Stereochemistry of Allylic Oxidation with Selenium Dioxide. Stereospecific Oxidation of *gem*-Dimethyl Olefins

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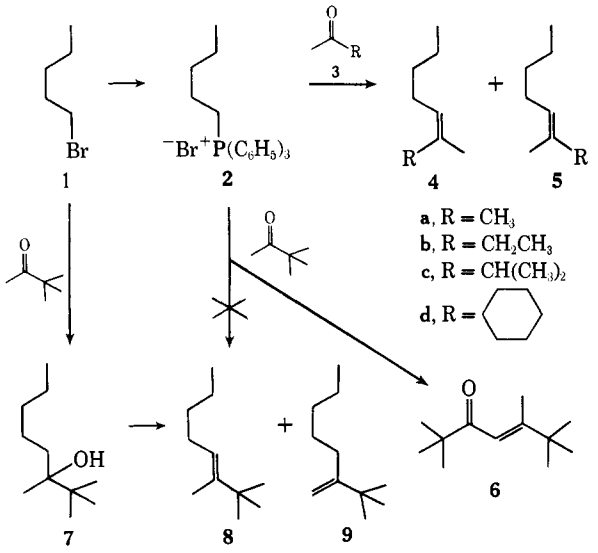
Abstract: The stereochemistry of allylic oxidation by selenium dioxide of a number of olefins has been studied. Olefins were prepared mostly by the Wittig reaction; pure stereoisomers were obtained by glpc separation from those reactions giving mixtures. Isomerization with thiophenol–azobisisobutyronitrile was employed to enrich reaction mixtures in the usually less abundant trans isomers. The sequence of reactivity toward oxidation by selenium dioxide in ethanol for trisubstituted olefins, following initial attack at the less substituted position, was $CH_2 > CH_3 > CH$. This mode of oxidation of *gem*-dimethyl olefins gave exclusively *trans*-alcohols or -aldehydes. Since the *cis*-alcohols are stereochemically stable in the reaction medium, this result established that the *trans*-alcohols (and the *trans*-aldehydes) were formed stereospecifically. Mechanistically, initial attack with selenium dioxide to form allylic selenite esters from different types of olefins, classified according to number of substituents, probably occurs by a number of pathways. However, the second step involving the solvolysis of the allylic selenite ester is best explained as SNi′ type of solvolysis to accommodate the stereochemical findings. These results present a new and reliable method for the synthesis of stereochemically pure, functionalized trisubstituted olefins.

In the synthesis of *dl*-sirenin and *dl*-isosirenin,[1,2] one of the key steps involved specific selenium dioxide oxidation of one methyl group of a *gem*-dimethyl olefin, resulting in an all-*trans*-aldehyde. A stereospecific product of this nature might not have been anticipated, since the mechanisms[3-6] postulated for selenium dioxide oxidation did not predict this result. Earlier work[7] had established certain rules and sites of oxidation in a trisubstituted olefin series and had shown that the reactivity sequence was $CH_2 > CH_3 > CH$. However, recently several apparent exceptions[6,8,9] to this reactivity sequence have been reported; hence it became increasingly clear that this earlier work, done prior to glpc and nmr, needed reinvestigation. Furthermore, stereochemical assignments had not been made on either the starting olefins or the oxidation products, making it of considerable interest to study the steric course of the oxidation on a select class of trisubstituted olefins.

Olefin Syntheses. Since both the *cis*- and the *trans*-olefins were needed for this study, a synthetic route was chosen involving Wittig reaction of 1-pentyltriphenylphosphonium bromide (**2**) and a ketone **3** using butyllithium to generate the ylide. The cis–trans ratios for the ethyl and the isopropyl olefin, **4** and **5**, using dimethyl sulfoxide as the solvent, were 55:45 and 82:12, respectively. The reaction did not take the usual course in the case of 3,3-dimethyl-2-butanone and the only olefinic product was 2,2,5,6,6-pentamethyl-4-hepten-2-one (**6**), arising from aldol condensation of the ketone. However, the desired olefin **8** was prepared by treating 1-bromopentane (**1**) with magnesium in ether followed by a dropwise addition of pinacolone to give alcohol **7**. Dehydration of **7** with thionyl chloride in pyridine at 0° gave a mixture of olefins **8** and **9**. The separation of these olefins was achieved on a 20% silver nitrate–silica gel column, followed by glpc separation, and resulted in pure *trans*-olefin **8**.



The preparative glpc separation of these olefins was accomplished on a 10% SE-30 column (34 ft × 3/8 in.). *cis*-Olefins were collected from the cis-enriched mixtures directly from the Wittig reaction. The trans derivatives were then obtained by isomerization, using the thiophenol–azobisisobutyronitrile procedure,[10] followed by glpc separation. Recently[11] selenium at 220° for 1–2 hr was used for isomerization of olefins; however, applying this procedure to the trisubstituted olefin **4c**, for example, gave a complex mixture as indicated by glpc and nmr. The disubstituted olefin isopropenylcyclohexane (**12**) was synthesized by the action of methyl cyclohexyl ketone (**11**) on methylenetriphenylphosphorane (**10**) in 62% yield.

(1) J. J. Plattner, U. T. Bhalerao, and H. Rapoport, *J. Amer. Chem. Chem.*, **91**, 4933 (1969).
(2) U. T. Bhalerao, J. J. Plattner, and H. Rapoport, *ibid.*, **92**, 3429 (1970).
(3) K. B. Wiberg and S. D. Nielsen, *J. Org. Chem.*, **29**, 3353 (1964).
(4) D. H. Olson, *Tetrahedron Lett.*, 2053 (1966).
(5) J. P. Schaefer, B. Horvath, and H. P. Klein, *J. Org. Chem.*, **33**, 2647 (1968).
(6) E. N. Trachtenberg and J. R. Carver, *J. Org. Chem.*, **35**, 1646 (1970); E. N. Trachtenberg, C. H. Nelson, and J. R. Carver, *ibid.*, **35**, 1653 (1970).
(7) A. Guillemonat, *Ann. Chim. (Paris)*, **11**, 143 (1939).
(8) S. P. Pathak and G. H. Kulkarni, *Chem. Ind. (London)*, 913 (1968).
(9) G. Buchi and H. Wuest, *J. Org. Chem.*, **34**, 857 (1969).
(10) D. S. Sgoutas and F. A. Kummerow, *Lipids*, 4, 283 (1969).
(11) J. C. Stowell, *J. Org. Chem.*, **35**, 244 (1970).

