Studies on New Catalytic Reactions via η^3-Allylruthenium Intermediates

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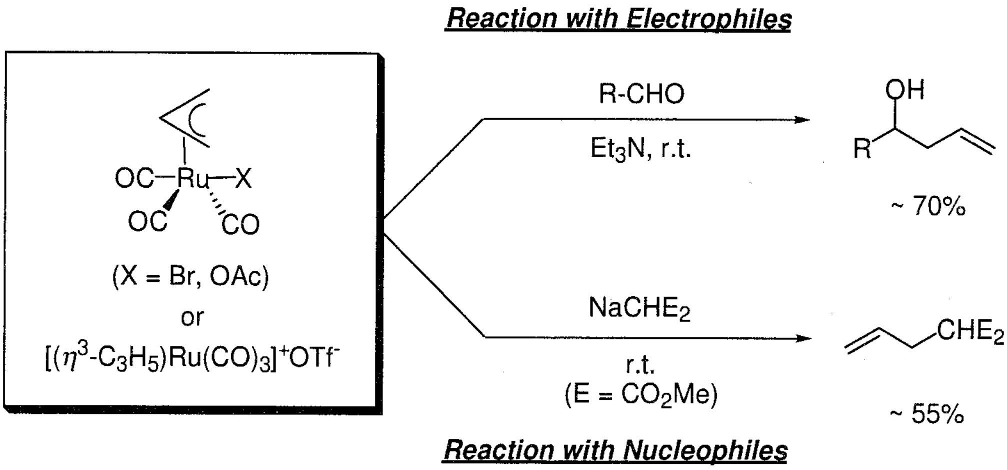
General Introduction

Recently, transition-metal complex-catalyzed organic synthesis with chemo-, regio- and stereoselectivity has been extensively studied. A variety of catalytic systems, which enable the introduction of the desired functional group into organic molecules and the selective transformation of many functional groups, have been designed and widely used in organic synthesis.[1] In particular, palladium-catalyzed reactions have found widespread utility in a number of important chemical processes.[2] Among them, palladium complex-mediated or catalyzed allylic substitution reactions have been especially studied in detail. Historically, η^3-allylpalladium complexes were first isolated and identified over 30 years ago, synthesized by the reaction of dienes with palladium(II) salts.[3] Since Tsuji and co-workers reported that η^3-allylpalladium chloride reacts with carbonucleophiles, such as malonates, acetoacetates, and enamines in 1965,[4] palladium complex-catalyzed allylic substitution reaction is now a well-established methodology in organic synthesis, and it is used to construct complex organic molecules.[5] Most of the work in this field has been devoted to mainly palladium complexes. Although a wide range of transition-metal complexes has recently been used for the reaction,[6] a general use of ruthenium catalysts has not been forthcoming. In early 1970's, the chemistry of ruthenium catalysis had been far behind from those of other transition-metal complexes, such as rhodium and palladium ones. Indeed, the chemistry of η^3-allylruthenium complexes is also undeveloped. With recent progress of the organometallic chemistry, however, the organic synthesis catalyzed by ruthenium complexes has attracted much attention, and a large number of useful catalytic reactions have been discovered.[7,8] In the ruthenium catalyses, the appropriate matching and tuning of the ruthenium catalysts with the ligands, substrates, and solvents used are always important.[7a-c]

Several η^3-allylruthenium complexes have been prepared and reported so far.[9] The representative methods of the introduction of an allyl group to a ruthenium complex are quite similar to those for other transition-metals. For example, (1) the reaction of ruthenium halides with allyl Grignard reagents,[10] (2) insertion of conjugated dienes into a hydrido-ruthenium bond,[11] and (3) oxidative addition of several allylic compounds to a low-valent ruthenium complex.[12] First η^3-allylruthenium complex, $(\eta^3\text{-}C_3H_5)RuX(CO)_3$ (X = Cl, Br, I), was synthesized by Pino and co-workers in 1968 by oxidative addition of allyl halides to $Ru_3(CO)_{12}$[12a], and some reactions of the chloro complex (X = Cl) with unsaturated compounds were reported.[13] Among the η^3-allylruthenium(II) complexes reported, we paid our attention to the reactivity of the $(\eta^3\text{-}C_3H_5)RuX(CO)_3$ complexes, since they would have a quite similar structure to an active ruthenium species in $Ru_3(CO)_{12}$-catalyzed allylation of aldehydes with allylic acetates.[14] Actually, detailed studies on the reactivities of a series of $(\eta^3\text{-}C_3H_5)RuX(CO)_3$ (X = Br, OAc or OTf) complexes revealed that the η^3-allylruthenium complexes bearing a CO ligand[15] act not only as electrophiles, in the same way as an η^3-allylpalladium generally, but also they act as nucleophiles (Scheme 1).[12d,16]

