

- $C_{\text{peripheral}} = 1.335$, $C_{\text{peripheral}} - C_{\text{peripheral}} = 1.442$, $C-H = 1.10$] gives uncorrected and corrected energy splittings of 0.92 and 1.22 eV, respectively. The total energy for this configuration was ~ 10 kcal/mol less stable than that obtained with the standard geometry given in Table I.
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Conformational Analysis and Chromic Acid Oxidation. The Rationalization of the Rates of Oxidation of Secondary Alcohols

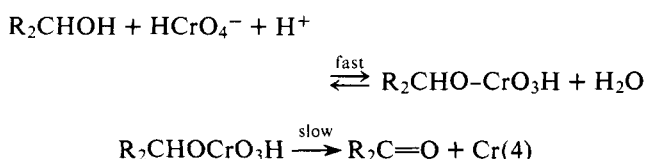
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Abstract: The strain of 47 secondary alcohols has been evaluated from force-field calculation of the corresponding methyl hydrocarbons. The rates of chromic acid oxidation of these alcohols to ketones are correlated with the strain change in going from the alcohol to the carbonyl product. The correlation which covers a rate range of 15 000 has a slope of -0.3 and a correlation coefficient of 0.91. On the grounds of this correlation it is concluded that the properties of the product are reflected in the transition state of oxidation.

Introduction

The understanding of the rates of oxidation of secondary alcohols to ketones with chromic acid represents a test case for conformational analysis and structure reactivity correlations.¹ Because of the wide synthetic applications of the reaction considerable attention has been directed toward the elucidation of the mechanism² which has been analyzed in great detail.³ The complete reaction scheme is complicated; however, if the very fast equilibrium reactions between alcohol and chromic acid, preceding the rate-determining step, as well as the reactions of the intermediate valence states of chromium are not considered, the oxidation rate expresses simply the conversion of the sp^3 -hybridized alcohol to the corresponding sp^2 -hybridized ketone. Under the conditions usually employed for reactivity studies (80–90% acetic acid, alcohol in large excess over chromic acid), the kinetically relevant steps of the reaction scheme are:



In general the steady-state approximation may be applied to the intermediate chromate ester, so that the oxidation rates reflect directly the energy difference between alcohol and the respective transition state. Because of this simplicity one might expect that rate constants for the oxidation of alcohols should be easy to interpret. This is, however, not the case. In particular, the nature of the transition state always remained controversial. The observation that axial hydroxyl groups on the cyclohexane ring are more reactive than their equatorial epimers was interpreted with a strain decrease in going from the sp^3 -hybridized alcohol to the sp^2 -hybridized ketone.⁴ This interpretation required a productlike transition state which was expected to lead a correlation between oxidation rates and ketone strain, as measured by the carbonyl stretching frequency.⁶ However, no such correlation could be established.⁵ Alternatively a rather eductlike transition state was also proposed,^{6,7} and the contradiction between these hypotheses could not be resolved.

Structure reactivity correlations require the evaluation of strain in educt and a hypothetical transition state. In the absence of entropy effects the strain difference between transition state and educt should be related to the activation energy. In recent times computer calculations have been used successfully for the determination of strain and have been applied to re-

Table I. Free-Energy Difference Between Epimeric Alcohols (ΔG_{eq}°) and Calculated Enthalpies of Epimerization of Methyl Compounds (ΔH_{epi})

No.	Alcohol	ΔG_{eq}° ^{a, b}	ΔH_{epi} ^a		
			Allinger	Engler	MINDO/3
1	2-Methylcyclohexanol	1.06	1.42 ^e	1.65 ^e	
2	3-Methylcyclohexanol	0.89	1.81 ^d		
3	4-Methylcyclohexanol	0.77	1.65	1.79	1.54
4	<i>cis</i> -3,5-Dimethylcyclohexanol	0.89	1.89 ^d		
5	3,3,5-Trimethylcyclohexanol	2.00	3.96	3.95	2.25
6	2,4,4-Trimethylcyclopentanol	0.94	2.12		
7	2-Norbornanol	1.06	0.83	0.86	0.51
8	Borneol	0.66	1.95		
9	Isonopinol	0.28	0.59		
10	Nopinol	2.07	2.23		
11	Isopinocampheol	1.56 ^c	2.80		
12	Bicyclo[3.2.1]octan-2-ol	1.25	1.00	1.06	
13	Bicyclo[3.2.1]octan-3-ol	2.50	4.68	3.97	1.17
14	Bicyclo[3.2.1]octan-8-ol	1.85	1.57	1.27	1.04
15	Bicyclo[3.3.1]nonan-2-ol	0.56	1.01	0.93	
16	<i>endo</i> -5,6-Trimethylene-2-norbornanol	4.16 ^c	5.11	3.61	
17	<i>endo</i> -Tetracyclo[4.4.0 ^{2,5} .1 ^{7,10}]dodecan-3-ol	4.21 ^c	5.23	4.53	

^a In kcal/mol. ^b Data from ref 19. ^c Determined from the rates of oxidation.¹⁹ ^d Reference 15c. ^e Reference 14b.

activity problems.^{7,8} The most striking example for this approach is Schleyer's correlation of the solvolysis rates of tertiary halides, with calculated strain differences between hydrocarbons and carbenium ions.⁹ We have applied the same procedure to the chromic acid oxidation of secondary alcohols¹⁰ and report here the results of our study.

