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Ruthenium-Catalyzed Oxidation of Alkenes, Alkynes, and Alcohols to Organic Acids with Aqueous Hydrogen Peroxide

Chi-Ming Che,* Wing-Ping Yip, and Wing-Yiu Yu[a]

Abstract: A protocol that adopts aqueous hydrogen peroxide as a terminal oxidant and $[(Me_3tacn)(CF_3CO_2)_2Ru^{III}(OH_2)]CF_3CO_2$ (**1**; Me_3tacn = 1,4,7-trimethyl-1,4,7-triazacyclononane) as a catalyst for oxidation of alkenes, alkynes, and alcohols to organic acids in over 80% yield is presented. For the oxidation of cyclohexene to adipic acid, the loading of **1** can be lowered to 0.1 mol%. On the one-mole scale, the oxidation of cyclohexene, cyclooctene, and 1-octanol with 1 mol% of **1** produced adipic acid (124 g, 85% yield), suberic acid (158 g, 91% yield), and 1-octanoic acid (129 g, 90% yield), respectively. The oxidative C=C bond-cleavage reaction proceeded through the formation of *cis*- and *trans*-diol intermediates, which were further oxidized to carboxylic acids via C−C bond cleavage.

Keywords: alcohols · alkenes · alkynes · oxidation · ruthenium

Introduction

The development of new processes for selective organic oxidations with environmentally friendly oxidants has potential practical applications in the synthesis of fine chemicals. Despite its importance, organic oxidations with molecular oxygen or hydrogen peroxide are difficult to control and usually result in mixtures of products. In the context of metal-catalyzed organic oxidations with H_2O_2 as a terminal oxidant, there have been extensive studies on early transition metal catalysts.[1] Recent papers by Noyori and coworkers[2] highlighted the use of sodium tungstate for transforming alkenes into carboxylic acids with H_2O_2 as oxidant. A notable feature of their work is that this one-pot reaction can be applied to a 100-g scale for cycloalkene oxidation, thus implying the feasibility of industrial/practical applications.

Ruthenium-catalyzed organic oxidations are well-documented for applications in organic synthesis.[1c,3] In the last few decades, a diverse range of structurally characterized oxoruthenium complexes were found to be highly reactive and undergo C−H bond hydroxylation and alkene epoxidation reactions.[4–7] Despite advances in the oxidation chemistry of oxoruthenium complexes,[4–7] studies on ruthenium-catalyzed organic oxidations with aqueous hydrogen peroxide as a terminal oxidant remain sparse. In the past ten years, there were reports by various research groups on the use of molecularly defined ruthenium catalysts for alkene and alcohol oxidations with H_2O_2.[8–10] Recently, Beller and co-workers[8] reported a protocol for ruthenium-catalyzed alkene epoxidation in *tert*-amyl alcohol that employed hydrogen peroxide as oxidant. Previously, we reported that $[(Me_3tacn)(CF_3CO_2)_2Ru^{III}(OH_2)]CF_3CO_2$ (**1**; Me_3tacn = 1,4,7-trimethyl-1,4,7-triazacyclononane) is an active catalyst for the oxidation of alkenes and alcohols by *tert*-butyl hydroperoxide (TBHP).[11] We also reported the stoichiometric alkene and alkyne oxidations by *cis*-$[(Me_3tacn)(CF_3CO_2)Ru^{VI}O_2]ClO_4$ to give *cis*-1,2-diols or dialdehydes in aqueous medium, the latter arising from C−C bond cleavage.[7a] Herein is a protocol for the oxidation of alkenes, alkynes, and alcohols, by using a slight excess of hydrogen peroxide as a terminal oxidant, to the corresponding carboxylic acids in the presence of **1** (0.2–1 mol%); complete reaction was attained within a reasonable time span (4 h).

Results and Discussion

We previously reported that **1** is an active catalyst for the oxidation of alkenes, alcohols, and alkanes by TBHP.[11] A

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silica-gel-supported Ru–Me_3tacn complex prepared by treating **1** with silica gel in absolute ethanol was found to be a useful heterogeneous catalyst for organic oxidations.[11a] Herein, the catalytic activity of **1** toward organic oxidations with aqueous hydrogen peroxide as a terminal oxidant is examined.

Oxidation of Alkenes

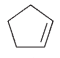
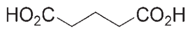
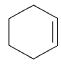
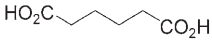
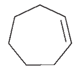
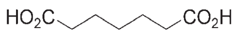
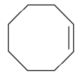
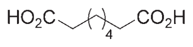
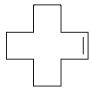
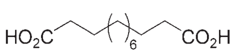
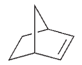
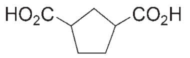
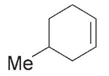
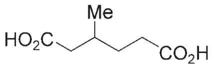
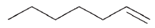
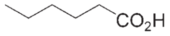
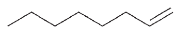
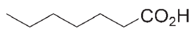
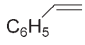
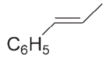
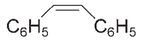
Aqueous H_2O_2 (35 %) was added slowly to a solution of cyclohexene (5 mmol) in aqueous *tert*-butanol (tBuOH/H_2O = 2:1 *v*/*v*) in the presence of **1** (50 μmol) at 60 °C. Complete substrate conversion was observed, with *cis*- and *trans*-1,2-cyclohexanediol (30 % and 68 % yield, respectively) being obtained (see Supporting Information). At room temperature, neither *cis*- nor *trans*-1,2-cyclohexanediol was formed, and the starting cyclohexene was fully recovered.

