samples, except for 1,4-cyclooctadiene and 3,3-dimethyl-1-pentene. The former was assumed to be the intermediate product in the isomerization of 1,5-cyclooctadiene to 1,3-cyclooctadiene, while the latter was assumed to be the intermediate in the hydrogenation of 3,3-dimethyl-1,4-pentadiene to 3,3-dimethylpentane. Authentic nortricyclene was obtained by treating a solution of the Grignard reagent of 3-bromonortricyclene[30] with anhydrous HCl. Bicyclo[3.3.0]oct-2-ene was a gift from Dr. P. R. Stapp.

Registry No.—$RuCl_2(CO)_2(PPh_3)_2$, 29079-66-1.

(30) Purchased from Aldrich Chemical Co.

The Role of Hydrate Formation in the Chromium(VI) Oxidation of Aldehydes[1]

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Reaction rates for the chromic acid oxidation of a series of aliphatic aldehydes have been determined and correlated with aldehyde hydration equilibria. A value of $\rho^* = -1.1$ for the oxidation of aldehyde hydrates has been obtained. The results support a mechanism consisting of a rate-limiting oxidative decomposition of a chromic acid ester of an aldehyde hydrate. The applicability of the mechanism to the oxidation of aromatic aldehydes is discussed. The deuterium isotope effect for the oxidation of pivaldehyde ($k_H/k_D = 7.9$) shows that even this aldehyde reacts "normally" by carbon–hydrogen rather than by a carbon–carbon cleavage.

We have earlier pointed out that the chromium(VI) oxidation of aldehydes can be better understood and correlated with the oxidation of alcohols if it is regarded as an oxidation of an aldehyde hydrate rather than of the free carbonyl compound.[2,3]

In the course of the investigation of the chromium(IV) oxidation of aldehydes[4] we needed to determine the chromium(VI) oxidation of a larger series of aliphatic aldehydes. Since a great deal more information on aldehyde hydration equilibria is now available,[5-11] we were able to analyze the data more completely than could be done at the time of our earlier investigation.[2]

Table I summarizes the experimental rate constants, k_{obsd}, for the chromic acid oxidation of a series of eight aliphatic aldehydes. Also given are the aldehyde hydrate dissociation constants, K_d, pertaining to the reaction $RCH(OH)_2 \rightleftarrows RCHO + H_2O$. From k_{obsd} and K_d, two sets of rate constants referring to the oxidation of the aldehyde in only one of the forms present in solution were computed. The values for k_H were obtained by assuming that only the hydrated form will appear in the rate law

$$v = k_H[Cr(VI)][RCH(OH)_2] \quad (1)$$

Conversely, the value for k_A was calculated using only the concentration of the free aldehyde according to the rate law[12]

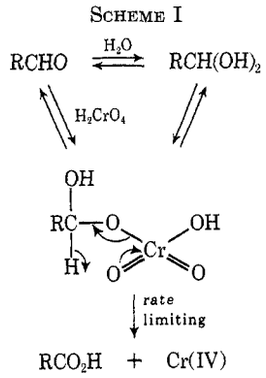
$$v = k_P[Cr(VI)][RCHO] \quad (2)$$

A plot of log k_H against Taft's substituent constants σ^* gives a good straight line (Figure 1; correlation coefficient 0.99, standard deviation 0.2) with a slope of $\rho^* = -1.1$.[13] On the other hand, the correlation of σ^* with k_A is much less satisfactory. The main deviation is observed for formaldehyde, which appears to be almost 1000 times more reactive than would be predicted from the $\sigma^*\rho^*$ plot based on the other aldehydes. When the value for formaldehyde is ignored, a straight line (correlation coefficient 0.97, standard deviation 0.16) giving a value of $\rho^* = 0.53$ may be obtained.

In the above results, the case of formaldehyde is of particular interest. If one assumes that the aldehyde reacts *via* the hydrate (eq 1), a rate constant, k_H, is obtained which compares well with the reactivities of other aldehydes. On the other hand, if only free formaldehyde could be oxidized, then one would have to assume that formaldehyde is about 1000 times more reactive than other aldehydes. This makes a mechanism consisting of a direct hydrogen transfer reaction between the free aldehyde and chromic acid (to yield, *e.g.*, $R\dot{C}{=}O$ or $RC^+{=}O$) very unlikely.

