Ruthenium-catalysed Aerobic Oxidation of Alcohols *via* Multistep Electron Transfer

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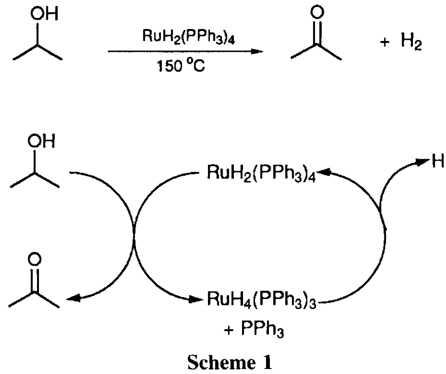
Aerobic oxidation of primary alcohols to aldehydes occurs under mild conditions at 20 °C *via* a triple catalytic system consisting of $RuCl(OAc)(PPh_3)_3$–hydroquinone–Co(salophen)(PPh_3) [H_2salophen = *N,N'*-bis(salicylidene)-*o*-phenylenediamine].

Oxidation of organic substrates is of importance in synthetic organic chemistry both in large-scale processes and in the manufacturing of fine chemicals.[1,2] From an economical and environmental point of view molecular oxygen is an attractive oxidant, and recently there has been a great interest in the development of mild metal-catalysed aerobic processes.[3,4]

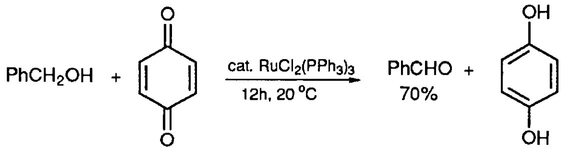
We recently developed several mild palladium-catalysed aerobic oxidations that proceed at room temperature *via* a multistep electron transfer involving a triple catalytic system.[4]



Scheme 1

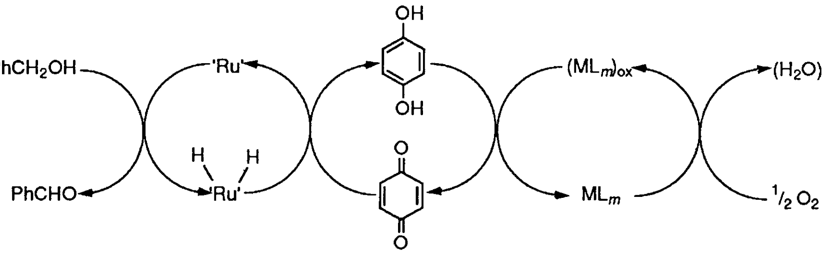
The general idea concerning these oxidations is that a macrocyclic metal complex serves as the oxygen-activating component, and a substrate-selective catalyst is used to obtain high selectivity with respect to a desired transformation. Now, if the barrier for electron transfer from the substrate-selective catalyst to the metal macrocycle catalyst is high, an electron-transfer mediator is needed for a mild reaction. In this communication we report a new, mild, aerobic, ruthenium-catalysed oxidation of alcohols based on this principle.

It has been reported that alcohols are dehydrogenated by ruthenium phosphine complexes.[5,6] In particular $RuH_2(PPh_3)_4$ and $RuH_2(PPh_3)_3$ were found to be efficient and also led to the production of H_2 with high turnover numbers if a temperature of 150 °C was employed (Scheme 1). Interestingly, the same ruthenium complexes have been utilized as hydrogenation catalysts.[7] The ability of ruthenium phosphine complexes to act as both dehydrogenation and hydrogenation catalysts is also reflected by their use in hydrogen-transfer



(1)

$$PhCH_2OH + {}^1/_2\,O_2 \xrightarrow[CH_2Cl_2,\ 20\,^\circ C]{\substack{\text{Cat. RuCl(OAc)(PPh}_3)_3\\ \text{Cat. hydroquinone}\\ \text{Cat. Co(salophen)(PPh}_3)}} \underset{\text{70 turnovers}}{PhCHO + H_2O} \quad (2)$$



Scheme 2 ML_m = Co(salophen)PPh$_3$; H_2salophen = *N,N′*-bis(salicylidene)-*o*-phenylenediamine

reactions.[6,8,9] In these reactions hydrogen acceptors such as ketones and α,β-unsaturated ketones[6–8] have been used. If benzoquinone could be used as the hydrogen acceptor the hydroquinone formed may continuously be reoxidized to benzoquinone by use of a metal macrocycle–oxygen system.[4] The role of the hydroquinone–benzoquinone would then be that of an electron-transfer mediator.