Selenium Dioxide Oxidation. Oxidation of the olefins was done essentially following the procedure reported in the earlier publications.[1,2] However, several trials were made to ascertain the effect of variation of time and molar ratio of selenium dioxide to olefin. Aldehydes were isolated using 2 mol of selenium dioxide after 10 hr (Table II), while for alcohols (Table I) the reaction was stopped after shorter times, using from 0.25 to 1.0 mol of selenium dioxide per mole of olefin. The cis–trans distribution of aldehydes was established with the use of nmr and glpc. The fact that the signals for cis- and trans-aldehydic protons appear in the region δ 9.9 and 9.3, respectively,[12] was used extensively to check the isomer distribution. The isomer distribution for allylic alcohols was ascertained by glpc and confirmed after collection by pmr and ^{13}C nmr, and comparison with structurally definitive allylic alcohols.

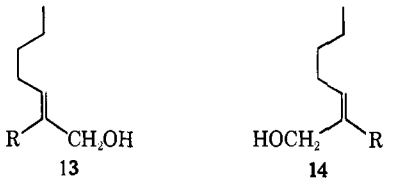
Table I. Oxidation of Trisubstituted Olefins **4** and **5** to Cis (**14**) and Trans (**13**) Primary Allylic Alcohols

Compd	R	Duration, hr	Moles of SeO_2/mol of olefin	Alcohol isomer, % Cis	Trans
4a	CH_3	1.5	1	<2	>98
	CH_3	0.75	1	<2	>98
	CH_3	3	0.25	<2	>98
	CH_3	1	0.25	<2	>98
5b	CH_2CH_3	1	1	*a*	*a*
5c	$CH(CH_3)_2$	4	1	14	86
	$CH(CH_3)_2$	1	0.25	14	86
4c	$CH(CH_3)_2$	3	1	14	86
8	(**5**, $C(CH_3)_3$)	2	1	30	70
8	(**5**, $C(CH_3)_3$)	20	2	30	70

[a] Ratio of cis to trans difficult to estimate since primary allylic alcohol is a very minor product of this oxidation.

Oxidation of the *gem*-dimethyl compound, 2-methyl-2-heptene (**4a**), was studied in considerable detail. In several experiments, the stereochemistry of the oxidation product was determined at 10-min intervals, by glpc, and the alcohol formed was found to be always trans (>98%). For comparison, *cis*-alcohol **14a** was synthesized independently[13] and compared with *trans*-alcohol **13a**, confirming the structures assigned by glpc, pmr,[12,14] and ^{13}C nmr. In its ^{13}C nmr absorption, the methylene group bearing the alcoholic function appeared at 58.40 and 66.62 ppm from benzene for *trans*- and *cis*-alcohols, respectively. This difference is characteristic and consistent with the fact that the steric interactions are known to produce upfield shifts of carbon resonances.[15–17] The *cis*-alcohol **14a** had *ca.* 1% trans impurity and this quantity was easily discernible. Furthermore, the stability of *cis*-alcohol **14a** in the reaction medium was tested under identical conditions; its pmr spectrum was identical with that of the starting *cis*-alcohol **14a**, and as analyzed by glpc, isomerization, if any, was less than 2%. Hence the allylic alcohol produced during the oxidation of the *gem*-dimethyl compound **4a** was stereospecifically trans (>98%).

The olefin, *cis*-3-methyl-3-octene (**4b**), gave two products, the major product (78%) resulting from the oxidation of the methylene of the ethyl group while the minor product (22%) was the aldehyde resulting from oxidation of the methyl group. In the case of olefins **4c** and **4d**, the product alcohols were the result of oxidation of the methyl rather than the isopropyl or cyclohexyl group and were isolated in 45–50% yields by stopping the reactions prior to completion. The allylic alcohols obtained in this manner and separated by glpc were trans, **13c** (86%), and cis, **14c** (14%), the structures and stereochemistry being established by ^{13}C nmr absorption of the methylene bearing the alcoholic function (cis 73.12, and trans 68.61 ppm from benzene, respectively) and other spectral data. A difference of *ca.* 5 or more ppm in the ^{13}C nmr absorption for the alcoholic methylene of isomeric allylic alcohols seems very consistent and becomes a definitive and useful tool in assigning structures to allylic alcohols without any chemical manipulation. The olefin **4c** was oxidized with excess selenium dioxide for 10 hr to give α,β-unsaturated aldehyde, the cis–trans ratio being 20:80. This mixture on sodium borohydride reduction and glpc separation gave isomerically pure alcohols **13c** and **14c** in the same ratio. This difference between the cis–trans ratio obtained on oxidation to the alcohols (14:86) and the aldehydes (20:80) is due to equilibration of the aldehydes under the reaction conditions. The mixture of allylic alcohols **13d** and **14d** obtained from the oxidation of *trans*-2-cyclohexyl-2-heptene (**4d**) could not be separated by glpc.



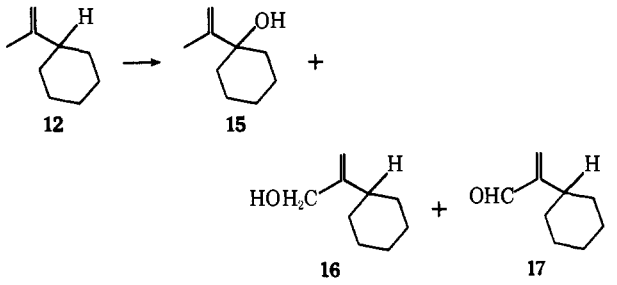
13 14

a, R = CH_3
b, R = CH_2CH_3
c, R = $CH(CH_3)_2$
d, R = C_6H_{11}
e, R = $C(CH_3)_3$

To ascertain any participation of the hydrogen of the isopropyl group of **4c**, the oxidation was done in a labeled solvent system (ethanol, T_2O) but no incorporation occurred. A lower selenium dioxide–olefin ratio and shorter duration (45 min) was tried but the product again was the result of oxidation of the methyl group (46% yield). No tertiary alcohol was isolated, but it is possible that a small amount of such an alcohol was formed and was lost through conversion to polar, nonvolatile material. Similarly, tertiary allylic alcohol arising from **4d** could not be isolated.

