Ruthenium Oxo Complexes as Organic Oxidants

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1 Introduction

Over the past decade the use of oxo complexes of ruthenium to effect catalytic regioselective homogenous oxidations has become increasingly important, and this review particularly emphasizes recent developments in the area of the oxidation of primary and secondary alcohols (RCH_2OH and R_2CHOH) to aldehydes, carboxylic acids, or ketones (RCHO, RCOOH, or R_2CO). With the ruthenium catalysts so far developed, the oxidation of alcohols is the reaction effected with the greatest efficiency. Although such oxidation is one of the commonest of organic transformations, few reagents will effect such reactions catalytically and without attacking sensitive linkages in the R group; most of the complexes described herein are sufficiently selective to tolerate such linkages.

Ruthenium and osmium are unique in at least two respects: they are the only elements in the Periodic Table to exhibit octavalency, and in their complexes they both cover the entire range of eleven oxidation states theoretically available to a transition metal, here VIII to −II inclusive, corresponding to electron configurations of d^0 to d^{10} inclusive. The oxo ligand O_2^{2-} is a strong σ and π donor and so would be expected to favour high metal oxidation states. With ruthenium and osmium it stabilizes the VIII and VII states in the homoleptic species $[MO_4]$ and $[MO_4]^-$, and when accompanied by other ligands (usually though not always 'hard' donors) it coordinates to ruthenium and osmium(VI), (V), and (IV) and also (in a bridging rôle) to ruthenium(III).

Because of their diversity in oxoruthenium complexes it seems logical to use oxidation states as a primary classification for the material of this review. The coverage here – which is very much inorganic in its emphasis – has been limited to reactions of those oxo complexes which have been reasonably well characterized, so that the very considerable body of often excellent work in which lower-valent ruthenium complexes have been used in conjunction with a variety of co-oxidants to effect specific oxidations is not covered. The latter subject has however been well reviewed elsewhere.[1]

2 Ruthenium(VIII)

The only well-defined complex is the tetraoxide $[RuO_4]$. Although this was known for over a century to be a very powerful oxidizing agent it was not until 1953 that its properties as an organic oxidant were first systematically explored. It is a rather non-selective oxidant, reacting with alkenes, alkynes, alcohols, diols, aromatics, and ethers, often causing multiple bond or aromatic ring rupture. Nevertheless it is easy to generate catalytically (hypochlorite, bromate, or periodate are commonly used co-oxidants), and it normally functions at room temperature. Its main use is probably for the conversion of hydroxyl groups on carbohydrates into carbonyl functions and for the oxidation of steroidal alcohols. Its applications to organic chemistry have recently been reviewed.[1]

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The mechanism of the stoicheiometric oxidation of propan-2-ol by $[RuO_4]$ in aqueous perchloric acid has been investigated. In 1 to 6.5M $HClO_4$ a hydride transfer appears to be the rate-determining step, while at higher acid concentrations the rate-determining step probably involves formation of carbonium ions. The overall reaction is thought to involve five electrons with Ru^{III} as the final product, and the involvement of radicals was thought to be unlikely since *cyclo*butanol is not cleaved in the reaction.[2]

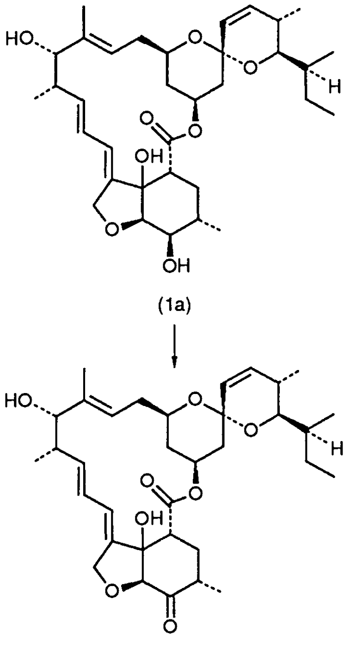
Attempts to modify the oxidative ability of $[RuO_4]$ by attachment of, for example, N-donor groups have not been successful; ruthenium(VI) complexes are formed.[3]

3 Ruthenium(VII)

The tetrahedral perruthenate ion, $[RuO_4]^-$ has long been known; in 1984 we studied its properties as a stoicheiometric oxidant towards alcohols in aqueous solution and also as the 18-crown-6 salt in benzene. In aqueous M NaOH solution primary alcohols are converted into carboxylic acids and secondary alcohols into ketones, but double bonds were cleaved (thus cinnamyl alcohol gave benzoic acid).[4] Kinetics of the stoicheiometric oxidation of propan-2-ol, mandelic acid and *cyclo*butanol by $[RuO_4]^-$ in aqueous base have been studied. It was concluded that the most likely mechanism involved formation of a radical intermediate and Ru^{VI} with substrate oxidation by the latter [presumably present as ruthenate(VI)]. The oxidation of *cyclo*butanol by $[RuO_4]^-$ under such conditions is attended by much C−C bond cleavage, the yield of *cyclo*butanone being only 33%, suggesting that one-electron processes are involved.[2]

