Alcohol Oxidation by Dioxygen and Aldehydes Catalysed by Square-Planar Cobalt(III) Complexes of Disubstituted Oxamides and Related Ligands

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The square-planar cobalt(III) complexes of *o*-phenylenebis(N'-methyloxamidate) (Me_2opba) and related oxamate (Meopba) and bis(oxamate) (opba) ligands catalyse the selective oxidation, by dioxygen and pivalaldehyde, of a wide range of secondary alcohols to the corresponding ketones, in good yields and under mild conditions in acetonitrile at room temperature. Thus, the oxidation of the series of α-alkylbenzyl alcohols PhCH(OH)R (R = Me, Et, *i*Pr, *t*Bu) results in the exclusive formation of ketones as a product of C–H bond cleavage, and no C–C bond cleavage products are observed in any case. The modulation of catalytic activity by ligand substituents among this series of cobalt catalysts highlights the role of oxocobalt(IV) species as the putative intermediates in these aerobic alcohol oxidation reactions. Relative reactivities for the oxidation of 1-phenylethanol increase in the order Me_2opba < Meopba < opba, which correlates with the oxidising power of the postulated Co^{IV}=O intermediate. In contrast, competitive reaction studies on the oxidation of the series of *para*-substituted 1-phenylethanol derivatives $XPhCH(OH)CH_3$ (X = H, OMe, Br, CF_3, NO_2) show little variation in relative rate (k_X/k_H) with the *para* substituent and no correlation with Hammett σ parameters. Overall, these results are more in line with a mechanism involving concerted hydride transfer in the oxidation of alcohols by high-valent oxocobalt species (rather than a hydrogen atom transfer or an electron transfer mechanism).

Introduction

The oxidation of alcohols to carbonyl compounds is a very important reaction in organic chemistry and numerous methods and reagents are available to achieve this transformation.[1] Traditionally, oxidations of alcohols have been performed with high-valent metal oxides or their mineral salts, notably of middle first row transition metals.[2] Common reagents of this type are: chromium(VI) oxide (CrO_3), potassium chromate(VI) (K_2CrO_4), potassium dichromate(VI) ($K_2Cr_2O_7$), manganese(IV) oxide (MnO_2) and potassium permanganate(VII) ($KMnO_4$). Potassium ferrate(VI) (K_2FeO_4) has recently also been added to this list.[2d] In most instances, these inorganic oxidants are required in stoichiometric amounts and are usually toxic, hazardous or both. Moreover, purification of the reaction products is often demanding and laborious. In recent years, there has been great interest in the search for new metal catalytic systems for the oxidation of alcohols that use hydrogen peroxide[3,4] or dioxygen[5−11] as the ultimate stoichiometric oxidant, due to their obvious economic and ecological advantages ("green chemistry"). However, the number of metal compounds capable of mediating dioxygen activation (through metal−O_2 adduct formation), thus leading to alcohol oxidation, is distinctly limited.[12−18] One possible alternative involves the use of an external reductant for initial activation of dioxygen (reductive O_2 activation). Aldehydes have been successfully used by Mukaiyama[19] and others[20] in this way (i.e., through the in situ generation of peracid from the aldehyde and O_2) for the aerobic epoxidation of olefins with a metal β-diketonate complex as catalyst.[21] Hence, during the last decade, a significant number of first row transition metal complexes with different ligand types (e.g., β-oxo iminate, β-oxo esterate, Schiff base, porphyrin, tetraazamacrocycle, oxamate and oxamidate) have been found to be effective catalysts for the oxidation of a variety of organic substrates using dioxygen in the presence of an aldehyde as oxidant.[19,22−29] This also includes the oxidation of alcohols catalysed by cobalt(II)−Schiff base[23a] or manganese(IV) oxamate[27b] complexes. However, fundamental studies focusing on a mechanistic understanding of these catalytic reactions are comparatively scarce, investigations of the role played by the metal complex itself particularly so.[20,24,26,28a]

In this context, we have recently reported on the preparation of square-planar anionic cobalt(III) complexes with the ligand *o*-phenylenebis(N'-methyloxamidate) (Me_2opba) and its oxamate (Meopba) and bis(oxamate) (opba) derivatives (Scheme 1).[29] This kind of tetraanionic polychelating ligand, with large electron-donor capacities thanks to the presence of the strongly basic amide groups, allows unusually high oxidation state complexes of late first row transition metal ions to be attained (Co^{III}, but also Ni^{III} [28a,30]

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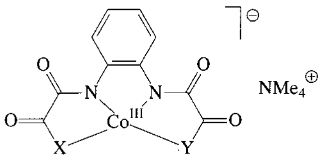
and Cu^{III} [31]).[32] In an earlier work, we used these cobalt oxamidate and/or oxamate complexes as catalysts in the epoxidation of olefins[29a] and the oxidative decarboxylation of α-hydroxy acids[29b] with dioxygen and pivalaldehyde. At the time, the mechanism by which these reactions might proceed was not considered in detail, although the catalytic activity was tentatively ascribed to a high-valent oxometal species by comparison with related catalytic systems based on cobalt complexes with amide-containing ligands, which epoxidise olefins with iodosylbenzene as oxidant.[33a,34] In general, higher oxidation state complexes of transition metals become progressively rarer the further to the right the element is in the periodic table.[32b] Thus, discrete high-valent M=O groups are not expected to be stable under ordinary conditions for any first row transition metal beyond iron;[35] however, reactive species such as $Co^{IV}=O$[33a] or $Ni^{IV}=O$[33b] may be capable of transitory existence when supported by strongly donor oxidative resistant ligands such as those used here.



X	Y	L	Complex
N(CH$_3$)	N(CH$_3$)	Me$_2$opba	**1**
N(CH$_3$)	O	Meopba	**2**
O	O	opba	**3**

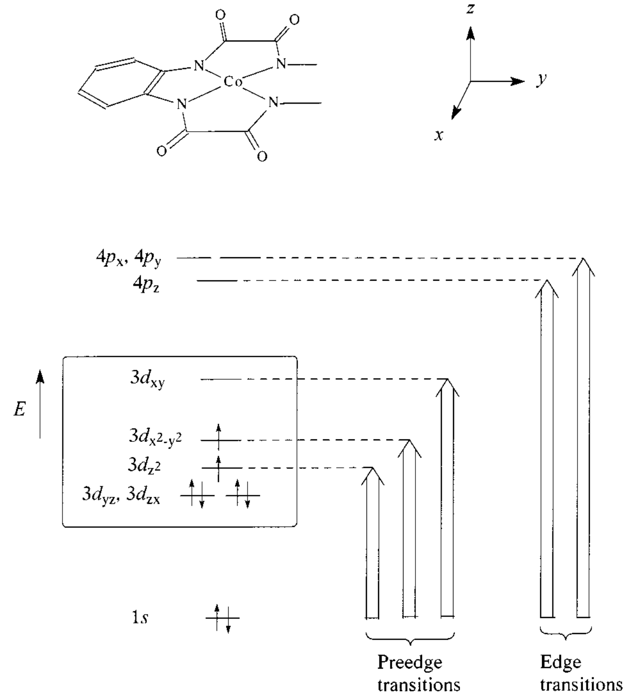
Scheme 1

Here we report on the detailed synthesis and general characterisation of the family of square-planar cobalt(III) complexes of general formula $(Me_4N)[Co(L)]\cdot nH_2O$ − where L stands for Me$_2$opba (n = 2), Meopba (n = 3) and opba (n = 4) complexes **1**−**3**, respectively − and their use as catalysts for the oxidation of alcohols with dioxygen in the presence of an aldehyde (Mukaiyama's conditions). Furthermore, we propose a rational mechanism for the cobalt-catalysed aerobic oxidation reactions, which accounts for our experimental results and, in particular, we present strong evidence for the participation of high-valent oxo-cobalt(IV) species as the actual oxidising agents.

Results

Synthesis and Characterisation of the Cobalt Catalysts

The tetramethylammonium salts of the square-planar cobalt(III) complexes with *o*-phenylenebis(*N'*-methyloxamidate) and related oxamate ligands were obtained in moderate yields (25−30%) by means of air oxidation of the corresponding cobalt(II) complexes, prepared in situ from reaction between a Co^{II} salt and the proligand in basic methanolic Me_4NOH solution.[36] Complexes **1**−**3** are sparingly soluble in aprotic solvents such as acetonitrile or dichloromethane, but very soluble in methanol and water, affording dark brown solutions. Solid-state variable-temperature (80−300 K) magnetic susceptibility measurements for all these complexes showed Curie law behaviour, with an estimated effective magnetic moment of about 3.0 μ_B. These data are consistent with intermediate spin triplet (S = 1) ground states, suggesting that **1**−**3** are tetracoordinated square-planar Co^{III} complexes, like their structurally characterised Cu^{II} and Cu^{III} analogues.[31] In fact, intermediate spin d^6 square-planar cobalt(III) complexes have previously been reported by Collins, for a related class of polyanionic chelating ligands incorporating N-amide donor groups.[34,37] In all these compounds, the intermediate spin state is a consequence of the large σ-field strength afforded by these ligands, which raises the energy of the $3d_{xy}$ molecular orbital that remains unoccupied. This situation is illustrated in Scheme 2 for complex **1**.



