# Ruthenium-catalyzed redox isomerization/transfer hydrogenation in organic and aqueous media: A one-pot tandem process for the reduction of allylic alcohols

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The hexamethylbenzene-ruthenium(II) dimer [{RuCl(μ-Cl)(η$^6$-C$_6$Me$_6$)}$_2$] **1** and the mononuclear bis(allyl)-ruthenium(IV) complex [RuCl$_2$(η$^3$:η$^2$:η$^3$-C$_{12}$H$_{18}$)] **2**, associated with base and a hydrogen donor, were found to be active catalysts for the selective reduction of the C=C bond of allylic alcohols both in organic and aqueous media. The process, which proceeds in a one-pot manner, involves a sequence of two independent reactions: (*i*) the initial redox-isomerization of the allylic alcohol, and (*ii*) subsequent transfer hydrogenation of the resulting carbonyl compound. The highly efficient transformation reported herein represents, not only an illustrative example of auto-tandem catalysis, but also an appealing alternative to the classical transition-metal catalyzed C=C hydrogenations of allylic alcohols. The process has been successfully applied to aromatic as well as aliphatic substrates affording the corresponding saturated alcohols in 45–100% yields after 1.5–24 h. The best performances were reached using (*i*) 1–5 mol% of **1** or **2**, 2–10 mol% of $Cs_2CO_3$, and propan-2-ol or (*ii*) 1–5 mol% of **1** or **2**, 10–15 equivalents of $NaO_2CH$, and water. The catalytic efficiency is strongly related to the structure of the allylic alcohol employed. Thus, in propan-2-ol, the reaction rate essentially depends on the steric requirement around the C=C bond, therefore decreasing with the increasing number of substituents. On other hand, in water the transformation is favoured for primary allylic alcohols *vs.* secondary ones.

## Introduction

The development of new methodologies aimed at improving the efficiency in organic synthesis is an important goal of contemporary chemistry. In particular, the replacement of multistep transformations by more straightforward “one-pot” processes has attracted considerable research efforts due to the obvious advantages of the latter, *i.e.* they minimize the overall reaction time, the generation of chemical waste and the energy consumption, therefore limiting the global cost of the synthetic pathway.[1] In this context, metal-catalyzed tandem reactions have attracted an increasing interest during the last decade.[2,3] These processes, which provide operationally simple synthetic procedures, are based on the ability of a unique organometallic precursor to promote two or more successive transformations in the same reaction medium.

It is well-established that transition-metal hydrides are the active catalytic species in transfer hydrogenation (TH) reactions,[4] being able to efficiently reduce carbonyl compounds into the corresponding alcohols. The best results, in terms of activity and selectivity, have been reported for catalytic systems based on ruthenium, rhodium and iridium complexes,[4,5] where the hydride-metal entity can be both preformed prior to the catalytic event or generated *in situ*. TH reactions are usually performed in propan-2-ol which acts both as solvent and the hydrogen source, acetone being formed along with the desired alcohol.

On the other hand, it has also been demonstrated that transition-metal hydrides are able to promote the redox-isomerization of allylic alcohols into the corresponding saturated ketones or aldehydes.[6] For this particular process, the highest activities are, in general, reached using iron-, ruthenium- and rhodium-based precursors.[6,7]

With these precedents in mind, it is reasonable to assume that a hydride-metal species associated with an appropriate hydrogen source, such as propan-2-ol, could be able to reduce the C=C bond of allylic alcohols through a two-step tandem process involving: (*i*) the initial redox-isomerization of the substrate, and (*ii*) the subsequent TH of the resulting carbonyl intermediate (Scheme 1). The overall transformation represents an appealing alternative to the classical transition-metal catalyzed C=C hydrogenations (Ru, Rh and Ir catalysts)[8] since it avoids the use of hydrogen gas, a hazardous and flammable reactant.

During the last years, the increasing awareness of environmental concerns has stimulated the development of metal-catalyzed reactions in aqueous media, since water represents the most benign and inexpensive solvent known.[9] In this context, it has been largely demonstrated that the two individual processes considered in Scheme 1, *i.e.* the redox-isomerization and the TH

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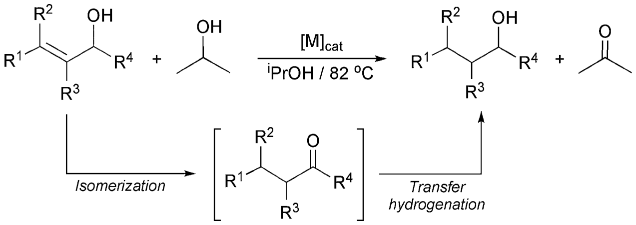
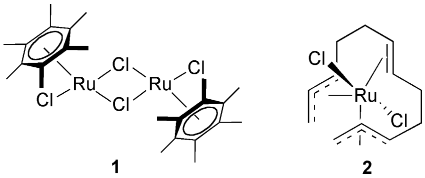


**Scheme 1** Reduction of allylic alcohols through an isomerization/TH tandem process using propan-2-ol as solvent and hydrogen donor.

steps, can be efficiently performed under aqueous conditions.[10,11] So, potentially, the planned tandem reduction of allylic alcohols could also be operative in water.

In this article, full details of our search for efficient catalysts for this tandem process are presented.[12,13] In particular, among the different metal precursors checked, excellent results in terms of activity, selectivity and scope have been reached with the dinuclear hexamethylbenzene-Ru(II) complex [{RuCl(μ-Cl)($\eta^6$-$C_6Me_6$)}$_2$] **1** and the mononuclear bis(allyl)-Ru(IV) derivative [$RuCl_2$($\eta^3$:$\eta^2$:$\eta^3$-$C_{12}H_{18}$)] **2** (see Fig. 1).



**1** **2**

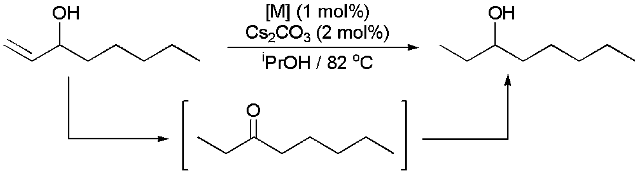
**Fig. 1** Structure of the ruthenium catalysts **1** and **2**.

## Results and discussion

### Reduction of allylic alcohols in organic medium: Catalyst screening and scope

Firstly, using the reduction of 1-octen-3-ol into octan-3-ol as a model reaction, the efficiency and selectivity of several commercially available or readily accessible metallic precursors was checked. Experiments were performed at 82 °C employing 2 mmol of substrate, 1 mol% of metal, 2 mol% of $Cs_2CO_3$[14] and propan-2-ol (0.1 M solutions of the allylic alcohol) as solvent and hydrogen source (see Table 1). Under these conditions, all of the precursors tested, with the exception of [$NH_4$]$_2$[$IrCl_6$] (entry 19), [Pd($PPh_3$)$_4$] (entry 21), $PdCl_2$ (entry 23), Pd(OAc)$_2$ (entry 24), [$PdCl_2$(cod)] (entry 25) and [$PdCl_2$($PPh_3$)$_2$] (entry 26), led to the almost total consumption of the substrate after 9 h of heating (≥96% conversion; GC determined). However, the selectivity of the process was found to be strongly dependent on the nature of the catalyst employed. Thus, only the arene-Ru(II) dimers [{RuCl(μ-Cl)($\eta^6$-arene)}$_2$] (arene = $C_6Me_6$, mesitylene, *p*-cymene, $C_6H_6$; entries 1–4), the mononuclear Ru(II) complex [$RuCl_2$($PPh_3$)$_3$] (entry 5), and the bis(allyl)-Ru(IV) derivatives [$RuCl_2$($\eta^3$:$\eta^2$:$\eta^3$-$C_{12}H_{18}$)] and [{RuCl(μ-Cl)($\eta^3$:$\eta^3$-$C_{10}H_{16}$)}$_2$] (entries 13–14), afforded the desired reduced alcohol as the major product (≥75% GC yield). In contrast, the rest of ruthenium precatalysts, as well as the rhodium, iridium, palladium and platinum ones, gave rise preferentially to the intermediate carbonyl compound octan-3-one, the formation of only small quantities of octan-3-ol being in these cases detected by GC (≤ 35%).