The isolation of an organic-soluble salt of perruthenate, $(Bu^n_4N)[RuO_4]$ ('TBAP') showed that, in non-aqueous rather than in aqueous media, $[RuO_4]^-$ is a remarkably gentle oxidant, stoicheiometrically oxidizing primary alcohols to aldehydes and secondary alcohols to ketones without competing double-bond attack.[5] The discovery[6] that this reaction could be made catalytic by using *N*-methylmorpholine *N*-oxide (NMO) as a co-oxidant (a co-oxidant previously and effectively used with lower-valent ruthenium complexes by Sharpless *et al.*[7]) and isolation of the more easily prepared tetra-n-propylammonium salt $(Pr^n_4N)[RuO_4]$ ('TPAP') has made this one of the most useful and versatile selective catalytic oxidants for alcohols available.[8] The salt is simply and inexpensively made from solutions of $RuCl_3.nH_2O$ and $NaIO_4$ in aqueous solution; the $[RuO_4]$ thus produced is swept out by air into a solution of molar aqueous $(Pr^n_4N)OH$ and K_2CO_3, whereupon the deep green reagent is precipitated in good yield. Salts with other organic cations, *viz.* PPh_4^+ and $(PPh_3)_2N^+$, may similarly be obtained.[9] An even simpler, recently developed procedure is to add $(Pr^n_4N)OH$ to an aqueous solution of $[RuO_4]^-$ generated by adding sodium bromate to ruthenium dioxide in molar carbonate.[10]

In a dichloromethane–acetonitrile solution the reagent, with *N*-methylmorpholine *N*-oxide (NMO) as co-oxidant, is an excellent oxidant of primary alcohols to aldehydes and of secondary alcohols to ketones; sensitive units such as allylic, epoxy, lactone, indole, silyl ether, acetal, and tetrahydropyranyl functions are unaffected by it. It has also been used for the oxidation of homoallylic alcohols to dienones and for selective oxidation of primary–secondary diols to lactones;[11a] since its inception in 1987 there have been some sixty publications concerning its applications as an oxidant,[8,11b] and it is increasingly being used in the fine organic chemicals industry. Typically it is used in 5 mol% quantities with 1 equivalent of the alcohol and 1.5 equivalents of NMO in dichloromethane–acetonitrile in the presence of 500 mg mmol^{-1} of powdered 4Å molecular sieves, the latter to remove water formed during the reaction. All oxidations are effected at room temperatures and are usually complete within 30 minutes.[8] Catalytic turnovers (*i.e.* moles of product/moles of catalyst) are high, in excess of 500 in some cases. An example of a reaction which would be difficult to carry out with conventional reagents is the oxidation of the secondary 5-hydroxy group of the 16-membered ring macrolide (1a) to the aldehyde (1b) without affecting the allylic 13-hydroxy group or the ether linkages; this step was an essential one in the total synthesis of the insecticide Avermectin B1$_a$.[11c]


(1a)

(1b)

The mechanism of oxidation by TPAP is not clear, however, and this aspect needs investigation. It oxidizes cyclobutanol to cyclobutanone in good yield (unlike the situation with $[RuO_4]^-$ in aqueous solution[2]) suggesting that one-electron processes do not play an important part, though the overall reaction from ruthenium(VII) to (IV) involves three electrons. It is possible that a sequence of two-electron steps similar to that proposed for chromium(VI) oxidation of alcohols is involved, *e.g.*

$$\begin{aligned} Ru^{VII} &\longrightarrow Ru^{V} \\ Ru^{V} + Ru^{VII} &\longrightarrow 2Ru^{VI} \\ Ru^{VI} &\longrightarrow Ru^{IV} \end{aligned}$$

Recent work in these laboratories shows that $[RuO_4]^+$ can be generated in aqueous solution from $RuCl_3.nH_2O$ and excess sodium bromate in aqueous molar carbonate solution at pH 11; the resulting catalytic $[RuO_4]^-$ – BrO_3^- system oxidizes, with good yields and turnovers, primary alcohols to carboxylic acids, secondary alcohols to ketones, activated primary alkyl halides to carboxylic acids, secondary alkyl halides to ketones, and primary nitroalkanes to carboxylic acids. Double bonds are, however, cleaved by the reagent (*e.g.* cinnamyl alcohol and cinnamyl halides are converted into benzoic acid). As with the *trans*-$[Ru(OH)_2O_3]^2$ – $S_2O_8^{2-}$ and *trans*-$[RuO_2(IO_5(OH))_2]^{6-}$ – IO_4^- reagents discussed below it is self-indicating: the yellow-green colour of $[RuO_4]^-$ reappears when the reaction with the substrate is complete.[10]

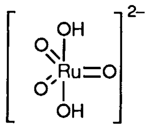
4 Ruthenium(VI)

A number of ruthenium(VI) oxidants have been studied, mostly but not exclusively for the oxidation of alcohols.

4.1 Complexes with O-Donor Ligands

4.1.1 With Hydroxo and Periodato Ligands

The simplest of these is the 'ruthenate' ion, long thought to be tetrahedral ($[RuO_4]^{2-}$) but now known, from *X*-ray studies of the potassium and barium salts, to contain the trigonal bipyramidal *trans*-$[RuO_3(OH)_2]^{2-}$ anion (2).[12]

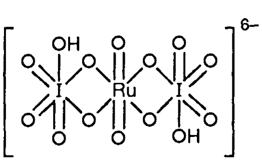

(2)