Scheme 2. Simplified electronic structure and electronic transitions for **1**; the boxed structure is the energy-level diagram of the frontier 3d molecular orbitals corresponding to an intermediate spin (S = 1) tetracoordinate square-planar cobalt(III) complex

In the absence of single crystals of complexes **1**−**3** suitable for X-ray diffraction, we decided to study the Co *K*-edge X-ray absorption spectra of **1**, as a representative example of this family of compounds, in order to obtain structural information data. The X-ray absorption near-edge structures (XANES) spectrum shown in Figure 1 confirms both the cobalt(III) oxidation state and the tetracoordinate square-planar CoN_4 surroundings of the metal ion.[38] Firstly, the intense edge features for **1** showed a general shift to higher energy relative to the edge of the hexaaquocobalt(II) cationic species, $[Co^{II}(H_2O)_6]^{2+}$, the spectrum of which is also shown in Figure 1 for comparison. The principal peaks corresponding to 1s → 4p transitions are located at 7728.4 and 7725.0 eV, respectively. This shift of 3.4 eV in the energy of the edge results mainly from the deeper binding energy of the 1s core electrons, caused by the increased effective nuclear charge of the metal ion. Thus, the shift in overall edge energy for complex **1** versus its cobalt(II) counterpart is direct evidence of an increased oxidation state; i.e., **1** is a genuine Co^{III} complex. Similar oxidation state-dependent edge and/or pre-edge shifts are also seen for other cobalt complexes.[39] Other features in the Co *K*-edges, notably the asymmetry of the edge of **1**, likewise indicate a symmetry reduction in coordination geometry from octahedral. A shoulder at 7720.0 eV in the low-energy tail of the principal peak (7728.4 eV) is evidenced by **1**, whilst the octahedral $[Co^{II}(H_2O)_6]^{2+}$ species shows a single peak (7725.0 eV). The energy difference of 8.4 eV between this shoulder and the main peak in **1** gives an estimate, for a square-planar metal environment, for the stabilisation of the $4p_z$ orbital of the metal relative to the nearly degenerate $4p_x$ and $4p_y$ orbitals, as illustrated in Scheme 2.

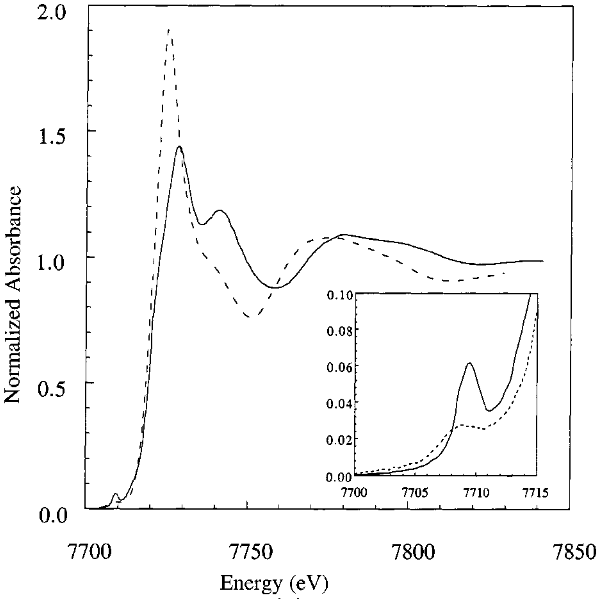


Figure 1. Co *K*-edge XANES spectra for **1** (solid line) and cobalt(II) sulfate aqueous solution (dashed line); the inset is an amplification of the pre-edge region

These findings were corroborated by examination of the weak pre-edge features shown in the inset of Figure 1. In fact, the 1s → 3d transitions in **1** appeared similarly shifted to higher energy and of marked intensity compared to those of the hexaaquocobalt(II) species. They are centred at 7709.5 and 7708.8 eV, respectively. On the other hand, the intensities of the pre-edge features are governed by the density of vacant states, according to the Fermi golden rule. Upon passing from high spin (S = 3/2) Co^{II} to intermediate spin (S = 1) Co^{III}, the $3d_{xy}$ metal orbital becomes vacant, thus explaining the observed increased intensity of the 1s → 3d transitions, since the $3d_{xy}$ orbital is empty in **1**, but singly occupied in $[Co^{II}(H_2O)_6]^{2+}$. The two distinct shoulders at 7708.3 and 7706.2 eV in the low-energy tail of the main 1s → $3d_{xy}$ transition for **1** may tentatively be assigned to the 1s → $3d_{x^2-y^2}$ and 1s → $3d_{z^2}$ transitions, as depicted in Scheme 2.[40] Furthermore, the analysis of the extended X-ray absorption fine structures (EXAFS) spectrum of **1** shown in Figure 2 reveals a tetracoordinate cobalt centre (rather than penta- or hexacoordinate) with two sets of Co−N distances of 1.88(2) and 1.97(2) Å, corresponding to the aromatic-substituted and aliphatic-substituted nitrogen amides, respectively. The fitting parameters used in the EXAFS calculation are summarised in Table 1 (details will be reported separately). As expected, the metal−ligand bond lengths are longer than those found for the related square-planar copper(III) complex $(Ph_4P)[Cu(Me_2opba)]\cdot CH_3CN$ (1.84−1.88 Å).[31a] It is also noteworthy that no metal−metal distances shorter than 4.0 Å were observed in the Fourier transforms of the EXAFS spectrum, thus confirming the monomeric nature of **1**.

The cyclic voltammogram of **1** in acetonitrile (25 °C, 0.1 mol dm^{-3} Et_4NClO_4) shows two reversible redox waves at formal potentials of −0.52 and 0.03 V vs. SCE. These waves correspond to the Co^{III}/Co^{II} and Co^{IV}/Co^{III} couples, respectively.[41] In this regard, it is noteworthy that Collins and co-workers have recently reported the preparation of stable square-planar formal cobalt(IV) complexes of tetraamide macrocyclic ligands and their use as stoichiometric electron-transfer oxidants.[42]

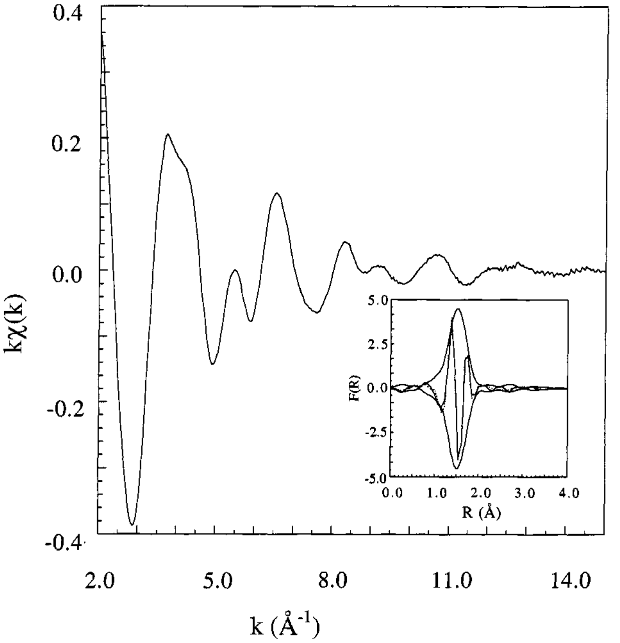


Figure 2. Co *K*-edge EXAFS spectrum for **1**; the inset is the experimental (solid line) and calculated (dashed line) imaginary parts of the Fourier transform of the EXAFS spectrum of **1** for the filter of the first shell, along with the envelope for the calculated one

Catalytic Oxidation of Alcohols

Our investigation began with an effort to optimise reaction conditions for the cobalt-catalysed oxidation of alcohols with dioxygen and aldehydes as oxidant, using 1-phenylethanol as a model substrate. The results are summarised in Table 2. Firstly, we tested the oxidation of 1-phenylethanol with **1** as catalyst, following a protocol similar to

Table 1. Summary of structural EXAFS data for **1**; the fit was performed using McKale's theoretical amplitudes and phases (A. G. McKale, B. W. Veal, A. P. Paulikas, *J. Am. Chem. Soc.* **1988**, *110*, 3763)

	N[a]	R [Å][b]	σ [Å][c]	Γ [Å][d]	ρ [%][e]
Co−N(aryl)	2	1·88(2)	0.04	1·5	2·0
Co−N(alkyl)	2	1.97(2)	0.06	1·5	2·0