This is a reason that ruthenium complexes can catalyze both nucleophilic[14,17] and electrophilic allylation reactions.[12d,18] The latter ruthenium-catalyzed allylic substitution reactions (electrophilic allylation reactions) proceeded in a highly regiospecific manner, in which substitution exclusively occurred at the more-substituted allylic terminus in η^3-allylruthenium intermediates. These facts prompted us to investigate further both the stereoselectivity and scope of the ruthenium-catalyzed allylic substitution reaction, and to develop novel ruthenium-catalyzed carbon-carbon bond forming reactions involving carbonylation as well as carbon-carbon bond cleaving reactions, in which formation of an η^3-allylruthenium species should contribute significantly to the driving force of these catalytic reactions.

Scheme 1



The purpose of this study is to discover novel ruthenium catalyst systems which has completely different catalytic activities from those of other transition-metal complexes, and to develop new methods for construction of carbon skeletons via η^3-allylruthenium intermediates.

This thesis is a summary of the results of a series of the studies on novel catalytic reactions via η^3-allylruthenium complexes, and is composed of Chapters 1 to 5.

Chapter 1 deals with ruthenium-catalyzed allylic substitution of cyclic allyl carbonates with nucleophiles, and the stereoselectivity and scope of the reaction were disclosed. As described previously, ruthenium-catalyzed allylic substitution of allylic carbonates with carbon- and nitrogen-nucleophiles found in our laboratory proceeded with unusual regioselectivity. However, catalysts, such as Ru(cod)(cot)[17a] [cod = 1,5-cyclooctadiene, cot = 1,3,5-cyclooctatriene] and Cp*RuCl(cod)[12d] [Cp* = pentamethylcyclopentadienyl], which were highly active for the allylic substitution of *acyclic* allyl carbonates, were totally ineffective for the allylic substitution of *cyclic* allyl carbonates. Thus, we have focused our efforts to improve and modify the ruthenium catalyst system, and finally found that CpRuCl(cod)/NH_4PF_6 [Cp = cyclopentadienyl] is a highly effective catalyst system for the allylic substitution of *cyclic* allyl carbonates. This catalyst system enables the first investigation of the stereochemical course of the ruthenium-catalyzed allylic substitution reaction.

Chapter 2 deals with the first ruthenium-catalyzed allylation of thiols with various allylic compounds. Although a wide range of nucleophiles, such as carbon-, nitrogen-, and oxygen-nucleophiles, and transition-metal catalysts, especially those involving palladium have been studied,[5] a general method for synthesizing allylic sulfides by the transition-metal complex-catalyzed allylation of sulfur nucleophiles has not yet been reported due to widespread belief that a lot of sulfur-containing compounds work as catalyst poisons.[19] However, on the basis of the first example of the transition-metal complex-catalyzed addition of organic disulfides to alkenes,[7b] the ruthenium complexes seem to be one of the most promising catalysts for the transformation of sulfur-containing compounds. Thus, we found that Cp*RuCl(cod) is a highly effective catalyst for the allylation of *both aliphatic and aromatic thiols*[20] with various allylic compounds. In the presence of a catalytic amount of Cp*RuCl(cod) (5 mol %) at room temperature for 1 h under an argon atmosphere in CH_3CN, general allylic sulfides were readily obtained in high yields. The regio- and stereochemical courses of the reaction were also investigated.

Chapters 3-5 deal with ruthenium complex-catalyzed novel carbon-carbon bond forming and cleaving reactions via η^3-allylruthenium intermediates.