Our approach is based on four hypotheses, namely that (a) the entropies of activation are constant in our series of compounds, (b) alcohol strain is equal to the strain of the corresponding methyl hydrocarbon, and (c) the carbonyl compound represents a model for the transition state. It is further assumed that, contrary to the Hammond principle, the transition state should not change its position on the reaction coordinate. Hypothesis a has been verified experimentally.¹¹ It was found that the average entropy of activation for oxidation of ten unhindered alcohols is -24.3 ± 1.0 eu. This allows the conclusion that the rate variations are due to variations in the enthalpies of activation as required for the applicability of strain calculations. For hindered alcohols such as di-*tert*-butylmethanol or 2,2,4,4-tetramethylcyclobutanol substantial deviations from the average value are observed; for these compounds hypothesis a is not correct, and they are expected to fall out of the correlation.

Alcohol Strain

It was first tried to calculate enthalpies of formation of alcohols directly by the semiempirical MINDO/3 method¹² with a computer program provided by Haselbach,¹³ University of Basle. This approach was abandoned when it appeared that we were unable to reproduce the correct stability order of axial and equatorial cyclohexanol. We then turned our attention to the empirical force-field calculations. A copy of the BIGSTRN program of Schleyer and Mislow became available to us thanks to the courtesy of the authors.¹⁴ The program contains both the Allinger¹⁵ and the Engler^{14b} force field. Both lack a parametrization for alcohols. The alcohol strain was therefore approximated by that of the corresponding methyl compounds following the idea of Becker¹⁶ and DeTar.⁸ The validity of the procedure was tested by comparison of the experimentally accessible free-energy difference ΔG_{eq}° between epimeric alcohols with the calculated enthalpies of epimerization ΔH_{epi} for the respective methyl compounds. Calculations were performed with the Allinger force field by means of the "pattern

search minimization".^{14b,17} The results are summarized in Table I. Results from calculations based on the Engler force field obtained from Jemmis,¹⁸ Princeton University, and from MINDO/3 calculations are included for comparison. In Figure 1 the ΔH_{epi} values obtained by means of the Allinger force field are plotted against ΔG_{eq}° . The plot shows that the calculations tend to overestimate the energy difference between epimeric alcohols by about 0.5 kcal/mol. The straight line has a slope of 1.12 and an intercept of 0.53 at the origin. This overestimation was expected because the steric requirements of a methyl group are always higher than those of the OH group. For example, the *A* value for CH₃ is 1.7, but for OH it is only ca. 1.0.²⁰ Use of hypothesis b for our calculation will in general result in an overestimation of strain for hindered hydroxyl groups, such as axial cyclohexanols and *endo*-norbornanols. The systematic error introduced should not exceed 1 kcal/mol, which corresponds to the deviation of the most crowded systems studied. Agreement between the Engler and Allinger force fields is usually quite good, as follows from Table I. The limited data for MINDO/3 calculations allow no definite conclusions, but it seems that they give similar results as the force-field method, although at higher cost.

Carbonyl Strain

Our hypothesis c states that the transition state for oxidation reflects the properties of the ketone. It is based on the observation of Sicher²¹ that there is a linear free-energy relationship between thermodynamic stability (ΔG_{eq}°) and reactivity of epimeric cyclohexanols, as expressed by

$$\Delta G_{eq}^\circ = RT \ln (k_a/k_e)$$

where k_a and k_e represent the rate constants for oxidation of the axial (k_a) and equatorial (k_e) epimer. The relationship of Sicher is applicable to other systems than cyclohexanols;²² however, from a more complete study it was found that a proportionality factor of 0.8 should be included,¹⁹ that is:

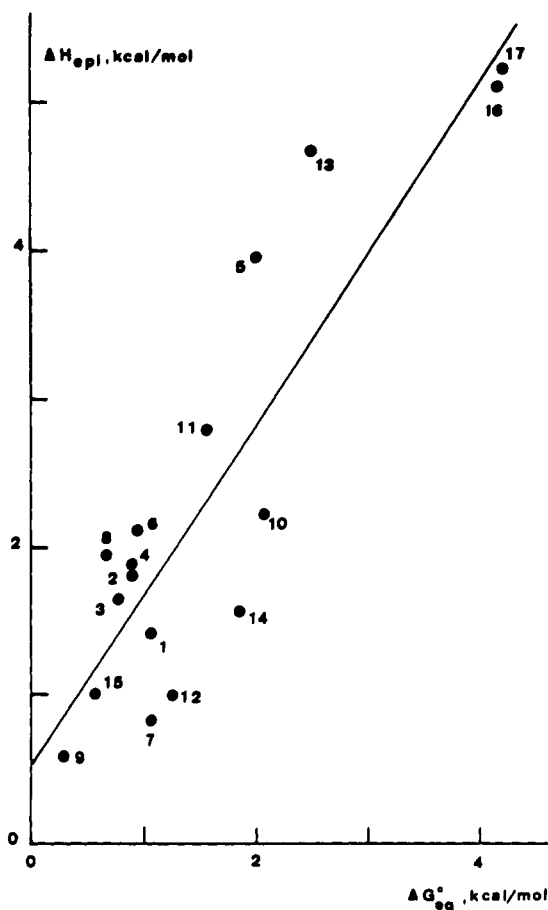
$$\Delta G_{eq}^\circ = 0.8RT \ln (k_a/k_e)$$

The relationship implies that transition states for oxidation of epimeric alcohols are energetically close. This is only possible if the hybridization at the reacting carbon is at least in part sp². Possible models for the transition state are therefore ketone, radical, and cation. The cation may be rejected because of the

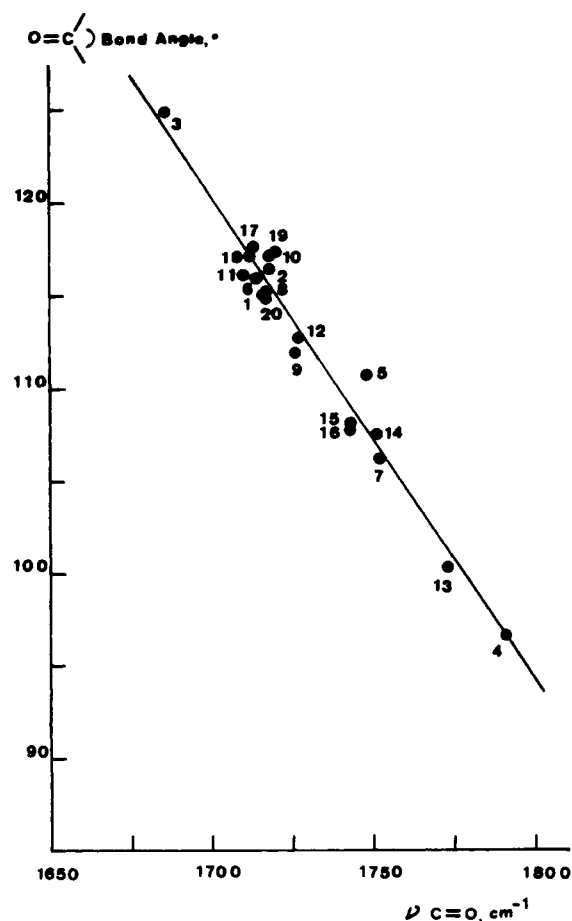
Table II. Calculated Internal Carbonyl Bond Angle and Experimental IR Carbonyl Stretching Frequency.

Ketone	No.	$\nu(\text{C}=\text{O})^a$	C=O bond angle (force field calcd)
4-Methylcyclohexanone	1	1716	115.0
Acetone	2	1718	116.4
Di- <i>tert</i> -butylketone	3	1686 ^c	124.9
Cyclobutanone	4	1791	96.6
Cyclopentanone	5	1748	110.7
Bicyclo[3.2.1]octan-3-one	6	1714	115.9
Bicyclo[3.2.1]octan-8-one	7	1752	106.2
Bicyclo[3.2.1]octan-2-one	8	1717	115.2
Bicyclo[3.3.1]noran-9-one	9	1726	111.9
Bicyclo[3.3.1]nonan-2-one	10	1720 ^d	117.3
Bicyclo[3.3.1]noran-3-one	11	1710 ^d	116.1
2-Adamantanone	12	1727	112.7
7-Norbornanone	13	1773	100.3
2-Norbornanone	14	1751	107.5
<i>endo</i> -5,6-Trimethylene-2-norbornanone	15	1743 ^b	108.1
<i>endo</i> -Tetracyclo[4.4.0.1 ^{2,5} .1 ^{7,10}]dodecan-3-one	16	1743 ^b	107.7
Pinocampnone	17	1713 ^e	117.6
Isopinocampnone	18	1712 ^e	117.1
Isonopinone	19	1718 ^f	117.1
Nopinone	20	1717 ^f	114.8

^a Values from ref 25 and 26. ^b Reference 28. ^c Reference 24. ^d Reference 27. ^e Reference 29. ^f Reference 30.