[a] The number N of neighbouring atoms was allowed to vary during the fitting procedure. − [b] R is the distance from the cobalt absorber (estimated errors are given in parentheses). − [c] σ is the Debye-Waller coefficient. − [d] The mean-electron-free path λ was chosen as $\lambda(k) = (1/\Gamma)[(\eta/k)^4 + k]$ with $\eta = 3.1$, and Γ was allowed to vary during the fitting procedure. − [e] ρ is the residual factor defined as $\Sigma(k\chi_{\mathrm{exp}} - k\chi_{\mathrm{th}})^2/\Sigma k\chi_{\mathrm{exp}}^2$.

that reported previously by Iqbal and co-workers.[23a] Thus, under dioxygen in the presence of isobutyraldehyde (aldehyde/alcohol 3:1 ratio) and with acetonitrile as solvent, complex **1** catalysed the oxidation of the alcohol at room temperature, to give the corresponding ketone in good yield (Entry 1). When noncoordinating solvents with lower electrophilic character, such as chloroform, dichloromethane, perfluorodecalin or fluorobenzene, were used, the conversion of 1-phenylethanol to acetophenone was less (Entries 2−5, respectively), probably due to the lower solubility of the cobalt complex in these solvents. On the other hand, air can be used instead of dioxygen without affecting the efficiency of the process. We then examined the influence of the aldehyde used as co-oxidant in the oxidation reaction of 1-phenylethanol catalysed by **1**. Thus, with pivalaldehyde instead of isobutyraldehyde, it was found that the yield of acetophenone was slightly improved (Entry 6). Of the C_2-C_5 aldehydes studied, however, pivalaldehyde and isobutyraldehyde were found to be most effective, as had previously been noted by Laszlo et al. for the olefin epoxidation.[43] It is also noteworthy that the use of benzaldehyde is totally ineffective under these conditions, even though it has recently been found by Choudary et al. to be the best reagent for the aerobic oxidation of secondary alcohols to ketones without any metal complexes present at all (dichloroethane, 80° C).[44]

We also studied catalysis by **1**−**3** of the oxidation of 1-phenylethanol by dioxygen and pivalaldehyde, in order to evaluate the effects of catalyst ligand structure on reactivity. Under these conditions (in acetonitrile at room temperature), the final degree of conversion after 24 h was identical for all three compounds (Entries 6 through 8). However, differences between each catalyst were displayed in comparative reaction experiments (details are given in the Exp. Sect.).[45] The time evolution of the acetophenone yield for the various monoanionic cobalt(III) complexes $[Co(L)]^-$, where L = Me_2opba, Meopba and opba, is depicted in Figure 3. The reaction profiles for the oxidation of 1-phenylethanol indicated that **3** was the best catalyst, with almost the final yield of conversion achieved within the first few hours of reaction, whilst **2** and **1** showed comparable catalytic efficiencies. For instance, the oxidation rate for the cobalt(III)−Me_2opba complex **1** has an apparent half-life relative to final conversion ($t_{1/2}$) of approximately 3.4 h. When a strongly basic amide nitrogen atom was substituted by a carboxylate oxygen atom in the cobalt(III)−Meopba complex **2**, $t_{1/2}$ was reduced to 2.5 h. With the cobalt(III)−opba complex **3**, which contains two amide nitrogen and two carboxylate oxygen donor atoms bound to the metal centre, $t_{1/2}$ was further reduced to less than 1.4 h. Hence, a correlation between catalytic activity and ligand electron donor capacity exists along this series of cobalt(III)−oxamidate and/or oxamate catalysts, as we also recently demonstrated for the epoxidation of olefins with dioxygen and pivalaldehyde catalysed by the square-planar nickel(II) analogues.[28a] On the other hand, we observed a threefold rate acceleration of the alcohol oxidation reaction when the aldehyde was added in several portions and an equivalent of base (Na_2CO_3 or K_2CO_3) was added after each addition of aldehyde, as demonstrated for **1** (Entries 9 and 10) (details are given in the Exp. Sect.).[46]

On the basis of this improved methodology, we used complex **1** as the catalyst while performing the aerobic oxidation of some representative alcohols to the corresponding carbonyl compounds in the presence of pivalaldehyde. The results are summarised in Table 3. Secondary alcohols, both benzylic and aliphatic, were selectively oxidised to give ketones in good yields, with concomitant oxidation of pivalaldehyde to pivalic acid. As was to be expected, the reaction times were greater for the nonactivated aliphatic secondary

Table 2. Oxidation of 1-phenylethanol with dioxygen and aldehydes

Entry[a][b]	Catalyst	Aldehyde	Solvent	Base	Time [h]	Yield [%][c]
1	**1**	isobutyraldehyde	CH_3CN		24	60
2	**1**	isobutyraldehyde	$CHCl_3$		24	46
3	**1**	isobutyraldehyde	CH_2Cl_2		24	44
4	**1**	isobutyraldehyde	perfluorodecalin		24	35
5	**1**	isobutyraldehyde	PhF		24	30
6	**1**	pivalaldehyde	CH_3CN		24	75
7	**2**	pivalaldehyde	CH_3CN		24	75
8	3	pivalaldehyde	CH_3CN		24	75
9	**1**	pivaladehyde	CH_3CN	Na_2CO_3[d]	8	75
10	**1**	pivalaldehyde	CH_3CN	K_2CO_3 [d]	8	75

[a] Reaction conditions: 1-phenylethanol (0.11 mmol) in 0.2 mL of solvent was added to a stirred mixture of cobalt catalyst (6.5×10^{-3} mmol) and aldehyde (0.33 mmol) in 0.2 mL of solvent, under O_2 with vigorous stirring at room temperature. − [b] In the absence of metal catalyst some extension of alcohol oxidation was observed. − [c] Yields refer to isolated and pure oxidation products. Acetophenone was the only oxidation product, as confirmed by ^1H NMR. − [d] Reaction conditions: see Exp. Sect.

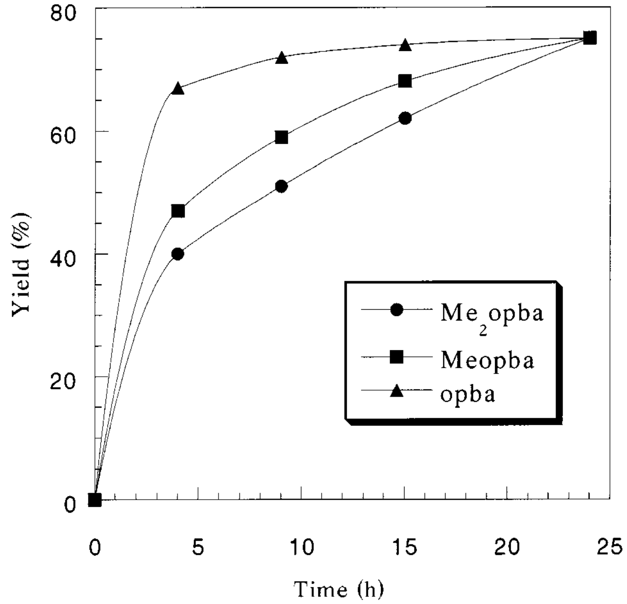


Figure 3. Time course of the oxidation of 1-phenylethanol with dioxygen and pivalaldehyde, catalysed by the various cobalt catalysts; the solid lines are interpolated curves

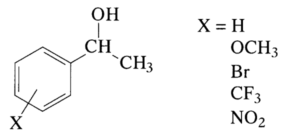
Table 3. Oxidation of alcohols with dioxygen and pivalaldehyde, catalysed by **1**

Entry[a][b]	Substrate	Time [h]	Yield [%][c]
1	1-phenylethanol	8	75
2	1,2-diphenylethanol	8	41
3	diphenylmethanol	2.5	76
4	2-undecanol	21	72
5	cyclododecanol	21	90
6	4-*tert*-butylcyclohexanol	48	88
7	*p*-nitrobenzyl alcohol	6.5	88[d]

[a] Reaction conditions: see Exp. Sect. – [b] In the absence of metal catalyst some extension of alcohol oxidation was observed. – [c] Yields refer to isolated and pure oxidation products. Ketones were the only oxidation products of secondary alcohols, as confirmed by ^{1}H NMR. – [d] The final oxidation product was *p*-nitrobenzoic acid exclusively.

alcohols tested (Entries 4–6), including linear chain alcohols such as 2-undecanol (Entry 4) and cyclic alcohols such as cyclododecanol (Entry 5), than for the activated benzylic series (Entries 1–3). Thus, the reaction time increases as the number of phenyl groups geminal to the hydroxy moiety decreases, being higher for 4-*tert*-butylcyclohexanol (Entry 6) and lower for diphenylmethanol (Entry 3), relative to that for 1-phenylethanol (Entry 1). It was notable that, during the oxidation of 4-*tert*-butylcyclohexanol, only 4-*tert*-butylcyclohexanone was obtained, and no traces were detected of the corresponding Baeyer–Villiger oxidation product, 4-*tert*-butylcaprolactone. In contrast, Kaneda et al. have recently shown that various cyclohexanone derivatives are efficiently oxidised to give lactones when using the combination of dioxygen and aldehydes in the absence of metal catalyst (tetrachloromethane, 40° C).[47] This observation suggests that peracid generated in situ from the autoxidation of the aldehyde with O_2 is not directly involved as a potential oxidising agent in our catalytic system and, consequently, that the metal complex plays an active role (see Discussion, below). However, under the same reaction conditions as used for the oxidation of secondary alcohols to ketones, the oxidation of primary benzylic alcohols afforded mixtures of starting material, aldehyde and the corresponding carboxylic acid, depending on the reaction time, as illustrated by *p*-nitrobenzyl alcohol (Entry 7). Moreover, complex and difficult to analyse mixtures were obtained for the oxidation of primary aliphatic alcohols.

