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Vanadium(V) Oxyanions: Formation of Cyclic Esters with Ethylene Glycol

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Abstract: The spontaneous esterification of ethylene glycol by vanadate in aqueous solution has been studied by ^{51}V NMR spectroscopy. From the variation in ethylene glycol concentration, vanadate concentration, and pH, the various products have been identified and structures assigned. The equilibrium constants between the various products have been obtained and pK_a's measured for those with ionizable hydrogens. The results show that 2-hydroxyethyl vanadate and bis(2-hydroxyethyl) vanadate are formed with K_1 and K_2 of 18.6 ± 1.0 and 4.9 ± 0.3, respectively, at pH 7.5, 0.805-13.7 M ethylene glycol, and 20 mM Tris-chloride. A cyclic species was also identified. This species was formed as a dimeric compound, and no evidence for significant proportions of the monomer was found. The equilibrium constant for formation of this product from the 2-hydroxyethyl vanadate was $2.5 \pm 0.2 \times 10^5$. From consideration of the equilibrium expressions required to fit the observations, from an NMR study of 1,2-propanediol in association with vanadate, and also from the widths of the various NMR resonances it was concluded that the vanadate and its acyclic derivatives are tetrahedral about vanadium whereas the cyclic derivative is pentacoordinate and trigonal-bipyramidal. It is formed as an anhydride of (1,2-ethanediolato)dihydroxooxovanadate(1−) with bridging occurring through apical positions of the two bipyramids.

Over the past decade there has been a developing interest in the chemistry and biochemistry of vanadium. Vanadium is apparently an essential nutrient which regulates cellular activities.[1,2] The activity of vanadium may derive from its ability to mimic the function of phosphate and to act as a transition-state analogue.

The aqueous chemistry of vanadium(V) oxyanions is very complex. This complexity arises in part from the ability of the vanadate ion (VO_4^{3-}) to undergo protonation and oligomerization reactions as pH and concentration are changed.[3-5] This propensity toward oligomerization and to the change in coordination geometry which frequently accompanies such reactions may lie at the source of the biological activity of vanadium. The tendency toward oligomerization may, to an extent, be expressed in biological systems by the spontaneous formation of esters of alcohols and diols.

Many of the problems arising from the oligomerization reactions of vanadate can be removed by working with sufficiently dilute solution and by rigorously controlling pH. Under such conditions detailed information concerning the spontaneous formation of ethyl and diethyl vanadate from ethanol and vanadate ion in aqueous solution has been obtained.[6]

Nuclear magnetic resonance (NMR) spectroscopy has proven to be an essential tool for such studies. Vanadium(V) signals occurring at a resonance frequency of 105 MHz are, in general, sufficiently well resolved to allow chemical structures to be assigned to all signals. High-field NMR spectrometers provide a distinct advantage over lower field spectrometers since ^{51}V signals tend to be quite broad because of quadrupolar relaxation, 50-100 Hz for compounds of nominally tetrahedral symmetry about vanadium and much broader as lower symmetry is obtained.[7]

Although there has been a considerable number of NMR investigations of isopolyanions of vanadium(V) in aqueous solution[5,7] there have been very few studies of the interactions between vanadate and alcohols and polyhydroxylic species in aqueous medium. The reactions of vanadate with 1,2-aromatic diols have been studied by stopped-flow spectroscopy,[8] but no information concerning the structure of the vanadate species formed was obtained. The results did show that there was a fast initial reaction over in about 40 ms which corresponded to the formation of a vanadate-diol complex. The second reaction, which was over in about 2 s, corresponded to the oxidation of the diol. Various other aromatic diol systems have been investigated, but no structural information has been reported.

NMR studies of aliphatic alcohols in aqueous solution with vanadate have shown that vanadate esters with tetrahedral geometry about vanadium are spontaneously formed.[6] Results of solubility studies of vanadium(IV) and vanadium(V) oxyanions in association with uridine and of enzymic inhibition studies were used as a basis for the proposal that uridine spontaneously forms cyclic pentacoordinate esters utilizing the 2′,3′ hydroxyl groups of the ribofuranoside ring.[9] X-ray and neutron diffraction studies of the uridine-vanadate-ribonuclease A complex clearly showed the trigonal-bipyramidal structure of the vanadate moiety.[10,11]

It has recently been reported that the trigonal-bipyramidal structure is spontaneously formed by vanadate upon esterification with various diols in aqueous solution[12] including uridine.[11,12] This structure is in keeping with that hypothesized by earlier workers.[9] Product stoichiometry and equilibrium parameters for the various reactions of ethylene glycol with vanadate in aqueous solution have been investigated by NMR spectroscopy, and the results are described here.