Other cycloalkenes such as cyclooctene and cyclopentene gave a mixture of *cis*- and *trans*-diols under the same reaction conditions. Similar reaction of cyclooctene with H_2O_2 (1.2 equiv) gave *cis*-cyclooctane-1,2-diol and cyclooctene oxide in 50 % and 42 % yield, respectively, based on complete substrate conversion. For the oxidation of cyclopentene, *cis*- and *trans*-cyclopentane-1,2-diol were obtained in 28 % and 57 % yield, respectively. These results are given in the Supporting Information.

As **1** is an effective catalyst for alkene epoxidation by TBHP,[11] and *cis*-[(Me_3tacn)(CF_3CO_2)$Ru^{VI}O_2$]ClO_4 can undergo stoichiometric alkene dihydroxylation in *tert*-butanol/H_2O,[7a] the *cis*- and *trans*-diol products described above may come from two or more reaction pathways. A possible pathway for the *trans*-diol products is the ring opening of the epoxide intermediates. We found that when the oxidation of cyclohexene was conducted under reflux conditions for 4 h, adipic acid was isolated in 88 % yield; neither the *cis*- nor the *trans*-diol was detected based on ^{1}H NMR spectroscopic analysis of the crude reaction mixture (Table 1, entry 2).

When 0.1 mol % catalyst was used, a longer reaction time of 12 h was required for complete reaction, and 2-cyclohexen-1-one and 2-cyclohexen-1-ol were obtained as side products. With 1 mol % of catalyst **1**, other cycloalkenes were oxidized to the corresponding dicarboxylic acids in ≥85 % yield (Table 1, entries 1–7). For the acyclic aliphatic terminal alkenes (Table 1, entries 8 and 9), oxidative C=C bond

Table 1. Oxidation of alkenes by aqueous H_2O_2 catalyzed by **1**.[a]

Entry	Alkene	Conversion [%]	Product	Yield [%][b]
1		100		85
2[c,d]		100		88
3		100		85
4		100		93
5		100		89
6		100		95
7		100		85
8		100		93
9		100		90
10[e,f]		100	$C_6H_5CO_2H$	80
11[e,f]	*m*-$ClC_6H_4CH{=}CH_2$	100	*m*-$ClC_6H_4CO_2H$	80
12[e,f]		100	$C_6H_5CO_2H$	82
13[e,f]		100	$C_6H_5CO_2H$	78

[a] 2.5 mL (25 mmol) of aqueous H_2O_2 was used. [b] Yield of isolated product. [c] Adipic acid was obtained in 35 % yield when distilled water (9 mL) was used as solvent; the low product yield is probably due to the high volatility of cyclohexene under reflux conditions. With 0.5 mol % **1**: adipic acid (76 %), 2-cyclohexen-1-one (8 %), 2-cyclohexen-1-ol (8 %); with 0.1 mol % **1**: adipic acid (60 %), 2-cyclohexen-1-one (15 %), 2-cyclohexen-1-ol (15 %). [d] With 1 mol substrate, introduction of H_2O_2 took 6 h for completion, and the reaction mixture was further heated at reflux for 6 h. [e] 17.5 % (25 mmol) aqueous H_2O_2 was added over 12 h and the reaction was further heated at reflux for 1 h. [f] Benzaldehyde was detected in 5–15 % yield with GC.

Abstract in Chinese:

用過氧化氫水溶液作氧化劑，[(Me_3tacn)(CF_3CO_2)$_2Ru^{III}$(OH_2)]CF_3CO_2 (**1**) 催化氧化烯烴、炔烴和醇爲有機酸，收率超過 80%。對於環己烯氧化成己二酸，催化劑 **1** 的用量可以低於 0.1 mol%。若使用 1 mol%的催化劑 **1**，將反應放大到 1 mol 的規模，環己烯、環辛烯和 1-辛醇分別被氧化爲己二酸（85%，124 g）、辛二酸（91%，158 g）和 1-辛酸（90%，129 g）。此類 C=C 雙鍵的氧化開鍵反應是通過先形成順-和反-二醇中間體，再進一步氧化斷裂 C–C 鍵，生成羧酸。

International Advisory Board Member

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cleavage to the corresponding carboxylic acids ($\geq 90\%$ yield) was observed.