We first studied the ruthenium-catalysed dehydrogenation of benzyl alcohol in the presence of benzoquinone. The use of the ruthenium dihydride complexes[5a] led to very poor conversions at room temperature. Since these complexes are also difficult to handle we turned our attention to $RuCl_2(PPh_3)_3$, which has been used in hydrogen-transfer reactions of alcohols, albeit at high temperature (150–180 °C).[6,8–10] We found that $RuCl_2(PPh_3)_3$-catalysed oxidation of benzyl alcohol using benzoquinone as the oxidant (hydrogen acceptor) proceeded smoothly at room temperature (eqn. 1). With the use of 1.2 mol% of the catalyst a good conversion with >98% selectivity was obtained within 12 h at 20 °C in benzene or methylene chloride. A kinetic study of this reaction revealed that the rate is not dependent on the benzoquinone concentration. The use of the quinone in only catalytic amounts with recycling of the hydroquinone to benzoquinone as previously described by us[4] therefore looked attractive. In our previously reported triple catalytic systems, hydroquinone was reoxidized to benzoquinone by molecular oxygen in the presence of a metal macrocyclic complex in a protic solvent or co-solvent under slightly acidic conditions. In the present non-protic solvents this particular reaction was less facile but was found to work with Co(salophen) in the presence of an extra axial ligand such as triphenylphosphine. The choice of solvent was critical and the oxidation of hydroquinone to benzoquinone catalysed by Co(salophen)(PPh_3) was more than ten times faster in methylene chloride than in benzene.

With the aim of obtaining a mild aerobic process we combined the oxidation system of eqn. (1) and that for reoxidation of hydroquinone. The conversion of the aerobic process, however, was very low with only three turnovers. We had previously observed[4,11] that chloride ligands strongly inhibit the oxidation of hydroquinone by the metal macrocycle–oxygen system. We therefore displaced one of the chlorides of $RuCl_2(PPh_3)_3$ by silver acetate which afforded $RuCl(OAc)(PPh_3)_3$. This improved the aerobic process and about 20–25 turnovers were obtained. A further improvement of this triple catalysis was obtained by the use of molecular sieves to remove the water formed† (eqn. 2, Scheme 2). The use of 0.6 mol% of $RuCl(OAc)(PPh_3)_3$, 2 mol% of Co(salophen)PPh_3, and 3 mol% of hydroquinone gave 70 turnovers (based on Ru) at 20 °C, which corresponds to a 42% yield of benzaldehyde (based on benzyl alcohol). With a slight increase in the amount of the ruthenium catalyst (1.2 mol%) the yield of benzaldehyde was improved to 60% under the same reaction conditions. No other oxidized products could be detected (>98% selectivity). Interestingly, the rate of this aerobic process is unchanged if the oxygen pressure is lowered. Thus, the same rate was observed whether the reaction was run under 1 atm of air or under 1 atm of O_2. Other alcohols were also oxidized by the present oxidation system. For example geraniol, cinnamyl alcohol and 2-naphthylmethanol were oxidized to their corresponding aldehydes at a rate comparable to that of the oxidation of benzyl alcohol.

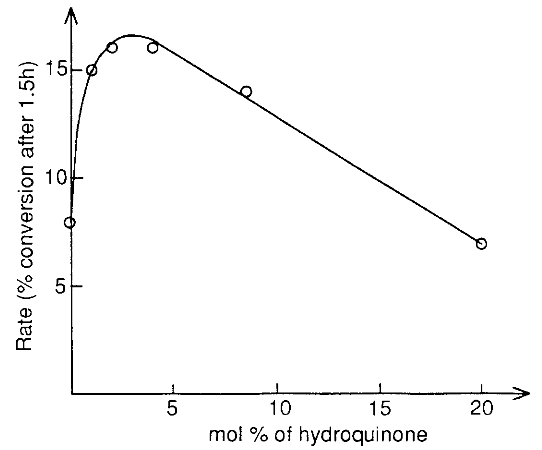


Fig. 1 Aerobic oxidation of $PhCH_2OH$ to PhCHO [1.2 mol% of $Ru(OAc)Cl(PPh_3)_3$, 1 mol% of Co(salophen)PPh_3]

We also investigated the dependence on hydroquinone of the rate of the reaction. As can be seen from Fig. 1, the rate increases with the concentration of hydroquinone and reaches a maximum at about 3 mol% of hydroquinone. Even with no added hydroquinone there is some reaction occurring, indicating a direct electron transfer, although less efficient, between the ruthenium hydride complex and the oxygen complex of the metal macrocycle.