Experimental Section

Materials. Reagent grade chemicals were used without further purification. Preparation of the vanadate solutions has been described.[13] Preparation of ethylene glycol, propylene glycol, and butylene glycol solutions and determination of glycol and water concentrations followed the procedures previously described for the study using ethanol-water mixtures.[6]

Methods. All NMR spectra were obtained at ambient temperature, 294 K, from a Bruker 9.4 T cryospectrometer operating at 105 MHz in the unlocked mode. Pulse widths of 45°, spectral widths of 20 kHz, and 0.05-s acquisition times were used for the majority of the spectra. Longer acquisition times were found to have no observable effect on relative intensities of the various signals observed. Relative peak intensities were obtained by using NMR software provided by the instrument manufacturer.

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Chemical shifts are reported relative to an external reference of $VOCl_3$ via a second reference of saturated Na_3VO_4 in water where the high-field resonance occurs at −572.9 ppm from $VOCl_3$. The low-intensity high-field resonance was chosen since it has been shown to have a pH-invariant chemical shift.[5]

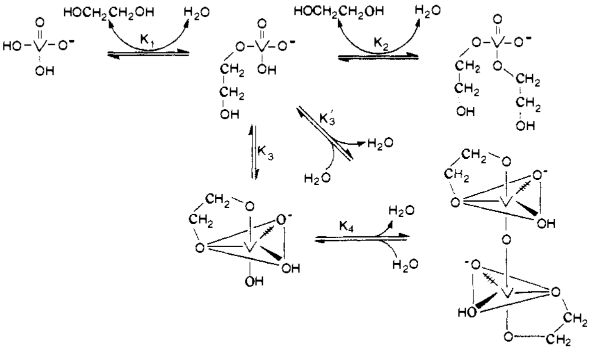
Ultraviolet spectra were obtained at room temperature on a Cary 210 spectrophotometer.

Results and Discussion

NMR investigation of aqueous ethanol solutions with vanadate showed that as ethanol concentration was increased the ^{51}V NMR spectra showed first the formation of one then an additional vanadate species. At pH 7.5, the three resonances observed in a sufficiently concentrated ethanol solution were identified as the tetrahedral species $VO_4H_2^-$, $CH_3CH_2OVO_3H^-$, and $(CH_3CH_2O)_2VO_2^-$.[6] When similar experiments using ethylene glycol instead of ethanol were performed, NMR signals attributable to similar mono- and diesters were observed. However, in addition a third resonance which occurred about 40 ppm to lower field (−522.1 ppm) was also observed. Various other diols were found to provide signals in the same region of the spectrum, in particular that of 2,3-butanediol which at a concentration of 4.4 M exhibited only a single resonance at −525.6 ppm. This provided the opportunity to study the product by ultraviolet (UV) spectroscopy since absorbances from the known tetrahedral species such as the ethylene glycol esters will be absent. A UV spectrum of vanadate in the absence of butanediol shows an absorbance at 270 nm. In the presence of sufficient butanediol to convert the vast majority of the vanadate into the product giving rise to the −525 ppm signal, the UV absorbance was shifted to 250 nm with a relatively much lower absorbance at 270 nm. This result is in accordance with a significant change in the chemical properties of the chromophore. This indicates that the vanadium nuclei giving rise to the NMR resonance at −525 ppm are in a chemically quite distinct environment from those giving rise to signals near −555 ppm.

The various NMR signals were studied as a function of ethylene glycol concentration, of vanadate concentration, and of pH. From these results it is proposed that the product giving rise to the −522 ppm signal in the NMR spectrum is the anhydride of the trigonal-bipyramidal cyclic ester, (1,2-ethanediolato)dihydroxooxovanadate(1−). A selected NMR spectrum showing all resonances and the associated species giving rise to those signals is displayed in Figure 1.

The interrelationships between the proposed compounds and the respective equilibrium constants are shown in eq 1.