**Figure 1.**

low value of -1.06 for Tafts ρ^* constant.²³ Calculations of the ketone strain were performed in the same way as the strain of the methylhydrocarbons with Allinger's carbonyl force field.^{15b} The reliability of the results was tested by comparison of the calculated internal carbonyl angle with the respective carbonyl

**Figure 2.** Calculated (BIGSTREN) internal carbonyl bond angles and IR carbonyl stretching frequencies. Data from Table II.

IR stretching frequencies. A linear relationship was obtained, as predicted by Halford²⁴ (Table II and Figure 2).

Oxidation Rates

In view of the various approximations in the approach and of the errors in the calculations, it was desirable to obtain rate data covering a range as large as possible. These were available

Table III. Rate Constants and Strain Difference Ketone-Methylhydrocarbon for Alcohol Oxidation^a

No.	Alcohol	log k_{rel}	log k_{corr}^b	Δ strain ^c
1	Cyclohexanol	0.00	0.00	1.74
2	2-Propanol	-0.22	0.01	0.08
3	Di- <i>tert</i> -butylmethanol	0.58	0.21	-3.17
4	Cyclobutanol	0.19	0.19	1.94
5	2,2,4,4-Tetramethylcyclobutanol	1.56	1.19	3.37
6	Cyclopentanol (envelope)	0.18	0.18	2.56
7	<i>trans</i> -2,4,4-Trimethylcyclopentanol (envelope)	0.15	0.07	2.14
8	<i>cis</i> -2,4,4-Trimethylcyclopentanol (envelope)	0.72	0.64	0.02
9	<i>trans</i> -4-Methylcyclohexanol	-0.12	-0.12	1.79
10	<i>cis</i> -4-Methylcyclohexanol	0.34	0.34	0.14
11	<i>cis</i> -3,5,5-Trimethylcyclohexanol	0.13	0.13	1.09
12	<i>trans</i> -3,5,5-Trimethylcyclohexanol	1.57	1.57	-2.87
13	2- <i>exo</i> -Norbornanol	0.18	0.10	1.07
14	2- <i>endo</i> -Norbornanol	1.00	0.92	0.24
15	7-Norbornanol	-0.85	-1.00	5.65
16	Borneol	1.40	1.21	-1.56
17	Isoborneol	1.69	1.50	-3.51
18	2- <i>exo</i> -Bicyclo[3.2.1]octanol	0.96	0.88	0.53
19	2- <i>endo</i> -Bicyclo[3.2.1]octanol	0.30	0.22	1.53
20	3- <i>exo</i> -Bicyclo[3.2.1]octanol	0.61	0.61	0.49
21	3- <i>endo</i> -Bicyclo[3.2.1]octanol	2.00	2.00	-4.19
22	8- <i>exo</i> -Bicyclo[3.2.1]octanol	-0.60	-0.75	3.69
23	8- <i>endo</i> -Bicyclo[3.2.1]octanol	1.10	0.95	2.12
24	9-Bicyclo[3.3.1]nonanol	0.86	0.71	1.27
25	2-Adamantanol	0.83	0.68	1.68
26	<i>endo</i> -5,6-Trimethylene- <i>exo</i> -2-norbornanol	0.38	0.30	0.30
27	<i>endo</i> -5,6-Trimethylene- <i>endo</i> -2-norbornanol	2.71	2.63	-4.81
28	<i>endo</i> -5,6-Trimethylene- <i>exo</i> -8-norbornanol	0.27	0.19	-0.64
29	<i>endo</i> -5,6-Trimethylene- <i>endo</i> -8-norbornanol	1.67	1.59	-1.94
30	α -Nopinol	2.25	2.17	-2.88
31	β -Nopinol	1.07	0.99	-0.65
32	α -Isonopinol	1.43	1.43	-3.41
33	β -Isonopinol	1.48	1.48	-4.00
34	Pinocampheol	1.28	1.20	-1.87
35	Isopinocampheol	1.40	1.32	-3.36
36	Neoisopinocampheol	2.32	2.24	-6.16
37	3- <i>endo</i> , <i>endo</i> -Tetracyclo[4.4.0.1 ^{2,5} .1 ^{7,10}]dodecanol	3.31	3.23	-7.79

^a Data from ref 10. ^b Calculated with $\rho^* = -1$ and σ^* values from ref 23b with respect to two CH_2 groups. ^c Δ strain = strain energy ($\text{R}_2\text{C}=\text{O}$) - strain energy (R_2CHCH_3), in kcal/mol.

only in part from the literature. The rate constants of some 35 alcohols were determined under the same reaction conditions. No significant deviations from available data in the literature were found, although conditions used in the literature vary slightly from ours.