The disubstituted olefin isopropenylcyclohexane (**12**), after oxidation for 1.25 hr, gave compounds **15**, **16**, and **17** in a ratio of 74:18:8, respectively; however, after 6.5 hr of reaction, the amount of tertiary allylic alcohol **15** had decreased markedly, indicating its instability in the reaction medium. These three compounds were isolated by glpc and their structures were confirmed by spectral analysis.

(12) K. C. Chan, R. A. Jewell, W. H. Nutting, and H. Rapoport, *J. Org. Chem.*, 33, 3382 (1968).
(13) E. J. Corey and H. Yamamoto, *J. Amer. Chem. Soc.*, 92, 226 (1970).
(14) H. C. Kretschmar and W. F. Erman, *Tetrahedron Lett.*, 41 (1970).
(15) D. M. Grant and B. V. Cheney, *J. Amer. Chem. Soc.*, 89, 5315 (1967).
(16) M. Jautelat, J. B. Grutzner, and J. D. Roberts, *Proc. Natl. Acad., Sci. U.S.*, 65, 288 (1970).
(17) J. B. Grutzner, M. Jautelat, J. B. Dence, and J. D. Roberts, *J. Amer. Chem. Soc.*, in press.



The oxidation results are summarized in Tables I and II. Isomer distributions for the allylic alcohols formed

Table II. Oxidation of Trisubstituted Olefins **4** and **5** to *cis*- and *trans*-Aldehydes

Compd	R	Duration, hr	Moles of SeO_2/mol of olefin	Aldehyde isomer, % Cis	Trans
4a	CH_3	10	2	<1	>99
4b	CH_2CH_3[a]	10	2	4	96
5b	CH_2CH_3[a]	10	2	4	96
4c	$CH(CH_3)_2$	10	2	20	80
5c	$CH(CH_3)_2$	10	2	20	80
4d		10	2	20	80
8	(**5**, $C(CH_3)_3$)[b]	20	2	45	55

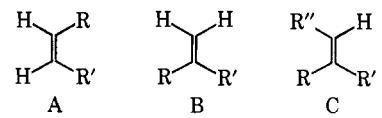
[a] The major product is the methyl ketone, arising from oxidation of the methylene of the ethyl group. [b] The yield of aldehyde in this case is only 8%.

are given in Table I and were determined by glpc, pmr, and ^{13}C nmr. The cis–trans isomer distribution for the α,β-unsaturated aldehydes in Table II, determined by nmr, were >99, 96, 80, and 80% trans for the olefins **4a**, **4b**, **4c**, and **4d**, respectively. To establish further the generality of the results of oxidation of the *gem*-dimethyl olefin **4a**, 2-methyl-2-pentene and 6-methyl-5-hepten-2-one (protected as the ethylene ketal) were oxidized and in each case the oxidation products (alcohols and aldehydes) were all trans (nmr), and conversion to their methyl esters[18] confirmed their isomeric purity. The *cis*-olefin **4c** and its trans derivative **5c** gave the same ratio of *cis*–*trans*-aldehydes, namely 20:80, establishing that the isomer distribution for these aldehydes was the result of an equilibration. This view was further supported by an experiment in which the stability of *cis*-alcohol **14a** was tested; the result indicated that *cis*-alcohol **14a** was stereochemically stable, but the small amount of aldehyde formed was all trans. The olefin **8** (**5**, R = $C(CH_3)_3$) with 2 mol of selenium dioxide for 20 hr gave a very low yield (8%) of the α,β-unsaturated aldehyde, the major products being the allylic alcohols **13e** and **14e**.

Discussion

Selenium dioxide oxidation of olefins can be visualized in two stages, the first involving the formation of the allylic selenite ester and the second the solvolysis of this ester. For the first step, formation of the allylic selenite ester **18**, **18′** has been suggested[5] to involve a cyclic transition state, but a two-step process as depicted below may be more probable in some cases. Recently, however, an oxaselenocyclobutane **19** has been postulated[6] as an intermediate to explain certain stereochemical findings. It was suggested that in formation of oxaselenocyclobutane **19**, a Markovnikov-type electrophilic addition occurs through an oxygen of selenium dioxide to generate positive character at the tertiary carbon, and this is followed by fast ring closure to **19**.

An assumption made in supporting the oxaselenocyclobutane intermediate[6] was that the reactivity sequence reported by Guillemonat[7] was incorrect. Some confusion exists on this point. Our results indicate that the preference for oxidation in the trisubstituted olefin series in ethanol is indeed $CH_2 > CH_3 > CH$ as reported;[7] however, in a disubstituted olefin series,[6] the reactivity sequence was different, *viz.* $CH > CH_2 > CH_3$, and the product composition we find from the oxidation of disubstituted olefin **12** supports this latter reactivity sequence.[6] Recently[19] results obtained with (+)-limonene using ethanol as the solvent also support this latter sequence, but the product composition and hence the reactivity sequence changed when the oxidation was done in acetic anhydride. In order to avoid confusion, since the mode of substitution of the olefin clearly influences the oxidation reaction, it was considered necessary to classify the olefins into three different groups, *viz.*, disubstituted symmetrical (cis-type A), disubstituted unsymmetrical (type B), and trisubstituted (type C) olefins.



The stereochemical findings[6] with A-type olefins seem to be consistent with the oxaselenocyclobutane intermediate. However, the observed reactivity sequence

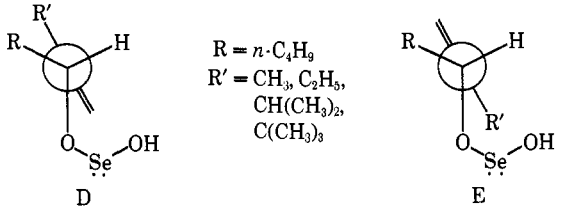
(18) E. J. Corey, N. W. Gilman, and B. E. Gamen, *J. Amer. Chem. Soc.*, **90**, 5616 (1968).

