar Lewis base solvents. Shirk and Shriver[17] have suggested that the AlH_4^- species exists in a solvent cage when placed in diethyl ether. This solvated species is similar to the currently accepted form of the Grignard complex solvation sphere. Benard et al.[18] have invoked a similar hypothesis to explain the results they obtained when reducing *N,N*-dimethyl-2-aminocyclohexanone with $LiAlH_4$ in benzene.

The most striking example of this effect, in our study, is surely the reduction of **1c**. At all the ERR values studied, at all the temperatures and with both reducing agents, the reduction was effectively stereospecific to yield the trans product. The "unimolecular" pathway must be greatly favored in this system. The reduction of **1e** is consistent with this explanation. Since the benzylic methyl group causes the ethereal oxygen to be a "neo" center, it seems that its reduction is not as stereospecific as that of **1c**. Association is therefore dramatically lessened and the "bimolecular" pathways compete.

The same result is not seen in comparing **1b** to **1d**. Because of the "neo" oxygen in **1d** the OH does not become OLi or OÃ1< as readily as does the OH in **1b**. Therefore no comparable direct comparison may be made as can be done with keto ethers **1c** and **1e**.

To further test our associative mechanism, the reduction of **1c** was repeated in dry benzene in an experiment similar to Benard's.[18] Using an equivalent amount of hydride, this reaction yielded, in 100% yield, the pure trans hydroxymethyl ether. Only starting material could be recovered from the reaction of **1a** with $LiAlH_4$ in dry benzene.

Our results are clearly consistent with Eliel's disproportionation scheme. It is possible, however, that for "unimolecular" pathway in **1a,b,d,** with $LiAlH_4$, internal hydride transfer is faster than the disproportionation pathways so that pathway a is followed and not pathway b. If this is true, the



pathway a pathway b

R = H or CH_3
R′ = alkyl

disproportionation scheme may be valid for only simple ketones and may not apply to polyfunctional carbonyl compounds.

The same kind of disclaimer may have to be applied to the competitive reduction of polyfunctional carbonyl compounds. It is legitimate for Eliel to compare the results of reductions of individual simple ketones, with equivalent or excess hydride, to the results of competitive reductions of pairs of simple ketones, with deficient hydride. Our results show that this methodology is inapplicable to polyfunctional carbonyl compounds since the isomer ratios of the products, for individual compounds, are shown to vary markedly in going from excess or equivalent hydride to deficient hydride.

Experimental Section

Melting points were determined on a Thomas-Hoover melting point apparatus and are uncorrected. Infrared spectra were recorded on a Perkin-Elmer 137 prism and a 337 grating spectrophotometer. Proton magnetic resonance spectra were recorded with a Varian A-60 spectrometer in $CDCl_3$ solutions (unless otherwise indicated) with tetramethylsilane as the internal standard. Chemical shifts are reported in parts per million (δ) downfield from Me_4Si. Analytic GLC determinations were achieved using an F & M Model 720 gas chromatograph, with a thermal conductivity detector, employing a 6 ft × 0.25 in. stainless steel column packed either with 10% SE-30 or 15% SE-30 on silanized 60–80 mesh Chromosorb W. Elemental analyses were performed by Galbraith Laboratories, Inc., Knoxville, Tenn.

The $LiAlH_4$ in diethyl ether was purchased from Ventron and the normality determined according to the procedure of Felkin.[19] Known solutions of the reductants in dry diethyl ether were prepared; care was taken to exclude moisture. Both solutions were stored over a desiccant.

2,2-Dimethylindandione (1a). This compound was prepared according to the procedure of Aebi[20] and the crude product was recrystallized from heptane: mp 105–106 °C (lit.[20] 106–107 °C); NMR δ 1.30 (s, 6 H), 8.0–8.2 (m, 4 H). Anal. Calcd for $C_{11}H_{10}O_2$: C, 75.87; H, 5.74. Found: C, 75.64; H, 5.87.