(1)

When in equilibrium in solution, the total vanadate (V_T) partitions among the various species represented above. The conservation equation, eq 2, can then be written as shown. The

$$[V_T] = [V_i] + [\text{monoester}] + [\text{diester}] + [\text{cyclic monomer}] + [\text{cyclic dimer}] \quad (2)$$

equilibrium constants of eq 1 are readily written as eq 3–7. There

$$K_1 = [\text{monoester}][H_2O]/[V_i][C_2H_4(OH)_2] \quad (3)$$

$$K_2 = [\text{diester}][H_2O]/[\text{monoester}][C_2H_4(OH)_2] \quad (4)$$

$$K_3 = [\text{cyclic monomer}]/[\text{monoester}] \quad (5)$$

$$K_4 = [\text{cyclic dimer}][H_2O]/[\text{cyclic monomer}]^2 \quad (6)$$

$$K_3' = [\text{cyclic dimer}][H_2O]/[\text{monoester}]^2 \quad (7)$$

is no evidence from the NMR spectrum for two cyclic esters; however, there may be overlap of resonances, so it is necessary to establish the presence or absence of the individual cyclic species. It is possible to test this by varying the proportions of vanadate in various solutions while maintaining constant pH and ethylene glycol concentration. Such a study also allows confirmation of the stoichiometry assigned to the acyclic mono- and diesters, 2-hydroxyethyl vanadate and bis(2-hydroxylethyl) vanadate. The results of the vanadium concentration study are given in Table I. The lack of dependence of the ratio of the sum of the acyclic mono- and diester to vanadate on total vanadate concentration is in accord with the formation of the above acyclic esters, as expected from the study of ethanol.[6]

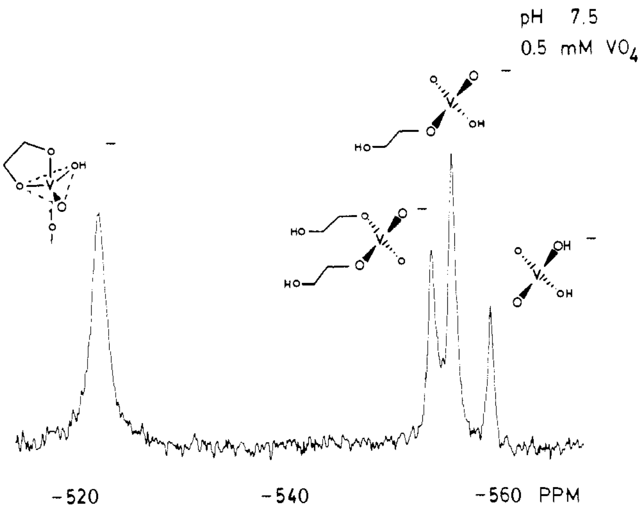


Figure 1. A vanadium-51 NMR spectrum showing the various resonances observed from an aqueous 5.64 M solution of ethylene glycol and the associated chemical species. The solution contained 2.0 × 10^{-2} M Tris-Cl buffer at pH 7.5 and 5.0 × 10^{-4} M vanadate added as Na_3VO_4.

Table I. Distribution of Vanadium among the Various Species as a Function of the Total Vanadium Atom Concentration[a]

$[V_T]$	cyclic ester	acyclic esters (mono, di)	$[V_i]$	acyclic esters/ $[V_i]$	cyclic ester/ acyclic esters
0.10	0.012	0.058	0.030	1.9	0.21
0.25	0.077	0.12	0.058	2.0	0.66
0.50	0.18	0.20	0.12	1.7	0.87
1.0	0.52	0.30	0.17	1.8	1.7

[a] Concentrations indicated are vanadium atom concentrations (mmol/L) obtained from relative intensities of the resonances assigned to the indicated species. Solutions contained the indicated concentrations of vanadate added as Na_3VO_4, 0.020 M Tris-Cl buffer at pH 7.5, and 3.22 M ethylene glycol.

On consideration of the formation of the cyclic esters it must be assumed that the possible esters give rise to NMR signals which are superimposed since no other signal is observed in the relevant region of the spectrum. It is possible to rewrite eq 5 by substitution from eq 3 to give eq 8 and, similarly, eq 6 with eq 8 to obtain eq

$$[\text{cyclic monomer}] = [V_i]K_1K_3[C_2H_4(OH)_2]/[H_2O] \quad (8)$$

9. Combination of eq 8 and 9 with eq 3 and 4 provides expression 10.

$$[\text{cyclic dimer}] = [V_i]^2(K_1K_3)^2K_4[C_2H_4(OH)_2]^2/[H_2O]^3 \quad (9)$$

$$\frac{[\text{cyclic monomer}] + [\text{cyclic dimer}]}{[\text{monoester}] + [\text{diester}]} = \frac{[V_i]K_1K_3{}^2K_4[C_2H_4(OH)_2]/[H_2O]^2}{1 + K_2[C_2H_4(OH)_2]/[H_2O]} + \frac{K_3}{1 + K_2[C_2H_4(OH)_2]/[H_2O]} \quad (10)$$

An NMR signal deriving from the cyclic dimer is proportional to twice its molar concentration since it contains two identical