Finally, we studied the aerobic oxidation of α-alkylbenzyl alcohol substrates in the presence of pivalaldehyde, with complex **1** as catalyst, in order to evaluate the influence of electronic and steric factors on reactivity. For the series of *meta*- and *para*-substituted 1-phenylethanol derivatives $XPhCH(OH)CH_3$ (Scheme 3), the results in Table 4 showed a rather small influence of the substituent group X in the phenyl ring on the final yield of ketone, independent of its electronic properties and/or substitution position. Moreover, this was confirmed in parallel competitive reaction experiments with the various *para*-substituted 1-phenylethanol derivatives $XPhCH(OH)CH_3$ where X = H, OMe, Br, CF_3 and NO_2 (details are given in the Exp. Sect.). The relative reactivity per hydrogen atom (k_{rel}) shows little variation and does not seem to depend on the nature of the *para* substituent, as illustrated in Table 5. For instance, the substrate with the electron-donating methoxy group gives a value of $k_{rel} = 0.66$ (Entry 2), intermediate between those found for the substrates with the electron-withdrawing trifluoro and nitro substituents, which are 1.01 and 0.44, respectively (Entries 4 and 5, respectively). Hence, it is apparent from these values that there is no correlation along this series of *para*-substituted alcohol substrates between relative reactivities and Hammett σ parameters.[48] It is interesting to note that similar results were very recently obtained by Lorber et al. for the aerobic catalytic oxidation of benzylic alcohols by an oxomolybdenum–copper system.[11] On the other hand, for the series of α-alkylbenzyl alcohol derivatives $PhCH(OH)R^2$ (Scheme 4), the results in Table 6 showed a net effect, depending on the nature of the attached alkyl group R^2, on the final yield of ketone. Thus, the overall yield of ketone decreases with the bulkiness of R^2, in the order Me > Et > *i*Pr > *t*Bu (Entries 1–4, respectively). This reflects the relative importance of steric effects along these series of α-alkylbenzyl alcohol substrates, compared with electronic ones.



$XPhCH(OH)CH_3$

Scheme 3

Table 4. Oxidation of 1-phenylethanol derivatives with dioxygen and pivalaldehyde, catalysed by **1**

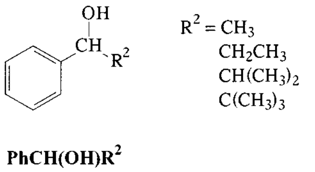
Entry[a][b]	Substrate	Time [h]	Yield [%][c]
1	1-phenylethanol	8	75
2	*p*-methoxy-1-phenylethanol	8	90
3	*p*-bromo-1-phenylethanol	8	74
4	*p*-trifluoromethyl-1-phenylethanol	8	85
5	*p*-nitro-1-phenylethanol	8	95
6	*m*-nitro-1-phenylethanol	8	95

[a] Reaction conditions: see Exp. Sect. – [b] In the absence of metal catalyst some extension of alcohol oxidation was observed. – [c] Yields refer to isolated and pure oxidation products. Ketones were the only oxidation products, as confirmed by ^{1}H NMR.

Table 5. Relative (to hydrogen) reactivities for the oxidation of *para*-substituted 1-phenylethanol derivatives with dioxygen and pivalaldehyde, catalysed by **1**

Entry[a]	Substrate	σ[b]	k_{rel}[c]
1	1-phenylethanol	0	1.00
2	*p*-methoxy-1-phenylethanol	−0.28	0.66
3	*p*-bromo-1-phenylethanol	0.26	0.32
4	*p*-trifluoromethyl-1-phenylethanol	0.53	1.01
5	*p*-nitro-1-phenylethanol	0.81	0.44

[a] Reaction conditions: see Exp. Sect. – [b] Values from ref.[48], p. 244. – [c] Slopes from plots of ratios of product yields [$XPhCOCH_3$]/[$PhCOCH_3$] vs. ratios of initial concentrations of alcohols [$XPhCH(OH)CH_3$]/[$PhCH(OH)CH_3$]. Yields refer to GLC determination. Ketones were the only oxidation products, as confirmed by GLC.



Scheme 4

Table 6. Oxidation of α-alkylbenzyl alcohols with dioxygen and pivalaldehyde, catalysed by **1**

Entry[a][b]	Substrate	Time [h]	Yield [%][c]
1	1-phenylethanol	8	75
2	1-phenylpropanol	8	65
3	1-phenylisobutyl alcohol	8	46
4	1-phenylneopentyl alcohol	8	36

[a] Reaction conditions: see Exp. Sect. – [b] In the absence of metal catalyst some extension of alcohol oxidation was observed. – [c] Yields refer to isolated and pure oxidation products. Ketones were the only oxidation products, as confirmed by ^{1}H NMR.

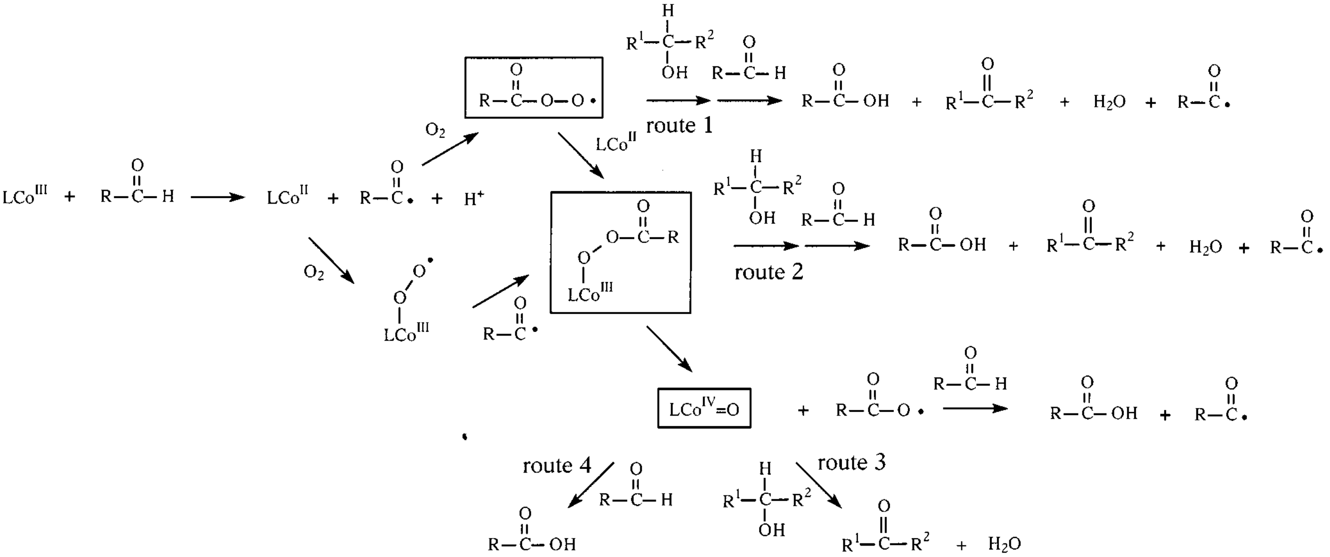
Discussion

In this section we discuss the mechanistic aspects of the cobalt-catalysed aerobic oxidation of alcohols derived from the study of substituent effects both in the catalyst and in the substrate, which are then compared with the available mechanistic proposals. We first describe the process of dioxygen activation by the cobalt complexes in the presence of aldehydes as reducing agents, and then the alcohol oxidation by high-valent oxocobalt species, which are postulated to be the active intermediates in these oxidation (dehydrogenation) reactions.