For styrene oxidation under the typical reaction conditions, that is, styrene (5 mmol), **1** (1 mol%), H_2O_2 (35%, slowly added over 3 h with a syringe pump), and aqueous *tert*-butanol (*t*BuOH/H_2O = 2:1 v/v, reflux, 4 h), benzaldehyde (53%) and benzoic acid (45%) were obtained. When a dilute hydrogen peroxide solution (17.5% *v*/*v*) was employed, and its introduction was extended to 12 h, benzoic acid was obtained in 80% yield (Table 1, entry 10). By this protocol, other aryl alkenes underwent similar oxidative C=C bond cleavage to give the corresponding organic acids in $\geq 78\%$ yield.

It is likely that the oxidation of alkenes to carboxylic acids with the **1**+H_2O_2 protocol would proceed via the formation of alcohol intermediates. In support of this postulation, **1** was found to be an effective catalyst for the oxidation of alcohols, including the aliphatic ones (Table 3, entries 3–6), to the corresponding carboxylic acids. *cis*-Cyclooctane-1,2-diol and *trans*-cyclohexane-1,2-diol were oxidized by the **1**+H_2O_2 (3.3 equiv) protocol (Table 3, entries 1 and 2) to the corresponding dicarboxylic acids in $\geq 96\%$ yield, and no 1,2-diketones were detected at the end of the reaction. When the reaction was performed with cyclohexane-1,2-dione as substrate, no substrate conversion was observed, and all the starting diketone was recovered.

Oxidation of Alkynes

It is known that ruthenium trichloride[12] and ruthenium nanoparticles[13] are efficient catalysts for the oxidation of alkynes by $NaIO_4$. We previously reported that alkynes can be stoichiometrically oxidized by *cis*-[(Me_3tacn)(CF_3CO_2)$Ru^{VI}O_2$]ClO_4 to 1,2-diketones.[7c] Herein we found that alkynes can be oxidatively cleaved to carboxylic acids with the **1**+H_2O_2 protocol.

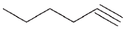
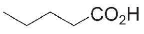
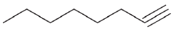
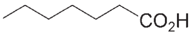
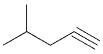
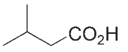
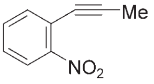
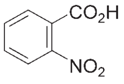
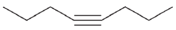
Treatment of 1-phenyl-1-propyne (5 mmol) with aqueous H_2O_2 (35%, 20 mmol) and **1** (50 μmol) in aqueous *tert*-butanol (9 mL, *t*BuOH/H_2O = 2:1 *v*/*v*) at reflux afforded benzoic acid in 83% yield, with 100% substrate conversion (Table 2, entry 1). No 1,2-diketone was detected. Similarly, 4-ethynyltoluene was oxidized to give 4-methylbenzoic acid in 88% yield (Table 2, entry 2).

Terminal alkynes such as 4-ethynyltoluene, 1-hexyne, 1-octyne, and 4-methylpentyne (Table 2, entries 2–5) underwent similar oxidative-cleavage reactions to give the corresponding carboxylic acids as a single product (75–88% yield) with 100% substrate conversion.

When (2-nitro)-1-phenyl-1-propyne was used as substrate (Table 2, entry 6), only 23% substrate conversion was obtained with 89% product yield. Similarly, oxidation of 4-octyne to butanoic acid proceeded with 89% product yield but only 36% substrate conversion (Table 2, entry 7).

It was reported that the formation of [3+2] cycloadducts[7c] took place in the reaction between alkynes and *cis*-[(Me_3tacn)(CF_3CO_2)$Ru^{VI}O_2$]ClO_4. However, we did not observe the corresponding [3+2] cycloadduct in the catalytic oxidation of alkyne with **1** as a catalyst (1 mol%) and aqueous H_2O_2 as a terminal oxidant by ESI-MS analysis of the reaction mixture, and no 1,2-diketone was detected. Furthermore, a control experiment with cyclohexane-1,2-dione as substrate revealed no substrate conversion. Although the mechanism underlying the catalytic alkyne oxidations requires further investigation, the formation of reactive oxoruthenium species from the **1**+H_2O_2 protocol under reflux conditions is plausible.

Table 2. Oxidation of alkynes by aqueous H_2O_2 catalyzed by **1**.[a]

Entry	Alkyne	Conversion [%]	Product	Yield [%][b]
1	$C_6H_5{-}{\equiv}{-}CH_3$	100	$C_6H_5CO_2H$	83
2	*m*-$MeC_6H_4{-}{\equiv}{-}H$	100	*m*-$ClC_6H_4CO_2H$	88
3		100		75
4		100		80
5		100		78
6		23		89
7		36		89

[a] Reaction conditions: **1** (1 mol%) was added to a mixture of *tert*-butanol (6 mL) and distilled water (3 mL) containing substrate (5 mmol). The reaction mixture was heated at reflux, during which aqueous H_2O_2 (2.0 mL, 20 mmol) was added over 3 h. The reaction mixture was then stirred for a further 1 h, and the product was purified by column chromatography. [b] Yield of isolated product.