This functions stoicheiometrically in aqueous base at room temperature as a two-electron oxidant, converting primary alcohols into carboxylic acids and secondary alcohols into ketones, the reaction being catalytic if excess persulphate is introduced as co-oxidant.[13] Although this catalytic *trans*-$[Ru(OH)_2O_3]^{2-}$ – $S_2O_8^{2-}$ reagent converts cinnamyl alcohol into cinnamic acid in high yield other allylic alcohols such as crotyl alcohol give only a low yield of β-methylacrylic acid, and clearly competing double-bond cleavage occurs.[4] This limits the utility of the reagent, as does the fact that it is usable only in aqueous base, in which many organic materials are insoluble and may also undergo condensation reactions. It does have attractive features, though: it is a self-indicating reagent, the initial orange-red colour becoming black (probably due to colloidal RuO_2) when the alcohol is added, but resuming its orange colour when the reaction is over. Reactions take about an hour at room temperatures with catalytic turnovers in the region of 450;[4] sonication of the reaction mixture considerably decreases the reaction times in some cases. Recently we have found that this *trans*-$[Ru(OH)_2O_3]^{2-}$ – $S_2O_8^{2-}$ reagent will also oxidize activated primary alkyl halides to carboxylic acids and secondary halides to ketones; it is more effective (in respect of yields and catalytic turnovers) than the $[RuO_4]^-$ – BrO_3^- system referred to above, perhaps because the higher pH (pH 14 for the ruthenate as against pH 11 for the perruthenate catalytic reagent) helps removal of halide more effectively. Moreover, the double bond in cinnamyl chloride (and bromide) is not cleaved by *trans*-$[Ru(OH)_2O_3]^{2-}$; cinnamic acid is formed in good yield from both. It is likely to be more effective at halide oxidations than the traditional Kornblum or Sommelet procedures. Primary nitroalkanes are also oxidized to carboxylic acids (a form of the Nef reaction).[10] The insoluble barium salt *trans*-$Ba[RuO_3(OH)_2]$ can be used as a stoicheiometric reagent for the oxidation of activated (benzylic) alcohols to aldehydes or ketones.[4]

The kinetics of the stoicheiometric oxidation of propan-2-ol, mandelic acid, and cyclobutanol by *trans*-$[RuO_3(OH)_2]^{2-}$ in M aqueous NaOH have been studied. It was suggested that addition to the α-C–H bond occurs to give an organometallic Ru^V intermediate which then reacts *via* a single-electron transfer reaction to give Ru^{IV} as a resonance-stabilized α-hydroxycarbocation. Unlike oxidations with aqueous $[RuO_4]^-$ in base under similar conditions it was found that cyclobutanol is oxidized to cyclobutanone in good yield (as we have noted for the catalytic *trans*-$[RuO_3(OH)_2]^{2-}$ – $S_2O_8^{2-}$ system) suggesting that a two-electron oxidation has occurred.[2]

Another reagent which functions as an oxidant for alcohols in aqueous base is *trans*-$[RuO_2\{IO_5(OH)\}_2]^{6-}$ (3). The *X*-ray crystal structure of the salt *trans*-$NaK_5[RuO_2\{IO_5(OH)\}_2]{:}8H_2O$

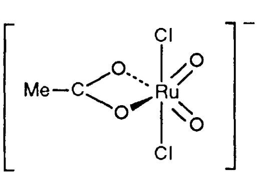
shows the *trans* oxo ligands (Ru=O 1.732 Å) and monoprotonated periodato ligands (Ru−O 2.003 Å). It is unusual in that both the ligands and the metal centre function as oxidants: stoicheiometrically it is an overall six-electron oxidant, two electrons going to the $\{I^{VII}O_5(OH)\}^{4-}$ ligand {which is reduced to $(I^{V}O_3{}^{-})$} and two to the metal $Ru^{VI}O_2^{2+}$ unit which is reduced to RuO_2. Its action is catalytic with excess periodate $(IO_4{}^{-})$ as co-oxidant, converting primary alcohols into carboxylic acids and secondary alcohols into ketones. Double bonds are cleaved (thus cinnamyl alcohol gives cinnamic acid), as are diol linkages. Although this *trans*-$[RuO_2\{IO_5(OH)\}_2]^{6-}$ − $IO_4{}^{-}$ reagent suffers from the same disadvantages as the *trans*-$[RuO_3(OH)_2]^{2-}$ − $S_2O_8^{2-}$ reagent (*i.e.* it functions in aqueous base and attacks some double bonds) it is, like the latter, self-indicating in colour (red − black − red) and gives high catalytic turnovers (*ca.*600).[14] It is also a good catalytic reagent for the oxidation of activated alkyl halides; primary benzylic halides are oxidized to acids and secondary halides to ketones.[15] Presumably, as with the $[RuO_4]^{-}$ − $BrO_3{}^{-}$ and the *trans*-$[RuO_3(OH)_2]^{2-}$ − $S_2O_8^{2-}$ reagents the basic medium assists removal of halide.



(3)

4.1.2 *With Carboxylato Ligands*

We have recently isolated complexes of the form *trans*-$[RuO_2(OCOR)Cl_2]^{-}$ (R = Me, Pr^n, Bu^n, CF_2H) and find these to be excellent two-electron oxidants in organic solvents for the conversion of primary alcohols into aldehydes and secondary alcohols into ketones, the action being catalytic in the presence of NMO as co-oxidant. The acetato complex has been the most intensively studied: as with TPAP there is no competing double-bond cleavage with substrates such as geraniol, citronellol, chrysanthemyl, and cinnamyl alcohols. Phosphines are oxidized to phosphine oxides, sulfides to sulfoxides and sulfones[16,17] (but our observation that the reagent oxidizes alkyl halides is in error: it is the NMO co-oxidant which does this[17]). The *X*-ray crystal structure of the complex (4) shows the anion to contain the unusual *cis* RuO_2 grouping (Ru=O 1.67 Å, ORuO angle 120.1°), and the acetato group is symmetrically bonded in bidentate fashion (Ru−O 2.13 Å) so that the overall structure is that of a distorted octahedron (4). However, if it is supposed that the midpoint of the two oxygen donor atoms of the acetate is the effective site of coordination of this ligand then the structure is that of an essentially undistorted trigonal bipyramid[16] and so can be regarded as being structurally related to the ruthenate(VI) anion.