In Chapter 3, the first intermolecular hydroacylation of 1,3-dienes with aldehydes using a Ru(cod)(cot)/PPh_3 catalyst system has been developed. Hydroacylation is a useful reaction for the synthesis of various ketones from alkenes and aldehydes, which proceeds through the activation of the formyl C-H bond.[21] We have already found that low-valent ruthenium complexes, such as $Ru_3(CO)_{12}$, Ru(cod)(cot), and $RuCl_2(PPh_3)_3$ showed a high catalytic activity for the formyl C-H bond activation.[22] Combination of this formyl C-H bond activation ability of ruthenium catalysts with η^3-allylruthenium chemistry realizes the first intermolecular hydroacylation of 1,3-dienes with aldehydes. In this reaction, carbon monoxide is not needed to suppress decarbonylation of aldehydes and to maintain the catalytic activity. The key intermediate is an (acyl)(η^3-allyl)ruthenium complex which undergoes reductive elimination to give the corresponding β,γ-unsaturated ketones.

Chapter 4 describes the new synthetic method of cyclopentenones via ruthenium-catalyzed intermolecular carbonylative cyclization of allylic carbonates with alkenes. The development of simple and general methods for the preparation of cyclopentenones is the current interest, owing to the wide abundance of this structural unit in a large number of natural products.[23] The representative strategy of construction of a cyclopentenone skeleton is cocyclization of alkynes, alkenes and carbon monoxide by transition-metal complexes (the Pauson-Khand reaction[24]), and many advances have been reported recently including a catalytic version of this reaction.[7a,25] Another related process, the carbonylative cyclization of allylic halides with alkynes promoted by nickel[26] and palladium[27] complexes via η^3-allyl intermediates, has been reported. The use of alkyne is essential for both the Pauson-Khand reaction and carbonylative cyclization reactions. During our investigation of the η^3-allylruthenium chemistry as well as the ruthenium-catalyzed Pauson-Khand reaction,[7a] we found that $[RuCl_2(CO)_3]_2/Et_3N$ and (η^3-

C_3H_5)RuBr(CO)$_3$/Et$_3$N are highly effective catalyst systems for carbonylative cyclization of allylic carbonates with *alkenes* to give the corresponding cyclopentenones in high yields.

Chapter 5 deals with the ruthenium-catalyzed β-allyl elimination leading to selective cleavage of a carbon-carbon bond in tertiary homoallyl alcohols. The development of efficient methods for cleavage of carbon-carbon bonds catalyzed by transition-metal complexes is now a central and challenging subject of modern organic synthesis.[28] Based on our study of ruthenium-catalyzed carbon-carbon bond activation,[7c] we found the first example of deallylation of tertiary homoallyl alcohols catalyzed by $RuCl_2(PPh_3)_3$. The driving force of this catalytic reaction would be the formation of the stable η^3-allylruthenium complex, which enables the first β-carbon (β-allyl) elimination from an (alkoxy)ruthenium intermediate. A synthetic application of the present reaction using cyclic homoallyl alcohols is also disclosed.

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Chapter 1

Ruthenium-Catalyzed Allylic Substitution of Cyclic Allyl Carbonates with Nucleophiles. Stereoselectivity and Scope of the Reaction

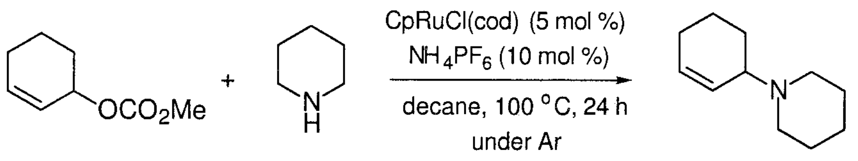
Abstract

CpRuCl(cod)/NH_4PF_6 [Cp = cyclopentadienyl, cod = 1,5-cyclooctadiene] is an effective catalyst system for the allylic substitution of cyclic allyl carbonates with nucleophiles. This catalyst system enables the first investigation of the stereochemical course of the ruthenium-catalyzed allylic substitution reaction, in which the reaction proceeds with an overall retention of configuration. The stoichiometric reaction of *trans*-5-(methoxycarbonyl)cyclohex-2-enyl chloride with Cp*RuCl(cod) [Cp* = pentamethylcyclopentadienyl] gave an unexpected complex Cp*Ru(η^6-$C_6H_5CO_2Me$)$^+$ by the rapid dehydrohalogenation/ dehydrogenation of the desired Cp*RuCl_2(η^3-$C_6H_8CO_2Me$) complex.