**Table 1** Metal catalyzed reduction of 1-octen-3-ol in propan-2-ol and in the presence of $Cs_2CO_3$.[a]



| Entry | Catalyst precursor | Time | Conv. | Yield[b] |
|---|---|---|---|---|
| 1 | [{RuCl(μ-Cl)($\eta^6$-$C_6Me_6$)}$_2$] **1** | 3.5 h | > 99% | 99% |
| 2 | [{RuCl(μ-Cl)($\eta^6$-mesitylene)}$_2$] | 6 h | > 99% | 95% |
| 3 | [{RuCl(μ-Cl)($\eta^6$-*p*-cymene)}$_2$] | 9 h | > 99% | 91% |
| 4 | [{RuCl(μ-Cl)($\eta^6$-$C_6H_6$)}$_2$] | 9 h | > 99% | 75% |
| 5 | [$RuCl_2$($PPh_3$)$_3$] | 9 h | > 99% | 92% |
| 6[c] | [Ru($\eta^3$-2-$C_3H_4$Me)$_2$(cod)] | 9 h | > 99% | 35% |
| 7[c] | [{$RuCl_2$(cod)}$_n$] | 9 h | > 99% | 26% |
| 8 | [$RuCl_2$(DMSO)$_4$] | 9 h | > 99% | 16% |
| 9 | [RuCl($\eta^5$-$C_5H_5$)($PPh_3$)$_2$] | 9 h | > 99% | 1% |
| 10 | [RuCl($\eta^5$-$C_9H_7$)($PPh_3$)$_2$] | 9 h | > 99% | 4% |
| 11 | $RuCl_3 \cdot nH_2O$ | 9 h | > 99% | 3% |
| 12 | [$Ru_3$(CO)$_{12}$] | 9 h | 98% | 2% |
| 13[d] | [$RuCl_2$($\eta^3$:$\eta^2$:$\eta^3$-$C_{12}H_{18}$)] **2** | 9 h | > 99% | 94% |
| 14[e] | [{RuCl(μ-Cl)($\eta^3$:$\eta^3$-$C_{10}H_{16}$)}$_2$] | 9 h | > 99% | 86% |
| 15 | $RhCl_3 \cdot nH_2O$ | 9 h | > 99% | 8% |
| 16[c] | [{Rh(μ-Cl)(cod)}$_2$] | 9 h | > 99% | 21% |
| 17[f] | [{Rh(μ-Cl)(nbd)}$_2$] | 9 h | > 99% | 20% |
| 18[g] | [{Rh(μ-Cl)(coe)$_2$}$_2$] | 9 h | > 99% | 18% |
| 19 | [$NH_4$]$_2$[$IrCl_6$] | 9 h | 0% | 0% |
| 20[c] | [{Ir(μ-Cl)(cod)}$_2$] | 9 h | > 99% | 15% |
| 21 | [Pd($PPh_3$)$_4$] | 9 h | 0% | 0% |
| 22[h] | [$Pd_2$(dba)$_3$] | 9 h | 96% | 6% |
| 23 | $PdCl_2$ | 9 h | 36% | 4% |
| 24 | Pd(OAc)$_2$ | 9 h | 29% | 2% |
| 25[c] | [$PdCl_2$(cod)] | 9 h | 64% | 7% |
| 26 | [$PdCl_2$($PPh_3$)$_2$] | 9 h | 1% | 0% |
| 27 | $PtCl_2$ | 9 h | > 99% | 10% |

[a] Reactions performed under $N_2$ atmosphere at 82 °C using 2 mmol of 1-octen-3-ol (0.1 M in propan-2-ol). [Substrate] : [M] : [$Cs_2CO_3$] ratio = 100 : 1 : 2. [b] Yield of octan-3-ol determined by GC. The differences between conversion and octan-3-ol yield correspond to the intermediate octan-3-one present in the reaction media. [c] cod = 1,5-cyclooctadiene. [d] $C_{12}H_{18}$ = dodeca-2,6,10-triene-1,12-diyl. [e] $C_{10}H_{16}$ = 2,7-dimethylocta-2,6-diene-1,8-diyl. [f] nbd = norbornadiene. [g] coe = cyclooctene. [h] dba = dibenzylideneacetone.

From this general catalyst screening, ruthenium clearly emerged as the metal of choice, with the hexamethylbenzene-Ru(II) dimer [{RuCl(μ-Cl)($\eta^6$-$C_6Me_6$)}$_2$] **1** leading to the best results in terms of both activity and selectivity (99% GC yield of octan-3-ol after only 3.5 h; entry 1).[15] Although related [{RuCl(μ-Cl)($\eta^6$-arene)}$_2$] dimers were also active in the tandem reduction process, their efficiency and selectivity were lower, decreasing with the donor capacity of the arene ligand, *i.e.* in the order $C_6Me_6$ > mesitylene, *p*-cymene > $C_6H_6$ (entries 1–4).

As far as Ru(IV) is concerned, the mononuclear derivative [$RuCl_2$($\eta^3$:$\eta^2$:$\eta^3$-$C_{12}H_{18}$)] **2** was found to be more active (94% GC yield after 9 h, entry 13) than the dimeric one [{RuCl(μ-Cl)($\eta^3$:$\eta^3$-$C_{10}H_{16}$)}$_2$] (86% GC yield after 9 h, entry 14). Remarkably, although these ruthenium(IV) complexes are among the most active catalysts presently known for the redox-isomerization of allylic alcohols,[10f–h,16] they were less efficient than [{RuCl(μ-Cl)(η$^6$-C$_6$Me$_6$)}$_2$] **1** in the reduction of 1-octen-3-ol (entries 13–14 *vs.* entry 1). This fact clearly indicates that the TH of the intermediate carbonyl compound is the rate limiting step of the tandem reduction process. In accord with this, monitoring the reduction of 1-octen-3-ol catalyzed by [{RuCl(μ-Cl)(η$^6$-C$_6$Me$_6$)}$_2$] **1** by GC (see Fig. 2) showed that the initial isomerization step readily takes place (*ca.* 15 min). In contrast, the evolution of the intermediate octan-3-one into the final saturated alcohol is very slow (3.5 h are required to obtain a quantitative yield of the desired octan-3-ol). A similar tendency was also observed with the rest of the ruthenium catalysts employed.[17]

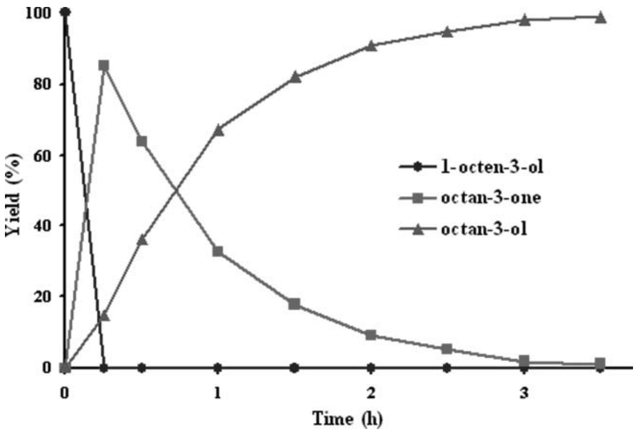
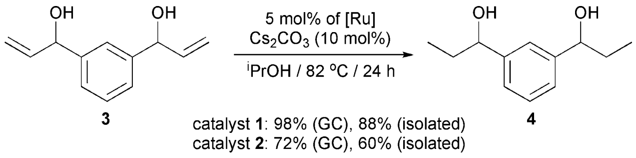


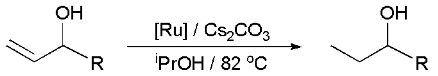
**Fig. 2** Product distribution as a function of time for the reduction of 1-octen-3-ol catalyzed by complex **1** (1 mol% of Ru).

In order to investigate the scope of this new catalytic transformation, the reduction of a broad array of allylic alcohols was studied using the most active Ru(II) and Ru(IV) catalysts, *i.e.* [{RuCl(μ-Cl)(η$^6$-C$_6$Me$_6$)}$_2$] **1** and [RuCl$_2$(η$^3$:η$^2$:η$^3$-C$_{12}$H$_{18}$)] **2**. The results obtained are collected in Tables 2–3 and Scheme 2.



**Scheme 2** Reduction of **3** catalyzed by complexes **1** and **2** in organic medium.

**Table 2** Reduction of monosubstituted allylic alcohols catalyzed by complexes [{RuCl(μ-Cl)(η$^6$-C$_6$Me$_6$)}$_2$] **1** and [RuCl$_2$(η$^3$:η$^2$:η$^3$-C$_{12}$H$_{18}$)] **2** in propan-2-ol and in the presence of Cs$_2$CO$_3$.[a]



| Entry | *R* | Cat. | % Ru | Time | Conv. | Yield[b] |
|---|---|---|---|---|---|---|
| 1 | H | **1** | 1 mol% | 5.5 h | >99% | 99% |
| 2 | | **2** | 1 mol% | 8 h | >99% | 98% |
| 3 | Me | **1** | 1 mol% | 5.5 h | >99% | 98% |
| 4 | | **2** | 1 mol% | 5.5 h | >99% | 99% |
| 5 | Et | **1** | 1 mol% | 3 h | >99% | 97% |
| 6 | | **2** | 1 mol% | 8.5 h | >99% | 93% |
| 7 | $^n$Pr | **1** | 1 mol% | 3.5 h | >99% | 99% |
| 8 | | **2** | 1 mol% | 8.5 h | >99% | 93% |
| 9 | $^n$Bu | **1** | 1 mol% | 3 h | >99% | 97% |
| 10 | | **2** | 1 mol% | 9 h | >99% | 91% |
| 11 | Bn | **1** | 1 mol% | 22 h | >99% | 98% |
| 12 | | **2** | 1 mol% | 24 h | >99% | 98% |
| 13 | Ph | **1** | 1 mol% | 10 h | >99% | 97% |
| 14 | | **2** | 1 mol% | 23 h | >99% | 99% |
| 15[c] | 4-C$_6$H$_4$OMe | **1** | 1 mol% | 22 h | >99% | 90% |
| 16 | | **2** | 1 mol% | 24 h | >99% | 83% |
| 17 | 3-C$_6$H$_4$OMe | **1** | 2 mol% | 15 h | >99% | 99% |
| 18 | | **2** | 2 mol% | 6 h | >99% | 99% |
| 19 | 4-C$_6$H$_4$F | **1** | 2 mol% | 24 h | >99% | 99% |
| 20 | | **2** | 2 mol% | 8.5 h | >99% | 98% |
| 21 | 4-C$_6$H$_4$Cl | **1** | 2 mol% | 24 h | >99% | 99% |
| 22 | | **2** | 5 mol% | 4 h | >99% | 99% |
| 23 | 2-Furanyl | **1** | 5 mol% | 5 h | >99% | 98% |
| 24 | | **2** | 5 mol% | 3.5 h | >99% | 99% |

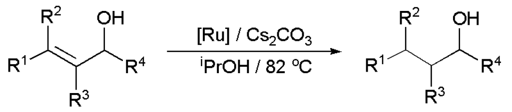
[a] Reactions performed under N$_2$ atmosphere at 82 °C using 2 mmol of the corresponding allylic alcohol (0.1 M in propan-2-ol). [Ru] : [Cs$_2$CO$_3$] ratio = 1 : 2. [b] Yield of the saturated alcohol determined by GC. The differences between conversion and yield correspond to the intermediate carbonyl compound present in the reaction media. [c] *ca.* 8% of 1-methoxy-4-propylbenzene is also formed.