The results obtained in this study thus agree well with the mechanism in which the rate-limiting step is the oxidative decomposition of a chromic acid ester of an aldehyde hydrate (Scheme I).

SCHEME I



(1) The support of this work by the National Science Foundation is gratefully acknowledged.

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(12) As all reactions were carried out at constant acidity, the acidity dependence of the oxidation reaction is not explicitly considered. Thus all rate constants used in this paper, k_{obsd}, k_H, and k_A, represent acidity-dependent rate constants.

(13) This value is in good agreement with the value of $\rho^* = -1.2$ obtained earlier from a much more limited set of experimental data.[2]

TABLE I

CHROMIUM(VI) OXIDATION OF ALIPHATIC ALDEHYDES IN WATER IN 0.2 M $HClO_4$ AT 25°

Registry no.	Aldehyde	K_d	Second-order rate constant, M^{-1} sec^{-1} × 10^3 k_{obsd}	k_H	k_A
50-00-0	HCHO	0.00055[b]	3.99 ± 0.28	3.99 ± 0.28	7250 ± 522
75-07-0	CH_3CHO	0.67[c,d]	2.80 ± 0.20	4.68 ± 0.31	7.30 ± 0.62
123-38-6	CH_3CH_2CHO	1.4[e]	4.35 ± 0.45	10.5 ± 1.1	7.50 ± 0.79
123-72-8	$CH_3CH_2CH_2CHO$	2.1[e]	4.41 ± 0.20	13.6 ± 0.5	6.47 ± 0.23
630-19-3	$(CH_3)_3CCHO$	4.1[f]	2.04 ± 0.08	10.5 ± 0.5	2.54 ± 0.11
107-20-0	$ClCH_2CHO$	0.027[g]	0.434 ± 0.040	0.445 ± 0.041	16.5 ± 1.5
79-02-7	Cl_2CHCHO[a]		0.0889 ± 0.0087	0.0889 ± 0.0087	
75-87-6	Cl_3CCHO	0.000036[e]	0.00598 ± 0.00069	0.00598 ± 0.00069	166.0 ± 18.0
41162-98-5	$(CH_3)_3CCDO$		0.258		
	$(CH_3)_2CHOH$[h]		0.746 ± 0.071		

[a] The value of the hydration equilibrium constant for Cl_2CHCHO is not available. It is assumed here that this value lies between those for $ClCH_2CHO$ and Cl_3CCHO, thus making $k_{obsd} = k_H$. [b] Reference 6. [c] Reference 7. [d] Reference 8. [e] Reference 9. [f] Reference 10. [g] Reference 11. [h] Included for comparison.

The chromic acid ester of the aldehyde hydrate in the above mechanism is in equilibrium with both the free aldehyde and the hydrate.[14] In principle, it is therefore immaterial whether the ester is thought of as being formed by a carbonyl addition reaction from the free aldehyde or by an esterification reaction from the hydrate. However, the latter proposal is much more useful as it results in an improved ability to understand and predict aldehyde oxidations and their relationship to the closely related oxidations of alcohols. For example, the relatively low reactivity of aromatic aldehydes[16] is readily understood as a consequence of the low degree of hydrate formations in aromatic aldehydes.

It is of interest to compare the ρ^* values determined in this study with the ρ values obtained earlier by Wiberg for a series of aromatic aldehydes in 91% acetic acid.[19,20] As aromatic aldehydes are hydrated only to a very small extent, the observed ρ values have to be compared with ρ^* obtained from the k_A values as defined by eq 2 for aliphatic aldehydes. Considering the difference in the nature of the aldehydes, in the solvent, and in the reactivity constant used, the similarity between Wiberg's values (ρ = 1.02[19] and 0.77[20]) and our value (ρ^* = 0.53) is satisfactory inasmuch as in both cases small positive values were obtained. This similarity offers additional support for our earlier suggestion that aliphatic and aromatic aldehydes react by the same mechanism (Scheme I) in which the rate-limiting step is the oxidative decomposition of a chromic acid ester of an aldehyde hydrate.