Introduction

The transition-metal complex-catalyzed substitution reaction of allylic alcohol derivatives with nucleophilic reagents is now a well-established methodology in organic synthesis, and is widely used to construct complex organic molecules.[1] Most of the work in this field has been devoted to palladium complexes for the design of chemo-, regio-, stereo-, and enantioselective catalyst systems,[2] and a wide range of transition-metal complexes has recently been used for the reaction.[3] However, a general use of ruthenium catalysts has not been forthcoming,[4] and examples are strictly limited to reports on the ruthenium-catalyzed highly regioselective allylic substitution of acyclic allyl carbonates with carbon-[5,6] and nitrogen- nucleophiles[6], in which substitution exclusively occurred at the more-substituted allylic terminus in η^3-allylruthenium intermediates. Essential to the use of this process in organic synthesis is control of the stereochemical course of the reaction, as well as the regiochemistry. Although ruthenium complexes often show interesting catalytic activity and product selectivity, which are quite different from those with palladium and other transition-metal complexes,[7] the appropriate matching and tuning of the ruthenium catalysts with the substrates, ligands, and solvents used are always important.[6,8] For example, catalysts, such as Ru(cod)(cot)[5] [cod = 1,5-cyclooctadiene, cot = 1,3,5-cyclooctatriene] and Cp*RuCl(cod)[6] [Cp* = pentamethylcyclopentadienyl], which were highly active for the allylic substitution of *acyclic* allyl carbonates, were totally ineffective for the allylic substitution of *cyclic* allyl carbonates. Thus, we have been continuing our effort to improve and modify the ruthenium catalyst system. After many trials, we finally found that CpRuCl(cod)/NH_4PF_6 [Cp = cyclopentadienyl] is a highly effective catalyst system for the allylic substitution of *cyclic* allyl carbonates (eq

1). We report here the development of this new catalyst system which enables the first investigation of the stereochemical course of the ruthenium-catalyzed allylic substitution reaction.

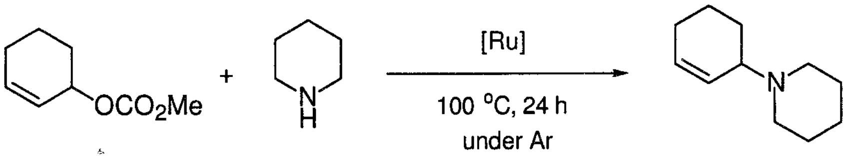


1a 2a 3a 86% (1)

Results and Discussion

We initially examined the catalytic activity of several ruthenium complexes in the reaction of cyclohex-2-enyl methyl carbonate (**1a**) with piperidine (**2a**), and the results are summarized in Table 1. The reaction of **1a** (1.0 mmol) with **2a** (2.0 mmol) in the presence of a catalytic amount of CpRuCl(cod) (5 mol %) and NH_4PF_6 (10 mol %) in decane (2.0 mL) at 100 °C for 24 h under an argon atmosphere gave the corresponding cyclic allylamine, *N*-(cyclohex-2-enyl)piperidine (**3a**), in 86% yield. Other ruthenium catalysts, such as Ru(cod)(cot),[5] $Ru_3(CO)_{12}$, $RuH_2(PPh_3)_4$,[4] $RuCl_2(PPh_3)_3$, and Cp*RuCl(cod),[6] were totally ineffective in the present reaction. Although the catalytic activity of CpRuCl(cod) *itself* was low, the concomitant use of NH_4PF_6 dramatically increased the catalytic activity, probably due to the formation of a coordinatively unsaturated cationic ruthenium species,[9] which is needed to overcome the steric hindrance of cyclic allyl carbonates. The PPh_3 ligand showed a negative effect in the reaction using the catalyst system of $CpRuCl(PPh_3)_2/NH_4PF_6$. The present reaction was also affected by the solvent, and the yield of **3a** drastically decreased in 1,4-dioxane and mesitylene. The best result was obtained in decane.