Dioxygen Activation by the Cobalt Complexes in the Presence of Aldehydes

The mechanism of the "Mukaiyama" oxidations attracts continuous interest among chemists working in the area of oxidations catalysed by metal complexes. The metal complex is assumed to play various roles in the catalytic oxidation of organic substrates by dioxygen plus aldehyde, as discussed in the work of Nam and Valentine on olefin epoxidation catalysed by metalloporphyrin and metallocyclam complexes (cyclam = 1,4,8,11-tetraazacyclotetradecane).[26a] Scheme 5 illustrates the situation as applied to the results in this study. Firstly, the metal assists in the initiation step, in the free radical autoxidation of the aldehyde to generate an acyl radical (Scheme 5, left). The acyl radical $RC(O)^{\cdot}$ then reacts with O_2 to give an acylperoxyl radical $RC(O)OO^{\cdot}$ (dioxygen activation step). The acylperoxyl radical generated in the autoxidation reaction oxidises the organic substrate either directly (route 1) or via a reactive metal acylperoxide intermediate (route 2).[49] The latter pathway, with a nickel acylperoxide involved as the active oxidant, has been suggested recently by Nolte and co-workers for olefin epoxidation, catalysed by nickel(II) β-diketonate complexes, with dioxygen and aldehydes.[20] In contrast, with the square-planar nickel(II)–cyclam complex, an outer-sphere electron transfer process occurs, leading to oxidation of Ni^{II} to Ni^{III}, with concomitant formation of the unreactive acylperoxide anion $RC(O)OO^-$ from the acylperoxyl radical $RC(O)OO^{\cdot}$.[26b] Clearly, this difference in reactivity arises from the stronger reducing power of the latter nickel(II) complex; the formal potentials for the redox couple Ni^{III}/Ni^{II} in CH_3CN at 25 °C are 1.24 and 0.67 vs. Ag^+/Ag for $Ni(acac)_2$ (acac = acetylacetonate)[50] and $Ni(cyclam)^{2+}$ complexes,[33b] respectively.

However, since cobalt(II) complexes are known to form superoxo complexes by reaction with dioxygen, it is also possible that formation of the cobalt(III) acylperoxide species takes place through the intermediacy of a superoxocobalt(III) complex on reaction with an acyl radical (Scheme 5, centre). This has been suggested previously by Nobile and co-workers for the epoxidation of olefins by dioxygen, catalysed by a cobalt(II) β-oxo esterate complex in the presence of an aldehyde.[24] As noted above, our cobalt(II) oxamate and/or oxamidate complexes are readily oxidised by O_2 to the corresponding square-planar cobalt(III) complexes. It cannot be ruled out that transient superoxo- and/or μ-peroxometal species might be involved in this metal oxygenation process. In this regard, it has previously been reported that the cobalt(II) pyridinamide complex with the related ligand *o*-phenylenebis(2′-pyridinecarboxamido) directly activates dioxygen (without any external reductant), by means of a superoxocobalt(III) intermediate, resulting then in the oxidation of phenols to the corresponding 1,4-benzoquinones.[51] Nonetheless, we think that the acylperoxyl radical, rather than the superoxo-



Scheme 5. Possible mechanistic pathways for cobalt-catalysed dioxygen activation by aldehydes; boxed structures represent key intermediates

cobalt(III) complex, is the actual intermediate in the cobalt-catalysed dioxygen activation in the presence of aldehydes. In fact, the reaction of O_2 with $RC(O)^{\cdot}$ to give $RC(O)OO^{\cdot}$ is known to be extremely fast, and it is unlikely that reaction of O_2 with the cobalt(II) complex would be rapid enough to compete.

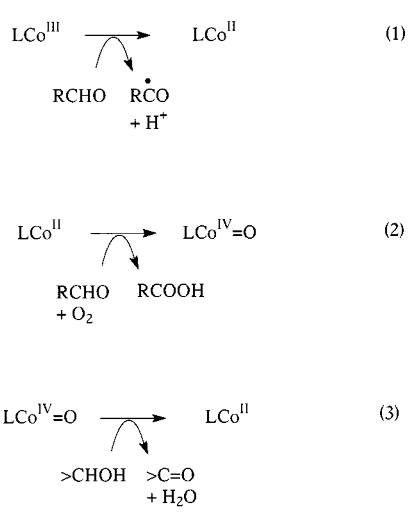
Anyway, whatever the reaction pathway leading to the metal acylperoxide complex (that is, through acylperoxyl radical and/or superoxometal intermediates), this transient metal acylperoxide species could eventually produce an oxometal species by homolytic O−O bond cleavage of the acylperoxide group, thereby generating an acyloxyl radical.[52] That being so, the ultimate active oxidising agent would be a high-valent oxometal species (route 3). A similar pathway has been proposed by Iqbal and co-workers for alcohol oxidations by dioxygen and isobutyraldehyde catalysed by a cobalt(II)−Schiff base complex.[23a] Finally, hydrogen atom abstraction from aldehyde by the formed acyloxyl radical $RCOO^{\cdot}$ affords the corresponding carboxylic acid as one of the final products, thus regenerating the initial acyl radical $RC(O)^{\cdot}$ which starts a new catalytic cycle (Scheme 5, right).

Alternatively, the carboxylic acid formed during the oxidation reaction could also arise from the side reaction of the aldehyde co-oxidant with the reactive oxometal species (route 4). In this case, the putative oxocobalt(IV) complex no longer reacts with the alcohol substrate to give the corresponding ketone (route 3) but, instead, it rapidly reacts with the aldehyde to give carboxylic acid as final product (route 4). More probably, the oxidation of primary alcohols to the corresponding aldehydes and then to carboxylic acids proceeds following routes 3 and 4, respectively. This view is further supported by the observation that the cobalt(III)-catalysed oxidation of 1-phenylethanol by dioxygen does not occur in the presence of benzaldehyde, benzoic acid being the sole oxidation product. Hence, we conclude that, at least for this aromatic aldehyde, the cobalt-catalysed aldehyde oxidation competes efficiently with the alcohol oxidation reaction. We have also verified that, in the absence of alcohol substrate, the cobalt(III) complex efficiently catalyses the oxidation of the aldehyde to carboxylic acid with dioxygen, even for the case of the other aliphatic aldehydes: namely pivalaldehyde and isobutyraldehyde. In fact, Mukaiyama and co-workers have already reported direct oxidation of aldehydes to the corresponding carboxylic acids with a nickel(II) β-diketonate catalyst.[53]

Overall, we consider this latter pathway, involving an oxocobalt(IV) as the active oxidant, very convincing, given the accessibility of the Co^{IV} oxidation state in this case, as evidenced by its electrochemical properties. In fact, we found that the cobalt(III)−Me_2opba complex is capable of undergoing two redox processes in acetonitrile. The first one occurs at a negative potential of −0.52 V vs. SCE and corresponds to a reversible reduction to the cobalt(II)−Me_2opba complex. The second one is a reversible oxidation at a moderately low positive potential of 0.03 V vs. SCE, which readily leads to the cobalt(IV)−Me_2opba complex, even if a ligand-centred oxidation of the benzene ring, leading to a Co^{III} organic radical species, cannot definitively be dismissed. On the other hand, the electronic properties of the ligand counterpart should modulate the reactivity of the oxocobalt(IV) intermediate responsible for the oxidation of the alcohol substrate. Accordingly, ligands with stronger donor properties are expected to stabilise the high-valent oxometal intermediate, attenuating its reactivity and thus generating a milder oxidant; conversely, weaker donor ligands would not stabilise the high-valent oxometal intermediate, which would become more reactive, making it a stronger oxidant.[54] As a matter of fact, reduction of the number of N-amide donor groups in the Meopba and opba ligands (see Scheme 1) diminishes the electron donor capacity (basicity)[31a] and, concomitantly, enhances the catalytic activity of the corresponding cobalt(III)−Meopba and cobalt(III)−opba complexes (see Figure 3). Thus, the trend in the reactivity observed along this series of complexes **1−3** correlates directly with the electron-deficient character of the metal catalyst; that is, the electrophilic nature of the postulated high-valent oxometal intermediate, as predicted by the proposed mechanism.