The system used in our work was 80% (by volume) acetic acid, 0.01 N in sulfuric acid. In preliminary studies the first-order dependency of the rate from $[\text{Cr}(6)]$ and $[\text{ROH}]$ was verified with cyclohexanol as substrate.³¹ The ρ^* reaction constant, verified on a series of six alcohols was -0.90 , in good agreement with values reported in the literature,²³ and the kinetic isotope effect for oxidation of 2-propanol 7.8.³² All rate constants were determined under pseudo-first-order conditions with alcohol at least in tenfold excess over chromic acid. The experimental procedure is described elsewhere.¹¹

As the alcohol oxidation with chromic acid is not only subjected to steric but also to electronic effects,² all rate constants were corrected for their different alkyl substitution in the α and α' position. This correction was obtained from the ρ^* value of -1.0 and the σ^* value given in ref 23b, by using two *n*-propyl substituents as reference ($\sigma^{*'} = 0$). The experimental rate constants, relative to cyclohexanol and the corrected values, together with the calculated strain difference between ketone and alcohol are represented in Table III. The details of the calculation have been published¹⁰ and will not be repeated here. The data for compounds not mentioned in ref 10 are given in Table IV. Figure 3 summarizes Tables III and IV.

Δ Strain represents in all but four cases the strain difference between ketone and hydrocarbon in their most stable conformation. For the cyclopentanols 6-8 the envelope conformation was assumed for hydrocarbon and ketone, although for the latter the half-chair form is more stable. For bicyclo[3.3.1]nonan-3-one (48) two minima were obtained, one corresponding to a chair-chair conformation ($\Delta H_f^\circ = -60.77$ kcal/mol), the other to a chair-boat conformation ($\Delta H_f^\circ = -56.20$ kcal/mol). Only the former is retained in Figure 3.

Discussion

In Figure 3 the relative rate constants for oxidation (in logarithmic units) are plotted against the strain difference (Δ strain) between ketone and methylhydrocarbon. The slope of the straight line is -0.28 , the intercept 0.643, the standard deviation 0.36, and the correlation coefficient 0.9063. The compounds 3 and 5, di-*tert*-butylcarbinol and tetramethylcyclobutanol, for which assumption a (identical entropies of activation) is incorrect, are not shown. 8-*endo*-Bicyclo[3.2.1]octanol (23) and 3-*exo*-bicyclo[3.3.1]nonanol (47) are the only compounds falling slightly outside of the limit of two standard deviations. The significance of this deviation is not clear; however, these alcohols fell also out of the correlation between stability and reactivity of epimeric alcohols.

The conclusion emerging from Figure 3 is clearly that there exists a relationship between oxidation rates and Δ strain. This implies that *the properties of the carbonyl product must, at*

Table IV. Oxidation Rates of Alcohols and Strain in Their Methyl Analogues and Ketones^a

No.	Alcohol	log k^b	log k_{corr}^b	$-\Delta H_f^\circ$ ^c	Strain	$-\Delta H_f^\circ$ ^c	Strain	Δ strain
				R ₂ CHCH ₃	energy ^d	R ₂ C=O	energy ^d	
38	2-Butanol	-0.18	0.43	36.69 ^e	0.66 ^e	57.27 ^g	0.05	-0.61
39	<i>trans</i> -2-Methylcyclohexanol	0.02 ^h	-0.06	43.25 ^e	1.79	62.25 ^g	2.80	1.01
40	<i>cis</i> -2-Methylcyclohexanol	0.62 ^h	0.54	41.83 ^e	3.21	62.25 ^g	2.80	-0.49
41	<i>trans</i> -3-Methylcyclohexanol	0.53 ^h	0.53	42.22 ^f	2.82	62.41 ^g	2.65	-0.17
42	<i>cis</i> -3-Methylcyclohexanol	-0.07 ^h	-0.07	44.03 ^f	1.01	62.41 ^g	2.65	1.64
43	<i>cis,cis</i> -3,5-Dimethylcyclohexanol	-0.05 ^h	-0.05	51.28 ^f	0.77	68.45 ^g	3.56	2.79
44	<i>trans,trans</i> -3,5-Dimethylcyclohexanol	0.70 ^h	0.70	49.39 ^f	2.66	68.45 ^g	3.56	0.90
45	<i>exo</i> -Bicyclo[3.3.1]nonan-2-ol	0.91	0.83	36.03	11.56	56.53	11.08	-0.48
46	<i>endo</i> -Bicyclo[3.3.1]nonan-2-ol	0.89	0.81	37.02	10.57	56.53	11.08	0.51
47	<i>exo</i> -Bicyclo[3.3.1]nonan-3-ol	0.85	0.85	37.39	10.20	60.75	6.86	-3.34
48	<i>endo</i> -Bicyclo[3.3.1]nonan-3-ol	1.51	1.51	36.03	11.56	60.75 ⁱ	6.86	(-4.71)
						56.20 ^k	11.41	(-0.15)
49	3- <i>exo,endo</i> -Tetracyclo[4.4.0.1 ^{2,5} .1 ^{7,10}]dodecan-ol	1.53	1.45	0.56	51.58	22.02	49.02	-2.56

