$[(CH_3)_3CNC]_4M(CO)_2$ (M = Mo and W) exhibited two closely spaced singlets in accord with the nonequivalence of *tert*-butyl isocyanide ligands trans to carbonyl groups and those trans to other *tert*-butyl isocyanide ligands (*i.e.*, trans to each other). The proton nmr spectra of two independent sublimed samples of $(CH_3)_3CNCMo(CO)_5$ each exhibited a triplet ($J = 2$ Hz) of uncertain origin but possibly arising from coupling of the *tert*-butyl protons with the spin 1 nitrogen atom. The chemical shifts of the *tert*-butyl isocyanide protons increased slightly upon successive replacement of carbonyl groups with the more weakly $\pi$-accepting *tert*-butyl isocyanide ligands (see discussion above) suggesting that the increased electron density on the metal atom from such a substitution can increase the shielding of the *tert*-butyl protons of the *tert*-butyl isocyanide ligands. Similarly, the nmr spectra of the *mer*-$[(CH_3)_3CNC]_3M(CO)_3$ derivatives indicate that *tert*-butyl isocyanide groups trans to other *tert*-butyl isocyanide ligands have slightly higher chemical shifts than

*tert*-butyl isocyanide ligands trans to carbonyl groups.

# Nuclear Magnetic Resonance Studies of 8-Quinolinol Complexes of Molybdenum(VI, V) and of Vanadium(V), as Models for Molybdenum–Flavin Interactions

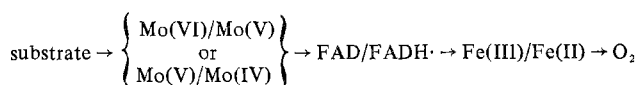LARRY W. AMOS and DONALD T. SAWYER*

The structures of the molybdenum(VI, V) and vanadium(V) complexes with 8-quinolinol (Q) and 2-methyl-8-quinolinol (2-Me-Q) in dimethyl sulfoxide solution have been investigated by proton nmr. The Mo(VI) and V(V) complexes with 8-quinolinol have the formulas $MoO_2Q_2$ and $VO(OH)Q_2$; infrared spectroscopy indicates that the metal oxo oxygens are cis to each other. The Mo(V) complex exists as an oxo-bridged dimer, $Mo_2O_3Q_4$, with the terminal oxo oxygens cis to the bridging oxygen. The 8-quinolinolate ligands appear to coordinate with the nitrogen donors bonded trans to the terminal (or bridging) oxygens. The nmr results indicate the existence of strong, covalent metal–ligand–oxygen bonding but, by virtue of the trans effect exhibited by the oxo oxygens, only weak, labile metal–nitrogen interactions. As a result of steric repulsion created by substitution at the 2 position of the ligand, there apparently is no, or extremely little, metal–nitrogen bonding in the Mo(VI) and V(V) chelates with 2-Me-Q. The implications of the weak Mo–N bonding for the molybdenum–flavin interaction in metalloflavoenzymes are discussed.

In addition to widespread industrial applications, molybdenum is an important trace element in living organisms. The presence and activity of molybdenum have been established for several enzymes including xanthine oxidase,[1] aldehyde oxidase,[2] nitrate reductase,[3] and nitrogenase.[4]

In xanthine oxidase and aldehyde oxidase there are two molybdenum atoms and two flavins per enzyme molecule.[5] Electron paramagnetic resonance (epr) signals have been observed for the enzymes[2,3,6–8] and have been attributed to both flavin radicals and paramagnetic molybdenum species.[6] The Mo(VI)/Mo(V) couple is believed to be important in some enzyme catalyses. Both oxidation states have been identified in nitrate reductase by 8-quinolinol complexation.[9,10] Molybdenum(V) has been detected by epr in all four of the enzymes in the presence of substrate.[2,3,7,8] On this basis, either the Mo(VI)/Mo(V) or the Mo(V)/Mo(IV) couple[11] is expected to be involved in the enzymatic oxidation–reduction reactions; the active molybdenum redox couple may vary from one enzyme to another.

Oxidation of substrates *via* molybdenum-containing enzymes generally is thought to occur by the process[2,6,12,13]

$$\text{substrate} \rightarrow \left\{ \begin{array}{c} \text{Mo(VI)/Mo(V)} \\ \text{or} \\ \text{Mo(V)/Mo(IV)} \end{array} \right\} \rightarrow \text{FAD/FADH} \cdot \rightarrow \text{Fe(III)/Fe(II)} \rightarrow O_2$$

FADH· is the protonated reduced form of flavin adenine dinucleotide (FAD). Depending on pH and substrate, the FAD/FADH· couple may precede the molybdenum couple in the electron transport scheme.[1]

Regardless of the direction of electron flow, the evidence indicates a close interaction between molybdenum and flavin

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in the enzymes. Epr spin-relaxation studies of FADH· have established that the flavin radical interacts with metal ions;[13] similar work by Beinert[12] indicates a molybdenum–flavin interaction.