An alternate interpretation involving other metal−oxygen active species such as $LCo^{III}-OOC(O)R$ (route 2), rather than $LCo^{IV}=O$ (route 3), predicts identical ligand inductive effects on reactivities, and consequently this cannot be taken as a definitive proof of the proposed reaction mechanism. Nevertheless, this result unambiguously demonstrates that free radicals such as $RC(O)OO^{\cdot}$ (route 1) are not directly implicated in the reaction with the alcohol substrate and, therefore, that the cobalt-catalysed oxidation of alcohols by dioxygen and aldehydes occurs by means of metal-based chemistry. We believe that partitioning between the metal acylperoxide and oxometal reaction pathways (routes 2 and 3, respectively) is significantly affected by the electronic nature of the metal complex used as catalyst; that is, the electronic properties of the ligand counterpart. Thus, *electron-deficient* metal complexes with weak-field ligands (and high formal redox potentials) show a tendency to react through metal acylperoxide species,[20] whereas *electron-rich* metal complexes with strong-field ligands (and low formal redox potentials), such as those used here, favour the formation of higher valent oxometal species.[28a] Interestingly, similar trends were found in related studies on the oxidation of hydrocarbons by cobalt(III) alkylperoxide complexes. Thus, it has been shown that, when relatively strong-field ligands are bonded to the cobalt centre, O−O bond homolysis leading to the oxocobalt(IV) species (arbitrary formulated as $LCo^{III}-O\cdot$), with concomitant formation of $RO^{\cdot}$ radicals, is the primary mode of decomposition of the $LCo^{III}-OOR$ complexes.[55]

On the basis of the above considerations, the active intermediate in our catalytic system would be an oxocobalt(IV) species formed by the oxidation of the cobalt catalyst by the combination of O_2 and aldehyde [Scheme 6, Equation (1) and (2)]. However, the detailed mechanism by which this oxocobalt(IV) species reacts with alcohol substrate to produce the corresponding carbonyl compound and water [Equation (3) in Scheme 6] is not yet clear.

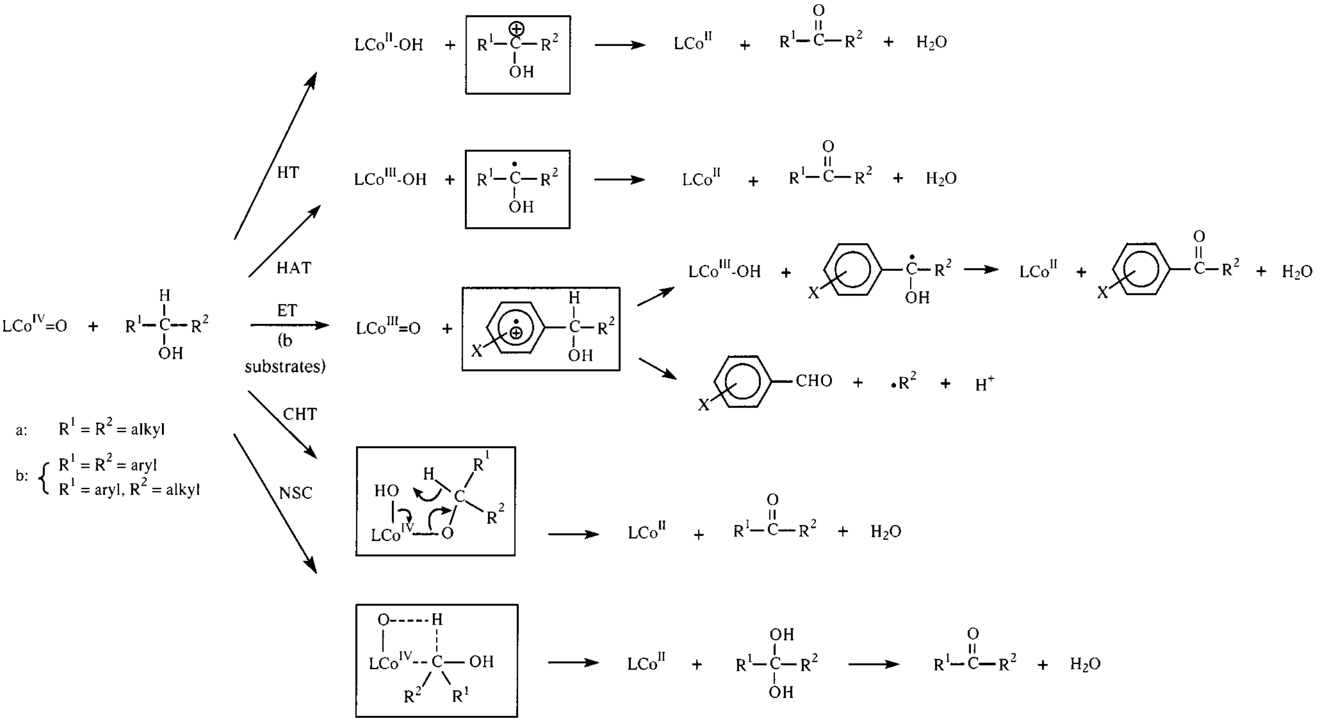


Scheme 6

Alcohol Oxidation by High-Valent Oxocobalt Species

The mechanism of alcohol oxidation by high-valent oxometal complexes is a matter of continuous debate, and various mechanistic proposals exist at present. These, as applied to this study, are illustrated in Scheme 7. The hydride transfer (HT) mechanism has been suggested in earlier work by Roecker and Meyer on alcohol oxidation by oxo(polypyridyl)ruthenium(IV) complexes.[56] According to this mechanism, the oxometal species abstracts a hydride from the alcohol substrate, forming an α-hydroxy carbon cation $>C(OH)^{+}$. Rapid acid-base equilibrium between the formed hydroxometal intermediate and the α-hydroxy carbon cation produces the corresponding ketone and water as final products. However, net hydride transfer could also occur through initial hydrogen atom abstraction from the alcohol by the oxometal species, thereby generating an α-hydroxy carbon radical $>C(OH)^{\cdot}$. The α-hydroxy carbon radical, being a strong reducing agent, reduces the hydroxometal intermediate to give the expected ketone and water. This hydrogen atom transfer (HAT) mechanism has been proposed by Baciocchi and co-workers for the oxidation of α-alkylbenzyl alcohols promoted by cytochrome P450 enzymes, in which the active oxidant is believed to be an oxo(protoporphyrin)iron(IV) radical complex.[57] With α-alkylbenzyl alcohols as substrates, however, the situation is far more complex and an additional mechanism, the electron transfer (ET) mechanism, can be envisaged.[57,58] In this case, an aromatic radical cation is initially formed by reaction with the putative electron transfer oxidant oxometal species, which can then either be deprotonated to produce an α-hydroxy carbon radical $>C(OH)^{\cdot}$ or, alternatively, can undergo β-carbon−carbon bond cleavage to give the corresponding aldehyde as one of the final products. The formation of the ketone from the α-hydroxy carbon radical $>C(OH)^{\cdot}$ then follows by a redox step with the hydroxometal intermediate, as in the HAT mechanism.

Nonetheless, for the two series of benzylic alcohols $XPhCH(OH)R^2$, with X = H, OMe, Br, CF_3, NO_2 and R^2 = Me, Et, *i*Pr, *t*Bu (see Scheme 3 and Scheme 4), the higher values of their single oxidation potentials (> 1.6 V vs. SCE) compared to that estimated for the active oxidant, presumably a oxocobalt(IV) species, make an ET mechanism thermodynamically unfavourable. This conclusion is further supported by the observation that no C−C bond fragmentation products were obtained. In all cases, the only product observed was the corresponding ketone resulting from C−H bond cleavage, and no traces either of *para*-substituted benzaldehydes or of their corresponding benzoic acids were observed, even in the cases in which the alkyl group substituent was *i*Pr or *t*Bu, for which the stability of the alkyl radical $R^{2\cdot}$ formed by C−C bond rupture is greater. Hence, we can reasonable conclude that aromatic radical cations as postulated in the ET mechanism are not involved in the oxidation of α-alkylbenzyl alcohols, but the



Scheme 7. Possible mechanistic pathways for alcohol oxidation by high-valent oxocobalt species; boxed structures represent key intermediates

question remains as to the identity of the actual intermediate. In fact, the trend observed in the relative reactivities of the various types of secondary alcohols, which is in the order aliphatic alcohols < α-alkylbenzyl alcohols < α-arylbenzyl alcohols, agrees with the stabilisation both of the formed α-hydroxy carbon cation $>C(OH)^+$ and of the α-hydroxy carbon radical $>C(OH)^{\cdot}$ in the postulated transition state and, consequently, does not permit distinction to be made between the HT and HAT mechanisms.