(19) A. F. Thomas and W. Bucher, *Helv. Chim. Acta*, **53**, 770 (1970).

in alicyclic systems of CH > CH_2 > CH_3 for B-type olefins and CH_2 > CH_3 > CH for C-type olefins cannot be explained by the involvement of oxaselenocyclobutanes as intermediates. The reactivity sequence of CH > CH_2 > CH_3 for B-type olefins together with CH_2 > CH_3 > CH for C-type olefins might be better explained by a carbonium ion intermediate or a cyclic transition state as previously suggested.[5] Models of olefins **12** and **4a–d** indicate that in the olefins of type B and C, ring closure to form oxaselenocyclobutane would be severely sterically inhibited; hence the reaction would proceed through a carbonium ion intermediate. For olefins like **4c**, **5c** (isopropyl), **8** (*tert*-butyl), and α-pinene,[20] only very small amounts of rearranged products were obtained, suggesting that the mechanism of oxidation was devoid of carbonium ion character and was consistent with a cyclic transition state in formation of the initial selenite ester.[5] Hence it does not appear possible to explain the initial attack of selenium dioxide on the various olefins (types A, B, and C) by any one single pathway; oxaselenocyclobutane intermediates, carbonium ion, and cyclic transition states all seem to apply in different circumstances.

The second step in the oxidation, involving the solvolysis of the allylic selenite ester, has been postulated[3,5,6] to proceed through a combination of SN2′- and SN1-type solvolyses, and in one case[6] it was admitted that an SN1′ mechanism could not be eliminated. Since the steric requirements and consequences for an SN2′ mechanism in cyclic systems are well established,[21] previous workers[3,5,6] were led to postulate solvolysis by this mechanism in order to account for the retention of configuration they observed with certain cyclic compounds. Furthermore, in acyclic compounds, the SN2′ mechanism predicts a mixture of cis and trans compounds, whose proportion will depend on conformational preference.[21–23]

Applying these concepts to the series of olefins at hand, we may consider the two rotamers D and E. For the dimethyl olefin **4a**, where the interaction between R



D E

and R′ is minimum for the series, roughly equal populations of D and E would be expected and an SN2′ mechanism should result[21–23] in a mixture of *cis*- and *trans*-alcohols. This is contrary to our finding that the product was *trans*-alcohol **13a** (>98%). Such a result is best explained by postulating the solvolysis of the allylic selenite ester to be a reaction of the SNi′ type, which does predict this highly stereospecific result. Furthermore, when the R and R′ interaction becomes largest (R′ = *tert*-butyl), favoring rotamer E and thereby inhibiting SNi′ solvolysis to some extent, the product then arises by a combination of SNi′ and SN1 reactions. The possibility of SN2′ type solvolyses operating to a small extent on E-type[24] rotamers when R = $CH(CH_3)_2$ and $C(CH_3)_3$ cannot be ruled out, but it does not appear to constitute a major reaction path.

These results clearly establish that for *gem*-dimethyl trisubstituted olefins selenium dioxide oxidation in aqueous ethanol proceeds stereospecifically to give *trans*-alcohols or -aldehydes in >98% specificity, thus resulting in a stereospecific synthesis of functionalized trisubstituted olefins. Finally, trans stereospecificity can now be assigned to those products of oxidation of *gem*-dimethyl olefins with selenium dioxide reported in the literature[7,25–32] where stereochemical assignments (a) were not made or (b) were made only after extensive purification.

Experimental Section[33]

1-Pentyltriphenylphosphonium Bromide (2). 1-Bromopentane (60.4 g) was heated under a nitrogen atmosphere at 80° for 10 hr with triphenylphosphine (115.2 g) in dry benzene (30 ml). The white solid cake was powdered, crystallized, and dried at 60° for 12 hr to give 153 g (93%) of **2**.

Anal. Calcd for $C_{23}H_{26}PBr$: C, 66.8; H, 6.3; P, 7.5; Br, 19.3. Found: C, 66.7; H, 6.3; P, 7.5; Br, 19.2.

Olefin Preparation. The olefins below were prepared by the following general procedure.

The phosphonium salt **2** (0.2 mol) was dissolved in dry DMSO (100 ml) and butyllithium (0.21 mol) was added to the reaction mixture, followed by stirring for 1 hr under a nitrogen atmosphere. The ketone (0.4 mol) then was added dropwise and the stirring continued for 8 hr at room temperature. Addition of water and extraction with hexane gave the crude reaction product. Purification (removal of phosphorus containing residue) was effected by chromatography on a silica gel column, and the olefins obtained in this manner were separated by glpc.

2-Methyl-2-heptene (4a) was obtained from acetone in 56% yield: bp 123°; nmr 5.03 (t, C=C*H*CH_2), 1.96 (m, C=CH$C\mathit{H}_2$), 1.63 (s, *cis*-C=CCH_3), 1.55 (s, *trans*-C=CCH_3), 1.5–1.4 (b, CH_2), 0.88 (t, $CH_2C\mathit{H}_3$).

(20) G. DuPont and W. Zacharewicz, *Bull. Soc. Chim. Fr.*, (5) 2, 533 (1935).

(21) G. Stork and W. N. White, *J. Amer. Chem. Soc.*, **78**, 4604, 4609 (1956). For a recent critical evaluation of the SN2′ mechanism, see F. G. Bordwell, *Accounts Chem. Res.*, **3**, 281 (1970).

(22) W. G. Young, I. D. Webb, and H. L. Goering, *J. Amer. Chem. Soc.*, **73**, 1076 (1951).

(23) P. B. D. de La Mare and C. A. Vernon, *J. Chem. Soc.*, 3325, 3331 (1952).

(24) Figures D and E have been drawn to permit better visualization; however, for SN2′ solvolysis, the C–O bond would be perpendicular to the plane of the olefin.

(25) H. L. Riley and N. A. C. Friend, *J. Chem. Soc.*, 2342 (1932).

(26) R. Delaby and E. Dupin, *Bull. Soc. Chim. Fr.*, (5) **5**, 931 (1938).

(27) K. J. Clark, G. I. Fray, R. H. Jaeger, and R. Robinson, *Tetrahedron*, **6**, 217 (1959).

(28) O. P. Vig, S. D. Sharma, and Inder Raj, *Indian J. Chem.*, **4**, 127 (1966).