Previous investigators have found sizable isotope effects in the oxidation of formaldehyde (k_H/k_D = 6.8)[21] and acetaldehyde.[22] It was of interest to determine the deuterium isotope effect in the chromic acid oxidation of pivaldehyde, because this aldehyde could possibly react with carbon–carbon bond cleavage, leading to a tertiary carbonium ion intermediate. The rather large observed primary isotope effect (k_H/k_D = 7.9) indicates that this aldehyde reacts normally, *i.e.*, with carbon–hydrogen bond breaking in the rate-limiting step.

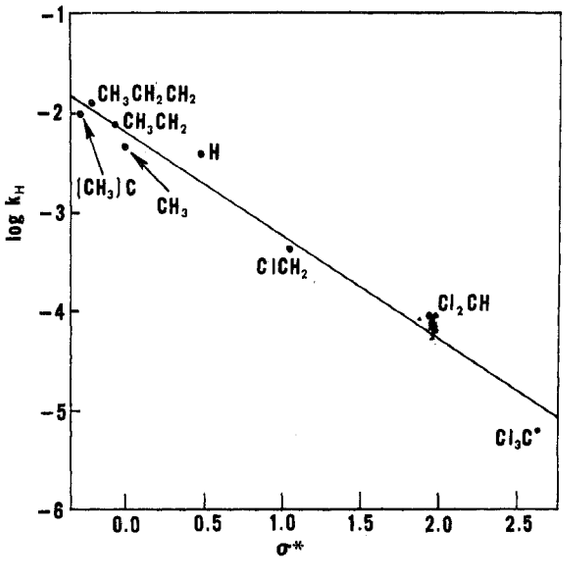

Figure 1.—The chromic acid oxidation of aldehyde hydrates.

Experimental Section

Acetaldehyde (Eastman Chemicals), butyraldehyde (Eastman Chemicals), propionaldehyde (Matheson Coleman and Bell), and chloroacetaldehyde (K & K Laboratory) were purified by fractional distillation through a 14-cm silvered vacuum-jacketed column packed with Nichrome Helipak. Formaldehyde was prepared by heating paraformaldehyde (Eastman Chemicals) in a round-bottom flask by immersing the flask in an oil bath at 180–200°.[23] The formaldehyde gas liberated was introduced into water in an erlenmeyer flask. Dichloracetaldehyde (City Chemicals) and pivaldehyde (K & K Laboratory) were purified by preparative gas–liquid chromatography using a 80 × 0.75 in. silicone rubber SE-30 stainless steel column. Trichloroacetaldehyde (Eastman Chemicals) was distilled through a 14-cm silvered vacuum-jacketed column packed with Nichrome Helipak under nitrogen atmosphere and in the dark.

1-Deuteriopivaldehyde was prepared by the controlled chromic acid oxidation of 1,1-dideuterioneopentyl alcohol,[24] which was prepared by the lithium aluminum deuteride reduction of ethyl pivalate.[25] The ir spectrum of the synthesized 1-deuteriopival-

(14) Evidence for the formation of a chromic acid ester of an aldehyde hydrate has been obtained by Kläning.[15]

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dehyde showed absorptions at 2040 and 2130 cm^{-1} indicative of the C–D stretching of the –CDO group. Its nmr spectrum showed only a single peak at δ 1.1 ppm and no absorption in the δ 8–12-ppm region, indicating the absence of the aldehydic proton. The deuterium content in the aldehyde was determined to be greater than 99% by mass spectroscopy.