Although all the substrates tested could be conveniently transformed into the corresponding saturated alcohols (GC yields ≥ 83%), the catalytic performances of compounds **1** and **2** were found to be strongly dependent on the substitution degree of the carbon–carbon double bond of the allylic alcohol employed. Thus, as a general trend, the efficiency of the isomerization/TH tandem process decreased with the increase of the number of substituents on the C=C unit, a tendency commonly observed in catalytic redox-isomerization reactions.[6]

Concerning the monosubstituted allylic alcohols (Table 2), as observed for 1-octen-3-ol, they were readily reduced in almost quantitative yields using low ruthenium loadings (1–2 mol% of Ru; entries 1–21 in Table 2). Only the reduction of 1-(furan-2-yl)-2-propen-1-ol required a higher catalyst loading (5 mol% of Ru; entries 23–24 in Table 2). The lower reactivity of this substrate is probably associated to the competitive coordination of the furyl and olefin units onto the active ruthenium species. Remarkably, catalysts **1** and **2** were also able to promote the double reduction of the bis(allylic alcohol) **3**, affording 1,3-bis(1-hydroxypropyl)benzene **4** in more than 72% GC-yield (Scheme 2). Solvent removal and chromatographic work-up on silica-gel allowed the isolation of pure samples of **4** (88% and 60% yield) whose identity was confirmed by NMR spectroscopy and MS fragmentation.[18]

Although disubstituted and trisubstituted allylic alcohols could also be reduced efficiently by the action of complexes **1** and **2**, in these cases longer reaction times and higher Ru loadings (3–5 mol%) were required to generate the corresponding saturated alcohols in good yields (see Table 3). In fact, only the reduction of *trans*-3-penten-2-ol (entries 7–8) and 2-methyl-2-propen-1-ol (entries 17–18), both containing the less sterically demanding methyl group as substituent on the C=C bond, could be conveniently performed using a ruthenium loading of 1 mol%. The lower reactivity of these di- and tri-substituted substrates stems from a drastic rate decrease in the initial isomerization step due to the sterically disfavoured coordination of the C=C bond to ruthenium.[19] This situation is exemplified in Fig. 3 which shows the reaction course (GC-monitoring) for the reduction of 2-cyclohexen-1-ol into cyclohexanol promoted by complex [RuCl$_2$(η$^3$:η$^2$:η$^3$-C$_{12}$H$_{18}$)] **2** (5 mol%). In this case, the

**Table 3** Reduction of allylic alcohols containing substituted C=C bonds catalyzed by complexes $[\{RuCl(\mu\text{-}Cl)(\eta^6\text{-}C_6Me_6)\}_2]$ **1** and $[RuCl_2(\eta^3{:}\eta^2{:}\eta^3\text{-}C_{12}H_{18})]$ **2** in propan-2-ol and in the presence of $Cs_2CO_3$.[a]



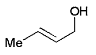
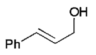
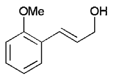
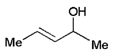
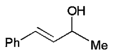
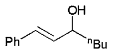
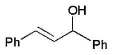
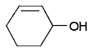
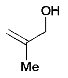
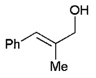
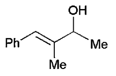
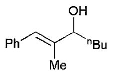
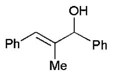
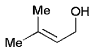
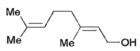
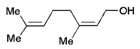
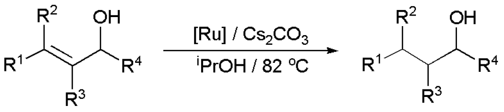
| Entry | Substrate | Cat. | % Ru | Time | Conv. | Yield$^b$ |
|---|---|---|---|---|---|---|
| 1 |  | **1** | 5 mol% | 3.5 h | >99% | 99% |
| 2 |  | **2** | 5 mol% | 4 h | >99% | 97% |
| 3 | | **1** | 5 mol% | 3 h | >99% | 99% |
| 4 |  | **2** | 5 mol% | 2.5 h | >99% | 99% |
| 5 | | **1** | 5 mol% | 5 h | >99% | 79% |
| 6 |  | **2** | 5 mol% | 5 h | >99% | 83% |
| 7 | | **1** | 1 mol% | 9 h | >99% | 97% |
| 8 |  | **2** | 1 mol% | 7 h | >99% | 97% |
| 9 | | **1** | 3 mol% | 7.5 h | >99% | 97% |
| 10 |  | **2** | 3 mol% | 24 h | >99% | 90% |
| 11 | | **1** | 5 mol% | 9 h | >99% | 90% |
| 12 |  | **2** | 5 mol% | 9 h | >99% | 98% |
| 13 | | **1** | 5 mol% | 22 h | >99% | 91% |
| 14 |  | **2** | 5 mol% | 4 h | >99% | 96% |
| 15 | | **1** | 3 mol% | 24 h | >99% | 99% |
| 16 |  | **2** | 3 mol% | 24 h | 94% | 90% |
| 17 | | **1** | 1 mol% | 9 h | >99% | 92% |
| 18 |  | **2** | 1 mol% | 9 h | >99% | 98% |
| 19 | | **1** | 5 mol% | 9 h | >99% | 98% |
| 20 |  | **2** | 5 mol% | 1.5 h | >99% | 99% |
| 21 | | **1** | 5 mol% | 6 h | >99% | 96% |
| 22 |  | **2** | 5 mol% | 4.5 h | >99% | 99% |
| 23 | | **1** | 5 mol% | 9.5 h | >99% | 93% |
| 24 |  | **2** | 5 mol% | 7 h | >99% | 94% |
| 25 | | **1** | 5 mol% | 9 h | >99% | 93% |
| 26 |  | **2** | 5 mol% | 7 h | >99% | 96% |
| 27 | | **1** | 5 mol% | 5 h | >99% | 90% |
| 28 | | **2** | 5 mol% | 22 h | >99% | 91% |
| 29 |  | **1** | 5 mol% | 24 h | >99% | 97% |
| 30 |  | **2** | 5 mol% | 24 h | >99% | 98% |
| 31 | | **1** | 5 mol% | 24 h | >99% | 90% |
| 32 | | **2** | 5 mol% | 23 h | 96% | 95% |

**Table 3** (*Contd.*)



[a] Reactions performed under $N_2$ atmosphere at 82 °C using 2 mmol of the corresponding allylic alcohol (0.1 M in propan-2-ol). [Ru] : $[Cs_2CO_3]$ ratio = 1 : 2. [b] Yield of the saturated alcohol determined by GC. The differences between conversion and yield correspond to the intermediate carbonyl compound present in the reaction media.

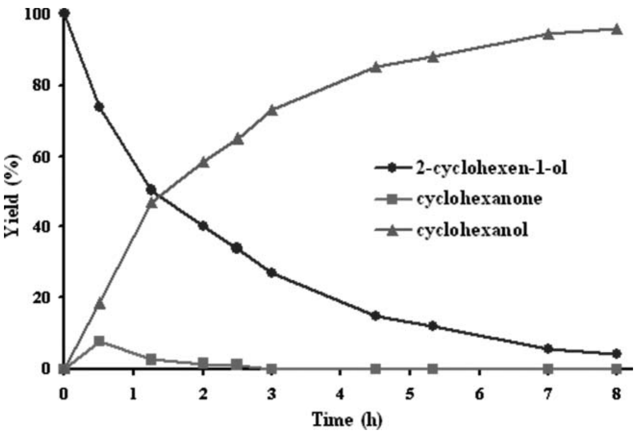


**Fig. 3** Product distribution as a function of time for the reduction of 2-cyclohexen-1-ol catalyzed by complex **2** (5 mol% of Ru).

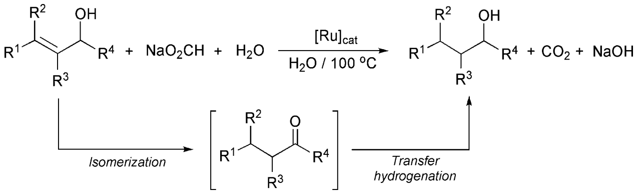
transfer hydrogenation step is clearly faster than the initial redox isomerization of the substrate, the proportion of the carbonyl intermediate, *i.e.* cyclohexanone, present in the reaction medium never exceeding 10%.