Oxidation of Alcohols and Aldehydes

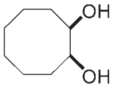
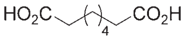
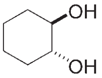
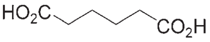
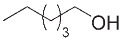
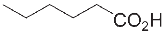
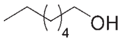
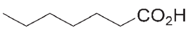
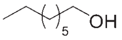
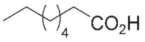
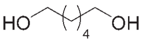
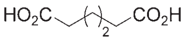
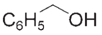
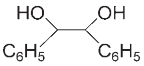
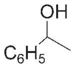
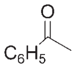
Previous studies revealed that primary alcohols are poor substrates for the **1**-catalyzed organic oxidations with TBHP.[11] Herein, when 1-hexanol was employed as substrate (Table 3, entry 3), 100% substrate conversion was obtained when a slight excess of hydrogen peroxide (2.2 equiv) was used, and hexanoic acid was isolated in 95% yield.

Other aliphatic and benzylic alcohols such as 1-heptanol, 1-octanol, 1,6-hexanediol, and benzyl alcohol could also be oxidized to the corresponding carboxylic acids in $\geq 92\%$ yield (Table 3, entries 4–7). For oxidation of benzyl alcohol, a longer reaction time was needed to obtain full substrate conversion (the introduction of H_2O_2 (17.5%) took 12 h for completion; see Experimental Section). Oxidation of hydrobenzoin and 1-phenylethanol (Table 3, entries 9 and 10) gave benzoic acid and acetophenone in 93% and 98% yield, respectively.

Although the **1**+H_2O_2 protocol successfully converted alcohols into carboxylic acids in good yields and selectivities, studies of the reaction mixture with ESI-MS revealed the presence of a single molecular ion cluster peak attributed to **1** (*m*/*z* = 516), and no other ruthenium species was identified.

As for aldehydes, benzaldehyde was fully converted into benzoic acid in 94% yield (Table 4, entry 1). Aliphatic alde-

Table 3. Oxidation of alcohols by aqueous H_2O_2 catalyzed by **1**.

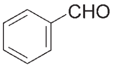
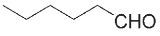
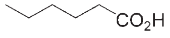
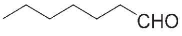
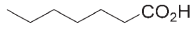
Entry	Alcohol	Conversion [%]	Product	Yield [%][a]
1[b]		100		97
2[b]		100		96
3[c]		100		95
4[c]		100		96
5[c]		100		92
6[d]		100		94
7[c,e,g]		100	$C_6H_5CO_2H$	93
8[c,f]	*m*-$FC_6H_4CH_2OH$	100	*m*-$FC_6H_4CO_2H$	83
9[b,f,g]		100	$C_6H_5CO_2H$	93
10[g]		100		98[h]

[a] Yield of isolated product. [b] 1.7 mL (17 mmol) of aqueous H_2O_2 was added. [c] 1.1 mL (11 mmol) of aqueous H_2O_2 was added. [d] 2.2 mL (22 mmol) of aqueous H_2O_2 was added. [e] At 60 °C, 20 % substrate conversion was detected. [f] 5–8 % benzaldehyde was detected with GC. [g] 17.5 % (11 mmol) aqueous H_2O_2 was added over 12 h and the reaction was further heated at reflux for 1 h. [h] Determined with GC.

hydes such as 1-hexanal and 1-heptanal could also be oxidized by the $\mathbf{1}+H_2O_2$ protocol to give the corresponding acids in up to 87 % yield and with 100 % substrate conversion (Table 4, entries 2 and 3).

For the **1**-catalyzed alkene and alcohol oxidations, only a trace amount of aldehyde was observed by GC and ^{1}H NMR spectroscopic analysis. It is likely that the alcohol was first oxidized to aldehyde, which was then further oxidized to the corresponding acid. At 298 K, the second-order rate constants for the oxidation of benzyl alcohol and benzaldehyde by *cis*-$[(\text{Tet-Me}_6)\text{Ru}^{VI}O_2](ClO_4)_2$ (Tet-Me_6 = *N,N,N′,N′*-tetramethyl-3,6-dimethyl-3,6-diazaoctane-1,8-diamine) are 1.6×10^{-2} and 1.4 $dm^3mol^{-1}s^{-1}$,[7d] respectively. These rate constants reveal that oxidation of aldehyde to carboxylic acid proceeds much faster than oxidation of alcohol to aldehyde by the Ru=O complexes. For the oxidation of 1-heptanol, introduction of H_2O_2 (1.1 equiv) led to 50 % substrate conversion, and heptanoic acid was detected exclusively.