All the liquid aldehydes were checked for purity on an F & M 5750 research chromatograph before being dissolved in water for oxidation studies. Because of the high volatility of some of these aldehydes, the concentration of the aqueous solutions was determined analytically. Solutions of formaldehyde, acetaldehyde, propionaldehyde, and butyraldehyde were determined by the hydroxylamine hydrochloride method.[26] Solutions of chloroacetaldehyde and dichloroacetaldehyde were determined by the dinitrophenylhydrazine method.[27]

Kinetic measurements were made by following the decrease in the chromium(VI) concentration spectrophotometrically at 432 nm using a Cary Model 15 double-beam spectrophotometer. All the kinetic experiments were run at 25°. The pseudo-first-order rate constant of the chromium(VI) oxidation of the aldehydes was obtained from the slope of the plot of log $(A_t - A_\infty)$ *vs.* time, where A_t and A_∞ were the absorbance at 432 nm of the reaction mixture at time t and at infinity, respectively. The second-order rate constants, k_{obsd}, were obtained from the pseudo-first-order rate constants and the analytical concentration of the aldehyde.

Registry No.—Chromium, 7440-47-3.

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(27) Reference 26, p 92.

Borane Reduction of 3-Substituted 2-Indolinones

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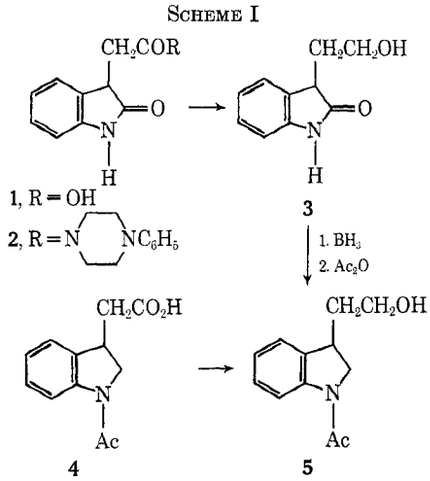
The utility of borane for the preparation of indolineethanols (**9**) by reduction of 3-(2-hydroxyethyl)-2-indolinones (**3**), alkyl 2-oxo-$\Delta^{3,\alpha}$-indolineglycolates (**7**), and alkyl 2-oxo-3-indolineacetates (**8**) is illustrated.

We required certain 3-indolineethanols as intermediates for another investigation, and their preparation from 3-substituted 2-indolinones by reductive procedures seemed a distinct possibility. The reduction of 2-indolinones by hydride reagents has been the subject of numerous reports which lack consistency. An early report[1] indicating that lithium aluminum hydride was useful for this purpose is unfounded.[2] However, several investigators have indicated that borane possesses the capacity for such reductions, although the efficiency of this agent for reduction of 2-indolinone and certain 3-substituted derivatives is subject to variability.[2c,3] In this laboratory application of the commercially available reagent[4] to 2-indolinone gave 46% of indoline. Accordingly, the utility of borane for the reduction of certain 3-substituted 2-indolinones was studied.

Initially the preparation of indolineethanol (**9a**) by reduction of the heretofore elusive "oxytryptophol" (**3**)[5] was undertaken. The required 3-(2-hydroxyethyl)-2-indolinone (**3**) was prepared by conversion of 2-oxo-3-indolineacetic acid (**1**)[6] into a mixed carbonic anhydride with ethyl chlorocarbonate; the formation of the anhydride was established by its conversion into the amide **2** with 1-phenylpiperazine (see Scheme I). Reduction of the anhydride with sodium borohydride[7] gave 52% of the required alcohol **3**. This material was then reduced with borane to give 49% of 3-indolineethanol which was characterized as the *N*-acetyl derivative **5**; the last compound also was prepared by reduction of 1-acetylindolineacetic acid (**4**)[8] with borane. The preparation of **5** by the second procedure further illustrates the sharp difference in rate of reaction with borane observed for carboxylic acids and amides.[9]

Scheme I



The above transformations met our requirements in principle. However, the preparation of **5** and congeners from 2-indolinones requires three successive reductions, for the synthesis of **1** can only be accomplished by catalytic hydrogenation of benzyl 2-oxo-$\Delta^{3,\alpha}$-indolineglycolate.[6] Therefore, we sought to circumvent the numerous operations by investigating the reduction of intermediates prior to **1**.

These studies were conducted with derivatives of 2-indolinone (**6a**), 5,6-dimethoxy-2-indolinone (**6b**),[10]

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