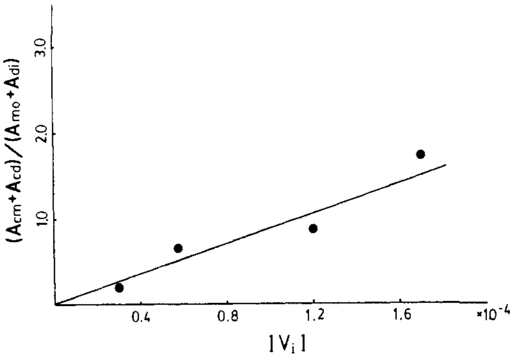


Figure 2. The ratio of areas of NMR signals from the cyclic esters to those from the acyclic esters are plotted as a function of the concentration of inorganic vanadate, $[V_i]$. The results are consistent with negligible amounts of monomeric cyclic ester in solution. The data used for this plot are given in Table I.

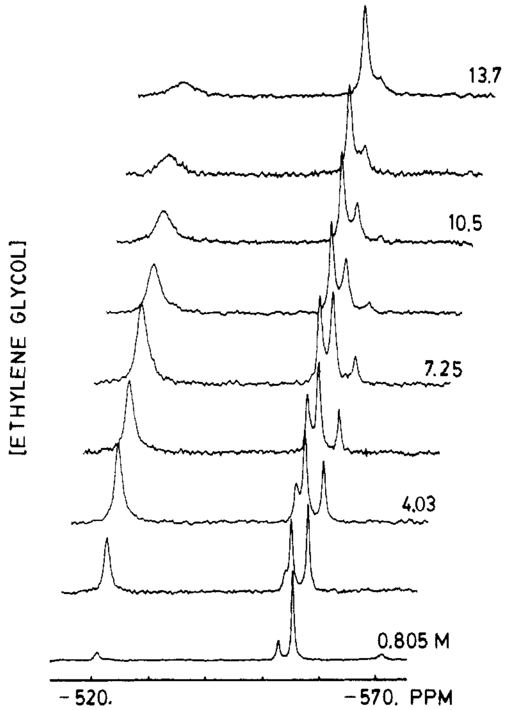


Figure 3. Vanadium-51 NMR spectra are shown at various ethylene glycol concentrations. The changes in the relative areas of the various signals determine the equilibrium constants for the reactions and delineate the stoichiometry of the components. Conditions are given with Table II.

vanadium nuclei. If the concentrations of eq 10 are written in terms of vanadium atom concentrations, A_{cm}, A_{cd}, A_{mo}, and A_{di} for cyclic monomer, cyclic dimer, acyclic monoester, and acyclic diester, respectively, then eq 10 can be rewritten as eq 11. In

$$\frac{A_{cm} + A_{cd}}{A_{mo} + A_{di}} = \frac{2[V_i]K_1K_3^2K_4[C_2H_4(OH)_2]/[H_2O]^2}{1 + K_2[C_2H_4(OH)_2]/[H_2O]} + \frac{K_3}{1 + K_2[C_2H_4(OH)_2]/[H_2O]} \quad (11)$$

this form the proportion of the cyclic monomer to the cyclic dimer is irrelevant. If $(A_{cm} + A_{cd})/(A_{mo} + A_{di})$ is plotted against inorganic vanadate (V_i) concentration at constant ethylene glycol and water concentration, eq 11 predicts a straight line which will have a nonzero y-intercept if cyclic monomer is present in solution. Figure 2 shows the experimental results obtained at pH 7.5. The data points are rather sparse since oligomerization problems are encountered at the higher vanadate concentrations. The results, however, are consistent with insignificant amounts of cyclic monomer being present in solution. Equation 11 of course predicts a small value for the intercept if K_3 is small, and again this means that an insignificant proportion of cyclic monoester is in solution. A similar result was obtained from experiments in which total vanadate concentration was varied at pH 9.0.

Table II. Distribution of Vanadium among the Various Species as a Function of Ethylene Glycol Concentration[a]

$C_2H_4(OH)_2$[b]	H_2O[b]	monoester[c]	diester[c]	cyclic dimer[c]	$[V_i]$[c]
0.805	53.0	0.0874		0.0546	0.354
1.61	50.6	0.123	0.0100	0.133	0.234
2.41	48.0	0.142	0.0265	0.183	0.149
3.22	45.6	0.158	0.0400	0.177	0.124
4.03	43.0	0.137	0.0615	0.216	0.0820
4.83	40.5	0.137	0.068	0.228	0.0680
5.64	38.0	0.136	0.085	0.230	0.0490
6.44	35.5	0.131	0.106	0.222	0.0405
7.25	33.0	0.122	0.115	0.225	0.0380
8.05	30.5	0.117	0.131	0.219	0.0320
8.86	28.0	0.107	0.162	0.210	0.0170
9.66	25.5	0.0975	0.179	0.207	0.0160
10.5	23.0	0.0935	0.198	0.197	0.0115
11.3	20.5	0.0940	0.201	0.193	0.005
12.1	18.0	0.0730	0.261	0.162	
12.9	15.5	*d*	*d*	0.156	
13.7	13.0	*e*	*e*	0.139	