The chemoselectivity shown by both complexes in the reduction of geraniol (entries 29–30, Table 3) and nerol (entries 31–32) merits to be highlighted. Thus, although these compounds present two carbon–carbon double bonds, only the reduction of the C=C in the α-position with respect to the alcohol group takes place, affording citronellol selectively. These results compete favourably with the poor selectivity usually observed in classical metal-catalyzed hydrogenations of this type of terpenoid, which in most cases give rise to reaction mixtures containing the unsaturated- and saturated-alcohol as well as cyclization products.[20]

It is also interesting to note that, in contrast to the tendency observed with monosubstituted allylic alcohols (Table 2), the mononuclear bis(allyl)-Ru(IV) complex $[RuCl_2(\eta^3{:}\eta^2{:}\eta^3\text{-}C_{12}H_{18})]$ **2** was found to be more efficient than the Ru(II) dimer $[\{RuCl(\mu\text{-}Cl)(\eta^6\text{-}C_6Me_6)\}_2]$ **1** for the reduction of di- and trisubstituted substrates (Table 3). In fact, only in a limited number of examples, such as *trans*-2-buten-1-ol (entries 1 *vs.* 2), *trans*-3-phenyl-2-propen-1-ol (entries 9 *vs.* 10), 2-cyclohexen-1-ol (entries 15 *vs.* 16), and 3-methyl-2-buten-1-ol (entries 27 *vs.* 28), the catalytic performance of complex **1** surpassed that of **2**. So, it can be concluded that when the TH is the rate-determining step of the tandem process, *i.e.* for the reduction of monosubstituted allylic alcohols, complex [{RuCl(μ-Cl)(η$^6$-$C_6Me_6$)}$_2$] **1** is more efficient than [$RuCl_2$(η$^3$:η$^2$:η$^3$-$C_{12}H_{18}$)] **2**, otherwise the efficiency of both catalysts is inverted.

### Catalytic reduction of allylic alcohols using water as solvent

The high stability of complexes [{RuCl(μ-Cl)(η$^6$-$C_6Me_6$)}$_2$] **1**[21] and [$RuCl_2$(η$^3$:η$^2$:η$^3$-$C_{12}H_{18}$)] **2**[10f,h] in water prompted us to explore the isomerization/TH tandem process in an aqueous medium (Scheme 3). The replacement of propan-2-ol by water makes necessary the introduction of an additive that could act as a hydrogen source. In this sense, the most popular reagent used in metal-catalyzed transfer hydrogenation processes to carbonyl compounds performed in water is sodium formate, which reacts with the metal precursor in this media to form the active hydride species and carbon dioxide.[11] As a consequence of the drastic experimental changes associated with the use of this reagent, a preliminary study to determine the optimal reaction conditions in aqueous media was necessary. To this end, the reduction of *trans*-3-phenyl-2-propen-1-ol (5 mmol) catalyzed by complex [{RuCl(μ-Cl)(η$^6$-$C_6Me_6$)}$_2$] (**1**; 1 mol% of Ru) in presence of sodium formate, in water at 100 °C, was chosen as the model reaction.

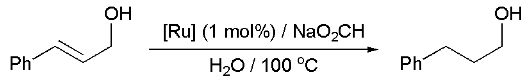


**Scheme 3** Reduction of allylic alcohols through an isomerization/TH tandem process in aqueous media.

Firstly, we screened the optimal $NaO_2CH$/substrate ratio performing experiments with 1 : 1 to 25 : 1 molar relations, maintaining constant the concentration of *trans*-3-phenyl-2-propen-1-ol (1 M solution in water). Thus, as shown in Table 4, when only one equivalent of sodium formate per allylic alcohol was used, complete reduction of the allylic alcohol could not be reached even after 20 h of heating (entry 1). However, the progressive increase of the $NaCO_2H$/substrate ratio up to 15 : 1 improved notably both the reaction rate and the yield. In particular, the use of a 15-fold excess of $NaCO_2H$ led to the quantitative formation of the desired 3-phenyl-propan-1-ol after only 7 h (entry 4, Table 4).[22] In contrast, no further enhancement of the catalytic activity of complex **1** could be achieved by using supplementary amounts of sodium formate (entries 5–6). This phenomena is not surprising, since previous studies have evidenced that the formation of the active hydride-species is strongly pH-dependent, being disfavoured at very high or very low pH values.[11e]

The influence exerted by the substrate concentration on the rate of the reduction process was also investigated. Thus, keeping the $NaO_2CH$/*trans*-3-phenyl-2-propen-1-ol molar ratio constant (15 : 1), we checked different concentrations of *trans*-3-phenyl-2-propen-1-ol in water, ranging between 0.25 and 1 M. As shown in Table 5, the best results were achieved using a 0.5 M solution. Thus, under these new conditions, quantitative conversion of *trans*-3-phenyl-2-propen-1-ol into 3-phenyl-propan-1-ol could be reached after only 5.5 h of heating (entry 3). Remarkably, this result using water as solvent competes favourably with that previously observed in organic medium (propan-2-ol) since a lower catalyst loading is required (entry 3 in Table 5 *vs.* entry 3 in Table 3).

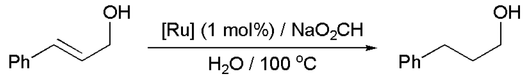
**Table 4** Influence of the $NaO_2CH$/substrate ratio in the reduction of *trans*-3-phenyl-2-propen-1-ol catalyzed by complex [{RuCl(μ-Cl)(η$^6$-$C_6Me_6$)}$_2$] **1** in water.[a]



| Entry | [Substrate] | $NaO_2CH$/substrate ratio | Time | Yield[b] |
|---|---|---|---|---|
| 1 | 1 M | 1 : 1 | 20 h | 70% |
| 2 | 1 M | 5 : 1 | 20 h | 99% |
| 3 | 1 M | 10 : 1 | 20 h | 98% |
| 4 | 1 M | 15 : 1 | 7 h | 99% |
| 5 | 1 M | 20 : 1 | 20 h | 63% |
| 6 | 1 M | 25 : 1 | 20 h | 60% |

[a] Reactions performed under $N_2$ atmosphere at 100 °C using 5 mmol of *trans*-3-phenyl-2-propen-1-ol (1 M in water). [Substrate] : [Ru] ratio = 100 : 1. [b] Yield of 3-phenyl-propan-1-ol determined by GC.

**Table 5** Influence of the substrate molar concentration in the reduction of *trans*-3-phenyl-2-propen-1-ol catalyzed by complex [{RuCl(μ-Cl)(η$^6$-$C_6Me_6$)}$_2$] **1** in water.[a]



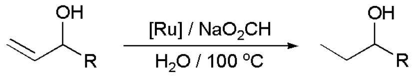
| Entry | [substrate] | $NaO_2CH$/substrate ratio | Time | Yield[b] |
|---|---|---|---|---|
| 1 | 0.25 M | 15 : 1 | 23 h | 99% |
| 2 | 0.33 M | 15 : 1 | 6 h | 98% |
| 3 | 0.5 M | 15 : 1 | 5.5 h | 99% |
| 4 | 1 M | 15 : 1 | 7 h | 99% |

[a] Reactions performed under $N_2$ atmosphere at 100 °C using 5 mmol of *trans*-3-phenyl-2-propen-1-ol. [Substrate] : [Ru] : [$NaO_2CH$] ratio = 100 : 1 : 1500. [b] Yield of 3-phenyl-propan-1-ol determined by GC.

In accord with all these observations, a substrate/Ru/$NaO_2CH$ ratio of 100 : 1 : 1500 and a molar concentration of 0.5 M of the substrate in water were considered as the optimal reaction conditions for the rest of our catalytic studies using [{RuCl(μ-Cl)(η$^6$-$C_6Me_6$)}$_2$] **1** as catalyst. We note that a similar optimization process was also carried out using the mononuclear Ru(IV) complex [$RuCl_2$(η$^3$:η$^2$:η$^3$-$C_{12}H_{18}$)] **1**, the optimal experimental conditions found in this case being only slightly different (a substrate/Ru/$NaO_2CH$ ratio of 100 : 1 : 1000 and a concentration 1.0 M of the substrate in water).