Electrochemical studies of riboflavin (Rib)[14] have established that the one-electron reduction product (Rib⁻ or HRib·) complexes with metal ions, while the oxidized form does not. Similar studies of the molybdenum–riboflavin system are in progress[11] and have special relevance to xanthine oxidase.

Because the nmr spectra of molybdenum–flavin complexes are expected to be complicated and difficult to obtain (limited solubility and stability), a preliminary investigation of a model system has been undertaken. 8-Quinolinol is structurally similar to HRib· when the isoalloxazine nucleus is in the enol form;[15,16] several complexes between molybdenum and 8-quinolinol are known.[17] In the complexes, the hydroxyl proton is displaced by the metal; flavin radicals in the enol form complex in the same manner.[18-20]



keto

enol
HRib·
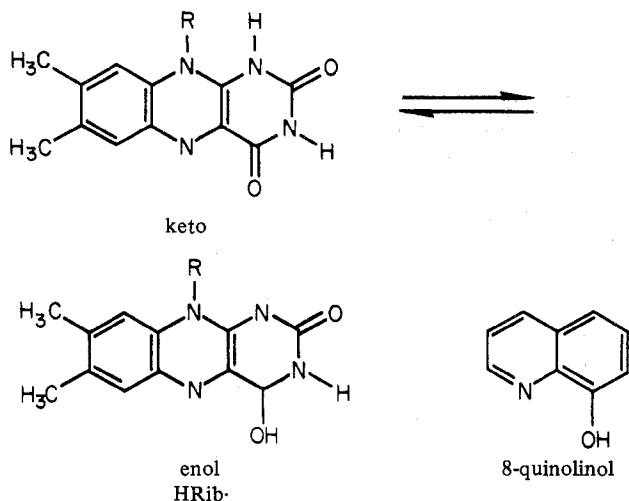
8-quinolinol

Because molybdenum complexes with 8-quinolinol are insoluble in water, dimethyl sulfoxide (DMSO) has been selected as the solvent. The use of an aprotic solvent in investigations of riboflavin model systems is in agreement with evidence that the protein fragment of flavoenzymes provides a nonaqueous environment.[21]

Although the structures of several 8-quinolinolate complexes have been determined by X-ray crystallography,[22-27] solution structures are more relevant models for the enzyme systems. The usefulness of nmr for the study of diamagnetic metal 8-quinolinolate chelates has been demonstrated by

Baker.[28,29] The electron densities at the various atoms in the aromatic rings of the ligand are sensitive to the delocalization of the nitrogen and oxygen lone electron pairs to the metal. Hence, the chemical shifts of the protons attached to the ring system are indicative of the types and strengths of the metal–ligand bonds;[28] additional shielding or deshielding of particular protons by local interactions yields information about the geometry of the chelate molecule.[28]

Because of the recent interest in vanadium as a trace metal in metabolic processes,[30-32] nmr investigations of the V(V) complex with 8-quinolinol have been included in the present study. The chemistries of vanadium(V) and -(IV) and molybdenum(VI) and -(V) are known to be similar, and vanadium can replace molybdenum in certain nitrogenases, although with a subsequent decrease in enzyme effectiveness;[30-32] a vanadium–flavin interaction is possible.

## Experimental Section

The proton nmr spectra were recorded on a Varian HA-100 nmr spectrometer, operated at 100 MHz. Dimethyl sulfoxide (DMSO) and dichloromethane ($CH_2Cl_2$) were used as solvents; each exhibits a large singlet resonance, which was used for the internal reference and spectrometer lock signal. The protons of DMSO and $CH_2Cl_2$ resonate at 2.678 ± 0.005 and 5.473 ± 0.005 ppm downfield, respectively, from those of tetramethylsilane; all chemical shifts are reported vs. the DMSO resonance.

The nmr spectra of 8-quinolinol, 2-methyl-8-quinolinol, 5-chloro-8-quinolinol and 5,7-dichloro-8-quinolinol were recorded as solutions in DMSO and in $CH_2Cl_2$. All four were sufficiently soluble in each solvent (at least 0.1 $M$) to obtain excellent single scan spectra. Due to the relatively low solubilities of the 8-quinolinolate complexes in DMSO (0.005–0.020 $M$), most of their spectra were obtained by use of a Varian Model C-1024 computer of average transients (CAT).

Samples of the complexes were prepared by making a saturated solution of the compound in 3 ml of DMSO and decanting 0.4–0.5 ml of the supernate into a high-precision nmr tube with a 1-ml syringe.

Infrared absorption spectra were recorded with a Perkin-Elmer Model 621 double-beam spectrophotometer over the range 4000–300 cm⁻¹ (2.5–33.3 $\mu$). Samples were prepared either as KBr disks or as finely dispersed suspensions of 2–3 mg of the solid compound in 3–4 drops of Nujol held between NaCl plates. Except for the absorptions of water and Nujol, the spectra were independent of the dispersing media.