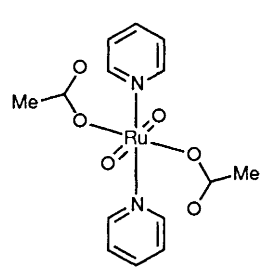
(4)

Preliminary investigations of the kinetics of the oxidation of propan-2-ol by $[RuO_2(OCOMe)Cl_2]^{-}$ in dichloromethane at room temperatures have been carried out in the presence of excess NMO, and the stoicheiometry of the overall reaction determined. Surprisingly it appears that *two* moles of *N*-methylmorpholine (NM) are produced per mole of propan-2-one rather than the expected 1:1 ratio, so presumably the overall reaction involves production of oxygen or, possibly, of hydrogen peroxide:

$$(CH_3)_2CHOH + 2NMO \rightarrow (CH_3)_2CO + 2NM + H_2O_2$$

The reaction appears to be first order in propan-2-one and in *N*-methylmorpholine. The precise rôle of the catalyst is not yet established.[18]

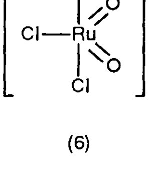
Another acetato complex, this time containing the more usual *trans*-RuO_2 unit, is $RuO_2(OCOMe)(py)_2$, made from *trans*-$Ba[RuO_3(OH)_2]$, pyridine, and acetic acid; the complexes $RuO_2(OCOR)(py)_2$, (R = Et, Pr, C_6H_5) were also made. The *X*-ray crystal structure (5) shows the *trans* configuration [Ru=O 1.726(1) Å]. It is a rather unselective stoicheiometric oxidant: *E*- and *Z*-*β*-methylstyrenes give the *cis* and *trans* epoxides, tetrahydrofuran gives *γ*-butyrolactone, and 2,6-di-t-butylphenol gives the t-butylated quinone and diphenylquinone, while PPh_3 is oxidized to Ph_3PO.[19]



(5)

4.2 Complexes with Halide Donor Ligands

We isolated $(Ph_4P)[RuO_2Cl_3]$ some years ago by reaction of *trans*-$[RuO_3(OH)_2]^{2-}$ with HCl and PPh_4Cl and found it to be an efficient stoicheiometric two-electron oxidant for alcohols, again converting primary alcohols into aldehydes and secondary alcohols into ketones without competing double bond attack. Thus geraniol, *E*-cinnamyl, and chrysanthemyl alcohols were converted into their aldehydes in high yield,[4] and the reagent was subsequently used in the total synthesis of the natural product isodrimeninol, an insect antifeedant.[20] More recently we have shown that its action may be rendered catalytic by the use of NMO as a co-oxidant,[21] its efficacy in this respect being similar to that of the $[RuO_2(OCOMe)Cl_2]$ − NMO reagent. Such comparability of reaction would be explicable if both reagents contained a *cis* RuO_2 grouping; that this was the case for $[RuO_2Cl_3]^{-}$ was suggested by our earlier Raman and infrared measurements[4] and has been confirmed by Kochi and Perrier who have shown by *X*-ray structural determinations that the anion in $[(Ph_3P)_2N][RuO_2Cl_3]$ is trigonal bipyramidal (6) with the oxo ligands in the equatorial plane (Ru=O 1.694 Å, ORuO angle 127.1°). In $(Ph_4P)[RuO_2Cl_3]$ the anion is disordered between trigonal bipyramidal and square-based pyramidal, the oxo ligands being *trans* in the latter case.[22] It is interesting to note that Kochi and Perrier find that $[RuO_2Cl_3]^{-}$ is, as a stoicheiometric reagent in dichloromethane at room temperatures, reactive towards double bonds and a variety of substrates (thus cyclohexene gives a mixture of cyclohexene-oxide, 2-cyclohexenone, 2-chlorocyclohexanone, and cyclohexenechlorohydrin; PPh_3 gives PPh_3PO, and the hindered phenol 2,6-di-t-butylphenol gives 2,6-di-t-butyl-*p*-benzoquinone and



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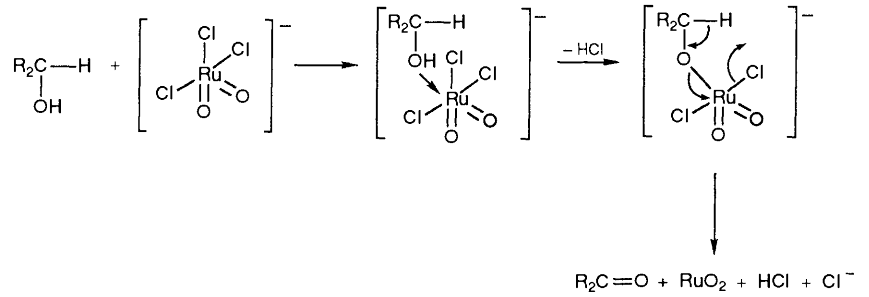


Scheme 1

3,5,3′,5′-tetra-t-butyldiphenoquinone.[22] Despite the apparent similarity in reaction conditions we find no competing double-bond attack in the reactions of $[RuO_2Cl_3]^-$ with unsaturated alcohols either under stoicheiometric[4] or catalytic[21] conditions (*i.e.* with NMO as co-oxidant); perhaps the rate of oxidation of the hydroxyl group is greatly in excess of that for double bonds.