A few other ruthenium-catalysed processes for the oxidation of alcohols to aldehydes or ketones are known.[12] These processes require an elevated temperature and O_2 pressure. The present multistep electron-transfer system leads to a very mild aerobic process that can be run under a reduced partial pressure of O_2 (air) at ambient temperature.

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† The deactivation by water can be explained by formation of the hydrate of the aldehyde, which can coordinate to ruthenium and possibly be slowly oxidized to benzoic acid.[6]

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References

1 A. H. Haines, *Methods for the Oxidation of Organic Compounds*, Academic Press, London, 1st part (Alkanes, alkenes . . .), 1985; 2nd part (Alcohols, alcohol derivatives . . .), 1988.

2 R. A. Sheldon and J. K. Kochi, *Metal-Catalyzed Oxidations of Organic Compounds*, Academic Press, New York, 1981; G. W. Parshall, *Homogeneous Catalysis*, Wiley-Interscience, New York, 1980.

3 For a review, see: B. Meunier, *Bull Soc. Chim. Fr.*, 1986, 578; J.-T. Groves and R. Quinn, *J. Am. Chem. Soc.*, 1985, **107**, 5790; R. A. Leising and K. J. Takeuchi, *Inorg. Chem.*, 1987, **26**, 4391; T. Okamoto, K. Sasaki and S. Oka, *J. Am. Chem. Soc.*, 1988, **110**, 1187; S. Davis and R. S. Drago, *J. Chem. Soc., Chem. Commun.*, 1990, 250.

4 J. E. Bäckvall, A. K. Awasthi and Z. D. Renko, *J. Am. Chem. Soc.*, 1987, **109**, 4750; J. E. Bäckvall and R. B. Hopkins, *Tetrahedron Lett.*, 1988, **29**, 2885; J. E. Bäckvall, R. B. Hopkins, H. Grennberg, M. Mader and A. K. Awasthi, *J. Am. Chem. Soc.*, 1990, **112**, 5160.

5 (*a*) D. Morton and D. J. Cole-Hamilton, *J. Chem. Soc., Chem. Commun.*, 1988, 1154; (*b*) S. Shinoda, H., Itagaki and Y. Saito, *J. Chem. Soc., Chem. Commun.*, 1985, 860 and refs. cited.

6 S.-I. Murahashi, T. Naota, K. Ito, Y. Maeda and H. Taki, *J. Org. Chem.*, 1987, **52**, 4319.

7 D. E. Linn, Jr., and J. Halpern, *J. Am. Chem. Soc.*, 1987, **109**, 2969.

8 Y. Sasson and J. Blum, *Tetrahedron Lett.*, 1971, 2167; Y. Sasson and J. Blum, *J. Org. Chem.*, 1975, **40**, 1887; Ishi, K. Osakada, T. Ikariya, M. Saburi and S. Yoshikawa, *J. Org. Chem.*, 1986, **51**, 2034; T. A. Smith and P. M. Maitlis, *J. Organomet. Chem.*, 1985, **289**, 385.

9 S. Ganguly, F. L. Joslin and D. M. Roundhill, *Inorg. Chem.*, 1989, **28**, 4562; D. Ma, and X. Lu, *J. Chem. Soc., Chem. Commun.*, 1989, 890; Y. Tsuji, S. Kutachi, K. Huh and Y. Watanabe, *J. Org. Chem.*, 1990, **55**, 580.

10 For stoichiometric dehydrogenations of alcohols see: H. Tomioka, K. Takai, K. Oshima and H. Nozaki, *Tetrahedron Lett.*, 1981, **22**, 1605; F. H. Jardine, *Progr. Inorg. Chem.*, 1984, **31**, 265. For catalytic oxidations with *N*-oxide or PhIO as oxidant, see: K. B. Sharpless, K. Akashi and K. Oshima, *Tetrahedron Lett.*, 1976, 2503; P. Müller and J. Godoy, *Tetrahedron Lett.*, 1981, **22**, 2361. In the latter oxidations reaction a ruthenium-oxo complex is probably involved.

11 H. Grennberg and J. E. Bäckvall, unpublished results.

12 C. Bilgrien, S. Davis and R. S. Drago, *J. Am. Chem. Soc.*, 1987, **109**, 3786; R. Tang, S. E. Diamond, N. Neary and F. Mares, *J. Chem. Soc., Chem. Commun.*, 1978, 562.