[a] Concentrations shown are vanadium atom concentrations obtained from relative intensities of the resonances assigned to the indicated species. Therefore, for correlations based on the assumption that the cyclic ester exists entirely as a dimer, the vanadium concentrations are double the dimer concentrations. Solutions contained the indicated concentrations of ethylene glycol ($C_2H_4(OH)_2$) and water, 5.0×10^{-4} M vanadate added as Na_3VO_4, and 2.0×10^{-2} M Tris-Cl buffer at pH 7.5. [b] Concentrations are molar quantities. [c] Concentrations are millimolar quantities. [d] 0.344 mmol, distributed between the mono- and diester. [e] 0.361 mmol, distributed between the mono- and diester.

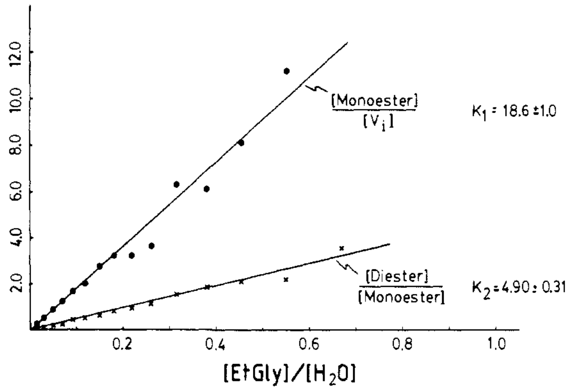


Figure 4. Determination of the equilibrium constants K_1 and K_2 for formation of 2-hydroxyethyl vanadate and bis(2-hydroxyethyl) vanadate. The ratios $[HOCH_2CH_2OVO_3H^-]/[VO_4H_2^-]$ and $[(HOCH_2CH_2O)_2VO_2^-]/[HOCH_2CH_2OVO_3H^-]$ are plotted as a function of $[HOCH_2CH_2OH]/[H_2O]$. The slopes provide K_1 and K_2. The data used are given in Table II.

Under the conditions of the experiments described here the cyclic dimer is essentially the only species giving rise to an NMR resonance at −522 ppm. There is, however, no reason to expect that significant proportions of monomeric cyclic esters will not occur in vanadate solutions with other diols.

Figure 3 shows the changes which occur in the ^{51}V NMR spectra as ethylene glycol concentration is varied. The results corresponding to this figure are given in Table II. For these studies the total vanadate concentration was maintained at 0.5 mM and the pH at 7.5. Constant pH in aqueous solutions of varying ethylene glycol concentration is not well defined; however, studies with various alcohols have shown significant deviations between pH readings and actual pH only at very high alcohol concentrations[14] which are not obtained here.

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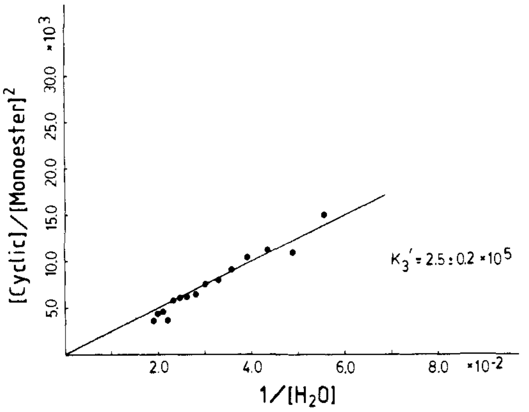

Figure 5. Determination of the equilibrium constant for formation of the cyclic ester anhydride. The ratio $[((OCH_2CH_2O)VO_2H)_2O^{2-}]/[HOCH_2CH_2OVO_3H^-]^2$ is plotted as a function of $1/[H_2O]$ to give a line of slope K_3'. The data used are shown in Table II.