3-Hydroxy-2,2-dimethylindanone (1b). This compound was prepared according to the procedure of Aebi[20] and the crude product was recrystallized from cyclohexane: mp 89.5–91 °C (lit.[20] 89–90 °C); NMR δ 1.16 (s, 3 H), 1.30 (s, 3 H), 2.15 (d, 1 H, J = 8 Hz), 4.96 (d, 1 H, J = 8 Hz), 7.76 (m, 4 H). Anal. Calcd for $C_{11}H_{12}O_2$: C, 75.00; H, 6.81. Found: C, 74.82; H:, 6.76.

3-Methoxy-2,2-dimethylindanone (1c). A procedure similar to that of Merz was followed.[21] To a solution of 0.783 g (4.44 mmol) of **1b** in 100 ml of methylene chloride was added 0.6 g of tetrabutylammonium iodide and 1.0 ml of 50% aqueous NaOH solution. After stirring vigorously for 0.5 h, 0.6 ml (6.32 mmol) of dimethyl sulfate was added with ice bath cooling and the mixture was stirred for 3 h. An additional 0.25 ml of dimethyl sulfate was added and the stirring continued for 0.5 h. A saturated NH_4Cl solution (5 ml) was added and the mixture was stirred for an additional 0.5 h. The crude product was poured into water and the organic phase separated and concentrated in vacuo. The residue was dissolved in ether and washed four times with 75 ml of H_2O. The combined ethereal layers were dried ($MgSO_4$) and concentrated in vacuo to yield a yellow oil, which was subjected to column chromatography (silica gel). Elution with $CHCl_3$ yielded the desired product: 0.707 g (84%); NMR δ 1.16 (s, 3 H), 1.35 (s, 3 H), 3.65 (s, 3 H), 4.51 (s, 1 H), 7.4–7.8 (m, 4 H). Anal. Calcd for $C_{12}H_{14}O_2$: C, 75.79; H, 7.36. Found: C, 75.47; H, 7.39.

3-Hydroxy-2,2,3-trimethylindanone (1d). To a solution of 0.8028 g (4.61 mmol) of **1a** in 75 ml of dry ether, cooled by a dry ice–acetone bath, was added 3.0 ml of 1.6 M (4.95 mmol, 10% excess) of methyllithium. After stirring for 1 h, the solution was warmed to room temperature and carefully hydrolyzed with water. The ethereal layer was washed once with 50 ml of water, and the aqueous layer was extracted thrice with 50 ml of ether. The combined ethereal layers were dried ($MgSO_4$) and concentrated in vacuo to yield a light green oil. This material was subjected to column chromatography (silica gel). Elution with $CHCl_3$ yielded unreacted starting material. Elution with 5% MeOH in $CHCl_3$ yielded 0.6013 g (68%) of product: bp 106.5–109 °C (0.3 mm); NMR (benzene-d_6) δ 1.06 (s, 3 H), 1.13 (s, 3 H), 1.27 (s, 3 H), 2.57 (s, 1 H), 7–8 (m, 4 H). Anal. Calcd for $C_{12}H_{14}O_2$: C, 75.79; H, 7.36. Found: C, 75.96; H, 7.55.

3-Methoxy-2,2,3-trimethylindanone (1e). This compound was prepared in an analogous manner to **1c.** In this case, a reaction time of 24 h was necessary. The yield was 62%: bp 92–101 °C (0.5 mm); NMR δ 1.09 (s, 3 H), 1.22 (s, 3 H), 1.52 (s, 3 H), 3.03 (s, 3 H), 7.5–7.8 (m, 4 H). Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.47; H, 7.84. Found: C, 76.29; H, 7.86.