All of the chemicals were reagent grade, or of comparable quality, and were used without further purification. 8-Quinolinol was obtained from Matheson Coleman and Bell and Allied Chemical; 2-methyl-8-quinolinol from Aldrich Chemical Co.; and 5-chloro-8-quinolinol from Columbia Organic Chemicals Co. Dimethyl sulfoxide was supplied by J. T. Baker Chemical Co. and dichloromethane by Mallinckrodt Chemical Works. The latter exhibited an nmr impurity peak at 3.70 ppm from DMSO; fortunately, the peak was far enough removed from the region of interest to have a negligible effect on the base line of the signal-averaged spectrum. Sodium molybdate dihydrate was obtained from Allied Chemical and ammonium metavandate from Fisher Scientific Co.

Simulated nmr spectra were calculated by use of the LAOCOON III computer program[33] on an IBM 360/50 equipped with a Calcomp plotter. The spectra were split into two three-proton halves for the purpose of calculation; the AMX pattern from the protons of the nitrogen ring (or, in the case of the 2-methyl substituted 8-quinolinols, a simple AB pattern), and the ABC pattern from the phenolic ring protons.

Preparation of the Complexes. 1. Dioxobis(8-quinolinolato)-molybdenum(VI). The $MoO_2Q_2$ complex was prepared by the method of Isbell.[34]

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Larry W. Amos and Donald T. Sawyer

**2. Dioxobis(5-chloro-8-quinolinolato)molybdenum(VI).** The synthesis of $MoO_2(5\text{-}Cl\text{-}Q)_2$ was analogous to that for the preceding complex. With vigorous stirring, 2.42 g (10 mmol) of $Na_2MoO_4 \cdot 2H_2O$, dissolved in 50 ml of 5% HCl, was added to 100 ml of acetone containing 3.69 g (20 mmol) of 5-chloro-8-quinolinol. The yellow-brown precipitate which formed immediately was digested for 5 hr on a low-temperature hot plate. The mixture was filtered, and the solid was washed with 95% ethanol, then with acetone, and allowed to dry in air for 4 days. Analysis indicates that the compound was isolated as $MoO_2(C_9H_5NOCl)_2$. *Anal.* Calcd for $MoC_{18}H_{10}N_2O_4Cl_2$: Mo, 19.78; C, 44.56; H, 2.08. Found: Mo, 19.60; C, 44.57; H, 2.26.

**3. Dioxobis(2-methyl-8-quinolinolato)molybdenum(VI).** Ten milliliters of 5 *F* HCl was added to a solution of 2.42 g (10 mmol) of $Na_2MoO_4 \cdot 2H_2O$ in 20 ml of water. The resulting solution was added, with vigorous stirring, to a solution of 3.18 g (20 mmol) of 2-methyl-8-quinolinol in 150 ml of 0.2 *F* HCl. The dark yellow precipitate, which formed when the solution was neutralized with concentrated NaOH, was digested for 2 hr on a hot plate then collected on a filter and dried for 1 hr at 120°. The finely crushed solid was purified by stirring it with 500 ml of refluxing methanol for 2 hr, filtering while hot, and washing the solid with a little methanol. The final product was allowed to dry in air for 2 days. Analysis indicates that the compound was isolated as $MoO_2(C_{10}H_8NO)_2$. *Anal.* Calcd for $MoC_{20}H_{16}N_2O_4$: Mo, 21.59; C, 54.06; H, 3.64. Found: Mo, 21.35; C, 53.92; H, 3.69.

**4. μ-Oxo-bis[oxobis(8-quinolinolato)molybdenum(V)].** Attempts to prepare $Mo_2O_3Q_4$ by the method of Isbell[34] resulted in a mixture of the desired product and uncomplexed 8-quinolinol, in about a 1:1 ratio. Washing the crude product with lower alcohols (methanol or ethanol) was found to be unsatisfactory as a method of purification, due to the solubility of $Mo_2O_3Q_4$ in these solvents. The yield was purified by heating the finely crushed product overnight in refluxing $CCl_4$. Analysis indicates that the compound was isolated as $Mo_2O_3$-$(C_9H_6NO)_4 \cdot H_2O$. *Anal.* Calcd for $Mo_2C_{36}H_{26}N_4O_8$: Mo, 22.99; C, 51.80; H, 3.15. Found: Mo, 23.20; C, 51.74; H, 2.99.

**5. Oxohydroxobis(8-quinolinolato)vanadium(V).** To prepare $VO(OH)Q_2$, 2.90 g (20 mmol) of 8-quinolinol was dissolved in 70 ml of 1 *M* acetic acid. Next, to this was added, dropwise, 1.17 g (10 mmol) of $NH_4VO_3$ dissolved in 100 ml of 0.2 *F* NaOH. A black precipitate formed, which was digested for 5 hr at a low hot plate temperature. The solid was collected on a fine-pore frit then dried at 120° to the reported blue-black product.[35-37] Analysis indicates that the compound was isolated as $VO(OH)(C_9H_6NO)_2$. *Anal.* Calcd for $VC_{18}H_{13}N_2O_4$: C, 58.07; H, 3.53. Found: C, 58.08; H, 3.25.