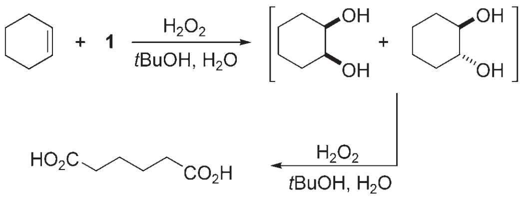
Table 4. Oxidation of aldehydes by aqueous H_2O_2 catalyzed by **1**.[a]

Entry	Aldehyde	Conversion [%]	Product	Yield [%][b]
1		100	$C_6H_5CO_2H$	94
2		100		85
3		100		87

[a] Reaction conditions: **1** (1 mol %) was added to a mixture of *tert*-butanol (6 mL) and distilled water (3 mL) containing substrate (5 mmol). The reaction mixture was heated at reflux, during which aqueous H_2O_2 (0.6 mL, 6 mmol) was added over 3 h. The reaction mixture was then stirred for a further 1 h, and the product was purified by column chromatography. [b] Yield of isolated product.

Scaled-Up Reactions

In the literature, most reported metal-catalyzed organic oxidations with hydrogen peroxide as a terminal oxidant were conducted on a millimole scale.[8–10] The recent tungstate-catalyzed cyclohexene oxidations by H_2O_2 reported by Noyori and co-workers[2] could be carried out on a 1-mol scale with 1 mol % catalyst in a one-pot process. We examined the feasibility of scaling up the $\mathbf{1}+H_2O_2$ oxidation with 1 mol of substrate. In the presence of **1** (6.29 g, 0.01 mol) and cyclohexene (82.15 g, 1 mol)/cyclooctene (110.2 g, 1 mol), dropwise introduction of aqueous hydrogen peroxide gave a yellow reaction mixture, the process of which took 6 h for completion. During the reaction, the color changed from yellow to purple, indicating the formation of $[(Me_3tacn)_2Ru^{III}{}_2(\mu\text{-}O)(\mu\text{-}CF_3CO_2)_2]^{2+}$.[7a] After the reaction mixture was heated at reflux for another 6 h, adipic acid (124 g; Scheme 1)/suberic acid (158 g) was obtained in 85 % and 91 % yield, respectively. At a lower catalyst loading (0.2 mol %), the oxidation of cyclohexene on a 1-mol scale took a longer time (12 h) for complete introduction of aqueous hydrogen peroxide, and the reaction mixture was heated at reflux for a further 8 h. Adipic acid was obtained in 70 % yield (102 g), and allylic oxidation products such as 2-cyclohexen-1-one and 2-cyclohexen-1-ol were obtained in 12 % and 13 % yield, respectively.



Scheme 1. Production of adipic acid with the $\mathbf{1}+H_2O_2$ protocol.

The scaled-up protocol is also applicable to the oxidation of alcohols. As an example, when aqueous hydrogen peroxide (2.2 mol) was added to a reaction mixture containing **1** (6.29 g, 0.01 mol) and 1-octanol (130.2 g, 1 mol), and the mixture heated at reflux for another 6 h, 1-octanoic acid was obtained in 90 % yield (129 g).

General Remarks

Oxidative-cleavage reactions of C=C and C≡C bonds with aqueous hydrogen peroxide as a terminal oxidant are reported in the literature.[14] Diols are usually proposed as reaction intermediates, which undergo Baeyer–Villiger oxidation to give cleavage products. By employing the same catalyst loading (1 mol %) and amount of hydrogen peroxide (4.4 equiv) as that of the Na_2WO_4-catalyzed alkene oxidations, **1**-catalyzed oxidation of cyclohexene gave similar results. When 1 mol cyclohexene was employed as substrate, the reaction took 12 h for completion, and adipic acid was obtained in 85 % yield. It was reported that the Na_2WO_4-catalyzed oxidation of cyclooctene and 1-octene by aqueous H_2O_2 gave the corresponding acids in 9 % and 36 % yield, respectively. For the similar **1**-catalyzed oxidation of cyclooctene and 1-octene, we obtained suberic acid and heptanoic acid in 93 % and 90 % yield, respectively. In previous work by Noyori and co-workers,[2] phenanthrene was oxidized to 2,2′-biphenyldicarboxylic acid in 41 % yield by the $Na_2WO_4+H_2O_2$ protocol. However, we did not observe any substrate conversion in the oxidation of phenanthrene, *p*-xylene, and toluene with the $\mathbf{1}+H_2O_2$ protocol. Recently, we reported that *cis*-$[(Me_3tacn)(CF_3CO_2)Ru^{VI}O_2]ClO_4$ underwent [3+2] cycloaddition with alkenes to give the corresponding Ru^{III} cycloadducts, further hydrolysis of which gave diol products with concomitant formation of $[(Me_3tacn)_2Ru^{III}_2(\mu\text{-}O)(\mu\text{-}CF_3CO_2)_2](ClO_4)_2$.[7a] Herein, when cyclooctene was employed as substrate (either at 60 °C or reflux), slow introduction of H_2O_2 into the reaction mixture containing cyclooctene and **1** in aqueous *tert*-butanol gave a yellow solution. This yellow solution displayed a distinct UV/Vis absorption peak at λ_{max} $(CH_2Cl_2) = 390$ nm. A single molecular cluster peak at $m/z = 529$ $[M]^+$, formulated as $[(Me_3tacn)(CF_3CO_2)\overline{Ru^{III}O(H)CH(CH_2)_6HCO}]^+$,[7a] was observed in the ESI-MS spectrum. Upon introduction of saturated aqueous $NaClO_4$ (2 mL) to the reaction mixture after complete substrate consumption, $[(Me_3tacn)_2Ru^{III}_2(\mu\text{-}O)(\mu\text{-}CF_3CO_2)_2](ClO_4)_2$ was obtained in 10 % yield. The residual yellow solution was analyzed with ESI-MS, which revealed a single prominent ion cluster peak at $m/z = 516$ that matches the formulation of **1**. A similar observation was noted for the **1**-catalyzed oxidation of cyclohexene (λ_{max} $(CH_2Cl_2) = 396$ nm, $m/z = 501$). If the oxidation was conducted at 60 °C, a mixture of *cis*- and *trans*-diol plus some allylic oxidation products (2-cyclohexen-1-ol and 2-cyclohexen-1-one) were obtained. We propose that the reaction between **1** and H_2O_2 gives one or more oxidizing intermediates, presumably via Ru=O species, which further undergoes cycloaddition with alkenes.