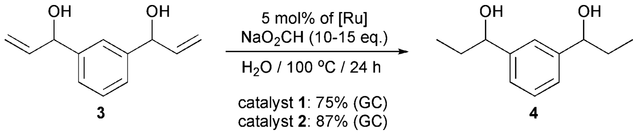
Using these optimal reaction conditions, the generality of this aqueous transformation was then explored. Results obtained for a family of monosubstituted allylic alcohols are collected in Table 6 and Scheme 4, while those involving allylic alcohols containing di- and trisubstituted C=C bonds are shown in Table 7. Surprisingly, in contrast with that observed using

**Table 6** Reduction of monosubstituted allylic alcohols catalyzed by complexes [{RuCl(μ-Cl)(η$^6$-$C_6Me_6$)}$_2$] **1** and [$RuCl_2$(η$^3$:η$^2$:η$^3$-$C_{12}H_{18}$)] **2** using water as solvent and $NaO_2CH$ as hydrogen source.



| Entry | R | Cat. | % Ru | Time | Conv. | Yield[c] |
|---|---|---|---|---|---|---|
| 1[a] | H | **1** | 1 mol% | 6 h | >99% | 99% |
| 2[b] | | **2** | 1 mol% | 2 h | >99% | 99% |
| 3[a] | Me | **1** | 1 mol% | 9 h | 98% | 61% |
| 4[b] | | **2** | 1 mol% | 24 h | >99% | 93% |
| 5[a] | Et | **1** | 5 mol% | 24 h | >99% | 86% |
| 6[b] | | **2** | 5 mol% | 24 h | >99% | 98% |
| 7[a] | $^n$Pr | **1** | 5 mol% | 24 h | >99% | 46% |
| 8[b] | | **2** | 5 mol% | 24 h | >99% | 45% |
| 9[a] | $^n$Bu | **1** | 5 mol% | 24 h | >99% | 41% |
| 10[b] | | **2** | 5 mol% | 24 h | >99% | 61% |
| 11[a] | $^n$Pent | **1** | 5 mol% | 24 h | >99% | 23% |
| 12[b] | | **2** | 5 mol% | 24 h | >99% | 67% |
| 13[a] | Bn | **1** | 5 mol% | 24 h | >99% | 98% |
| 14[b] | | **2** | 5 mol% | 20 h | >99% | 82% |
| 15[a] | Ph | **1** | 5 mol% | 24 h | >99% | 79% |
| 16[b] | | **2** | 5 mol% | 24 h | >99% | 82% |
| 17[a] | 4-$C_6H_4$OMe | **1** | 5 mol% | 24 h | >99% | 55% |
| 18[b] | | **2** | 5 mol% | 24 h | 68% | 65% |
| 19[a] | 3-$C_6H_4$OMe | **1** | 5 mol% | 24 h | >99% | 75% |
| 20[b] | | **2** | 5 mol% | 20 h | >99% | 80% |
| 21[a] | 4-$C_6H_4$F | **1** | 5 mol% | 24 h | >99% | 82% |
| 22[b] | | **2** | 5 mol% | 24 h | >99% | 65% |
| 23[a] | 4-$C_6H_4$Cl | **1** | 5 mol% | 24 h | >99% | 87% |
| 24[b] | | **2** | 5 mol% | 19 h | >99% | 92% |
| 25[a] | 2-Furanyl | **1** | 5 mol% | 24 h | >99% | 99% |
| 26[b] | | **2** | 5 mol% | 6 h | >99% | 94% |

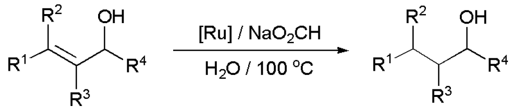
[a] Reactions performed in a sealed tube under $N_2$ atmosphere at 100 °C using 5 mmol of the corresponding allylic alcohol (0.5 M in $H_2O$). [substrate] : [Ru] : [$NaO_2CH$] ratio = 100 : 1 : 1500. [b] Reactions performed in a sealed tube under $N_2$ atmosphere at 100 °C using 5 mmol of the corresponding allylic alcohol (1.0 M in $H_2O$). [substrate] : [Ru] : [$NaO_2CH$] ratio = 100 : 1 : 1000. [c] Yield of the saturated alcohol determined by GC. The differences between conversion and yield correspond to the intermediate carbonyl compound present in the reaction media.



**Scheme 4** Reduction of **3** catalyzed by complexes **1** and **2** in water.

propan-2-ol as solvent, the rate of the global process does not seem to be governed by the substitution degree of the carbon–carbon double bond. Thus, for example, the reduction of a monosubstituted substrate, such as 1-propen-3-ol, required 24 h to generate pentan-3-ol in 86–98% yield (entries 5–6, Table 6), while 2-methyl-3-phenyl-prop-2-en-1-ol, a trisubstituted allylic alcohol, was quantitatively converted into 2-methyl-3-phenyl-propan-1-ol in only 5 h (entries 19–20, Table 7) using the same ruthenium loadings (5 mol%). Apparently, the overall reaction is favoured when the carbonyl intermediate is an aldehyde, *i.e.* those reactions involving primary alcohols.[23] In these cases, the reduction process could be efficiently performed with a low catalyst loading (1 mol% of Ru; entries 1–2 in Table 6, and entries 1–4 and 29–32 in Table 7) or in short reaction times (entries 5–6, 17–20 and 27–28 in Table 7).

**Table 7** Reduction of allylic alcohols containing substituted C=C bonds catalyzed by complexes [{RuCl(μ-Cl)(η$^6$-$C_6Me_6$)}$_2$] **1** and [$RuCl_2$(η$^3$:η$^2$:η$^3$-$C_{12}H_{18}$)] **2** using water as solvent and $NaO_2CH$ as hydrogen source.



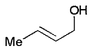
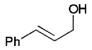
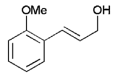
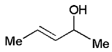
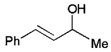
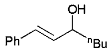
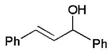
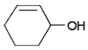
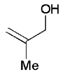
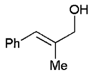
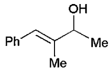
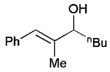
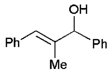
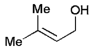
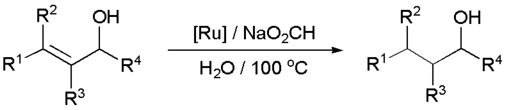
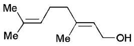
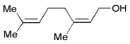
| Entry | Substrate | Cat. | % Ru | Time | Conv. | Yield[b] |
|---|---|---|---|---|---|---|
| 1[a] |  | **1** | 1 mol% | 9 h | >99% | 96% |
| 2[b] |  | **2** | 1 mol% | 11 h | >99% | 99% |
| 3[a] | | **1** | 1 mol% | 5.5 h | >99% | 99% |
| 4[b] |  | **2** | 1 mol% | 24 h | >99% | 98% |
| 5[a] | | **1** | 5 mol% | 8.5 h | >99% | 79% |
| 6[b] |  | **2** | 5 mol% | 1 h | >99% | 83% |
| 7[a] | | **1** | 5 mol% | 6.5 h | 98% | 13% |
| 8[b] |  | **2** | 5 mol% | 9 h | >99% | 93% |
| 9[a] | | **1** | 5 mol% | 24 h | 93% | 93% |
| 10[b] |  | **2** | 5 mol% | 20 h | >99% | 98% |
| 11[a] | | **1** | 5 mol% | 24 h | >99% | 87% |
| 12[b] |  | **2** | 5 mol% | 24 h | >99% | 71% |
| 13[a] | | **1** | 5 mol% | 24 h | >99% | 83% |
| 14[b] |  | **2** | 5 mol% | 20 h | >99% | 67% |
| 15[a] | | **1** | 5 mol% | 4 h | >99% | 99% |
| 16[b] |  | **2** | 5 mol% | 8 h | >99% | 99% |
| 17[a] | | **1** | 5 mol% | 5 h | >99% | 99% |
| 18[b] |  | **2** | 5 mol% | 3 h | >99% | 96% |
| 19[a] | | **1** | 5 mol% | 5 h | >99% | 99% |
| 20[b] |  | **2** | 5 mol% | 2 h | >99% | 99% |
| 21[a] | | **1** | 5 mol% | 24 h | 93% | 73% |
| 22[b] |  | **2** | 5 mol% | 20 h | >99% | 84% |
| 23[a] | | **1** | 5 mol% | 24 h | >99% | 69% |
| 24[b] |  | **2** | 5 mol% | 24 h | >99% | 7% |
| 25[a] | | **1** | 5 mol% | 24 h | >99% | 36% |
| 26[b] |  | **2** | 5 mol% | 24 h | >99% | 45% |
| 27[a] | | **1** | 5 mol% | 9 h | >99% | 99% |
| 28[b] | | **2** | 5 mol% | 9 h | >99% | 87% |

**Table 7** *(Contd.)*



| Entry | Substrate | Cat. | % Ru | Time | Conv. | Yield[b] |
|---|---|---|---|---|---|---|
| 29[a] |  | **1** | 1 mol% | 24 h | >99% | 37% |
| 30[b] |  | **2** | 1 mol% | 30 h | >99% | 93% |
| 31[a] | | **1** | 1 mol% | 24 h | >99% | 43% |
| 32[b] | | **2** | 1 mol% | 23 h | >99% | 99% |

[a] Reactions performed in a sealed tube under $N_2$ atmosphere at 100 °C using 5 mmol of the corresponding allylic alcohol (0.5 M in $H_2O$). [substrate] : [Ru] : [$NaO_2CH$] ratio = 100 : 1 : 1500. [b] Reactions performed in a sealed tube under $N_2$ atmosphere at 100 °C using 5 mmol of the corresponding allylic alcohol (1.0 M in $H_2O$). [substrate] : [Ru] : [$NaO_2CH$] ratio = 100 : 1 : 1000. [c] Yield of the saturated alcohol determined by GC. The differences between conversion and yield correspond to the intermediate carbonyl compound present in the reaction media.

In this sense, the bis(allyl)-Ru(IV) catalyst **2** was able to reduce quantitatively and chemoselectively the terpenoids geraniol (entry 30 in Table 7) and nerol (entry 32 in Table 7) into citronellol employing only 1 mol% of Ru. These results contrast favourably with those obtained in propan-2-ol where 5 mol% of Ru was required to achieve similar conversions (entries 30 and 32 in Table 3). However, we must mention that when the arene-Ru(II) dimer **1** was tested in the reduction of these substrates (entries 29 and 31), low yields were observed due to the competitive formation of several unidentified by-products.