2,2-Dimethylindan-1,3-diol (2a). To a properly dried reaction vessel equipped with a reflux condenser, a mechanical stirrer, and an addition funnel was added 2.3 g (0.06 mol) of $LiAlH_4$ in 60 ml of dry diethyl ether. To this mixture was added slowly a solution of 10.0 g (0.05 mol) of **1a** in 30 ml of dry ether. After the addition was completed, the reaction mixture was refluxed for 6 h. The mixture was cooled and the excess $LiAlH_4$ destroyed by the successive addition of 3 ml of water, 3 ml of 15% NaOH, and 6 ml of water. The precipitate was placed in a Soxhlet extractor and extracted with ether for 24 h. The ethereal extract was dried ($MgSO_4$) and concentrated in vacuo to yield 8.4 g (86%) of the diol, mp 113–116 °C. Fractional recrystallization from $CHCl_3$ yielded the cis diol: mp 161–162.5 °C; NMR δ cis diol 0.95 (s, 3 H), 1.11 (s, 3 H), 2.1 (d, 1 H, J = 8 Hz), 4.53 (d, 1 H, J = 8 Hz), 7.4 (m, 4 H), trans diol 1.05 (s, 6 H), 1.83 (d, 1 H, J = 8 Hz), 4.81 (d, 1 H, J = 8 Hz), 7.4 (m, 4 H). Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.16; H, 7.86. Found: C, 73.86; H, 8.15.

3-Methoxy-2,2-dimethylindanol (2c). This compound was similarly prepared from **1c.** The $LiAlH_4$ reduction yielded 97% of essentially the pure trans compound (vide supra). It was recrystallized from cyclohexane: mp 92–94 °C; NMR (benzene-d_6) δ 0.97 (s, 3 H), 1.09 (s, 3 H), 1.88 (d, 1 H, J = 10 Hz), 3.20 (s, 3 H), 3.83 (s, 1 H), 4.32 (d, 1 H, J = 10 Hz), 7.1–7.4 (m, 4 H). Anal. Calcd for $C_{12}H_{16}O_2$: C, 75.00; H, 8.33. Found: C, 75.05; H, 8.43.

2,2,3-Trimethylindan-1,3-diol (2d). This compound was similarly prepared from **1d.** The $LiAlH_4$ reduction yielded 90% of a mixture consisting of the cis and trans diols. They were recrystallized from cyclohexane: mp 73 –93 °C; NMR δ cis diol 0.90 (s, 3 H), 1.11 (s, 3 H), 1.40 (s, 3 H), 2.40 (s, 2 H), 4.53 (s, 1 H), 7.38 (m, 4 H), trans diol 0.84 (s, 3 H), 1.16 (s, 3 H), 1.51 (s, 3 H), 2.40 (s, 2 H), 4.95 (s, 1 H), 7.38 (m, 4 H). Anal. Calcd for $C_{12}H_{16}O_2$: C, 75.00; H, 8.33. Found: C, 74.81; H, 8.39.

3-Methoxy-2,2,3-trimethylindanol (2e). This compound was similarly prepared from **1e.** The $LiAlH_4$ reduction yielded 90% of a mixture consisting of the cis and trans hydroxy ethers. After drying under a vacuum: mp 107 –112 °C; NMR (acetone-d_6) δ cis ether 0.68 (s, 3 H), 1.19 (s, 3 H), 1.39 (s, 3 H), 1.80–1.92 (br s, 1 H), 2.92 (s, 3 H), 5.07 (s, 1 H), 7.22–7.39 (m, 4 H), trans ether 0.89 (s, 3 H), 1.09 (s, 3 H), 1.29 (s, 3 H), 1.80–1.97 (br s, 1 H), 3.12 (s, 3 H), 4.3 (s, 1 H), 7.22–7.39 (m, 4 H). Anal. Calcd for $C_{13}H_{18}O_2$: C, 75.73; H, 8.73. Found: C, 75.47; H, 8.91.

Analytical Reduction Procedure. To a properly dried reaction vessel was added volumetrically a known amount of the compound to be reduced in dry diethyl ether. The solution was either heated to reflux or cooled to the proper reaction temperature and the appropriate amount of hydride was added. The amount of hydride added was varied so that the equivalent reduction ratio (ERR) ranged from 0.5, excess hydride to 2.0, deficient hydride. Upon completion of the hydride addition, aliquots were periodically removed. These were hydrolyzed with 15% NaOH; the ethereal solution was filtered, then

dried ($MgSO_4$) and concentrated in vacuo. When $LiAl(O\text{-}t\text{-}Bu)_3H$ was used as the reducing agent, the hydrolyzed solution was washed several times with water to remove the *t*-BuOH, followed by a similar workup procedure. The mixture of crude products was subjected to two methods of analysis. In the NMR method, the residue was dissolved in $CDCl_3$ and with the aid of the LSR, $Eu(fod)_3$,[22] the methyl resonances were sufficiently separated so that an integration could be obtained. In the GLC method, dissolution of the residue in dry pyridine and silylation with a mixture of hexamethyldisilazane and trimethylchlorosilane[23] was followed by gas chromatography. Both of these procedures yielded the relative amounts of each stereoisomer.