Based on these observations, we suggest that the **1**-catalyzed oxidation of alkenes by H_2O_2 proceeds through the formation of diols as intermediates. The **1**-catalyzed H_2O_2 oxidation of alkene to carboxylic acid is analogous to the tungstate-catalyzed oxidation of cyclohexene;[2] the latter was proposed to proceed through multiple steps, which include diols and α-hydroxy ketone intermediates, followed by a subsequent Baeyer–Villiger oxidation.[2]

The reaction of **1** with H_2O_2 in the absence of organic substrates was monitored by ESI-MS and UV/Vis spectral analysis. From an aqueous solution of *tert*-butanol (9 mL, tBuOH/$H_2O = 2{:}1$ v/v) containing **1** (0.01 mmol) and H_2O_2 (4.4 mmol) at reflux/60 °C, aliquots of the reaction mixture were taken for analysis. According to the ESI-MS analysis, molecular cluster peaks at $m/z = 516$ ($[(Me_3tacn)(CF_3CO_2)_2Ru^{III}(OH_2)]^+$) and $m/z = 899$ ($\{[(Me_3tacn)_2Ru^{III}_2(\mu\text{-}O)(\mu\text{-}CF_3CO_2)_2](CF_3CO_2)\}^+$) were detected. No ion cluster peak ($m/z = 417$) corresponding to $[(Me_3tacn)(CF_3CO_2)RuO_2]^+$ was observed. According to previous work,[7e] $[(Me_3tacn)(CF_3CO_2)Ru^{VI}O_2]^+$ shows a strong absorption peak at 320 nm; however, in the present case, only weak absorption peaks at 261 and 545 nm attributed to $[(Me_3tacn)_2Ru^{III}_2(\mu\text{-}O)(\mu\text{-}CF_3CO_2)_2]^{2+}$ were found in the UV/Vis spectrum of the reaction mixture. We determined the second-order rate constants for the reaction of $[(Me_3tacn)(CF_3CO_2)Ru^{VI}O_2]^+$ with cyclohexene and cyclooctene to be 233 and 872 $dm^3 mol^{-1} s^{-1}$, respectively. It is likely that any *cis*-$[(Me_3tacn)(CF_3CO_2)Ru^{VI}O_2]^+$ formed in the reaction mixture would rapidly react with C=C bonds, rendering its detection difficult.

In the absence of organic substrates at 60 °C/reflux with **1** (10 μmol), H_2O_2 (35 %, 4.4 mmol), and aqueous *tert*-butanol (9 mL, tBuOH/$H_2O = 2{:}1$ v/v), no oxygen gas was evolved over the 3-h process of adding H_2O_2. This is in contrast to the reported ruthenium trichloride that spontaneously decomposes H_2O_2 even at room temperature.[15] Notably, no oxygen was evolved in the reaction of catalytic/stoichiometric amounts of *cis*-$[(Me_3tacn)(CF_3CO_2)Ru^{VI}O_2]ClO_4$ with H_2O_2.

Conclusions

In summary, an environmentally friendly protocol has been developed for catalytic oxidation of alkenes, alkynes, and alcohols to give the corresponding carboxylic acids. In the literature, the reported ruthenium-catalyzed organic oxidations with hydrogen peroxide as a terminal oxidant require a ruthenium catalyst loading of up to 5 mol %[9] and up to 15 equivalents of hydrogen peroxide.[8b] Herein, only 1 mol % of catalyst **1** and a nearly stoichiometric amount of hydrogen peroxide (10 % excess) were used. Our preliminary results showed that under aerobic conditions, treatment of cycloheptene (5 mmol) with **1** (1 mol %) in aqueous *tert*-butanol (9 mL) for 14 h gave *cis*- and *trans*-1,2-cycloheptanediol in 31 % and 65 % yield, respectively, with 13 % alkene consumption. Our effort to develop an efficient protocol for ruthenium-catalyzed organic oxidations with air as a terminal oxidant is in progress.