(29) W. M. Sathe, K. K. Chakravarti, M. V. Kadival, and S. C. Bhattacharyya, *ibid.*, **4**, 393 (1966).

(30) P. Naegeli and G. Weber, *Tetrahedron Lett.*, 959 (1970).

(31) M. Matsui, Y. Yamada, and M. Nonoyama, *Agr. Biol. Chem.*, 26, 351 (1962).

(32) L. Crombie, C. F. Doherty, and G. Pattenden, *J. Chem. Soc. C*, 1076 (1970).

(33) All boiling points are uncorrected; infrared spectra were recorded as liquid films on a Perkin-Elmer 237 spectrometer and are reported in reciprocal centimeters, cm^{-1}. Nmr spectra are reported as δ values relative to TMS (δ 0) and were obtained in CCl_4 unless otherwise noted on a Varian T-60 or HA-100 spectrometer. Mass spectra were obtained with CEC-21-103 or CEC-21-110B/spectrometers at 70 eV. Glpc analyses were done on an Aerograph gas chromatograph, Model A-90-P. Olefins were analyzed on a 10% SE-30 (20 ft × 0.25 in.) and oxidation products on 20% FFAP (15 ft × 0.25 in.) columns. Preparative glpc was done on a 10% SE-30 (35 ft × 3/8 in.) column on a Hewlett Packard preparative gas chromatograph, Model 775. Thin layer chromatography was done on silica gel and column chromatography on silica gel under nitrogen pressure. A description of the instrument used to measure the ^{13}C is presented elsewhere;[34] all spectra were determined in the pulse mode; the free induction decay was accumulated and then Fourier transformed. The accuracy and the reproducibility for any given spectrum are ±1 Hz, and are referred to benzene, 15.08 MHz (neat, external D_2O lock).

(34) (a) W. Horsley, H. Sternlicht, and J. S. Cohen, *J. Amer. Chem. Soc.*, **92**, 680 (1970); (b) D. E. Jones, Ph.D. Thesis, Department of Chemistry, University of California, Berkeley, 1970.

Anal. Calcd for C_8H_{16}: C, 85.6; H, 14.4. Found: C, 85.5; H, 14.1.

cis–trans-**3-Methyl-3-octene** was obtained from 2-butanone in 70% yield; cis–trans ratio, 55:45; retention time at 65°, cis, 89 min, 20 sec; trans, 91 min, 40 sec.

cis-**3-Methyl-3-octene** (**4b**) had nmr 5.08 (t, C=C*H*CH_2), 2.4–2.0 (b, C=CHC*H*$_2$), 1.72 (s, C=CC*H*$_3$), 1.5–1.2 (b, CH_2), 1.0 (t, CH_3).

Anal. Calcd for C_9H_{18}: C, 85.6; H, 14.4. Found: C, 85.4; H, 14.1.

trans-**3-Methyl-3-octene** (**5b**) had nmr 5.07 (t, C=C*H*CH_2), 2.4–2.0 (b, C=CHC*H*$_2$), 1.62 (s, C=CC*H*$_3$), 1.5–1.2 (b, C*H*$_2$$CH_3$), 1.06 (t, CH_3).

Anal. Found: C, 85.3; H, 14.1.

cis–trans-**2,3-Dimethyl-3-octene** was obtained from 3-methyl-2-butanone in 63% yield; cis–trans ratio 85:15; retention time at 65°, cis, 107 min, 11 sec; trans, 112 min, 16 sec.

Isomerization of 2,3-Dimethyl-3-octene with Thiophenol and Azobisisobutyronitrile. A cis–trans mixture of 2,3-dimethyl-3-octene (**4c, 5c**) (140 mg), thiophenol (296 mg), and 3 mg of azobisisobutyronitrile in benzene (1 ml) was heated in a sealed tube at 65° for 8 hr. The reaction mixture was taken up in ether and washed with cold 5% sodium hydroxide and then with water. Removal of ether and glpc analysis indicated that the cis–trans isomer ratio had changed from 85:15 to 25:75 and the two isomers were separated by glpc.

cis-**2,3-Dimethyl-3-octene** (**4c**) had nmr 4.98 (t, C=C*H*CH_2), 2.78 (b, C*H*CH_3), 2.3–2.0 (b, C=CHC*H*$_2$), 1.51 (s, C=CC*H*$_3$), 1.3 (d, CHC*H*$_3$), 1.5–1.3 (b, CH_2).

Anal. Calcd for $C_{10}H_{20}$: C, 85.6; H, 14.4. Found: C, 85.8; H, 13.9.

trans-**2,3-Dimethyl-2-octene** (**5c**) had nmr 5.02 (t, C=C*H*CH_2), 2.78 (b, C*H*CH_3), 2.3–2.0 (b, C=CHC*H*$_2$), 1.5–1.3 (b, CH_2), 1.40 (s, C=CC*H*$_3$), 1.28 (d, CHC*H*$_3$).

Anal. Found: C, 85.9; H, 14.2.

cis–trans-**2-Cyclohexyl-2-heptene** was obtained from methyl cyclohexyl ketone in 62% yield: the cis–trans ratio was 86:14; retention time (85°) cis, 117 min, 8 sec; trans, 121 min, 31 sec.

cis-**2-Cyclohexyl-2-heptene** (**4d**) had nmr 5.0 (C=CH), 2.51 (b, >CH), 1.71 (s, C=CC*H*$_3$), 0.89–2.0 (b, CH_2).

Anal. Calcd for $C_{13}H_{24}$: C, 86.6; H, 13.4. Found: C, 86.4; H, 13.1.

Wittig Reaction with 3,3-Dimethyl-2-butanone. Phosphonium salt **2** (33.1 g), butyllithium in hexane (50 ml, 1.6 *M*), and 3,3-dimethyl-2-butanone (14 g) in 100 ml of dry DMSO (at room temperature or at 55°) gave 2.3 g of **2,2,5,6,6-pentamethyl-4-hepten-2-one** (**6**): ir 1685 (C=O); nmr 6.3 (bs, C=CH), 2.3 (s, C=CC*H*$_3$), 1.2 (s, C(C*H*$_3$)$_3$); mass spectrum *m/e* 182 (M^+).