It is important to note that, regardless of the substrate employed, in all the catalytic reactions performed in water, the rate limiting step is the transfer hydrogenation of the carbonyl intermediate. The enhanced reactivity observed with primary allylic alcohols could be therefore ascribed to the lower steric requirements of the C=O bond of the transient aldehyde intermediates. Indeed, the most common TH mechanisms involve the coordination of the carbonyl function to the metal center,[4] a process which would be sterically favoured for aldehydes *vs.* ketones.

## Conclusions

In this work, an operationally simple and highly efficient procedure for the selective reduction of the C=C bond of allylic alcohols has been developed. This one-pot catalytic transformation, involving the use of the commercially available ruthenium complexes [{RuCl(μ-Cl)($\eta^6$-$C_6Me_6$)}$_2$] **1** and [$RuCl_2$($\eta^3$:$\eta^2$:$\eta^3$-$C_{12}H_{18}$)] **2**,[24] is based on a novel tandem process consisting of the initial redox isomerization of the allylic alcohol into the corresponding carbonyl compound and subsequent transfer hydrogenation of the latter from propan-2-ol. For the less sterically demanding substrates (monosubstituted C=C bonds), the TH is the rate determining step and the arene-ruthenium(II) derivative **1** was found to be the catalyst of choice. In contrast, for crowded allylic alcohols (di- and trisubstituted C=C bonds), the redox isomerization becomes the slowest step and the bis(allyl)-ruthenium(IV) catalyst **2** provides the highest activities in these cases.

Moreover, the reduction process can also be efficiently performed in water. In this environmentally benign medium, the TH of the intermediate carbonyl compound is the rate-limiting step regardless of the nature of the allylic alcohol. Consequently, the best performances are obtained starting from primary allylic alcohols, since the TH of aldehydes *vs.* ketones proceeds faster.

In summary, the new methodology for the reduction of C=C bonds of allylic alcohols presented herein is believed to be of interest for a wide range of synthetic chemists since: (*i*) it represents an appealing alternative to the classical C=C hydrogenations with $H_{2(g)}$[8] avoiding the use of this hazardous reactant, (*ii*) it provides an efficient synthetic approach which allows the use of an aqueous reaction medium,[25] (*iii*) it is selective towards C=C bonds in the α-position with respect to the alcohol group and (*iv*) it can be conveniently performed on a preparative scale (see details in the Experimental).

## Experimental

### General methods

The manipulations were performed under an atmosphere of dry nitrogen using a vacuum-line and standard Schlenk or sealed tube techniques. Solvents were dried by standard methods and distilled under nitrogen before use. All reagents were obtained from commercial suppliers and used without further purification with the exception of compounds [{RuCl(μ-Cl)($\eta^6$-arene)}$_2$] (arene = $C_6Me_6$ **1**, mesitylene, *p*-cymene, $C_6H_6$),[26] [$RuCl_2$($\eta^3$:$\eta^2$:$\eta^3$-$C_{12}H_{18}$)] **2**,[27] [{RuCl(μ-Cl)($\eta^3$:$\eta^3$-$C_{10}H_{16}$)}$_2$],[28] [$RuCl_2(PPh_3)_3$],[29] [Ru($\eta^3$-2-$C_3H_4Me$)$_2$(cod)],[30] [{$RuCl_2$(cod)}$_n$],[31] [$RuCl_2(DMSO)_4$],[32] [RuCl($\eta^5$-$C_5H_5$)($PPh_3$)$_2$],[33] [RuCl($\eta^5$-$C_9H_7$)($PPh_3$)$_2$],[34] [{Rh(μ-Cl)(cod)}$_2$],[35] [{Rh(μ-Cl)(nbd)}$_2$],[36] [{Rh(μ-Cl)(coe)}$_2$],[37] [{Ir(μ-Cl)(cod)}$_2$],[38] 1-phenyl-3-buten-2-ol,[39] 1-(4-methoxyphenyl)-2-propen-1-ol,[40] 1-(3-methoxyphenyl)-2-propen-1-ol,[41] 1-(4-chlorophenyl)-2-propen-1-ol,[42] 1-(4-fluorophenyl)-2-propen-1-ol,[43] 1-(furan-2-yl)-2-propen-1-ol,[44] 1,1′-(1,3-phenylene)-2-dipropen-1-ol,[45] *trans*-2-methyl-1-phenyl-1-hepten-3-ol,[7f] *trans*-3-methyl-4-phenyl-3-buten-2-ol,[46] *trans*-1-phenyl-1-hepten-3-ol,[47] and *trans*-2-methyl-1,3-diphenyl-2-propen-1-ol,[48] which were prepared by following the methods reported in the literature. GC measurements were made on Hewlett-Packard HP6890 equipment using a HP-INNOWAX cross-linked poly(ethyleneglycol) (30 m, 250 μm), a Supelco Beta-Dex™ 120 (30 m, 250 μm), or a Supelco Gamma-Dex™ (30 m, 250 μm) column. GC-MS measurements were performed on Agilent 6890 N equipment coupled to a 5973 mass detector (70-eV electron impact ionization) using a HP-1MS column.

### General procedure for the catalytic reduction of allylic alcohols using propan-2-ol as solvent

In a Schlenk flask fitted with a condenser, the corresponding allylic alcohol (2 mmol), the ruthenium catalyst **1** or **2** (0.01–0.1 mmol; 1–5 mol% of metal) and $Cs_2CO_3$ (0.02-0.2 mmol; 2–10 mol%) were dissolved in propan-2-ol (20 $cm^3$) under inert atmosphere. The reaction mixture was then stirred at 82 °C for the indicated time (see Tables 2–3 and Scheme 2), the course of the reaction being monitored by regular sampling and analysis by gas chromatography. The identity of the resulting saturated alcohols, as well as the carbonyl intermediates, was assessed by comparison with commercially available, or independently synthesized (following reported procedures), pure samples and by their fragmentation in GC-MS. Analytically pure samples of the saturated alcohols can be obtained by solvent removal and chromatographic work-up of the residue on silica-gel using a mixture of EtOAc–hexane (1 : 10) as eluent (yields of isolated product were usually 70–80%).

We note that all these reactions can be performed in a preparative scale. *Representative example*: Under nitrogen atmosphere, 1-phenyl-2-propen-1-ol (2.68 g, 20 mmol), complex **1** (0.067 g, 0.1 mmol), $Cs_2CO_3$ (0.132 g, 0.4 mmol) and propan-2-ol (200 $cm^3$) were introduced in a Schlenk flask and the reaction mixture stirred at 82 °C for 15 h (almost quantitative yield by GC). After removal of the solvent under vacuum, flash chromatography (silica-gel) of the residue using a mixture of EtOAc–hexane (1 : 10) as eluent afforded 2.45 g (17.99 mmol) of analytically pure 1-phenyl-propan-1-ol (90% yield).

### General procedure for the catalytic reduction of allylic alcohols using water as solvent and complex [{RuCl(μ-Cl)($\eta^6$-$C_6Me_6$)}$_2$] 1 as catalyst

In a sealed tube, the corresponding allylic alcohol (5 mmol), complex **1** (0.025-0.125 mmol; 1–5 mol% of Ru) and $NaO_2CH$ (5.15 g, 75 mmol) were mixed in water (10 $cm^3$) under inert atmosphere. The reaction mixture was then stirred at 100 °C for the indicated time (see Tables 6–7 and Scheme 4), the course of the reaction being monitored by regular sampling and analysis by gas chromatography. The resulting saturated alcohols can be isolated from the aqueous solution after saturation with NaCl, extraction with diethyl ether (3 × 10 $cm^3$), drying with anhydrous $MgSO_4$, concentration to a small volume (*ca.* 5 $cm^3$) and subsequent chromatographic work-up on silica-gel using a mixture of EtOAc–hexane (1 : 10) as eluent.

### General procedure for the catalytic reduction of allylic alcohols using water as solvent and complex [$RuCl_2$($\eta^3$:$\eta^2$:$\eta^3$-$C_{12}H_{18}$)] 2 as catalyst

In a sealed tube, the corresponding allylic alcohol (5 mmol), complex **2** (0.05-0.25 mmol; 1–5 mol% of Ru) and $NaO_2CH$ (3.43 g, 50 mmol) were mixed in water (5 $cm^3$) under inert atmosphere. The reaction mixture was then stirred at 100 °C for the indicated time (see Tables 6–7 and Scheme 4), the course of the reaction being monitored by regular sampling and analysis by gas chromatography. Purification of the saturated alcohols can be performed as described in the precedent section.

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## Notes and references

1 See, for example: (*a*) L. F. Tietze, *Chem. Rev.*, 1996, **96**, 115; (*b*) S. F. Mayer, W. Kroutil and K. Faber, *Chem. Soc. Rev.*, 2001, **30**, 332; (*c*) J. M. Lee, Y. Na, H. Han and S. Chang, *Chem. Soc. Rev.*, 2004, **33**, 302.