$LiAlH_4$ Reduction of 1c in Benzene. To a properly dried reaction vessel was added 0.0747 g (0.394 mmol) of **1c** in 50 ml of dry benzene. The solution was heated to reflux and 0.22 ml (0.197 mmol) of a 0.9 M $LiAlH_4$ solution was added (the ether solvent was evaporated off immediately). After a 24-h reflux period, the reaction mixture was hydrolyzed with 15% NaOH, the mixture was concentrated in vacuo, and the crude product dissolved in ether. The ether solution was washed once with 60 ml of water and the aqueous layer thrice with 25 ml of ether. The combined ethereal layers were dried with $MgSO_4$, followed by concentration in vacuo, to yield an oil. Upon NMR analysis, the oil produced the same spectrum as the reduction run in diethyl ether, i.e., the trans hydroxy ether. A similar experiment with **1a**, the dione, failed to yield any of the reduction products.

Registry No.—**1a**, 17190-77-1; **1b**, 59269-93-1; **1c**, 59269-94-2; **1d**, 59269-95-3; **1e**, 59269-96-4; *cis*-**2a**, 54884-33-2; *trans*-**2a**, 54884-34-3; *trans*-**2c**, 59269-97-5; *cis*-**2d**, 59269-98-6; *trans*-**2d**, 59269-99-7; *cis*-**2e**, 59270-00-7; *trans*-**2e**, 59270-01-8; $LiAlH_4$, 16853-85-3; $LiAl(O\text{-}t\text{-}Bu)_3H$, 17476-04-9.

References and Notes

(1) Presented at the 169th National Meeting of the American Chemical Society, Philadelphia, Pa., April 1975.
(2) Taken in part from the Ph.D. Thesis of D. V. Petrocine, Villanova University, 1975.
(3) J. Cawley and D. Petrocine, *J. Org. Chem.*, **40**, 1184(1975).
(4) H. M. Walborsky, *J. Org. Chem.*, **18**, 702 (1953).
(5) G. I. Fujimoto and Paulos, *Tetrahedron Lett.*, 4477 (1965).
(6) M. Akhtar and S. Marsh, *J. Chem. Soc. C*, 937 (1966).
(7) J. Martin, W. Parker, B. Shroot, and T. Steward, *J. Chem. Soc. C*, 101 (1967).
(8) J. H. Stocker, P. Sidisunthorn, B. H. Benjamin, and C. J. Collins, *J. Am. Chem. Soc.*, **82**, 3913 (1960).
(9) H. Dwart and T. Takeshita, *J. Am. Chem. Soc.*, **84**, 2833 (1962).
(10) H. B. Henbest, *Proc. Chem. Soc., London*, 159 (1963).
(11) H. B. Henbest and J. McEntree, *J. Chem. Soc.*, 4478 (1961).
(12) K. Alder and M. Fremery, *Tetrahedron*, **14**, 190 (1961).
(13) H. Haubenstock and E. Eliel, *J. Am. Chem. Soc.*, **84**, 2363 (1962).
(14) W. G. Dauben, G. J. Fonken, and D. S. Noyce, *J. Am. Chem. Soc.*, **78**, 2579 (1956).
(15) E. Eliel and Y. Senda, *Tetrahedron*, **26**, 2411 (1970).
(16) (a) H. O. House, "Modern Synthetic Reactions", 2d ed, W. A. Benjamin, New York, N.Y., 1974, p 48; (b) S. S. Pizey, "Synthetic Reagents", Vol. I, Wiley, New York, N.Y., 1974.
(17) A. E. Shirk and D. F. Shriver, *J. Am. Chem. Soc.*, **95**, 5904 (1973).
(18) C. Benard, M. T. Maurette, and A. Lattes, *Tetrahedron Lett.*, 2763 (1973).
(19) H. Felkin, *Bull. Soc. Chim. Fr.*, 347 (1971).
(20) E. Aebi, *Pharm. Acta Helv.*, **38**, 407 (1963).
(21) A. Merz, *Agnew. Chem., Int. Ed. Engl.*, **12**, 846 (1973).
(22) (a) $Eu(fod)_3$, tris(1,1,1,2,2,3,3-heptafluoro-7,7-dimethyl-4,6-octanedionato)europium(III), Ventron's Eu-Resolve-II; (b) R. E. Sievers, "Nuclear Magnetic Resonance Shift Reagents", Academic Press, New York, N.Y., 1973.
(23) (a) R. Ressenden and D. Crowe, *J. Org. Chem.*, **25**, 598 (1960); (b) A. Pierce, "Handbook of Silylation", Pierce Chemical Co., Ill., 1972, pp 10–11.