**6. Oxohydroxoaquobis(2-methyl-8-quinolinolato)vanadium(V).** The 2-methyl-8-quinolinolato complex of vanadium(V), $VO(OH)$-$(H_2O)_2(2\text{-}Me\text{-}Q)_2$, was prepared by a previously reported method.[38] The crude product was recrystallized from solvent grade methanol after stirring it with 500 ml of the hot solvent and filtering. The dark red filtrate was concentrated to about 75 ml. The solid which was obtained was darker yellow and fluffier than the initial yield. Analysis indicates that one coordinated water molecule was removed, probably in the recrystallization step, with the product isolated as $VO(OH)$-$(H_2O)(2\text{-}Me\text{-}Q)_2$. *Anal.* Calcd for $VC_{20}H_{19}N_2O_5$: C, 57.42; H, 4.59. Found: C, 57.39; H, 4.67.

## Results

**Infrared Absorption Spectra.** The infrared spectra of the Mo(VI) complexes are quite similar to those for normal 8-quinolinol complexes with divalent and trivalent metal ions, with the exception of the 950–850-cm$^{-1}$ region. As reported previously,[39] Mo(VI) chelates exhibit two strong bands in this region, which are assigned to the stretching modes of the $MoO_2$ units. In the case of the $MoO_2Q_2$, $MoO_2(5\text{-}Cl\text{-}Q)_2$, and $MoO_2(2\text{-}Me\text{-}Q)_2$ complexes, these symmetric and

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**Table I.** Chemical Shifts for the Protons of the Ligands in Molybdenum(VI, V) and Vanadium(V) 8-Quinolinolato Complexes[a]

| Compd | $\delta_2$ | $\delta_3$ | $\delta_4$ | $\delta_5$ | $\delta_6$ | $\delta_7$ |
|---|---|---|---|---|---|---|
| A. 8-Quinolinol | | | | | | |
| $Mo^{VI}O_2Q_2$ | 5.99 | 5.02 | 5.97 | 5.01 | 5.17 | 4.90 |
| $Mo^{VI}O_2Q_2(CH_2Cl_2)^b$ | 6.02 | 4.80 | 5.68 | 4.84 | 5.08 | 4.84 |
| $Mo^VO_3Q_4$ | 5.98 | 4.99 | 5.98 | 5.00 | 5.13 | 4.87 |
| $VO(OH)Q_2$ | 6.34 | 5.23 | 6.16 | 4.97 | 5.02 | 4.72 |
| HQ | 6.27 | 4.94 | 5.72 | 4.81 | 4.87 | 4.57 |
| $HQ(CH_2Cl_2)^b$ | 6.25 | 4.88 | 5.61 | 4.81 | 4.93 | 4.67 |
| B. 2-Methyl-8-quinolinol | | | | | | |
| $Mo^{VI}O_2(2\text{-}Me\text{-}Q)_2$ | | 4.83 | 5.73 | 4.85 | 4.98 | 4.69 |
| $VO(OH)(H_2O)(2\text{-}Me\text{-}Q)_2$ | | 4.88 | 5.66 | 4.76 | 4.90 | 4.67 |
| $2\text{-}Me\text{-}Q$ | | 4.81 | 5.58 | 4.76 | 4.80 | 4.53 |

[a] $\delta_n$ represents the chemical shift of proton $n$ in ppm *vs.* DMSO. [b] For $CH_2Cl_2$ as solvent; chemical shifts referenced to DMSO. All other entries for DMSO solutions.

antisymmetric modes are observed at 927 and 900, 936 and 911, and 933 and 906, respectively.

The dimeric molybdenum(V) complex, $Mo_2O_3Q_4$, shows a single strong band at 932 cm$^{-1}$ for the Mo=O stretch. The remainder of the spectrum resembles those of typical metal 8-quinolinolates. The vanadium(V) complexes characteristically exhibit a strong, broad band which occurs at 950 cm$^{-1}$ for $VO(OH)Q_2$ and at 940 cm$^{-1}$ for $VO(OH)(H_2O)$-$(2\text{-}Me\text{-}Q)_2$.

**Nuclear Magnetic Resonance Spectra.** The nmr chemical shifts for the protons of the complexes are tabulated in Table I; data for the uncomplexed ligands are included for comparison. Assignments have been made on the basis of previous experience[28,29] and refined by computer techniques. The complexes each exhibit only a single set of resonances (except for the freshly prepared solution of $VO(OH)(H_2O)(2\text{-}Me\text{-}Q)_2$), which indicates that the ligands in each complex are magnetically equivalent.