2 Some examples of illustrative reviews on metal-catalyzed tandem processes: (*a*) G. A. Molander and C. R. Harris, *Chem. Rev.*, 1996, **96**, 307; (*b*) P. Eilbracht, L. Bärfacker, C. Buss, C. Hollmann, E. Kitsos-Rzychon, C. L. Kranemann, T. Rische, R. Roggenbuck and A. Schmidt, *Chem. Rev.*, 1999, **99**, 3329; (*c*) G. Poli, G. Giambastiani and A. Heumann, *Tetrahedron*, 2000, **56**, 5959; (*d*) S.-I. Ikeda, *Acc. Chem. Res.*, 2000, **33**, 511; (*e*) S. F. Mayer, W. Kroutil and K. Faber, *Chem. Soc. Rev.*, 2001, **30**, 332; (*f*) J.-C. Wasilke, S. J. Obrey, R. T. Baker and G. C. Bazan, *Chem. Rev.*, 2005, **105**, 1001; (*g*) C. Bruneau, S. Dérien and P. H. Dixneuf, *Top. Organomet. Chem.*, 2006, **19**, 295.

3 For a highly formative review on tandem catalysis see: D. E. Fogg and E. N. dos Santos, *Coord. Chem. Rev.*, 2004, **248**, 2365.

4 For recent reviews, see: (*a*) S. E. Clapman, A. Hadzovic and R. H. Morris, *Coord. Chem. Rev.*, 2004, **248**, 2201; (*b*) S. Gladiali and A. Alberico, *Chem. Soc. Rev.*, 2006, **35**, 226; (*c*) J. S. M. Samec, J.-E. Bäckvall, P. G. Andersson and P. Brandt, *Chem. Soc. Rev.*, 2006, **35**, 237; (*d*) T. Ikariya and A. J. Blacker, *Acc. Chem. Res.*, 2007, **40**, 1300.

5 For recent examples of highly efficient catalysts, see: (*a*) W. Baratta, G. Chelucci, S. Gladiali, K. Siega, M. Toniutti, M. Zanette, E. Zangrando and P. Rigo, *Angew. Chem., Int. Ed.*, 2005, **44**, 6214; (*b*) W. Baratta, K. Siega and P. Rigo, *Adv. Synth. Catal.*, 2007, **349**, 1633; (*c*) W. Baratta, M. Ballico, G. Esposito and P. Rigo, *Chem.–Eur. J.*, 2008, **14**, 5588; (*d*) W. Baratta, G. Chelucci, S. Magnolia, K. Siega and P. Rigo, *Chem.–Eur. J.*, 2009, **15**, 726.

6 For reviews, see: (*a*) R. C. van der Drift, E. Bouwman and E. Drent, *J. Organomet. Chem.*, 2002, **650**, 1; (*b*) R. Uma, C. Crévisy and R. Grée, *Chem. Rev.*, 2003, **103**, 27; (*c*) V. Cadierno, P. Crochet and J. Gimeno, *Synlett*, 2008, 1105.

7 For recent examples of highly efficient catalysts, see: (*a*) M. Ito, S. Kitahara and T. Ikariya, *J. Am. Chem. Soc.*, 2005, **127**, 6172; (*b*) B. Martín-Matute, K. Bogár, M. Edin, F. B. Kaynak and J.-E. Bäckvall, *Chem.–Eur. J.*, 2005, **11**, 5832; (*c*) P. Crochet, M. A. Fernández-Zúmel, J. Gimeno and M. Scheele, *Organometallics*, 2006, **25**, 4846; (*d*) L. Mantilli and C. Mazet, *Tetrahedron Lett.*, 2009, **50**, 4141; (*e*) L. Mantilli, D. Gérard, S. Torche, C. Besnard and C. Mazet, *Angew. Chem., Int. Ed.*, 2009, **48**, 5143.

8 Examples of metal-catalyzed hydrogenation of allylic alcohols can be found in: (*a*) H. Takaya, T. Ohta, S. Inoue, M. Katimura and R. Noyori, *Org. Synth.*, 1995, **72**, 74; (*b*) Y. Sun, C. Le Blond, J. Wang, D. G. Blackmond, J. Laquidara and J. R. Sowa Jr, *J. Am. Chem. Soc.*, 1995, **117**, 12647; (*c*) D. G. Blackmond, A. Lightfoot, A. Pfaltz, T. Rosner, P. Schnider and N. Zimmermann, *Chirality*, 2000, **12**, 442; (*d*) Z. Yang, M. Ebihara and T. Kawamura, *J. Mol. Catal. A: Chem.*, 2000, **158**, 509; (*e*) N. Makihara, S. Ogo and Y. Watanabe, *Organometallics*, 2001, **20**, 497; (*f*) S. Nanchen and A. Pfaltz, *Helv. Chim. Acta*, 2006, **89**, 1559; (*g*) Q. Chen and F.-L. Qing, *Tetrahedron*, 2007, **63**, 11965.

9 See, for example: (*a*) J. C. Li and T. H. Chan, *Organic Reactions in Aqueous Media*, John Willey & Sons, New York, 1997; (*b*) A. S. Matlack, *Introduction to Green Chemistry*, Marcel Dekker, New York, 2001; (*c*) U. M. Lindström, *Chem. Rev.*, 2002, **102**, 2751; (*d*) M. Lancaster, *Green Chemistry: An Introductory Text*, RSC, Cambridge, 2002; (*e*) C.-J. Li, *Chem. Rev.*, 2005, **105**, 3095; (*f*) C.-J. Li and L. Chen, *Chem. Soc. Rev.*, 2006, **35**, 68; (*g*) *Organic Reactions in Water: Principles, Strategies and Applications*, ed. U. M. Lindström, Blackwell, Oxford, 2007; (*h*) S. Y. Tang, R. A. Bourne, R. L. Smith and M. Poliakoff, *Green Chem.*, 2008, **10**, 268.

10 Examples of redox-isomerizations of allylic alcohols in aqueous media can be found in: (*a*) D. V. McGrath, R. H. Grubbs and J. W. Ziller, *J. Am. Chem. Soc.*, 1991, **113**, 3611; (*b*) T. Karlen and A. Ludi, *Helv. Chim. Acta*, 1992, **75**, 1604; (*c*) D. V. McGrath and R. H. Grubbs, *Organometallics*, 1994, **13**, 224; (*d*) H. Schummann, V. Ravindar, L. Meltser, W. Baidossi, Y. Sasson and J. Blum, *J. Mol. Catal. A: Chem.*, 1997, **118**, 55; (*e*) V. Cadierno, P. Crochet, S. E. García-Garrido and J. Gimeno, *Dalton Trans.*, 2004, 3635; (*f*) V. Cadierno, S. E. García-Garrido and J. Gimeno, *Chem. Commun.*, 2004, 232; (*g*) V. Cadierno, S. E. García-Garrido, J. Gimeno, A. Varela-Álvarez and J. A. Sordo, *J. Am. Chem. Soc.*, 2006, **128**, 1360; (*h*) V. Cadierno, P. Crochet, S. E. García-Garrido and J. Gimeno,

*Curr. Org. Chem.*, 2006, **10**, 165; (*i*) A. E. Díaz-Álvarez, P. Crochet, M. Zablocka, C. Duhayon, V. Cadierno, J. Gimeno and J. P. Majoral, *Adv. Synth. Catal.*, 2006, **348**, 1671; (*j*) P. Crochet, J. Díez, M. A. Fernández-Zúmel and J. Gimeno, *Adv. Synth. Catal.*, 2006, **348**, 93; (*k*) M. Fekete and F. Joó, *Catal. Commun.*, 2006, **7**, 783; (*l*) T. Campos-Malpartida, M. Fekete, F. Joó, A. Kathó, A. Romerosa, M. Saoud and W. Wojtków, *J. Organomet. Chem.*, 2008, **693**, 468; (*m*) B. Lastra-Barreira, J. Díez and P. Crochet, *Green Chem.*, 2009, **11**, 1681, DOI: 10.1039/b914789f.

11 Examples of TH reactions in aqueous media can be found in: (*a*) F. Joó and A. Bényei, *J. Organomet. Chem.*, 1989, **363**, C19; (*b*) D. J. Darensbourg, F. Joó, M. Kannisto, A. Kathó and J. H. Reibenspies, *Organometallics*, 1992, **11**, 1990; (*c*) D. J. Darensbourg, F. Joó, M. Kannisto, A. Kathó, J. H. Reibenspies and D. J. Daigle, *Inorg. Chem.*, 1994, **33**, 200; (*d*) H. Y. Rhyoo, R.-J. Park and Y.-K. Chung, *Chem. Commun.*, 2001, 2064; (*e*) S. Ogo, T. Abura and Y. Watanabe, *Organometallics*, 2002, **21**, 2964; (*f*) F. Joó, *Acc. Chem. Res.*, 2002, **35**, 738; (*g*) Y. Ma, H. Liu, L. Chen, X. Cui, J. Zhu and J. Deng, *Organometallics*, 2003, **22**, 2103; (*h*) P. N. Liu, J. G. Deng, Y. Q. Tu and S. H. Wang, *Chem. Commun.*, 2004, 2070; (*i*) X. Wu, X. Li, F. King and J. Xiao, *Angew. Chem., Int. Ed.*, 2005, **44**, 3407; (*j*) J. Mao, B. Wan, F. Wu and S. Lu, *Tetrahedron Lett.*, 2005, **46**, 7341; (*k*) D. S. Matharu, D. J. Morris, G. J. Clarkson and M. Wills, *Chem. Commun.*, 2006, 3232; (*l*) X. Wu and J. Xiao, *Chem. Commun.*, 2007, 2449; (*m*) X. Wu, X. Li, A. Zanotti-Gerosa, A. Pettman, J. Liu, A. J. Mills and J. Xiao, *Chem.–Eur. J.*, 2008, **14**, 2209; (*n*) C. Wang, X. Wu and J. Xiao, *Chem.–Asian J.*, 2008, **3**, 1750.