Anal. Calcd for $C_{12}H_{22}O$: C, 79.1; H, 12.2. Found: C, 78.9; H, 12.3.

2,2,3-Trimethyl-3-octanol (**7**). The Grignard reagent was prepared by adding 1-bromopentane (15.1 g) in ether (50 ml) to magnesium turnings (2.4 g-atoms) covered with ether (50 ml) and then heating the mixture under reflux for 2 hr. 3,3-Dimethyl-2-butanone (5g) was added dropwise to the Grignard reagent and the reaction was refluxed for 5 hr. After the creamy tan mixture had stood overnight, it was poured over crushed ice (50 g) and to it 6 *N* sulfuric acid (30 ml) was added. Extraction with ether, removal of solvent, and purification on silica gel gave 8.6 g (50%) of **7**; nmr 2.1 (s, C—OH), 1.08 (s, C(C*H*$_3$)$_3$), 0.9–1.6 (b, CH_2).

Anal. Calcd for $C_{11}H_{24}O$: C, 76.7; H, 14.0. Found: C, 76.3; H, 13.7.

trans-**2,2,3-Trimethyl-3-octene** (**8**). The octanol **7** (3.44 g) was dissolved in dry pyridine (10 ml) and thionyl chloride (2.62 g) was added dropwise at 0°. Maintaining this temperature, the reaction was stirred for 4 hr. Addition of ice–water and extraction with ether gave an oily liquid. Separation of olefins on a 20% silver nitrate–silica gel column gave 1.5 g (50%) of the *trans*-octene **8**; nmr 1.05 (s, C(C*H*$_3$)$_3$), 1.2–1.4 (b, CH_2), 1.6 (s, C=CC*H*$_3$), 5.09 (t, C=C*H*CH_2).

Anal. Calcd for $C_{11}H_{22}$: C, 85.6; H, 14.4. Found: C, 85.4; H, 14.3.

Isopropenylcyclohexane (**12**). Methyltriphenylphosphonium iodide (8.08 g) was dissolved in dry dimethyl sulfoxide (65 ml) and butyllithium (1.6 *M*, 12.5 ml) was added under a nitrogen atmosphere. The ylide **10** was stirred for 45 min and then methyl cyclohexyl ketone (**11**, 5 g) was added. After 4 hr the reaction mixture was evacuated at 0.1 mm and the volatile olefin was collected in a trap cooled in liquid nitrogen to give 1.59 g (66%) of **12**: nmr 4.8 (s, C=CH_2), 2.0 (b, >CH), 1.70 (s, C=CC*H*$_3$), 1–2 (b, CH_2).

Anal. Calcd for C_9H_{16}: C, 87.0; H, 13.0. Found: C, 86.8; H, 12.8.

cis-**2-Methyl-2-hepten-1-ol** (**14a**). Ethyltriphenylphosphonium bromide (37.1 g) was dissolved in dry tetrahydrofuran (150 ml) at −78° and butyllithium (1.6 *M*, 62.5 ml) was added slowly under an argon atmosphere. Valeraldehyde (8.6 g) then was added dropwise and the reaction mixture was stirred for 5 min at −78°, followed by the addition of butyllithium (1.6 *M*, 62.5 ml). The deep red ylide was allowed to reach 0° and then paraformaldehyde (6.06 g) was added to the reaction mixture. Stirring was continued at 0° for 1 hr and then for 10 hr at room temperature followed by addition of ice–water and extraction into ether to give 7.3 g (65% yield) of *cis*-alcohol **14a**. Purification was completed on a silica gel column under a nitrogen atmosphere: glpc (FFAP) retention time 18 min, 20 sec, 130°, flow rate 60 ml/min; pmr 5.17 (t, C=CHC*H*$_3$), 4.0 (s, CH_2OH), 3.94 (bs, OH), 1.73 (s, C=CC*H*$_3$), 1.8–2.0 (b, C=CHC*H*$_2$), 1.0–1.6 (b, CH_2), 0.8 (t, C*H*$_2$$CH_3$); ^{13}C nmr ($CDCl_3$), 66.62 (CH_2OH) ppm from benzene.

Anal. Calcd for $C_8H_{16}O$: C, 74.9; H, 12.6. Found: C, 74.6; H, 12.4.

trans-**2-Methyl-2-hepten-1-ol** (**13a**). 2-Methyl-2-heptene (**4a**, 224 mg) and selenium dioxide (448 mg) were refluxed in 95% ethanol (40 ml) for 10 hr. Evaporation of the ethanol, extraction with ether, and evaporation gave 152 mg (60%) of the aldehyde which was added dropwise in 95% ethanol (5 ml) to a solution of sodium borohydride (76 mg) in ethanol (15 ml), and the reaction stirred for 4 hr at 5°. Addition of water and extraction with ether gave the *trans*-alcohol **13a**; glpc (FFAP) retention time 20 min, 35 sec, 130°, flow rate 60 ml/min; pmr 5.28 (t, =C*H*CH_2), 3.89 (s, C*H*$_2$OH), 1.8–2.0 (b, C=CHC*H*$_2$), 1.6 (s, C=CC*H*$_3$), 1.0–1.5 (b, CH_2), 0.88 (t, C*H*$_2$$CH_3$); ^{13}C nmr ($CDCl_3$), 58.40 (CH_2OH) ppm from benzene.

Anal. Calcd for $C_8H_{16}O$: C, 74.9; H, 12.6. Found: C, 74.7; H, 12.4.

Selenium Dioxide Oxidations of Olefins to Allylic Alcohols. Selenium dioxide (0.5–1 mmol) in 95% ethanol (30 ml) was refluxed with the olefin (2 mmol) for periods ranging from 45 min to 3 hr. Removal of the ethanol, extraction with ether, washing with sodium bicarbonate, and evaporation of the solvent gave the crude oxidation product. Purification was accomplished on a silica gel column using 3% ethyl acetate–benzene for elution. Glpc analysis indicated no changes took place on the column. Formation of the α,β-unsaturated aldehydes was observed to the extent of 5–20%.