^a For compounds not mentioned in ref 10. ^b Rate constants at 25 °C relative to cyclohexanol in 80% (by volume) acetic acid, 0.01 N sulfuric acid. ^c Calculated standard enthalpies of formation at 25 °C, in kcal/mol. ^d Strainless increments according to Allinger.^{15a} ^e Reference 14b. ^f Reference 15c. ^g Reference 15b. ^h Reference 19, 21. ⁱ Chair-chair conformation. ^k Chair-boat conformation.

least in part, be reflected in the transition state for alcohol oxidation with chromic acid. Although the overall trend is quite clear, the approach may fail when small energy differences are involved. Particular difficulties are caused by conformationally flexible compounds. In the cyclopentanol series we arbitrarily select a conformation for the ketone (envelope) which is not the most stable one, on the grounds that there should be a minimal conformational change in going to the transition state. This procedure may be questioned, and the results for acyclic and other flexible systems must be considered with caution.

The main and most fundamental problem in the approach comes from the fact that the overall rate spread corresponds only to 5.7 kcal in enthalpies of activation, while Δ strain covers 15 kcal/mol. On the other hand the free-energy relationship between stability and reactivity toward oxidation¹⁹ indicates that the transition states for oxidation of epimeric alcohols are to 80% equivalent. As a consequence one might expect that to a range of 15 kcal in Δ strain should correspond a variation in the enthalpies of activation by 12 kcal. This is, however, not the case. Part of the disagreement may be caused by our approximation b, namely that methyl strain equals hydroxyl strain. The approximation tends to overestimate in particular the strain of hindered alcohols, although not much of the unhindered ones. We believe that the more important contribution comes from approximation c. The carbonyl group is only partly developed in the transition state, as the carbinol hydrogen and the chromic acid are still bound to the molecule. The ketone model used to calculate the properties of the transition state accounts adequately for the relief of strain present in the alcohol, but it leads to an overestimation of angle strain in the activated complex. Wilcox has proposed²² that "in the transition state the hybridization of the remaining carbon-carbon bonds more nearly approximates the starting alcohol (ca. sp³) than the final ketone (ca. sp²)", because small displacements of the interacting groups greatly alter the steric repulsions. However, the approach of Wilcox is based on the relative reactivities of epimeric alcohols alone and allows no conclusions to be made with respect to the relevance of ketone strain in the transition state. Our correlation shows that the strain in the carbonyl product is reflected in the transition state of the alcohol oxidation, but that the oxidation is more sensitive to changes in nonbonded interactions than to changes in the angle strain. On the grounds of our calculations we are not able

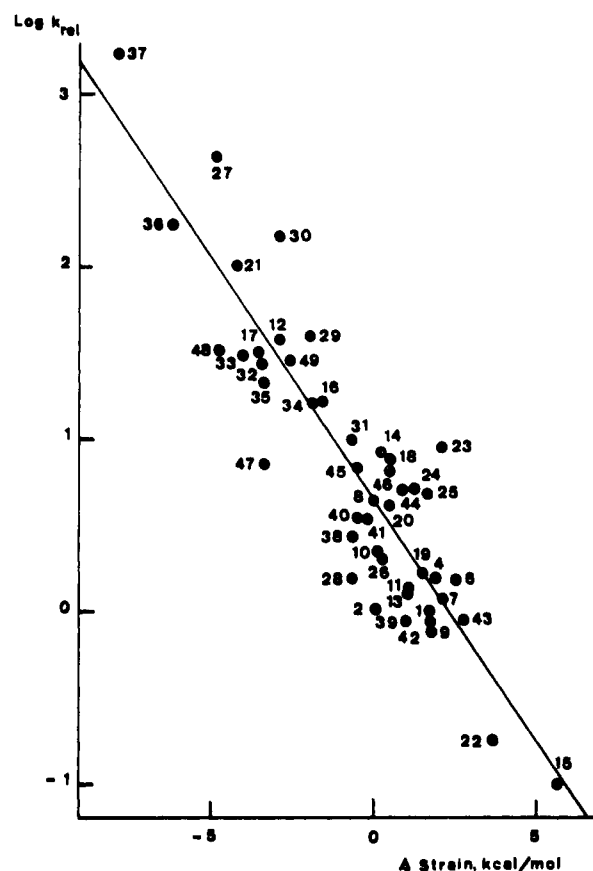


Figure 3. Plot of log K_{cor} vs. Δ strain. Data from Tables III and IV. Slope, -0.28; correlation coefficient, 0.91; standard deviation, 0.36.

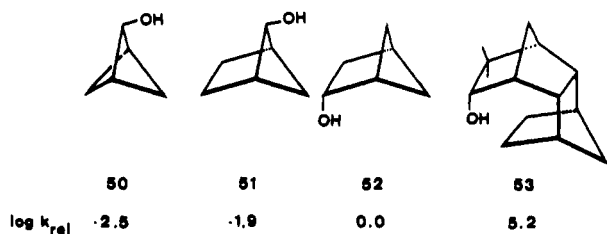
to draw detailed conclusions on the precise geometry of the transition state.