Interestingly, for the series of *para*-substituted 1-phenylethanol derivatives $XPhCH(OH)CH_3$, the relative reactivities vary only slightly, and in an essentially random manner, with the *para* substituent X (X = H, OMe, Br, CF_3, NO_2), as shown by the attempted Hammett correlation of $\log(k_{rel})$ vs. σ illustrated in Figure 4. The absence of any correlation between the electronic properties of the *para* substituent and the oxidation reaction rate is surprising, at least in principle, given the extensive charge transfer expected for either a hydride transfer or a hydrogen atom transfer step. Thus, it seems unlikely to us that these alcohol oxidation reactions proceed through polar transition states with substantial charge transfer from the substrate to the electrophilic oxocobalt species, such as those postulated in the HT and HAT mechanisms. In general, nonlinear Hammett plots can be due to such diverse causes as complications arising from side-reactions, steric effects from large *para* substituents and, particularly, cyclic transitions states.[48] More probably, in our case, the oxidation proceeds through prior formation of an alkoxide metal complex, with concomitant deprotonation of the alcohol substrate, by the coordinatively unsaturated pentacoordinate oxometal species. A concerted process involving the transfer of the α-hydrogen atom of the alkoxo group to the hydroxometal species as a hydride, through a five-membered cyclic nonpolar transition state, thus affords the corresponding ketone and water as final products (see Scheme 7). This concerted hydride transfer (CHT) mechanism has been proposed by Lorber et al. for the aerobic oxidation of alcohols by an oxomolybdenum(VI) complex.[11] On the other hand, the trend observed in the relative reactivities of the series of α-alkylbenzyl alcohol derivatives $PhCH(OH)R^2$, which is in the order Me > Et > *i*Pr > *t*Bu, further supports this mechanism. In fact, the good correlation found between the steric properties of the alkyl group R^2 substituent and the oxidation reaction yield merely reflects the steric requirements associated with the coordination of the alcohol substrate to the oxometal species in the postulated transition state for the CHT mechanism.

Of course, an alternative, nonsynchronous concerted (NSC) mechanism for the alcohol oxidation reaction, adapted from that proposed recently by Newcomb[59] and Shilov[60] for hydrocarbon hydroxylation promoted by cytochrome P450 enzymes and model chemical systems,[61] would also be consistent with our findings regarding the influence of electronic and steric effects on reactivity. In this case, a prior [2+2] concerted addition of the C−H bond across the M=O bond gives the pentacoordinate α-hydroxy carbon intermediate $M^{IV}(OH)[C(OH)R^1R^2]$ (Scheme 7, bottom), different from the tricoordinate α-hydroxy carbon radical intermediate in the HAT mechanism. Intramolecular reorganisation within the four-membered nonpolar cyclic intermediate, involving an oxygen rebinding step, gives a *gem*-diol $>C(OH)_2$, and then the expected ketone after dehydration. Indeed, the stabilisation of this organo-

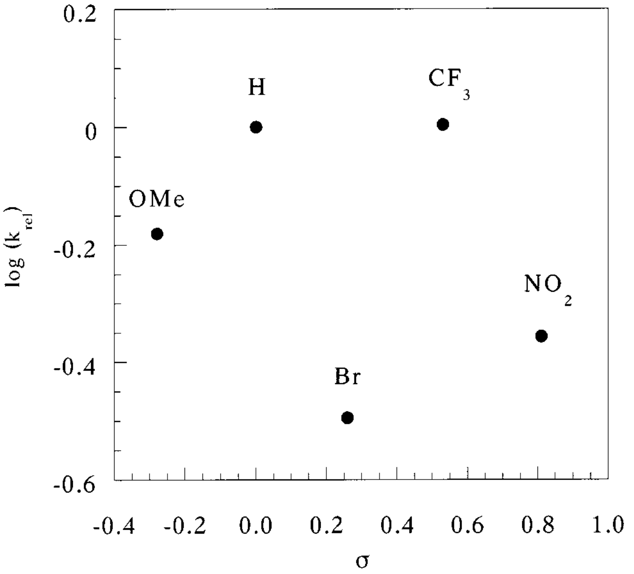


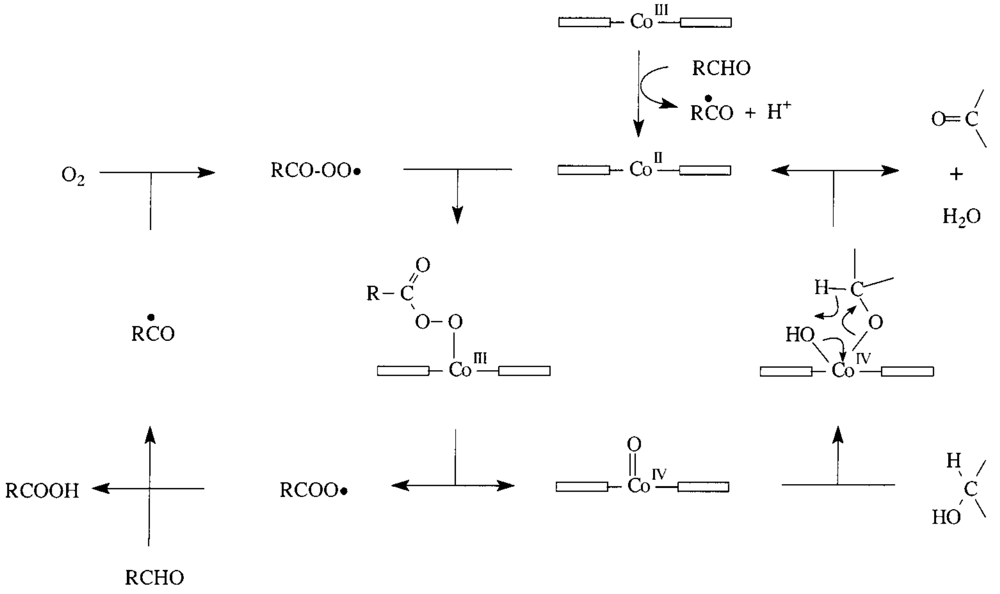
Figure 4. Hammett plot for the oxidation of the various *para*-substituted 1-phenylethanol substrates with dioxygen and pivalaldehyde, catalysed by **1** (data from Table 5)

cobalt(IV) intermediate, a common reactive species in cobalt chemistry,[62,63] would be very sensitive to the steric properties of the alkyl group substituent R^2, as found experimentally. We, however, prefer the former CHT mechanistic interpretation, because of the relatively higher stability of the five-membered cyclic transition state (compared to the four-membered one of the latter), which should probably favour the formation of this species as a reaction intermediate. Moreover, from a chemical point of view, high-valent metal complexes are unlikely to produce α-hydroxy carbon metal derivatives from alcohols; in fact, being hard acids, they ought rather to prefer to react with the O−H functional group, a harder base than the C−H group, to yield the corresponding metal alkoxide derivative through a CHT mechanism.

In summary, the cobalt-catalysed aerobic oxidation of alcohols with co-oxidation of aldehydes to carboxylic acids can be interpreted as shown in Scheme 8: reaction between Co^{III} and the pivalaldehyde reducing agent generates Co^{II}, which is then able to react with the acylperoxyl radicals (obtained from the free radical autoxidation of the aldehyde by O_2) to produce a transient $Co^{IV}{=}O$ species responsible for alcohol oxidation. This proceeds through coordination of the alcohol substrate to $Co^{IV}{=}O$, followed by β-hydride elimination from the bound alkoxo substrate by $Co^{IV}{-}OH$ to form the carbonyl compound and water as final products, with regeneration of the Co^{II} catalyst.

Conclusion

We have shown here that, in the presence of a cobalt catalyst with bis(*N*,*N′*-disubstituted oxamides) and related ligands (complexes **1**−**3**), the oxidation of secondary alcohols with dioxygen and pivalaldehyde proceeds smoothly in acetonitrile at room temperature, exclusively yielding the ketone, together with pivalic acid derived from pivalaldehyde. However, this method is limited to secondary alcohols, since primary ones give aldehydes which themselves react further, in competition with the pivalaldehyde, to give the corresponding acids as final products. Moreover, we have previously shown that in the oxidation of α,α-disubstituted α-hydroxy acids, a class of tertiary alcohols, C−C bond cleavage highly efficiently gives CO_2 and the corresponding ketones containing one carbon atom less.[29b] Thus, this and earlier work by us demonstrates that this family of square-planar cobalt(III) oxamidate and/or oxamate complexes, with the use of aldehydes as co-oxidants, are efficient homogeneous catalysts for the aerobic oxidation of a wide range of organic substrates (including alcohols and olefins[29a]).



Scheme 8. Proposed mechanism for the cobalt-catalysed aerobic oxidation of alcohols, with co-oxidation of aldehydes to carboxylic acids

This catalytic system is also noteworthy because of the possible intermediates that are implicated as active oxidising agents. Thus, our current results provide indirect but convincing evidence for the formation of high-valent oxometal species, which are analogous to the oxoiron(IV) (ferryl) complex proposed as the actual oxidant in a large variety of C−H bond oxidations promoted by the family of cytochrome P450 enzymes.[64,65] These also include the oxidation of α-alkylbenzyl alcohols reported recently by Baciocchi et al.[57] In our case, oxocobalt(IV) species would be derived by oxygen atom transfer from the acylperoxyl radical (generated by metal-mediated free-radical autoxidation of the aldehyde with O_2) to the lower valent cobalt(II) complex. Attempts to isolate and characterise these high-valent oxometal intermediates are in progress in order to give definitive solid proof for the postulated mechanism through complete kinetic studies of substrate oxidation under stoichiometric conditions.