2-Methyl-2-heptene (**4a**) oxidized as above for 1.5 hr gave 178 mg of product. Glpc separation and comparison with independently prepared samples (above) established the product composition as >98% *trans*-**2-methyl-2-hepten-1-ol** (**13a**) and <2% *cis*-**2-methyl-2-hepten-1-ol** (**14a**). In a similar experiment 2-ml aliquots were analyzed after every 10 min and glpc analysis of these aliquots indicated that the *cis*-alchol **14a** always comprised <2% of the alcohol mixture.

The stability of *cis*-**2-methyl-2-hepten-1-ol** (**14a**) to the reactions conditions was tested by treating **14a** (128 mg) and selenium dioxide (56 mg) in 95% ethanol (20 ml) at reflux for 1 hr. By glpc (FFAP, retention time 18 min, 18 sec, 130°, flow rate 60 ml/min) and nmr, ir, and tlc the *cis*-alcohol **14a** was shown to remain unchanged. Aldehyde (~10%) was formed during the reaction; it was trans as shown by nmr since the aldehydic proton signal[12] appeared at δ 9.24.

cis-**2,3-Dimethyl-3-octene** (**4c**) oxidized as above for 4 hr gave 152 mg (50% yield) of oxidation product after silica gel chromatography. Glpc (FFAP) at 140° showed three major fractions: A, 20%; B, 12%; and C, 68%.

Fraction A was a mixture of cis and trans α,β-unsaturated aldehyde; its characterization is given below.

Fraction B was characterized as *cis*-**2-isopropyl-2-hepten-1-ol** (**14c**): retention time (140°) 25 min, 20 sec; pmr 5.3 (t, C=C*H*CH_2), 4.13 (s, C*H*$_2$OH), 2.38 (m, C*H*$(CH_3)_2$), 2.08 (b, C=CHC*H*$_2$), 1.2–1.5 (b, CH_2), 1.06 (d, CH(C*H*$_3$)$_2$; ^{13}C nmr ($CDCl_3$) 68.01 (C=CCH_2OH) ppm from benzene.

Anal. Calcd for $C_{10}H_{20}O$: C, 76.9; H, 12.9. Found: C, 76.8; H, 13.0.

Fraction C was characterized as *trans*-**2-isopropyl-2-hepten-1-ol** (**13c**); retention time (140°) 30 min, 10 sec; pmr 5.30 (t, C=C*H*-CH_2), 3.96 (s, C*H*$_2$OH), 2.91 (m, C*H*$(CH_3)_2$), 2.07 (b, C=CHC*H*$_2$), 1.2–1.5 (b, CH_2), 1.06 (d, CH(C*H*$_3$)$_2$); ^{13}C nmr ($CDCl_3$ 63.50 (C=CC*H*$_2$OH) ppm from benzene.

Anal. Found: C, 76.7; H, 12.8.

trans-**2-Cyclohexyl-2-heptene** (**4d**) oxidized as above for 5 hr gave a 41% yield of oxidation product after silica gel chromatography. Glpc at 180° showed one major peak with a shoulder,

and the isomeric mixture could not be resolved into pure components; mass spectrum *m/e* 196.1826 (M^+, $C_{13}H_{24}O$).

trans-**2,3-Dimethyl-3-octene (5c)** oxidized as above for 3 hr gave 158 mg (52% yield) of oxidation product after a silica gel chromatography. Glpc showed that the product composition was essentially the same as from the cis isomer **14c** but an additional peak (retention time 12 min, 35 sec, 8%) appeared after the α,β-saturated aldehyde mixture. The other three peaks were shown to be identical with the fractions A, B, and C obtained from oxidation of the *cis*-olefin **4c**.

trans-**2,2,3-Trimethyl-3-octene (8)** oxidized as above for 2 hr gave 225 mg (63% yield) of oxidation product. Glpc analysis indicated that the major product was a mixture of *trans*-alcohol **13e** (70%) and *cis*-alcohol **14e** (30%) while the α,β-unsaturated aldehyde was present to the extent of <5%.

trans-**2-*tert*-Butyl-2-hepten-1-ol (13e)** had retention time (160°) 28 min, 8 sec; pmr 1.1 (s, $C(CH_3)_3$), 0.9–1.5 (b, CH_2), 2.17 (b, $C{=}CHCH_2$), 4.07 (s, CH_2OH), 5.37 (t, $C{=}CHCH_2$); ^{13}C nmr ($CDCl_3$) 67.58 (CH_2OH) ppm from benzene.

Anal. Calcd for $C_{11}H_{22}O$: C, 77.6; H, 13.0. Found: C, 77.4; H, 12.8.

cis-**2-*tert*-Butyl-2-hepten-1-ol (14e)** had retention time (160°) 26 min, 17 sec; nmr 1.1 (s, $C(CH_3)_3$), 1.0–1.5 (b, CH_2), 2.17 (b, $C{=}CHCH_2$), 4.13 (s, CH_2OH), 5.33 (t, $C{=}CHCH_2$); mass spectrum *m/e* 170.1671 (M^+, $C_{11}H_{22}O$).

Isopropenylcyclohexane (12) oxidized as above for 1.25 hr gave 141 mg (50% yield) of oxidation product. Glpc (125°) showed three main fractions: A, 8%; B, 18%; and C, 74%.

Fraction A was **2-cyclohexylacrylaldehyde (17)**; retention time 9 min, 25 sec; nmr ($CDCl_3$), 9.53 (s, CHO), 6.23 (s, C=CH), 5.92 (s, C=CH), 2.98 (b, >CH), 1.0–2.0 (b, CH_2); mass spectrum *m/e* 138.1046 (m^+, $C_9H_{14}O$).

Fraction B was **2-cyclohexylallyl alcohol (16)**: retention time 12 min, 40 sec; nmr 5.14 (s, C=CH), 5.07 (s, C=CH), 4.13 (s, CH_2OH), 3.99 (bs, **OH**), 1.4–1.8 (m, CH_2).

Anal. Calcd for $C_9H_{16}O$: C, 77.1; H, 11.5. Found: C, 76.8; H, 11.3.

Fraction C was **1-isopropenylcyclohexanol (15)**: retention time 15 min, 25 sec; nmr 5.0 (s, C=CH), 5.8 (bs, C=CH), 1.75 (s, $C{=}CCH_3$), 1.2–1.6 (m, CH_2).

Anal. Calcd for $C_9H_{16}O$: C, 77.1; H, 11.5. Found: C, 76.8; H, 11.4.