Electrochemical Reduction of Geranial, Farnesal, and Crotonaldehyde[1]

Judy C. Johnston, James D. Faulkner, Leon Mandell,* and R. A. Day, Jr.

Department of Chemistry, Emory University, Atlanta, Georgia 30322

Received February 2, 1976

The electrolytic reduction of the α,β-unsaturated aldehydes **11**, **12**, and **13** was studied and the nature of the coupling products determined. Attempts at effecting substrate orientation by carrying out the reductions in micelles were unsuccessful. The reduction of crotonaldehyde was repeated and an earlier report[4] found to be in error.

The electrochemical reduction of α,β-unsaturated aldehyde systems in acidic media results in the formation of a short-lived radical anion, which abstracts a proton from the solvent to produce an enol radical. Dimerization of this radical may take place via three different pathways:

Pathway A, the coupling of two β radicals ("tail to tail"), results in a dialdehydic compound (**2**), which may undergo an aldol condensation to produce compound **5** or **6**. Pathway B, the "head to tail" coupling of a carbonyl radical with a β radical, yields compound **3**, which may cyclize to form compound **7** or **8**. Finally, pathway C, the coupling of two carbonyl radicals ("head to head") affords a 1,2 diol (glycol), compound **4**.

One might expect steric factors to play a role in determining which pathway is favored. With acrolein (**9**) Misono[2] found compound **6** (R = R′ = H) to be the major product. This seems to indicate a preference for pathway A ("tail to tail") as the mode of coupling for the enol radical. Hindrance to the β position of acrolein should decrease products resulting from pathway A. Indeed, when the β position is subtituted with two methyl groups, as in 3-methylcrotonaldehyde (**11**) Miller[3] reported no products formed from pathway A. The methyl groups, however, are apparently not large enough to eliminate completely participation of the β radical in the coupling reaction, as evidenced by the fact that the major product from the electrochemical reduction of 3-methylcrotonaldehyde was that formed from pathway B.

We were interested to see whether increasing the size of one of the R groups at the β position would result in any decrease in the products resulting from pathway B ("head to tail" coupling) and thus make head to head coupling the prime route followed. To this end we repeated the reduction of 3-methylcrotonaldehyde,[3] and performed electrochemical reductions on geranial (**12**) and farnesal (**13**). Further, in order to determine what effect there would be in orienting the substrate during the electrochemical reduction, the electrolyses were repeated in micellar solutions. It seemed reasonable to assume that by using micelle solutions the β position would be buried in the micelle while the carbonyl position would be exposed to the reducing (aqueous) phase. This ideally would result in the formation of only the glycol (**4**).

The aldehydes required for this investigation were available by short preparative schemes. 3-Methylcrotonaldehyde was prepared according to Miller.[3] Geranial was obtained by simple manganese dioxide oxidation of the corresponding commercially available alcohol. *trans,trans*-Farnesol was obtained by spinning band separation from commercially available farnesol, and was subsequently oxidized with man-