The $[RuO_2Cl_3(OPPh_3)]^-$ ion, made from RuO_4 and HCl with PPh_3, is an oxidant towards alcohols comparable in efficacy with $[RuO_2Cl_3]^-$.[21] However, the red *trans*-$[RuO_2Cl_4]^{2-}$ ion (generated[22] in solution from $[RuO_2Cl_3]^-$ and excess Cl^-), in the presence of excess Cl^- with NMO as co-oxidant, is substantially less effective in its oxidative abilities towards alcohols, as is $[RuO_2Cl_3(py)]^-$:

$$[RuO_2Cl_3]^- \sim [RuO_2Cl_3(OPPh_3)]^- > [RuO_2Cl_4]^{2-} \sim [RuO_2Cl_3(py)]^-$$

Clearly it is not external charge which is of primary importance. It is more likely that the first two members of this series have in effect a vacant coordination site (triphenylphosphine oxide is an easily displaced ligand) whereas the last two do not. The *trans*-$[RuO_2Cl_4]^{2-}$ anion was used in the presence of excess of Cl^- (to reduce dissociation of Cl^-), and the pyridine molecule, unlike PPh_3PO, is firmly attached to the metal in $[RuO_2Cl_3(py)]^-$.[21]

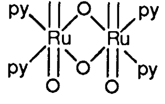
A possible outline mechanism for oxidation of secondary alcohols by $[RuO_2Cl_3]^-$ is given in Scheme 1.

4.3 Complexes with N-Donor Ligands

4.3.1 With Pyridine (py)

The complex $[RuO_2(OCOMe)(py)_2]$ has already been mentioned. Recently we synthesized a wide variety of neutral, cationic, and anionic oxoruthenium(VI) complexes containing coordinated pyridine, substituted pyridines (R-py), or related ligands, in most cases from with RuO_4 or *trans*-$[RuO_3(OH)_2]^{2-}$ and the ligand with appropriate pH control.[3,23]

The neutral complexes take the form $[Ru_2O_6(R\text{-}py)_4]$ where (R-py) is pyridine, 4-t-butylpyridine (4-$\mathrm{Bu^t}$py), $\frac{1}{2}$bipy, nicotinic acid, or pyridine-2-carboxylic acid. These were made from RuO_4 and the ligand but also, in the case of $[Ru_2O_6(py)_4]$, from *trans*-$[RuO_3(OH)_2]^{2-}$ and pyridine with HCl or HPF_4. The pyridine complex was shown by an *X*-ray crystal structure determination to have structure (7) in which the Ru_2O_2 bridge is planar (Ru–O 1.91 Å, RuORu angle 100°) but the *trans* oxo ligands are significantly distorted from linearity (Ru=O 1.72 Å, ORuO angle 160.5°). This bending occurs away from the Ru_2O_2 bridge and towards the pyridine molecules, and is likely to arise from electron pair – electron pair repulsions between these oxo ligands and the oxygen atoms in the tightly bound bridge moiety.[23] The same basic type of structure is likely for the other dimeric $[Ru_2O_6(R\text{-}py)_4]$ complexes. The neutral species *trans*-$[RuO_2(py)_2Cl_2]$ and *trans*-$[RuO_2(bipy)Cl_2]$ are made from RuO_4, HCl, and the ligand,[24] and *trans*-$[RuO_3(OH)_2]^{2-}$, R-py, and HCl yield *trans*-$[RuO_2(R\text{-}py)_2Cl_2]$ (R-py = py, 4-$\mathrm{Bu^t}$py, and 4-chloropyridine).[3] The cationic *trans*-$[RuO_2(py)_4](BF_4)_2$ and anionic species $(RH)[RuO_2Cl_3(R)]$ (R = py, 4-$\mathrm{Bu^t}$py, 3-methylpyridine, 3,4-dimethylpyridine) were made by similar procedures.[3] In all cases the *trans* arrangement of oxo ligands was established by the Raman and infrared spectra of the solids and, in some cases, of the solutions.



(7)

All these complexes oxidize primary alcohols to aldehydes and secondary alcohols to ketones in good yield; their action is catalytic in the presence of NMO as co-oxidant. Double bonds or allylic double bonds are not attacked (*e.g.* in citronellol and geraniol); catalytic turnovers of up to 135 with NMO and up to 85 with $(\mathrm{Bu^n_4N})[IO_4]$ as co-oxidant have been achieved.[3] As oxidants however they differ in several respects from the oxoruthenium(VII) and other oxoruthenium(VI) reagents so far described. First, they function stoicheiometrically as overall four-electron oxidants [rather than the two-electron oxidations given by the oxoruthenium(VI) species described above]. Attempts to isolate oxoruthenium(IV) species such as the known *trans*-$[RuO(py)_4Cl]^+$ from reactions of these pyridine complexes have so far failed, but it is likely that the reactions do proceed *via* oxoruthenium(IV) species.[23] The fact that ruthenium(II) species are the final products of these reactions presumably arises because, as a mild π-acceptor, pyridine and its analogues stabilize the d^6 configuration of ruthenium(II), whereas there is no such stabilization by the co-ligands (hydroxide, carboxylate *etc.*) in the other oxidants so far discussed. The second unusual aspect is that there is definite, though unspectacular, aerobic catalysis of the oxidations of alcohols by $[Ru_2O_6(py)_4]$, *trans*-$[RuO_2(py)_4]^{2+}$, and *trans*-$[RuO_2Cl_3(4\text{-}\mathrm{Bu^t}py)]^-$ at room temperatures in the absence of NMO but in the presence of air or dioxygen, whereas there is no such aerobic catalysis whatsoever for the other oxoruthenium(VII) and -ruthenium(VI) complexes discussed so far. In acetonitrile solution catalytic turnovers of 12 were observed for $[Ru_2O_6(py)_4]$ and for *trans*-$[RuO_2Cl_3(4\text{-}\mathrm{Bu^t}py)]^-$ when dioxygen was bubbled through the solutions. The use of dioxygen under pressure did not increase the turnovers nor did addition of copper(II) acetate (commonly used to assist aerobic oxidations), but at 50 °C the use of copper(II) acetate with dioxygen at ambient pressure gave turnovers of up to 30 for primary and secondary alcohols.[23] It is not clear why coordinated pyridine helps such reactions, nor why the turnovers are so low (formation of an inert μ-oxo dimer of ruthenium(IV) is a possibility).