Immediately after dissolving in DMSO, the spectrum of $VO(OH)(H_2O)(2\text{-}Me\text{-}Q)_2$ exhibits two sets of ligand resonances. After the solution has stood for 1 day, one set of resonances is noticeably reduced, compared to the larger set, and all the peaks are broadened.

The similarity between the spectrum of $Mo_2O_3Q_4$ and that of the monomeric Mo(VI) complex, $MoO_2Q_2$, initially was suspect. Because care had not been taken to exclude oxygen from the solution, the spectrum that was obtained was thought to be the result of air oxidation of the dimeric complex. However, deaeration of the DMSO with argon before dissolving the compound followed by immediate recording of the spectrum yields the same result. Furthermore, when a vacuum line is used to degas the solvent three times and distil it into an nmr tube containing the solid, the spectrum again corresponds to the results given in Table I. The diamagnetic dimeric Mo(V) complex is quite stable with respect to air oxidation; solutions prepared without prior deaeration of the solvent retain their purple color for 2 to 3 weeks before beginning to fade.

## Discussion and Conclusions

**Structure of $MoO_2$ and $VO(OH)$ Units.** Although molybdenum(VI) is capable of existing as numerous monomeric and dimeric oxomolybdenum species,[17] it generally complexes octahedrally as the dioxomolybdenum(VI) ($MoO_2^{2+}$) entity. Compounds also are known which contain the trioxomolybdenum(VI) unit ($MoO_3$)[40] and the oxo-bridged dimeric

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species, $\mu$-oxo-bis(dioxomolybdenum(VI) $(Mo_2O_5{}^{2+})$.[41]

For all of the molybdenum(VI) complexes whose structures have been determined by X-ray crystallography, the terminal oxygen atoms are cis with respect to each other;[17] that is, they occupy adjacent positions in the octahedron. Even in the $MoO_3$ systems, no two terminal oxygens are trans across the molybdenum.[17,40] For the dimeric chelates, the terminal oxygens on each molybdenum atom are cis, not only to each other but also to the bridging oxygen.

The same situation exists in oxomolybdenum(V) chemistry, only with the additional condition that no Mo(V) coordination compound contains more than one double-bonded terminal oxygen atom per molybdenum.[17] The known oxomolybdenum(V) species are monomeric $MoO^{3+}$ and the dimeric units with single[42-43] and double[44] oxygen bridges ($Mo_2O_3{}^{4+}$ and $Mo_2O_4{}^{2+}$, respectively).

The infrared spectra in the molybdenum–oxygen stretching region are well characterized.[43-47] Those compounds which contain two double-bonded terminal oxygens ($Mo=O_t$) exhibit two strong bands at approximately 900 cm$^{-1}$; these are known to be the symmetric and antisymmetric stretch modes for the cis-$MoO_2$ units.[46] Molybdenum(V) compounds exhibit only one such band because they have but one terminal oxygen per molybdenum. Besides the terminal oxygen stretch bands, the dimeric species usually exhibit an antisymmetric stretch for the bridge systems, Mo–$O_b$–Mo and

$$Mo\overset{/\ O_b\ \backslash}{\underset{\backslash\ O_b\ /}{}}Mo$$
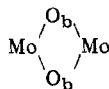
The band for this mode appears in the region from 700 to 900 cm$^{-1}$ but is unassignable in the present complexes due to the presence of ligand bands in that region.

The infrared spectra of the 8-quinolinol complexes in the present work are consistent with these generalizations. The Mo(VI) complexes all exhibit the two characteristic $Mo=O_t$ stretch bands, which indicates that they contain the cis-$MoO_2{}^{2+}$ unit. The strong band at 932 cm$^{-1}$ for the $Mo=O_t$ stretch in $Mo(V)_2O_3Q_4$ agrees well with the value of 940 cm$^{-1}$ reported by Mitchell.[17]

On the basis of similarities between the chemistries of molybdenum(VI) and vanadium(V) and the results from previous studies,[48,49] the metal oxygens in the 8-quinolinol complexes of vanadium(V) probably are cis to each other. While the vanadium exists as intact cis-$VO_2$ units in complexes with oxalate,[48] EDTA,[48,49] and related ligands,[49] the central unit in the 8-quinolinolate system is the oxohydroxovanadium(V) ion, $VO(OH)^{2+}$. Although early workers concluded[35-38] that the terminal oxygen and the hydroxo group were situated trans across the vanadium ion, this conclusion is questionable because of recent dipole moment measurements[50] of the $VO(OMe)Q_2$ and $VO(OMe)(2-Me-Q)_2$ com-

plexes. On the basis of the large values obtained (5.24 and 4.55 units, respectively), the metal oxygens in these chelates must be cis; the trans structure would yield a dipole moment of ~1.6 D.

The $V=O_t$ stretch is easily assigned to a strong, slightly broadened band at 950–940 cm$^{-1}$; the broadening may be attributed to a slight coupling with the V–OH stretch mode. Due to the plethora of ligand absorptions in the region below 900 cm$^{-1}$, observed for all metal 8-quinolinolates, definite assignments cannot be made for the V–OH stretches.