Selenium Dioxide Oxidation of Olefins to α,β-Unsaturated Aldehydes. The olefin (2 mmol) and selenium dioxide (4 mmol), in 95% ethanol (40 ml) were heated under reflux for 10 hr. Isolation of products from the reaction mixture in the manner described above gave the crude α,β-unsaturated aldehydes.

cis-**3-Methyl-3-octene (4b)** gave 182 mg (65% yield) of oxidation product after silica gel chromatography. Glpc showed the presence of two fractions: A, 22%, and B, 78%.

Fraction B, *trans*-**3-methyl-3-octen-2-one,** had retention time 13 min, 10 sec; nmr 6.55 (t, $C{=}CHCH_2$), 2.08 (s, $COCH_3$), 2.0–2.38 (m, $C{=}CHCH_2$), 1.72 (s, $C{=}CCH_3$), 1.4 (m, CH_2), 0.9 (bt, CH_2CH_3).

Anal. Calcd for $C_9H_{10}O$: C, 77.1; H, 11.5. Found: C, 76.8; H, 11.3.

Fraction A, *trans*-**2-ethyl-2-hepten-1-ol,** had retention time 11 min, 20 sec; nmr 9.23 (s, *trans* CHO), 6.4 (t, $C{=}CHCH_2$), 2.0–2.4 (q, $C{=}CCH_2$), 1.4 (m, CH_2), 0.9 (bt, CH_2CH_3).

Anal. Calcd for $C_9H_{10}O$: C, 77.1; H, 11.5. Found: C, 76.7; H, 11.3.

cis-**2,3-Dimethyl-3-octene (4c)** (2.8 g) and selenium dioxide (4.4 g) in refluxing ethanol (120 ml) for 10 hr gave 1.8 g (58%) of the oxidation product which, by nmr and glpc, contained mostly aldehyde and a small amount of allylic alcohol. Glpc of the aldehyde at 130°, retention time 11 min, 42 sec, gave a cis–trans mixture of **2-isopropyl-2-hepten-1-al** in the ratio of 20:80 as estimated by nmr: nmr 10.01 (s, *cis*-CHO), 9.25 (bs, *cis*-CHO), 6.33 (t, $C{=}CHCH_2$), 2.93 (m, $(CH_3)_2CH$), 2.33 (m, $C{=}CHCH_2$), 1.12 (d, $CHCH_3$), 1.2–1.5 (m, CH_2), 0.98 (m, CH_2CH_3); mass spectrum *m/e* 154 (M^+).

Anal. Calcd for $C_{10}H_{18}O$: C, 77.9; H, 11.8. Found: C, 77.6; H, 11.5.

trans-**2,3-Dimethyl-3-octene (5c)** gave an oxidation product identical with that obtained from oxidation of the cis isomer **4c**.

cis-**2-Cyclohexyl-2-heptene (4b)** gave 251 mg of oxidation product, essentially a cis–trans mixture (20:80) of α,β-unsaturated aldehydes: nmr ($CDCl_3$) 10.05 (s, *cis*-CHO), 9.3 (s, *trans*-CHO), 6.30 (t, $C{=}CHCH_2$), 3.33 (m, HC–), 2.3 (m, $C{=}CCH_2$), 0.9–1.8 (m, CH_2).

Anal. Calcd for $C_{13}H_{22}O$: C, 80.3; H, 11.4. Found: C, 80.0; H, 11.1.

Ethylene Ketal of 6-Methyl-5-hepten-2-one. 6-Methyl-5-hepten-2-one (62 g) was treated with ethylene glycol (50 g) in the presence of *p*-toluenesulfonic acid (200 mg) in benzene in the usual manner. Ketal (62.58 g) was obtained: bp 58° (1.5 mm); nmr 5.4 (t, $C{=}CHCH_2$), 3.9 (s, OCH_2CH_2O), 1.69 (s, $C{=}CCH_3$), 1.60 (s, $C{=}CCH_3$), 1.0 (s, CH_3).

Oxidation of 21.2 g of the above ketal with 20 g of selenium dioxide in 150 ml of ethanol gave 8.9 g (33%) of *trans*-2-methyl-6-oxo-2-hepten-1-al: bp 102° (1 mm); nmr 9.27 (s, *trans*-CHO), 6.7 (t, $C{=}CHCH_2$), 3.9 (s, OCH_2CH_2O), 1.73 (s, $C{=}CCH_3$), 1.0 (s, CH_3).

Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.2; H, 8.8. Found: C, 65.2; H, 8.8.

Methyl *trans*-2-Methyl-6-oxo-2-heptenoate Ethylene Ketal. *trans*-2-Methyl-6-oxo-2-hepten-1-al ethylene ketal (6.7 g) was stirred with a mixture of sodium cyanide (9.6 g), acetic acid (2.6 g), and manganese dioxide (79.9 g) in dry methanol for 12 hr at 25°. Filtration and evaporation of the solvent gave 5.81 g of methyl *trans*-2-methyl-6-oxo-2-heptenoate ethylene ketal: bp 110° (bath temperature) (1.1 mm); retention time (150°, 5% SE-30, 10 ft) 14 min, 19 sec; nmr ($CDCl_3$) 6.8 (t, $C{=}CHCH_2$), 3.9 (s, OCH_2CH_2O), 3.72 (s, CO_2CH_3), 1.8–2.2 (b, $C{=}CHCH_2$), 1.72 (s, $C{=}CCH_3$), 1.0 (s, CH_3).

Anal. Calcd for $C_{11}H_{18}O_4$: C, 61.7; H, 8.5. Found: C, 61.5; H, 8.5.

trans-**2-Methyl-2-penten-1-al.** 2-Methyl-2-pentene (1.6 g) in 95% ethanol (100 ml) was refluxed for 2 hr, under a nitrogen atmosphere, with selenium dioxide (2.29 g). Isolation in the usual manner, followed by silica gel chromatography, gave *trans*-2-methyl-2-penten-1-al (45% yield), identical with an authentic specimen[12] in ir, nmr, and glpc. Oxidation of 2-methyl-2-pentene has been reported[7] to give 2-methyl-2-penten-1-ol acetate using selenium dioxide in acetic acid and acetic anhydride.