Finally, in connection with these pyridine complexes, it is of interest to note that pyridinium or substituted pyridinium salts of *trans*-$[RuO_2Cl_4]^{2-}$ will abstract one pyridine ligand from the cation in solution:

$$(R\text{-}pyH)_2[RuO_2Cl_4] \rightarrow (R\text{-}pyH)[RuO_2Cl_3(R\text{-}py)] + (R\text{-}pyH)Cl$$

where (R-py) is 4-Bu^{t}py, 3-methylpyridine, or 3,4-dimethylpyridine.[21]

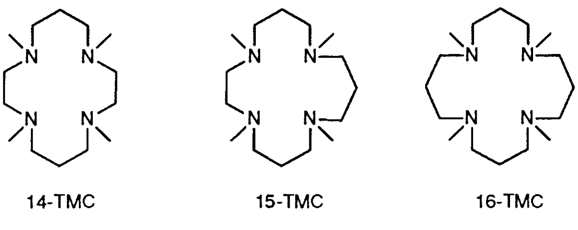
4.3.2 With 2,2′-Bipyridyl (bipy) and 1,10-Phenanthroline (phen) Ligands

We have already mentioned [Ru$_2$O$_6$(bipy)$_2$]; it has limited solubility and so is not suitable for oxidations,[23] and surprisingly [RuO$_2$(bipy)Cl$_2$][24] seems to function only as a stoicheiometric oxidant[4] though this really needs reinvestigation. Lack of solubility is also a problem with *trans*-[RuO$_2$(LL)$_2$]$^{2+}$ (LL = phen, bipy), made from [Ru(OH)H$_2$O)(LL)$_2$]$^{2+}$ and cerium(IV), but the more soluble *trans*-[RuO$_2$(dmbipy)$_2$]$^{2+}$ (dmbipy = 5,5′-dimethyl-2,2′-bipyridyl) will effect, albeit stoicheiometrically, a wide range of oxidations, *e.g.* of alkenes to epoxides, secondary alcohols to ketones, and cyclohexene to cyclohexenone. For the alcohol oxidations a hydride abstraction mechanism was proposed, [Ru(OH)(H$_2$O)(LL)$_2$]$^{2+}$ being formed.[25] The complex *cis*-[RuO$_2$(dmp)$_2$]$^{2+}$, made by oxidation of [Ru(H$_2$O)$_2$(dmp)$_2$]$^{2+}$ with cerium(IV) (dmp = 2,9-dimethyl-1,10-phenanthroline) will catalytically epoxidize norbornene, cyclohexene, and *trans*-β-styrene under 3 atm. of dioxygen at 50 °C, and Drago has sought to rationalize the oxidizing behaviour of *cis* and *trans* dioxoruthenium(VI) complexes towards alkenes by the use of INDO/1 semi-empirical MO models.[26]

4.3.3 With Porphyrin and Macrocyclic N-Donor Ligands

Most, though not all of the oxidation work in this area is stoicheiometric rather than catalytic. The 5,10,15,20-tetramesitylporphinato (TMP) complex *trans*-[RuO$_2$(TMP)] can be made by oxidation of [Ru(CO)(TMP)] with PhIO or peroxy acids, or by treatment of [RuL$_2$(TMP)] (L = THF, CH$_3$CN) with dioxygen. The complex will, at ambient temperatures and pressures, catalyse the aerobic epoxidation of a number of alkenes (*e.g. cyclo*octene, *cis* and *trans* β-methylstyrene, norbornene) over a 24 hour period; it functions as an overall four-electron oxidant.[27]

Much work has been carried out on macrocyclic N-donor tetra-aza complexes of *trans*-dioxoruthenium(VI) species *trans*-[RuO$_2$(R-TMC)]$^{2+}$, *e.g.* 1,4,8,11-tetramethyl-1,4,8,11-tetra-azacyclotetradecane (14-TMC), 1,4,8,12-tetramethyl-1,4,8,11-tetra-azacyclotetradecane (15-TMC), and 1,4,8,13-tetramethyl-1,4,8,13-tetra-azacyclotetradecane (16-TMC) (8).