**Solution Structures of the 8-Quinolinolato Complexes.** Consideration of the manner in which the 8-quinolinol ligands complex to the cis-$MoO_2{}^{2+}$ or -$VO(OH)^{2+}$ entities must take account of the fact that the nmr spectrum for each complex exhibits only one set of ligand resonances. That is, the ligands in any one complex are magnetically equivalent. This indicates that either the complex possesses a twofold axis of symmetry in solution, or the 8-quinolinolates in the chelate are far enough removed from the site of asymmetry that they are in essentially identical environments.

Atovmyan[25] has shown that the $MoO_2Q_2$ complex exists in the crystalline state as the structure illustrated by Figure 1. The molecule exhibits nearly perfect $C_{2v}$ symmetry. The $Mo=O_t$ bonds are strong (Mo–$O_t$ distance, 1.71 Å) and the $MoO_2$ unit definitely is cis ($O_t$–Mo–$O_t$ angle, 104°).

An important result from Atovmyan's work is the long Mo–N bond length of 2.32 Å. Long metal–ligand bonds at the positions trans to the terminal oxygens are common, not only for oxomolybdenum systems but also in compounds of vanadium, niobium, tantalum, tungsten, and rhenium with metal–ligand multiple bonds. This trans effect is not observed in the simpler 8-quinolinolato complexes, such as $ZnQ_2$,[22] $CuQ_2$,[22,23] and $PdQ_2$,[24] where the M–N bond lengths (2.10–1.97 Å) are the same as the M–O bond lengths (2.07–1.92 Å).

**Bonding Effects on the Chemical Shifts.** In previous work on metal 8-quinolinolates, the chemical shifts of the ligand protons have been correlated with five types of metal–ligand bonding.[28] For the purposes of the present study, however, only two of the five cases require consideration. The first case yields predicted proton chemical shifts when the metal–oxygen bond is covalent and the ligand nitrogen is strongly coordinated. The net effect is the same as total protonation of both the ligand oxygen and nitrogen atoms, and the resulting spectrum will be that of 8-quinolinol in acidic solution. Case 2 corresponds to the situation in which the metal–oxygen bond is covalent and there is no metal–nitrogen interaction; the result will be similar to 8-quinolinol itself, corrected for hydrogen bonding between the hydroxyl group and the nitrogen. Both cases and their average are summarized in Table II. The remaining cases discussed by Baker and Sawyer involve ionic metal–oxygen bonding and do not apply to the present systems.[28]

The analogous calculations have been made for 2-methyl-8-quinolinol; the predicted proton chemical shifts for the two limiting bonding cases are shown in Table II. The average of the case 1 and case 2 predictions also is presented and can be considered representative of a covalent metal–oxygen bond and a weakened metal–nitrogen bond.

**Effects of Shielding by Neighboring Groups.** Other effects which influence the nmr spectrum are due to the close proximity of the ligands to each other in a rigid chelate struc-

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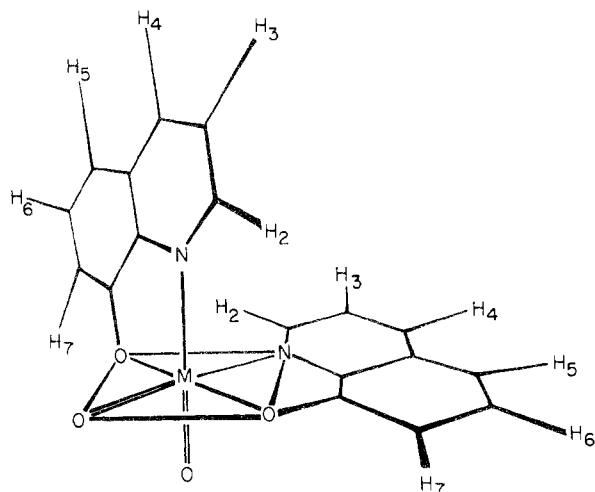(50) A. V. Savitskii, S. Ya. Skachilova, and I. Yu. Kokoreva, *Russ. J. Inorg. Chem.*, 12, 435 (1967).

**Figure 1.** Structure of a generallized *cis*-dioxo metal complex with 8-quinolinol.

**Table II.** Corrected Proton Chemical Shifts in Limiting Bonding Cases[a]

| Case | $\delta_2$[b] | $\delta_3$ | $\delta_4$ | $\delta_5$ | $\delta_6$ | $\delta_7$ |
|------|------|------|------|------|------|------|
| A. 8-Quinolinolato Complexes | | | | | | |
| 1 | 6.22 | 5.48 | 6.59 | 5.15 | 5.15 | 5.02 |
| 2 | 6.02 | 4.90 | 5.71 | 4.82 | 4.87 | 4.73 |
| Av | 6.12 | 5.19 | 6.15 | 4.99 | 5.01 | 4.88 |
| B. 2-Methyl-8-Quinolinolato Complexes | | | | | | |
| 1 | | 5.26 | 6.32 | 5.08 | 5.11 | 4.97 |
| 2 | | 4.76 | 5.58 | 4.76 | 4.80 | 4.68 |
| Av | | 5.01 | 5.95 | 4.92 | 4.95 | 4.82 |