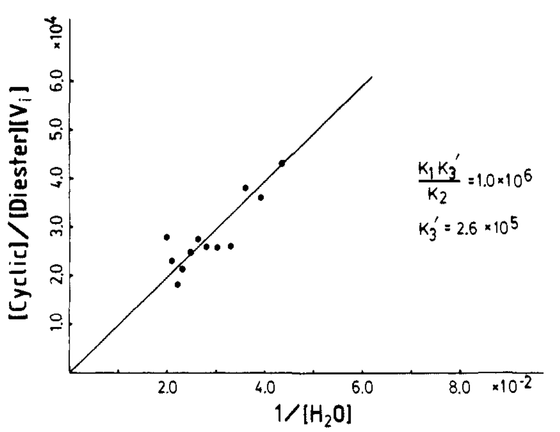

Figure 6. The product of equilibrium constants, K_1K_3'/K_2 is determined from a plot of $[((OCH_2CH_2O)VO_2H)_2O^{2-}]/[(HOCH_2CH_2O)_2VO_2^-][V_i]$ vs. $1/[H_2O]$. From the known K_1 and K_2, K_3' can be evaluated. The data used are given in Table II.

Figure 4 shows the results of plotting the relevant quantities of eq 3 and 4 to obtain K_1 and K_2, the equilibrium constants for formation of the acyclic mono- and diesters, respectively. The values obtained were $K_1 = 18.6 \pm 1.0$ and $K_2 = 4.9 \pm 0.3$. These values are in good accord with those measured for the formation of ethyl vanadate and diethyl vanadate, $K_1 = 10.4$ and $K_2 = 2.3$, where there are only one-half as many hydroxyl groups per molecule. It should be noted that the experimental results are in accord with the production of only one water for each ethylene glycol used up in the reaction; therefore, neither of these products can be a cyclic tetrahedral ester.

The equilibrium constant, K_3' is readily obtained from eq 7, and a plot is shown in Figure 5. The value obtained is $K_3' = 2.5 \pm 0.2 \times 10^5$. A check on this value of K_3' can be made by noting that eq 12 can readily be derived. The product, K_1K_3'/K_2, of eq

$$\frac{[\text{cyclic dimer}]}{[\text{diester}]} = \frac{K_1K_3'[V_i]}{K_2[H_2O]} \qquad (12)$$

12 can be obtained as shown in Figure 6. From the independently determined values of K_1 and K_2 (Figure 4) a K_3' value of 2.6×10^5 is obtained which agrees very well with that determined from Figure 5. One further measure of K_3' can be made by using eq 13, which is readily derived from eq 3 and 5. Figure 7 shows the

$$[\text{cyclic dimer}] = [V_i]^2K_1^2K_3'\frac{[C_2H_4(OH)_2]^2}{[H_2O]^3} \qquad (13)$$

plot corresponding to eq 13. A value of $K_1^2K_3' = 8.1 \times 10^7$ was obtained for the slope from which $K_3' = 2.3 \times 10^5$ was calculated by using the known K_1. These three determinations of K_3' agree extremely well with each other, which indicates that the values of K_1 and K_2 are 'good' values; otherwise, such agreement would not be expected. In view of the self-consistency within the above sets of data, it is clear that neglect of the monomeric species is justified.

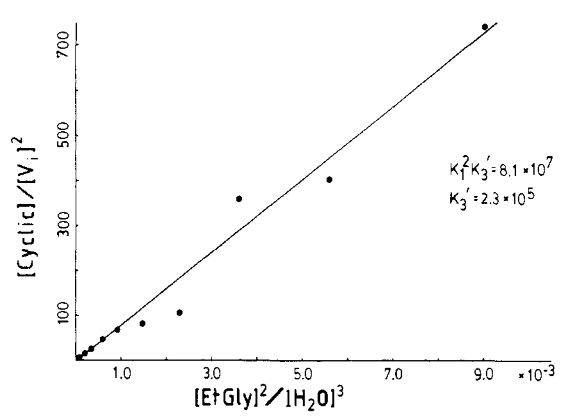

Figure 7. The product of equilibrium constants, $K_1^2K_3'$, is determined from a plot of $[((OCH_2CH_2O)VO_2H)_2O^{2-}]/[V_i]^2$ vs. $[HOCH_2CH_2OH]^2/[H_2O]^3$. From the known K_1, K_3' can be calculated to give the indicated value. The data used are from Table II.