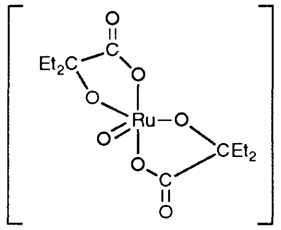


(8)

A general method of preparation for these is the oxidation of [Ru(H$_2$O)$_2$(R-TMC)]$^{3+}$ with H$_2$O$_2$; the *X*-ray crystal structures for the perchlorate salts of the 15- and 16-TMC complexes show the Ru=O distances to be 1.718 and 1.705 Å respectively. These species exhibited slight aerobically assisted catalysis of benzyl alcohol to benzaldehyde (*e.g.* catalytic turnovers of 2.5 to 2.8 over 18 hours) under ambient conditions. Stoicheiometrically they oxidize cyclohexene at its allylic carbon atom to give 2-cyclohexen-1-one as the only product.[28]

5 Ruthenium(V)

Ruthenium(V) complexes are rare, and this is particularly true of oxoruthenium(V) species. Reaction[9,29] of [RuO$_4$]$^-$ with a variety of α-hydroxy carboxylic acids HOCR′R″COOH (R′ = R″ = Me; R′ = R″ = Et; R′ = Me, R″ = Et; R′ = Ph, R″ = Me) gave [RuO(O$_2$COCR′R″)]$^-$. The *X*-ray crystal structure of the 2-hydroxy-2-ethylbutyrato complex (Pr$^n_4$N)[RuO(O$_2$COEt$_2$)$_2$] shows the anion of this to have a trigonal bipyramidal structure with the oxo ligand (Ru=O 1.697 Å) and the two deprotonated hydroxo ligands (Ru–O 1.860 Å) in the equatorial plane, the axial positions being occupied by the deprotonated carboxylato oxygen atoms (Ru–O 2.008 Å) (9).[29] The 2-hydroxy-2-ethylbutyrato complex is, in the presence of NMO, a catalyst for the oxidation of activated (benzylic) alcohols to aldehydes or ketones and of PPh$_3$ to PPh$_3$O, but the reactions are slow and the turnovers for alcohols undistinguished (*ca.*25); the reagent is in this respect much inferior to most of the ruthenium(VI) complexes discussed above and to [RuO$_4$]$^-$.



(9)

The oxoruthenium(V) species *trans*-[RuOX(R-TMC)]$^{2+}$ (X = Cl$^-$, NCO$^-$, N$_3$$^-$) have been generated electrochemically and these are catalysts for the electro-oxidation of benzyl alcohol to benzaldehyde, though activity is gradually lost over a few cycles. A salt *trans*-[Ru^{V}O$_2$(14-TMC)](ClO$_4$) has also been isolated.[28] The [Ru^{V}O(EDTA)]$^-$ complex is likely to be potentially useful as an oxidant.[30]

The mono-oxo species [Ru^{V}O(N$_4$O)]$^{2+}$ {N$_4$O = 2-hydroxy-2-(2-pyridyl)ethyl[bis(2-(2-pyridyl)ethyl)]amine}, made by oxidation of [Ru(H$_2$O)[N$_4$O)]$^{2+}$ with cerium(IV), is an effective though non-specific stoicheiometric oxidant, oxidizing alcohols to aldehydes or ketones, cleaving double bonds and oxidizing cyclohexane and adamantane. For the oxidation of alcohols mechanisms involving a two-electron hydride transfer or a one-electron hydrogen abstraction process were suggested.[31]

6 Ruthenium(IV)

All the reported oxoruthenium(IV) complexes are mono-oxo species, most are paramagnetic and all contain at least one N-donor ligand. Relatively few of these mild oxidants function catalytically however.

The complex [RuO(py)(bipy)$_2$]$^{2+}$, made by the oxidation with cerium(IV) of [RuO(py)(bipy)$_2$]$^{2+}$, has been much studied; in dichloromethane solution it will catalytically epoxidize alkenes with hypochlorite as co-oxidant. Thus styrene is oxidized to styrene oxide, *trans*-stilbene to *trans*-stilbene oxide and *cis*-stilbene to a mixture of 95% of the *cis* and 5% of the *trans* isomers. With periodate or hypochlorite as a co-oxidant it will also catalytically oxidize benzhydrol to benzophenone, but there is considerable double-bond cleavage side reaction to give benzaldehyde. Similar reactions are observed with [RuO(bipy)(terpy)]$^{2+}$, and the latter has been used as an electrocatalytic oxidant for a variety of substrates including alcohols. Thus propan-2-ol gives acetone and ethanol gives a mixture of acetaldehyde and acetone.[32] The study by Meyer *et al.* of the mechanism of the stoicheiometric oxidation of alcohols by the paramagnetic *cis*-[RuO(py)(bipy)$_2$]$^{2+}$ is probably the most detailed yet reported for such oxidations by oxoruthenium species.[33] The studies were carried out both in aqueous solution and in acetonitrile with a range of primary and secondary alcohols, and a large C–H kinetic isotope effect observed. It was shown that the redox step almost certainly involves a two-electron hydride transfer, the overall reaction for a secondary alcohol being

$$\begin{aligned}&[\mathrm{Ru^{IV}O(py)(bipy)_2}]^{2+} + \mathrm{R_2CHOH} \rightarrow \\ &\qquad [\mathrm{Ru^{II}(OH_2)(py)(bipy)_2}]^{2+} + \mathrm{R_2CO}\end{aligned}$$