12 Part of this work has been preliminary communicated: V. Cadierno, J. Francos, J. Gimeno and N. Nebra, *Chem. Commun.*, 2007, 2536.

13 After the publication of our seminal work, Mizuno and co-workers have described that supported ruthenium hydroxides (Ru(OH)$_x$/Al$_2$O$_3$ or Ru(OH)$_x$/TiO$_2$) can also act as efficient heterogeneous catalysts for this transformation: (*a*) J. W. Kim, T. Koike, M. Kotani, K. Yamaguchi and N. Mizuno, *Chem.–Eur. J.*, 2008, **14**, 4104; (*b*) K. Yamaguchi, T. Koike, J. W. Kim, Y. Ogasawara and N. Mizuno, *Chem.–Eur. J.*, 2008, **14**, 11480.

14 Both individual steps, *i.e.* the allylic alcohol isomerization and the TH of the carbonyl intermediate, require the use of a base as co-catalyst to promote the formation of the active metal-hydride species. As expected, very low conversions (0–15%) of the substrate were observed in the absence of base.

15 Further attempts to improve the activity by changing the reaction conditions failed. In particular, other bases (Li$_2$CO$_3$, Na$_2$CO$_3$, K$_2$CO$_3$, LiOH·H$_2$O, NaOH, KOH, CsOH·H$_2$O, NaO$^t$Bu, KO$^t$Bu) and [Ru] : [base] ratios (from 1 : 1 to 1 : 24) were checked without success.

16 Using [RuCl$_2$($\eta^3$:$\eta^2$:$\eta^3$-C$_{12}$H$_{18}$)] **2** and [{RuCl($\mu$-Cl)($\eta^3$:$\eta^3$-C$_{10}$H$_{16}$)}$_2$] as catalysts TOF values of 429 h$^{-1}$ and 3000 h$^{-1}$, respectively, were attained in the isomerization of 1-octen-3-ol into octan-3-one in refluxing THF (0.2 mol% Ru; 0.4 mol% of Cs$_2$CO$_3$), while, under the same reaction conditions, the Ru(II) dimer [{RuCl($\mu$-Cl)($\eta^6$-C$_6$Me$_6$)}$_2$] led to a TOF value of only 125 h$^{-1}$. See references 10f–g.

17 Remarkably, in the case of the bis(allyl)-ruthenium(IV) derivatives [RuCl$_2$($\eta^3$:$\eta^2$:$\eta^3$-C$_{12}$H$_{18}$)] **2** and [{RuCl($\mu$-Cl)($\eta^3$:$\eta^3$-C$_{10}$H$_{16}$)}$_2$] the graphs obtained showed that the initial isomerization step is finished after only 5–10 min of heating. This observation is in complete accord with the higher performances of these complexes *vs.* [{RuCl($\mu$-Cl)($\eta^6$-C$_6$Me$_6$)}$_2$] in redox isomerization processes (see ref. 16).

18 A. Inoue, K. Kitagawa, H. Shinokubo and K. Oshima, *J. Org. Chem.*, 2001, **66**, 4333.

19 Coordination of the carbon–carbon double bond is a key step in the different catalytic cycles proposed for the metal-catalyzed redox isomerization of allylic alcohols. For mechanistic discussions see ref. 6.

20 See, for example: (*a*) U. K. Singh, M. N. Sysak and M. A. Vannice, *J. Catal.*, 2000, **191**, 181; (*b*) F. Zaccheria, N. Ravasio, A. Fusi, M. Rodondi and R. Psaro, *Adv. Synth. Catal.*, 2005, **347**, 1267; (*c*) P. Mäki-Arvela, N. Kumar, A. Nasir, T. Salmi and D. Y. Murzin, *Ind. Eng. Chem. Res.*, 2005, **44**, 9376; (*d*) F. Goettmann, P. Le Floch and C. Sanchez, *Chem. Commun.*, 2006, 2036; (*e*) P. Claus, F. Raif, S. Cavet, S. Demirel-Gülen, J. Radnik, M. Schreyer and T. Fässler, *Catal. Commun.*, 2006, **7**, 618; (*f*) J. C. Serrano-Ruiz, A. Sepúlveda-Escribano, F. Rodríguez-Reinoso and D. Duprez, *J. Mol. Catal. A: Chem.*, 2007, **268**, 227; (*g*) M. D. Bhor, A. G. Panda, S. R. Jagtap and B. M. Bhanage, *Catal. Lett.*, 2008, **124**, 157; (*h*) M. Ueno, T. Suzuki, T. Naito, H. Oyamada and S. Kobayashi, *Chem. Commun.*, 2008, 1647.

21 V. Cadierno, J. Francos and J. Gimeno, *Chem.–Eur. J.*, 2008, **14**, 6601.

22 In spite of the insolubility of complex **1** in water, the reduction process proceeded efficiently. A close examination of the reaction mixture showed that it was an emulsion rather than a homogeneous solution, the catalytic reaction probably taking place at the interface.

23 Aldehydes have previously proven to be especially reactive in metal-catalyzed TH processes under NaO$_2$CH/H$_2$O conditions. See ref. 11.

24 Complexes **1** and **2** are commercialized by TCI Laboratory Chemicals and Strem Chemicals Inc., respectively.

25 We note that a related Ru-catalyzed isomerization/hydrogenation tandem process in aqueous media has been reported: P. Csabai and F. Joó, *Organometallics*, 2004, **23**, 5640.

26 (*a*) M. A. Bennett and A. K. Smith, *J. Chem. Soc., Dalton Trans.*, 1974, 233; (*b*) M. A. Bennett, T. N. Huang, T. W. Matheson and A. K. Smith, *Inorg. Synth.*, 1982, **21**, 74.

27 J. K. Nicholson and B. L. Shaw, *J. Chem. Soc. A*, 1966, 807.

28 (*a*) L. Porri, M. C. Gallazzi, A. Colombo and G. Allegra, *Tetrahedron Lett.*, 1965, **6**, 4187; (*b*) A. Salzer, A. Bauer, S. Geyser and F. Podewils, *Inorg. Synth.*, 2004, **34**, 59.

29 P. S. Hallman, T. A. Stephenson and G. Wilkinson, *Inorg. Synth.*, 1970, **12**, 237.

30 J. Powell and B. L. Shaw, *J. Chem. Soc. A*, 1968, 159 .

31 M. O. Albers, T. V. Ashworth, H. E. Oosthuizen and E. Singleton, *Inorg. Synth.*, 1989, **26**, 68.

32 I. P. Evans, A. Spencer and G. Wilkinson, *J. Chem. Soc., Dalton Trans.*, 1973, 204.

33 (*a*) M. I. Bruce, C. Hameister, A. G. Swincer and R. C. Wallis, *Inorg. Synth.*, 1982, **21**, 78; (*b*) M. I. Bruce, C. Hameister, A. G. Swincer and R. C. Wallis, *Inorg. Synth.*, 1990, **28**, 270.

34 L. A. Oro, M. A. Ciriano, M. Campo, C. Foces-Foces and F. H. Cano, *J. Organomet. Chem.*, 1985, **289**, 117.

35 (*a*) G. Giordano and R. H. Crabtree, *Inorg. Synth.*, 1979, **19**, 218; (*b*) G. Giordano and R. H. Crabtree, *Inorg. Synth.*, 1990, **28**, 88.

36 E. W. Abel, M. A. Bennett and G. Wilkinson, *J. Chem. Soc.*, 1959, 3178.

37 A. Van Der Ent and A. L. Onderdelinden, *Inorg. Synth.*, 1973, **14**, 92.

38 J. L. Herde, J. C. Lambert and C. V. Senoff, *Inorg. Synth.*, 1974, **15**, 18.

39 M. K. Gurjar and P. Yakambram, *Tetrahedron Lett.*, 2001, **42**, 3633.

40 S. Laabs, W. Münch, J. W. Bats and U. Nubbemeyer, *Tetrahedron*, 2002, **58**, 1317.

41 B. Schmidt, *J. Org. Chem.*, 2004, **69**, 7672.

42 D. M. Speare, S. M. Fleming, M. N. Beckett, J.-J. Li and T. D. H. Bugg, *Org. Biomol. Chem.*, 2004, **2**, 2942.

43 N. Marion, R. Gealageas and S. P. Nolan, *Org. Lett.*, 2007, **9**, 2653.

44 U. M. Krishna, G. S. C. Srikanth and G. K. Trivedi, *Tetrahedron Lett.*, 2003, **44**, 8227.

45 G. Dyker, D. Kadzimirsz and G. Henkel, *Tetrahedron Lett.*, 2003, **44**, 7905.

46 T. N. Grant and F. G. West, *J. Am. Chem. Soc.*, 2006, **128**, 9348.

47 B. D. Stevens, C. J. Bungard and S. G. Nelson, *J. Org. Chem.*, 2006, **71**, 6397.

48 N. S. Nudelman and G. V. García, *J. Org. Chem.*, 2001, **66**, 1387.