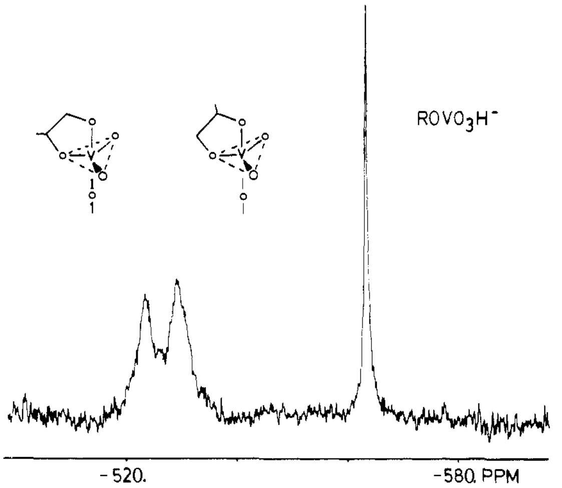

Figure 8. A ^{51}V NMR spectrum of the products of the reaction of vanadate with 1,2-propanediol. The two resonances near −526 ppm are assigned to cyclic esters where the methyl group is adjacent either to an apical oxygen or to an equatorial oxygen in the bipyramidal structure. The solution contained 2.63 M 1,2-propanediol, 5.0×10^{-4} M vanadate added as Na_3VO_4, and 5.0×10^{-2} M Tris-Cl buffer at pH 7.5.

Although the data in Table II were analyzed in terms of the assumption that the resonance at −521.7 ppm is due entirely to cyclic dimer, it is recognized that a small fraction of the intensity of this resonance must be from the cyclic monomer. Points to be considered here are that, based on the experimental results just discussed, the formation of the cyclic dimer proceeds from the acylic monoester by the production of only 1 mol of water and this is accompanied by a large change in the chromophore as evidenced by the UV study of butanediol and vanadate. This means that the vanadate group of the mono- and diesters and of vanadate itself must be tetrahedral since if they were octahedral in character, then more than 1 mol of water would be produced in forming the cyclic dimer shown. Conversely, it also means that, if the cyclic product were octahedral, then vanadate and its alkyl esters must be pentacoordinate. There is evidence, however, that the cyclic product cannot be octahedral. This evidence is provided by NMR studies of asymmetric diols such as 1,2-propanediol. The NMR spectrum of the product of this compound with vanadate unlike that with ethylene glycol and 2,3-butanediol shows two resonances near −520 ppm. The relative intensity of these resonances is constant with varying vanadate concentration, and they therefore cannot derive from the cyclic monomer and dimer giving rise to separated signals. The origin of the two resonances evidently lies in the fact that the methyl group is adjacent either to an oxygen in an apical position or an oxygen in an equatorial position of a trigonal-bipyramidal structure. Figure 8 shows a spectrum demonstrating this behavior. In the spectrum shown in Figure 8 the resonances due to vanadate and the acyclic esters, indicated by $ROVO_3H^-$, are not resolved. These species do give rise to individual resonances at higher pH values. At present we cannot determine which of the resonances near −520 ppm is due to which of the indicated cyclic species. Other evidence that the cyclic vanadate ester is pentacoordinate derives from the observation that this species tends to give rise to NMR signals which are broader than those assigned to the acyclic species, as can be seen in Figures 1, 3, and 8. Broad resonances derive from efficient quadrupole relaxation, a consequence of low symmetry at the vanadium nucleus. It is extremely unlikely that, if the cyclic species were octahedral, it would give rise to significantly broader resonances than pentacoordinate species which the vanadate and the two acyclic esters would then by necessity be. One further point to be made is that when viscous solvents such as ethylene glycol (Figure 3) replace water in a stepwise fashion the −522 ppm resonance broadens much faster than the −555 ppm resonances. If the tumbling rate of the two types of molecules were slowed proportionately, that species with the largest quadrupole coupling constant would show preferential broadening. Large quadrupole coupling constants derive from low symmetry at the vanadium nucleus. Thus the evidence strongly favors pentacoordinate cyclic species and tetrahedral acyclic species. There are alternatives to pentacoordinate structures which should be considered. There is evidence that the binuclear product cannot have bridging glycols. Experimentally only 1 mol of water is produced as the product is formed from 2-hydroxyethyl vanadate. Bridging by the glycol would not require the formation of water since the coordination sphere is expanded. If the coordination sphere were not expanded, 2 mol of water would be produced. Alternatively, if bridging occurred via only one glycol, then two different types of tetrahedral vanadium species would be produced other than those already identified. The two species would be bridged by a glycol group, and one of the two would have attached an additional nonbridging alcohol. There is no reason to expect tetrahedral species such as those considered above to give NMR signals out of the range of other tetrahedrally coordinated vanadates. Formation of such tetrahedral species is also not supported by the UV evidence which indicates a large change in the chromophore as the species giving rise to the −522 ppm resonance is formed. The only viable structure which involves bridging via glycols is one with two bridging glycols and also an anhydride bridge between the two pentacoordinate structures. The evidence here cannot rule out such a compound; however, we have found complexes with lactate which give rise to NMR signals at −518 ppm and which are monomeric species.[15] It thus seems unlikely that bridging through the glycol unit occurs.