There is probably an initial pre-association step

$$\begin{aligned}&\mathrm{(py)(bipy)_2Ru^{IV}({=}O)^{2+}} + \mathrm{R_2CHOH} \rightleftharpoons \\ &\qquad \mathrm{(py)(bipy)_2Ru^{IV}({=}O)^{2+},HC(OH)R_2}\end{aligned}$$

followed by a hydride transfer redox step:

$$\begin{aligned}&\mathrm{(py)(bipy)_2Ru^{IV}({=}O)]^{2+},HC(OH)R_2^{2+}} \rightarrow \\ &\qquad [\mathrm{(py)(bipy)_2Ru{-}O{-}{-}{-}H{-}{-}{-}C(OH)R_2}]^{2+}\end{aligned}$$

$$\begin{aligned}&[\mathrm{(py)(bipy)_2Ru{-}O{-}{-}{-}H{-}{-}{-}C(OH)R_2}]^{2+} \rightarrow \\ &\qquad \mathrm{(py)(bipy)_2Ru^{II}{-}OH^{+},R_2COH^{+}}\end{aligned}$$

which is then followed by separation and rapid proton equilibration:[33]

$$\begin{aligned}&\mathrm{(py)(bipy)_2Ru^{II}{-}OH^{+},R_2COH^{+}} \rightarrow \\ &\qquad [\mathrm{(py)(bipy)_2Ru^{II}(OH_2)}]^{2+} + \mathrm{R_2CO}\end{aligned}$$

The intermediates in this mechanism were examined by an INDO/1 MO calculation of the epoxidation catalysed by ruthenium(IV) oxo systems.[34] Meyer *et al.* have recently studied the oxidation by $[\mathrm{RuO(py)(bipy)}]_2^{2+}$ of hydroquinone to *p*-benzoquinone and provide evidence that the reaction proceeds *via* a proton-coupled electron transfer.[35]

The species $[\mathrm{RuO(bipy)_2(LR_3)}]^{2+}$ ($\mathrm{LR_3}$ = tertiary phosphine or arsine) are made by oxidation of $[\mathrm{Ru(H_2O)(bipy)_2(LR_3)}]^{2+}$ with cerium(IV) and are effective stoicheiometric oxidants for alcohols to aldehydes and ketones, sulfides to sulfoxides, and phosphines to phosphine oxides. Studies were made in aqueous and non-aqueous media and, for the former, it was found that the rate of oxidation was dependent on the nature of $\mathrm{LR_3}$ and on the hydrophobic nature of the target alcohol. For the oxidation of alcohols a hydride transfer step was suggested in which there is a synchronous transfer of a proton and two electrons from the alcohol followed by a fast proton transfer.[36]

Oxidation of *trans*-$[\mathrm{Ru(NO)Cl(py)_4}]^{2+}$ with hypochlorite yields the paramagnetic *trans*-$[\mathrm{RuOCl(py)_4}]^{2+}$, and the *X*-ray crystal structure of the perchlorate shows the cation to contain a long Ru=O distance of 1.862 Å. With alcohols ROH it gives $[\mathrm{Ru^{III}(OR)Cl(py)_4}]^{2+}$ (R = Me, Et, Pr^n).[37] We find that it also acts as a catalytic oxidant, with NMO or PhIO as co-oxidants, for the oxidation of benzylic alcohols to aldehydes. However yields are only moderate and turnovers low, up to 8.[23]

The macrocyclic complexes *trans*-$[\mathrm{RuOX(R\text{-}TMC)}]^{2+}$ ($\mathrm{X = Cl^-, NCO^-, N_3^-}$) all have Ru=O distances of 1.765 Å, substantially shorter[28] than the 1.862 Å found in *trans*-$[\mathrm{RuOCl(py)_4}]^{2+}$.[36] These macrocyclic complexes will oxidize benzyl alcohol to benzaldehyde, there being slight aerobic catalysis (as there is with *trans*-$[\mathrm{RuO_2(R\text{-}TMC)}]^{2+}$) with catalytic turnovers of up to 6 over a 21 hour period at room temperatures. A two-electron process was suggested.[28]

7 Ruthenium(III)

The trinuclear species $[\mathrm{Ru_3O(OCOR)_6L_3}]^{n+}$ (R = Me, Et; L = $\mathrm{H_2O}$, $\mathrm{PPh_3}$; n = 0, 1) will catalyse the oxidation of primary alcohols to aldehydes and of secondary alcohols to ketones at 65 °C under 3 atm. of dioxygen; under such conditions high catalytic turnovers were observed (near 1000 over 143 hours for $[\mathrm{Ru_3O(OCOEt)_6(PPh_3)_3}]$). With the perfluorobutyrato (pfb) complex $[\mathrm{RU_3O(pfb)_6(Et_2O)_3}]\mathrm{(pfb)}$ aerobic catalysis of alkene oxidation occurs at 65 °C.[38] Recently electrochemical evidence has been obtained for the existence of $\{[\mathrm{Ru^{III,III}(bipy)_2(OH)}]_2\mathrm{O}\}^{2+}$, $\{[\mathrm{Ru^{III,IV}(bipy)_2(OH)}]_2\mathrm{O}\}^{5+}$, $\{[\mathrm{Ru^{IV,V}(bipy)_2O}]_2\mathrm{O}\}^{3+}$, and $\{[\mathrm{Ru^{V,V}(bipy)_2O}]_2\mathrm{O}\}^{4+}$.[39]

8 Conclusions and Future Perspectives

This review has sought to show that well-defined, easily prepared oxoruthenium complexes can be used to carry out a number of useful organic transformations. In a catalytic rôle some of them are particularly efficient for the mild and selective oxidation of alcohols, tolerating the presence of sensitive functional groups often attacked by other oxidizing reagents. There is much scope for advance in the field: synthetic procedures for the design of new oxoruthenium complexes are now well developed and it should be possible to refine further the selectivity of oxidations, to extend the number of functional groups oxidized, and to effect chiral oxidations.

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