[a] $\delta$ in ppm *vs.* DMSO.  [b] Corrected for a M–N distance of 2.3 Å.

ture. The interaction of local magnetic fields of one ligand with the protons of a neighboring ligand can cause shielding or deshielding of those protons, depending on the geometrical configuration of the chelate. Reference to Figure 1 indicates that the ligands are arranged such that proton 2 of one ligand is situated directly over the oxygen of the other ligand. Proton 2 is thus shielded by the oxygen lone pairs, and the magnitude of the shielding can be approximated by the relationship given by McConnell[51]

$$\Delta\sigma = (\Delta\chi/3r^3 N_0)(1 - 3\cos^2\gamma)$$

where $\Delta\chi$ is the anisotropy due to the electron pairs in the direction perpendicular to the M–O–C plane, $N_0$ is Avogadro's number, $r$ is the distance from proton 2 to the oxygen in centimeters, and $\gamma$ is the angle between the proton 2–oxygen line and the axis perpendicular to the M–O–C plane. A value of $-8.4 \times 10^{-30}$ cm$^3$/molecule has been used for the anisotropy, $\Delta\chi/N_0$.[52] The value of $\Delta\sigma$ has been calculated from molecular models, keeping the M–O bond length constant at 2.0 Å and varying the M–N distance from 2.0 to 2.8 Å. Proton 2 is the only one which is noticeably affected by the oxygen; the remaining protons are too far away to experience any shielding from this source.

The other primary effect on the chemical shift of a proton is the electron currents in the ring system of the adjacent ligand. On the basis of the results of Johnson and Bovey,[53] protons 2 and 3 experience additional shieldings of about 0.10 and 0.05 ppm, respectively, from the rings of the neighboring 8-quinolinolate ligand.

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**Table III.** Anisotropic Shielding of Proton 2 in 8-Quinolinol Complexes Due to Oxygen Lone Pair and Ring Current Effects[a]

| M–N bond length | $\Delta\sigma$ | M–N bond length | $\Delta\sigma$ |
|------|------|------|------|
| 2.0 | +0.56 | 2.4 | +0.27 |
| 2.2 | +0.35 | 2.6 | +0.22 |
| 2.3 | +0.30 | 2.8 | +0.18 |

[a] Bond length in Å; $\Delta\sigma$ in ppm (positive $\Delta\sigma$ represents a shift of the proton resonance to lower $\delta$).

The total anisotropic shielding of proton 2 as a function of the M–N distance from the two primary effects is summarized in Table III. These corrections have been applied to the limiting bonding cases in Table II. The chemical shifts of proton 2 in the table have been corrected to correspond to a metal–nitrogen distance of 2.3 Å.

**Molybdenum(VI, V) and Vanadium(V) Complexes with 8-Quinolinol.** The observed chemical shifts of $MoO_2Q_2$, both in DMSO and in $CH_2Cl_2$, are consistent with the crystal structure determined by Atovmyan.[25] Most of them fall between those of case 2 and those of the average of cases 1 and 2. The proton 6 chemical shift, which is larger than predicted by case 2, cannot be explained easily. It may indicate a specific deshielding effect caused by proton 2 of the other ligand; better agreement is observed in the 2-methyl-8-quinolinolates. The molybdenum–nitrogen bonds clearly are weak in solution, which is analogous to the solid phase condition. The bonds between the ligand oxygens and molybdenum appear to retain their covalent nature in solution.

Virtually the identical situation exists in the diamagnetic molybdenum(V) dimeric complex, $Mo_2O_3Q_4$ (I, below);[34]



I
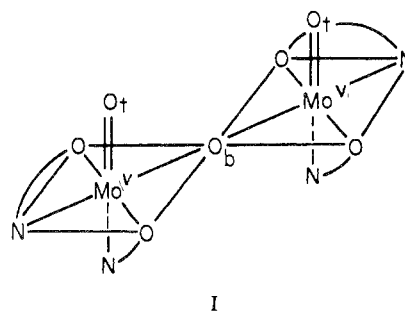
the chemical shifts of the protons in this chelate are the same, within experimental error, as those observed for $Mo^{VI}O_2Q_2$.

The idea of a trans effect from the bridging oxygen of I initially appears suspect, because $O_b$ traditionally is drawn as being singly bonded to each molybdenum. However, the presence of two d electrons allows $\pi$ interactions across the $Mo-O_b-Mo$ linkage, involving one d orbital of each molybdenum and two p orbitals of the bridging oxygen.[42] Hence, a trans effect by the bridging oxygen in $Mo_2O_3Q_4$ is reasonable and has been observed[42] in the ethyl xanthate system. The average Mo–S bond trans to the terminal oxygens is 2.70 Å, while the sulfurs trans to the bridging oxygen are 2.54 Å from molybdenum.