The strain calculations allow prediction of oxidation rates for alcohols not yet measured. Such predictions are useful for selective oxidations of polyfunctional molecules in synthesis and in order to extend the rate range from our calculations. For example, compounds 50–53 are predicted to be oxidized with the following rate constants (relative to cyclohexanol), by means of the equation $\log k_{\text{rel}} = -0.28 \Delta \text{ strain} + 0.64$.

Table V. MINDO/3 Calculations

Alcohol	$\log k_{\text{corr}}^a$	$\Delta H_f^\circ{}^b$ R_2CHCH_3	$\Delta H_f^\circ{}^b$ R_2COH	$\Delta\Delta H_f^\circ{}^c$	Strain ^{b,d} R_2CHCH_3	$\Delta H_f^\circ{}^b$ $R_2C=O$	Strain ^{b,d} $R_2C=O$	Δ strain ^e
2-Propanol	0.01	-24.97	-50.31	-25.34	7.14	-53.26	-1.13	-8.27
Cyclopentanol	0.18	-28.54	-52.41	-23.87	4.35	-58.06	-5.14	-9.49
trans-4-Methylcyclohexanol	-0.12	-34.80	-60.43	-25.63	10.24	-64.62	0.44	-9.80
cis-4-Methylcyclohexanol	0.34	-33.26	-60.24	-26.98	11.78	-64.62	0.44	-11.34
cis-3,3,5-Trimethylcyclohexanol	0.13	-19.41			40.69	-49.61	30.51	-10.18
trans-3,3,5-Trimethylcyclohexanol	1.57	-17.16			42.94	-49.61	30.51	-12.43
2-exo-Norbornanol	0.10	6.98	-17.13	-24.11	44.19	-24.92	32.31	-11.88
2-endo-Norbornanol	0.92	7.49	-17.13	-24.62	44.70	-24.92	32.31	-12.39
7-Norbornanol	-1.00	7.61	-17.31	-24.92	44.82	-27.77	29.46	-15.36
3-exo-Bicyclo[3.2.1]octanol	0.61	-10.04	-36.52	-26.48	32.36	-40.65	21.77	-10.59
3-endo-Bicyclo[3.2.1]octanol	2.00	-8.87	-36.52	-27.65	33.53	-40.65	21.77	-11.76
8-exo-Bicyclo[3.2.1]octanol	-0.75	-10.17	-36.43	-26.26	32.23	-45.03	17.39	-14.84
8-endo-Bicyclo[3.2.1]octanol	0.95	-9.13	-35.91	-26.78	33.27	-45.03	17.39	-15.88
9-Bicyclo[3.3.1]nonanol	0.71	-20.73			26.86	-56.64	10.97	-15.89

^a Data from Table III. ^b MINDO/3 calculations. ^c ΔH_f° ($R_2COH - \Delta H_f^\circ R_2CHCH_3$) in kcal/mol. ^d Strainless increments from Allinger.^{15a} ^e Strain $R_2C=O$ - strain R_2CHCH_3 , in kcal/mol.



MINDO/3 Calculations

Because of the overestimation of carbonyl strain by our ketone model for the transition state of oxidation the radical model was also calculated:



These calculations could not be handled by the force-field method (no parametrization available). Therefore the MINDO/3 program was used. As before, the enthalpies of formation of the methylhydrocarbons were determined instead of those of the alcohols. The results of the calculations are reproduced in Table V. A plot of $\log k$ vs. $\Delta\Delta H_f^\circ$ (ΔH_f° radical - $\Delta H_f^\circ RCH_3$) produced a trend in the correct direction. However, the scatter in the data was too high as to allow safe conclusions. Similarly, when the enthalpies of formation for ketones were calculated by this method a reasonable trend was obtained. In this case, the correlation broke down when ketones substituted with two tertiary carbon atoms were included (see Table V).

Conclusions

The procedure used in this work for the rationalization of relative reactivities is based on the evaluation of strain in starting compounds (alcohols) and products (ketones). The accuracy of the method can be improved if better force fields for functional groups become available. The basic assumption of representing the transition state by the product (or a reactive intermediate) limits the reliability of the approach. It requires proportionality between strain in the transition state and the respective model. This proportionality can only be achieved if all individual interactions change continuously and to the same degree during the reaction, which usually is not the case. The approach will therefore only work as long as the model used for representing the transition state is sufficiently close to the latter. Otherwise substantial systematic errors are introduced by this procedure.

In the chromic acid oxidation of alcohols, experimental evidence suggests that nonbonded interactions in the alcohols should have disappeared to about 80%, while the carbonyl strain is only in part built up. The calculations, however, consider only the total strain difference of ketone-hydrocarbon. This discrepancy could, in principle, be overcome by modifying the force constant for deformation of the internal carbonyl bond angle. It was not done here because we feel it more useful to discuss reactivity in terms of ground-state properties of molecules instead of properties of hypothetical transition states.