Experimental Section

All solvents and substrates were purified by standard procedures, **1** was prepared according to the method in the literature,[11c] and characterization of organic products was referenced to authentic samples. Dropwise introduction of aqueous hydrogen peroxide was carried out with a syringe pump.

General Procedure

1 (1 mol %) was added to a mixture of *tert*-butanol (6 mL) and distilled water (3 mL) containing substrate (5 mmol). Aqueous H_2O_2 was then added to the reaction mixture at reflux over 3 h. For oxidation of aromatic substrates, H_2O_2 (17.5 %) was added dropwise over 12 h, and the reaction mixture was stirred for another 1 h. The reaction mixture was first cooled in an ice/salt bath, and all the unreacted H_2O_2 was removed by adding saturated aqueous sodium bisulfite (3 mL). After the internal standard (1,4-dichlorobenzene) was added, the products were extracted with diethyl ether (5×20 mL), and the combined extracts were dried over anhydrous $MgSO_4$ and filtered. The aliquots were taken for product identification and quantification with GC or NMR spectroscopic analysis.

For reactions on the 1-mol scale, **1** (0.01 mol) was added to a mixture of *tert*-butanol (1200 mL) and distilled water (600 mL) containing substrate (1 mol). Aqueous H_2O_2 (500 mL) was then added to the reaction mixture at reflux over 6 h, and the reaction mixture was stirred for another 6 h. The unreacted H_2O_2 was removed by adding saturated aqueous sodium bisulfite (100 mL). *tert*-Butanol was recycled by simple distillation at 83 °C, and water was further distilled off to give a viscous layer containing residual solvent and crude product. The product was extracted with diethyl ether (5×200 mL), and the combined extracts were dried over anhydrous $MgSO_4$ and filtered. The ethereal layer was evaporated to dryness by a rotary evaporator to give the corresponding carboxylic acid products (Scheme 1).

Acknowledgements

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[1] a) J. Brinksma, J. W. de Boer, R. Hage, B. L. Feringa in *Modern Oxidation Methods* (Ed.: J.-E. Bäckvall), Wiley-VCH, Weinheim, **2004**, p. 295; b) S.-I. Murahashi, N. Komiya in *Biomimetic Oxidations Catalyzed by Transition Metal Complexes* (Ed.: B. Meunier), Imperial College Press, London, **2000**, p. 563; c) T. V. Lee in *Comprehensive Organic Synthesis, Vol. 7* (Eds.: B. M. Trost, I. Fleming, S. V. Ley), Pergamon, Oxford, **1991**, p. 291.

[2] a) R. Noyori, M. Aoki, K. Sato, *Chem. Commun.* **2003**, 1977; b) K. Sato, M. Aoki, R. Noyori, *Science* **1998**, *281*, 1646; c) K. Sato, M. Aoki, M. Ogawa, T. Hashimoto, D. Panyella, R. Noyori, *Bull. Chem. Soc. Jpn.* **1997**, *70*, 905.

[3] a) S.-I. Murahashi, N. Komiya, Y. Oda, T. Kuwabara, T. Naota, *J. Org. Chem.* **2000**, *65*, 9186; b) K. Yamaguchi, K. Mori, T. Mizugaki, K. Ebitani, K. Kaneda, *J. Am. Chem. Soc.* **2000**, *122*, 7144; c) T. K. M. Shing, E. K. W. Tam, *Tetrahedron Lett.* **1999**, *40*, 2179; d) A. Dijksman, I. W. C. E. Arends, R. A. Sheldon, *Chem. Commun.* **1999**, 1591; e) A. Bleloch, B. F. G. Johnson, S. V. Ley, A. J. Price, D. S. Shephard, A. W. Thomas, *Chem. Commun.* **1999**, 1907; f) T. Naota, H. Takaya, S.-I. Murahashi, *Chem. Rev.* **1998**, *98*, 2599; g) T. K. M. Shing, E. K. W. Tam, V. W.-F. Tai, I. H. F. Chung, Q. Jiang, *Chem. Eur. J.* **1996**, *2*, 50; h) W. P. Griffith, S. V. Ley, G. P. Whitcomb, A. D. White, *J. Chem. Soc. Chem. Commun.* **1981**, 1625.

[4] For reviews, see: a) C.-M. Che, T.-C. Lau in Comprehensive Coordination Chemistry II: From Biology to Nanotechnology, *Vol. 5* (Eds.: J. A. McCleverty, T. J. Meyer), Elsevier Pergamon, Amsterdam, **2004**, p. 733; b) C.-M. Che, W.-Y. Yu, *Pure Appl. Chem.* **1999**, *71*, 281; c) S.-I. Murahashi, T. Naota in *Comprehensive Organometallic Chemistry II, Vol. 12* (Eds.: E. W. Abel, F. G. A. Stone, G. W. Wilkinson), Pergamon, Oxford, **1995**, p. 1177; d) W. P. Griffith, *Chem. Soc. Rev.* **1992**, *21*, 179.