The results for the vanadium(V) chelate, $VO(OH)Q_2$, also are consistent with long, labile V–N bonds; the chemical shifts generally agree with those predicted for the intermediate case. The major discrepancy that is observed for proton 2 can be due to a number of causes. Simple lengthening of the V–N bond will decrease the shielding of the proton by the oxygen lone pair. Alternatively, solvation effects can be invoked as the explanation. The observation of only one set

of ligand resonances indicates that the hydroxo group proton either is dissociated or is hydrogen bonded between the terminal oxygens. DMSO would be involved in either process; its behavior as a solvent is poorly understood and some specific interaction between DMSO and proton 2 is possible.

**Molybdenum(VI) and Vanadium(V) Complexes with 2-Methyl-8-Quinolinol.** The observed chemical shifts for both the Mo(VI) and V(V) 2-methyl-8-quinolinolates indicate extremely weak or nonexistent metal–nitrogen interactions. Because the data agree so well with the case 2 predictions, the conclusion is that there is no metal–nitrogen coordination in these complexes.

The steric problems resulting from substitution at the 2 position can be realized by reference to Figure 1. The methyl group hydrogens are repelled by the coordinated oxygen of the neighboring ligand; the repulsion is minimized by cleavage of the M–N bond. Space-filling CPK models demonstrate the steric problem most effectively; only by disconnecting the metal–nitrogen linkage is the methyl group given sufficient space to allow its hydrogens to clear the oxygen when rotating.

On the basis of elemental analysis, the yellow vanadium(V)-(2-Me-Q)$_2$ complex contains only one coordinated water molecule. The nmr spectrum, taken immediately after the solid dissolves in DMSO, exhibits two sets of ligand resonances. Although the phenolic ring proton resonances are difficult to distinguish, the chemical shifts of proton 4 (5.87 and 5.66 ppm) and proton 3 (5.02 and 4.88 ppm) in each set can be deduced. When the spectrum is recorded again after 1 or 2 days, only the spectrum given in Table I remains. The values of $\delta_3$ and $\delta_4$ for the ligand spectrum which disappears upon standing indicate that this ligand initially is weakly coordinated to vanadium through the nitrogen atom (see Table IIB). However, at equilibrium, the ligand nitrogens appear to have dissociated from the vanadium. On the basis of the change in color from yellow to olive green upon standing in DMSO, the coordinated water probably is displaced by DMSO molecules that also occupy the coordination sites left open by the ligand nitrogens.

**Implications of Molybdenum Complexes with 8-Quinolinol for Xanthine Oxidase.** A major objection to the validity of 8-quinolinol complexes with molybdenum as models for molybdenum–flavin interactions in enzymes such as xanthine oxidase is the stoichiometries of the two systems. The Mo(VI) and Mo(V) chelates with 8-quinolinol exhibit a 2:1 ligand-to-metal ratio, whereas the enzyme systems are known to have one flavin entity per molybdenum (formally, two FAD and two molybdenums per enzyme molecule).

However, this difference in metal–ligand ratio probably does not affect the nature of the metal–ligand bonding of molybdenum. The presence of flavin and molybdenum in a 2:2 ratio, coupled with the tendency of molybdenum to dimerize, indicates that the molybdenum species in the enzyme may be dimeric. Furthermore, recent work[11] on the molybdenum–riboflavin system indicates that the relevant species in DMSO is the 2:2 dioxo-bridged Mo(V) complex, [Mo$_2$O$_4$(OH)$_2$Rib$_2$]$^{2-}$. The double-oxygen-bridge system results in each molybdenum having one terminal (Mo=O$_t$) and two bridging (Mo–O$_b$–) oxygens; in such Mo(V) species, the three oxygens around each molybdenum are cis with respect to each other.[44] Assuming that the flavin complexes to the metal at the O(4) and N(5) sites, as with numerous other metal ions,[18-20] then the flavin nitrogen donor will be trans to one of the oxo oxygens of the molybdenum. Therefore, regardless of the stoichiometric difference, the weak Mo–N bonding found in the 8-quinolinolates (due to the trans effect from the terminal and bridging oxygens) probably is paralleled in molybdenum–flavin complexes.

The interaction between molybdenum and flavin generally is thought to be stronger after an electron is accepted from an oxidizable substrate than before. The present results are in agreement with a weak initial interaction. Epr results[54,55] indicate that the molybdenum of xanthine oxidase initially accepts an electron from the substrate. The process most likely involves formation of a complex between molybdenum and the substrate; the existence of a weak interaction between molybdenum and the flavin molecule is expected to allow room for the temporary complexation. After the substrate has been oxidized and has dissociated from the active site, the resulting molybdenum–flavin complex may undergo stronger interaction to delocalize the electron through the flavin to iron and finally to molecular oxygen.

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