Experimental Section

General Remarks: All chemicals were of reagent grade quality and were purchased from commercial sources and used as received. Noncommercial alcohols were prepared according to literature procedures reported elsewhere. The proligands *o*-phenylenebis(*N*′-methyloxamide), the methyl ester of *o*-phenylene(*N*′-methyloxamide)(oxamic acid) and the diethyl ester of *o*-phenylenebis(oxamic acid) were prepared as described earlier.[31a]

Physical Techniques: NMR spectra were recorded with Varian Unity 300 (299.95 MHz for ^1H; 75.43 MHz for ^{13}C) or Bruker AC 200 (200.1 MHz for ^1H; 50.3 MHz for a ^{13}C) spectrometers. $CDCl_3$ was used as solvent and internal standard ($CHCl_3$: $\delta_H = 7.24$; $\delta_C = 77.0$). − IR spectra were recorded with a Perkin−Elmer 882 spectrophotometer as KBr pellets or as oils between NaCl plates. − Electronic spectra were measured with a Perkin−Elmer Lambda 2 spectrophotometer. − Low-resolution mass spectra (EI) were obtained with a FISONS Instruments VG Autospec spectrometer at 70 eV. GLC analyses were performed with a Trace GC 2000 (Thermo Quest) using a 30 m × 0.25 mm high-resolution gas chromatography column coated with methylpolysiloxane (5% phenyl). − Melting points (uncorrected) were determined with a Büchi 535 apparatus. − TLC analyses were performed on 0.25 mm Merck silica gel plates (60 F_{254}) using UV light or by charring with anisaldehyde/AcOH/H_2SO_4 (1:100:1). − Column chromatography was carried out on silica gel 60 (200 SDS, 0.035−0.070 mm) or on Brockmann I deactivated basic aluminium oxide. − Cyclic voltammetry was performed with a Princeton Applied Research Model 362 scanning potentiostat, using a glassy carbon disk as working electrode and Ag/$AgClO_4$ as reference electrode. − Variable temperature magnetic susceptibility measurements were carried out with a pendulum-type susceptometer in the temperature range 80−300 K under an applied magnetic field of 10 KOe. − Elemental analyses (C, H N) were performed by the Microanalytical Service of ICSN (CNRS, France).

X-ray Absorption Study: XANES (X-ray Absorption Near Edge Structures) and EXAFS (Extended X-ray Absorption Fine Structures) spectra of powdered samples of **1** and aqueous solutions of cobalt(II) sulfate were collected at LURE (Laboratoire d'Utilisation du Rayonnement Electromagnetique, Paris−Sud University) on the storage ring DCI with a energy of 1.85 GeV and a mean intensity of 300−200 mA. The measurements were carried out at the Co *K*-edge in the transmission mode on the EXAFS III spectrometer equipped with a two-crystal monochromator (Si 311 for XANES and Si111 for EXAFS, 0.5 mm entrance slit for both XANES and EXAFS). The spectra of **1** were recorded at 10 K in a helium cryostat designed for X-ray absorption spectroscopy, while those of cobalt(II) sulfate were recorded at room temperature in a multipurpose X-ray absorption cell designed for solution studies. A detailed description of the operating mode is given in ref.[67] − XANES and standard EXAFS data analyses were performed with the "GALAAD"[68] and "EXAFS pour le MAC"[69] programs, following a well-known procedure described elsewhere.[67,70]

$(Me_4N)[Co(Me_2opba)]\cdot 2H_2O$ (1), $(Me_4N)[Co(Meopba)]\cdot 3H_2O$ (2) and $(Me_4N)[Co(opba)]\cdot 4H_2O$ (3): A 25% methanol solution (10.0 mL) of Me_4NOH (25.0 mmol) was added to a suspension of the corresponding proligand (5.0 mmol) in methanol (100 mL). A methanolic solution (50 mL) of $Co(ClO_4)_2\cdot 6H_2O$ (5.0 mmol) was then added dropwise, with vigorous stirring, under aerobic conditions at room temperature. The reaction mixture was further stirred for 1 h under an air current to complete metal oxidation. The final dark brown-reddish reaction mixture was filtered under vacuum to eliminate solid particles (mainly the Me_4NClO_4 salt, together with a presumed polymeric cobalt complex), reduced to ca. 10 mL in a rotary evaporator, and treated successively with ether and acetone to give a brown-reddish oil. Complexes **1**−**3** were obtained as very hygroscopic, dark brick-red powders after treatment of the corresponding oils with acetonitrile with stirring for a few hours. They were rapidly filtered off, dried under vacuum and stored in a dessiccator over NaOH pellets (ca. 0.6 g, 25−30% yield). − Satisfactory elemental analyses (C, H, N) were obtained. − $C_{16}H_{26}CoN_5O_6$ (443.3): calcd. C 43.31, H 5.87, N 15.79; found C 43.69, H 5.84, N 16.01 for **1**. − $C_{15}H_{25}CoN_4O_8$ (448.3): calcd. C 40.19, H 5.62, N 12.50; found C 40.52, H 5.33, N 12.29 for **2**. − $C_{14}H_{24}CoN_3O_{10}$ (453.3): calcd. C 37.10, H 5.34, N 9.27; found C 37.20, H 5.56, N 9.57 for **3**. − IR; ν(CO)/cm^{-1} (KBr): 1605s for **1**; 1610s and 1615(sh) for **2**; 1625vs and 1660s for **3**. − UV/Vis (CH_3CN): λ (ε/dm^3 mol^{-1} cm^{-1}) = 390(sh), 375(sh), 350 (5100), 265 (17100) and 245 nm (18400) for **1**; 375(sh), 340 (7600) and 240 nm (18700) for **2**; 385(sh), 350 (6800), 275 (sh) and 230 nm (17500) for **3**.

General Procedure for the Alcohol Oxidation Reactions: A solution of alcohol (0.11 mmol) in 0.2 mL of acetonitrile was added to a stirred mixture of complex **1** (6.5×10^{-3} mmol) in 0.2 mL of acetonitrile under dioxygen at room temperature. Aldehyde was added in three portions (3 × 0.11 mmol) at regular intervals during the course of the reaction, and 1 equiv. of base (Na_2CO_3 or K_2CO_3) was added after each addition of aldehyde, with constant stirring. The reaction mixture was stirred vigorously until the time indicated in the corresponding table had elapsed. Consumption of the starting alcohol and formation of the corresponding ketone during the course of the reaction were monitored by TLC. The reaction mixture was separated by flash column chromatography on silica gel or basic alumina. All compounds exhibited spectral data consistent with their structures.

Typical Procedure for the Comparative Alcohol Oxidation Reactions: Solution mixtures of the appropriate cobalt catalyst, complexes **1**−**3** (6.5×10^{-3} mmol), and pivalaldehyde (0.33 mmol) in 0.2 mL of acetonitrile were charged with a solution of 1-phenylethanol (0.11 mmol) in 0.2 mL of acetonitrile under dioxygen, with vigorous stirring at room temperature, until the time indicated in Figure 2 had elapsed. The reaction mixtures were separated by flash column chromatography on silica gel. Yields refer to isolated and pure oxidation products. Acetophenone was the only oxidation product, as confirmed by ^{1}H NMR.

Typical Procedure for the Competitive Alcohol Oxidation Reactions: Solution mixtures containing varying amounts (0.1−0.4 mmol) of 1-phenylethanol and another *para*-substituted derivative $XPhCH(OH)CH_3$ (where X = OMe, Br, CF_3 and NO_2) in 1.5 mL of acetonitrile were stirred with a mixture of complex **1** (6.5×10^{-3} mmol) and pivalaldehyde (0.33 mmol) in 0.5 mL of acetonitrile under dioxygen at room temperature for 4 h. The reaction mixtures were filtered (syringe), the products were analysed by comparison with authentic samples, and their yields estimated by GLC, using internal standards. Ketones were the only oxidation products. The total quantity of the two competing alcohols was maintained at about 0.5 mmol in all runs. Under these conditions, less than 10% of the alcohols was converted into the corresponding ketones. − Data analyses of competitive reactions of *para*-substituted 1-phenylethanol derivatives were performed by following a well-known procedure described elsewhere.[66] Plots of ratios of product yields from $XPhCH(OH)CH_3$ and $PhCH(OH)CH_3$ versus ratios of initial concentrations of $XPhCH(OH)CH_3$ and $PhCH(OH)CH_3$ gave excellent straight lines (correlation coefficients $r = 0.999-0.994$). Relative (to hydrogen) reactivities of *para*-substituted 1-phenylethanol derivatives (k_{rel}) were obtained from the slopes of these plots by the least squares method.

Acknowledgments

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