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Polyolithium Compounds. 8. Synthesis of Allenes and Acetylenes from Perlithiopropyne, Trilithiobutryne, and Dilithio-3-methylbutryne^{1,2}

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Abstract: The polyolithiation of 1- and 2-butyne to give trilithiobutryne, MeC_3Li_3 , and 3-methylbutryne to give dilithio-3-methylbutryne, $\text{Me}_2\text{C}_3\text{Li}_2$, have been investigated. Reactions of these polymetalated hydrocarbons and the lithiocarbon C_3Li_4 with dialkyl sulfates, chlorosilanes, and chlorogermanes yield polysubstituted allenenes and acetylenes, in ratios dependent on the steric size of the derivatizing agents. Reaction of C_3Li_4 and $\text{Me}_2\text{C}_3\text{Li}_2$ with ethyl iodide produced oxidative coupling products. The infrared spectra of polyolithiated acetylenes are reinterpreted in terms of propargylide and allenic anions.

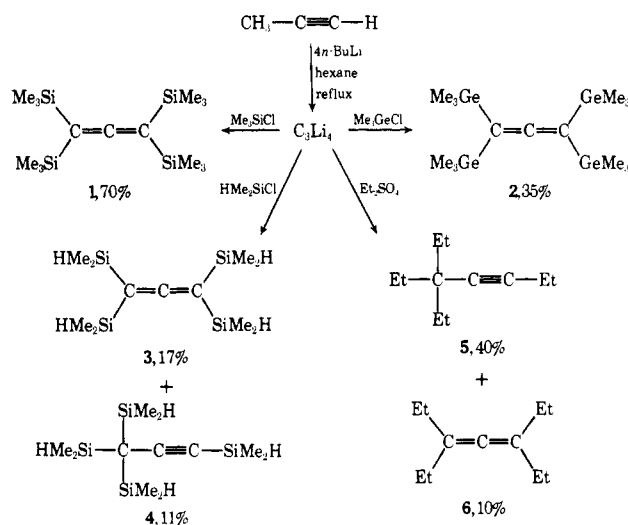
Introduction

The chemistry of poly- and perlithiated hydrocarbons has been a subject of continuing interest in recent years. Since West, Carney, and Mineo^{3,4} prepared C_3Li_4 by the dropwise addition of propyne to four equivalents of *n*-butyllithium and Eberly and Adams⁵ polymetalated 1-butyne and 1,2-butadiene using *n*-butyllithium, numerous papers have appeared on the subject of polyolithiation.⁶⁻¹⁴ Especially exciting is a recent paper by Shimp and Lagow who reported C_3Li_4 to be the major product in the high-temperature reaction of lithium atoms with carbon vapor.¹⁵ In this paper we report the preparation of dilithio-3-methylbutryne, $\text{Me}_2\text{C}_3\text{Li}_2$, from 3-methylbutryne; trilithiobutryne, MeC_3Li_3 , from both 1- and 2-butyne; and the use of C_3Li_4 , MeC_3Li_3 , and $\text{Me}_2\text{C}_3\text{Li}_2$ as intermediates in the synthesis of allenenes and acetylenes. In addition we have reexamined the infrared spectra of these and other polyolithium compounds and propose structures for these species.

Results

Tetralithiopropyne (C_3Li_4). The lithiocarbon C_3Li_4 reacts with organic or organometallic substrates in the presence of tetrahydrofuran (THF) to give either allenic or acetylenic derivatives or both. With trimethylchlorosilane⁴ and trimethylchlorogermane the products are tetrasubstituted allenenes **1** and **2** (see Scheme I). With dimethylchlorosilane both the allenic **3** and acetylenic **4** tetrakis derivatives are observed. Reaction of C_3Li_4 with diethyl sulfate yielded the first hydrocarbon derivatives, the acetylene **5** and the allene **6**.¹⁶ ¹H NMR, IR, UV, and mass spectral data for all compounds shown are in full agreement with proposed structures. Yields have not been optimized.

Scheme I



Addition of C_3Li_4 to an excess of ethyl iodide in THF at -78°C resulted in no simple derivatives; however, a compound of formula $\text{C}_{14}\text{H}_{20}$ was isolated in 13% yield. The ¹H NMR spectrum of this coupling product consists of two equally intense overlapping quartets at δ 1.0 and 1.2 (12 H), and two overlapping quartets at δ 2.0–2.6 (8 H). The IR shows an internal acetylene stretch at 2200 cm^{-1} . The UV spectrum has a λ_{max} at 263 nm with a shoulder at 273 nm (ϵ 11 400 and 9650, respectively), suggesting a triene skeleton.¹⁹ From these data the product was identified as 5,6-diethyl-5-decen-3,7-