[5] Selected examples for oxoruthenium(IV): a) J. R. Bryant, J. M. Mayer, *J. Am. Chem. Soc.* **2003**, *125*, 10351; b) E. L. Lebeau, R. A. Binstead, T. J. Meyer, *J. Am. Chem. Soc.* **2001**, *123*, 10535; c) W.-H. Fung, W.-Y. Yu, C.-M. Che, *J. Org. Chem.* **1998**, *63*, 7715; d) J. M. Mayer, *Acc. Chem. Res.* **1998**, *31*, 441; e) W.-C. Cheng, W.-Y. Yu, K.-K. Cheung, C.-M. Che, *J. Chem. Soc. Dalton Trans.* **1994**, 57.

[6] Selected examples for *trans*-dioxoruthenium(VI): a) E. Gallo, A. Caselli, F. Ragaini, S. Fantauzzi, N. Masciocchi, A. Sironi, S. Cenini, *Inorg. Chem.* **2005**, *44*, 2039; b) E. L. Lebeau, T. J. Meyer, *Inorg. Chem.* **1999**, *38*, 2174; c) C.-M. Che, W.-T. Tang, W.-T. Wong, T.-F. Lai, *J. Am. Chem. Soc.* **1989**, *111*, 9048; d) A. Dovletoglou, T. J. Meyer, *J. Am. Chem. Soc.* **1994**, *116*, 215; e) S. Perrier, J. K. Kochi, *Inorg. Chem.* **1988**, *27*, 4165; f) J. T. Groves, R. Quinn, *J. Am. Chem. Soc.* **1985**, *107*, 5790.

[7] Selected examples for *cis*-dioxoruthenium(VI): a) W.-P. Yip, W.-Y. Yu, N. Zhu, C.-M. Che, *J. Am. Chem. Soc.* **2005**, *127*, 14239; b) W.-H. Cheung, W.-P. Yip, W.-Y. Yu, C.-M. Che, *Can. J. Chem.* **2005**, *83*, 521; c) C.-M. Che, W.-Y. Yu, P.-M. Chan, W.-C. Cheng, S.-M. Peng, K.-C. Lau, W.-K. Li, *J. Am. Chem. Soc.* **2000**, *122*, 11380; d) W.-C. Cheng, W.-Y. Yu, C.-K. Li, C.-M. Che, *J. Org. Chem.* **1995**, *60*, 6840; e) W.-C. Cheng, W.-Y. Yu, K.-K. Cheung, C.-M. Che, *J. Chem. Soc. Chem. Commun.* **1994**, 1063; f) C.-K. Li, C.-M. Che, W.-F. Tong, W.-T. Tang, K.-Y. Wong, T.-F. Lai, *J. Chem. Soc. Dalton Trans.* **1992**, 2109; g) C. L. Bailey, R. S. Drago, *J. Chem. Soc. Chem. Commun.* **1987**, 179.

[8] a) S. Bhor, G. Anilkumar, M. K. Tse, M. Klawonn, C. Döbler, B. Bitterlich, A. Grotevendt, M. Beller, *Org. Lett.* **2005**, *7*, 3393; b) M. K. Tse, C. Döbler, S. Bhor, M. Klawonn, W. Mägerlein, H. Hugl, M. Beller, *Angew. Chem.* **2004**, *116*, 5367; *Angew. Chem. Int. Ed.* **2004**, *43*, 5255.

[9] V. Kogan, M. M. Quintal, R. Neumann, *Org. Lett.* **2005**, *7*, 5039.

[10] A. S. Goldstein, R. H. Beer, R. S. Drago, *J. Am. Chem. Soc.* **1994**, *116*, 2424.

[11] a) W.-H. Cheung, W.-Y. Yu, W.-P. Yip, N.-Y. Zhu, C.-M. Che, *J. Org. Chem.* **2002**, *67*, 7716; b) W.-H. Fung, W.-Y. Yu, C.-M. Che, *J. Org. Chem.* **1998**, *63*, 2873; c) W.-C. Cheng, W.-H. Fung, C.-M. Che, *J. Mol. Catal. A* **1996**, *113*, 311.

[12] D. Yang, F. Chen, Z.-M. Dong, D.-W. Zhang, *J. Org. Chem.* **2004**, *69*, 2221.

[13] C.-M. Ho, W.-Y. Yu, C.-M. Che, *Angew. Chem.* **2004**, *116*, 3365; *Angew. Chem. Int. Ed.* **2004**, *43*, 3303.

[14] a) E. Antonelli, R. D'Aloisio, M. Gambaro, T. Fiorani, C. Venturello, *J. Org. Chem.* **1998**, *63*, 7190; b) Y. Ishii, K. Yamawaki, T. Ura, H. Yamada, T. Yoshida, M. Ogawa, *J. Org. Chem.* **1988**, *53*, 3587.

[15] M. Klawonn, M. K. Tse, S. Bhor, C. Döbler, M. Beller, *J. Mol. Catal. A* **2004**, *218*, 13.

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