There is the possibility that the product is a dimer of a square-pyramidal complex. If so, bridging cannot occur through the apical position since asymmetric diols give rise to two resonances in the ^{51}V NMR spectrum. This can only occur if the points of attachment of the individual glycol oxygens are chemically distinct. Thus, if the product is square-pyramidal, anhydride formation occurs through oxygens of the pyramid base. Such a structure cannot be ruled out. It should, however, be noted that uridine in the presence of vanadate gives rise to a resonance at −522 ppm[11,12] and that X-ray studies of a uridine–vanadate–enzyme complex clearly show the trigonal-bipyramidal structure around the vanadium atom.[10,11]

The chemical shift of the cyclic dimer is pH independent, occurring at −521.7 ppm throughout the range of pH studied, from pH 5.0 to pH 10. At pH 11 no signal for either this compound or the acyclic diester was observed. This observation is consistent with neither of these species having an ionizable proton with a pK_a within the range studied. The chemical shifts of vanadate and its acyclic monoester were both strongly pH dependent, with a positive shift from −560.4 and −556 to −532.8 and −534.4 ppm for the two compounds, respectively. The acyclic vanadate diester showed a small chemical shift dependence on pH, decreasing from −553.4 ppm at pH 7 to −550.4 ppm at pH 10 with the majority of the shift occurring between pH 9 (−552.9 ppm) and pH 10 (−550.4 ppm). Unfortunately at higher pH, no resonance was observed for this species. The origin of this small change in chemical shift of the acyclic diester resonance is not clear since it has no ionizable protons. There may, however, be an effect of pH on the solvation of the ester group involving the free hydroxyl residues of the two glycol groups. It presumably is related to the presence of the extra hydroxyl groups since diethyl vanadate does not show a similar chemical shift dependence on pH.[6]

It is difficult to know whether the analogous monoester shows a similar effect, and this presents problems when using the pH dependence of chemical shifts to determine the dissociation constants. Throughout the range of pH of this study the chemical shift of each vanadium species is related to the pH by eq 14, where

$$\mathrm{pH} = \mathrm{p}K_{\mathrm{a}_2} + \log \frac{|\delta_{\mathrm{L}}| - |\delta|}{|\delta| - |\delta_{\mathrm{H}}|} \tag{14}$$

$|\delta_{\mathrm{L}}|$ is the absolute value of the limiting chemical shift at low pH and $|\delta_{\mathrm{H}}|$ is that corresponding to high pH while $|\delta|$ is the observed shift. A plot of pH vs. the chemical shift term gives a line of unit slope with a y-intercept equal to the pK_{a_2}. When the experimental values for the monoester were plotted, a curve instead of a straight line was obtained. It was, however, found that, if the high pH limiting shift were corrected by −1.5 ppm to −535.9 ppm where the −1.5 ppm correction adopted is one-half the 3 ppm shift observed for the vanadate diester at high pH, then a straight line of unit slope is obtained as required by eq 14. The pK_{a_2} obtained was 8.9 ± 0.1 under the conditions of 5.64 M ethylene glycol, 20 mM Tris-chloride, and 0.5 mM total vanadate. The corresponding pK_{a_2} obtained for vanadate was 8.8 ± 0.1. This last value agrees well with that obtained for vanadate in ethanol solution where a pK_{a_2} of 8.3 ± 0.1 was measured.[6] 2-Hydroxyethyl vanadate in aqueous ethylene glycol is about the same strength acid as ethyl vanadate in aqueous ethanol where a pK_{a_2} of 8.9 was also obtained.[6]

Conclusion

From the results of this study it was concluded that ethylene glycol reacts with inorganic vanadate in aqueous solution to form the acyclic esters 2-hydroxyethyl vanadate and bis(2-hydroxyethyl) vanadate. The vanadate moiety in these esters is tetrahedral, and the behavior of these species is similar to that of ethyl vanadate and diethyl vanadate. A cyclic derivative is also formed from vanadate and ethylene glycol, in which both oxygens of the diol are bound to the vanadium atom. The evidence is in accord with trigonal-bipyramidal geometry about the vanadium atom. This product does not have an ionizable proton with a pK_a within the range 5.0–11.0. It exists essentially entirely as an anhydride containing two pentacoordinate vanadium atoms linked through an oxygen atom with each subunit of the anhydride containing one ethylene glycol residue. The monomeric unit of the anhydride is proposed to be (1,2-ethanediolato)dihydroxooxovanadate(1−).

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(15) Tracey, A. S.; Gresser, M. J.; Parkinson, K. M., unpublished results.