Table 1. Effects of the Catalyst and the Solvent on the Synthesis of **3a** by the Reaction of **1a** with **2a**[a]

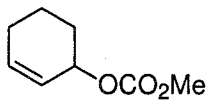
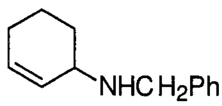
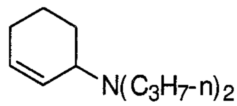
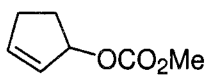
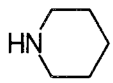
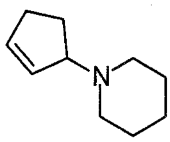
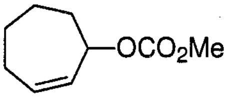
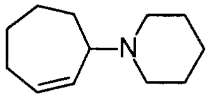
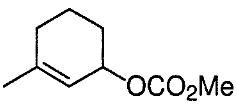
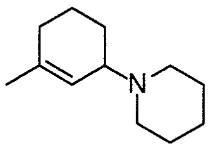
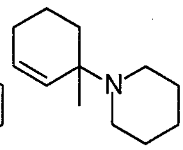
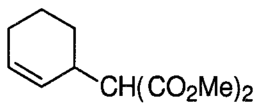


1a **2a** **3a**

Run	Catalyst	Additive[b]	Solvent	Yield (%)[c]
1	Ru(cod)(cot)	-	Decane	4
2	$Ru_3(CO)_{12}$	-	Decane	0
3	$RuH_2(PPh_3)_4$	-	Decane	8
4	$RuCl_2(PPh_3)_3$	-	Decane	10
5	Cp*RuCl(cod)	-	Decane	0
6	CpRuCl(cod)	-	Decane	27
7	CpRuCl(cod)	NH_4PF_6	Decane	86
8	CpRuCl(cod)	NH_4PF_6	*N*-Methylpiperidine	75
9	CpRuCl(cod)	NH_4PF_6	1,4-Dioxane	18
10	CpRuCl(cod)	NH_4PF_6	Mesitylene	15
11	$CpRuCl(PPh_3)_2$	NH_4PF_6	Decane	55

[a]A mixture of **1a** (1.0 mmol), **2a** (2.0 mmol), Ru complex (0.050 mmol), and solvent (2.0 mL) in a 20-mL Pylex flask was heated at 100 °C for 24 h under an argon atmosphere. [b]NH_4PF_6 (0.10 mmol) was used. [c]GLC yield based on the amount of **1a** charged.

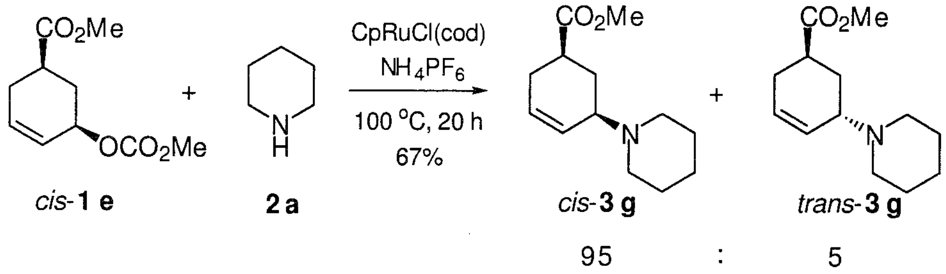
Table 2. $CpRuCl(cod)/NH_4PF_6$-Catalyzed Allylic Substitution of Cyclic Allyl Carbonates with Nucleophiles[a]

Cyclic Allylic Carbonate	Nucleophile	Product	Isolated Yield (%)[b]
 **1a**	$PhCH_2NH_2$ **2b**	 **3b**	65
1a	$(n\text{-}C_3H_7)_2NH$ **2c**	 **3c**	83
 **1b**	 **2a**	 **3d**	75
 **1c**	**2a**	 **3e**	65
 **1d**	**2a**	 **3f**  **3f'**	88[c]
1a	$NaCH(CO_2Me)_2$ **4a**	 **5a**	92

[a]Cyclic allylic carbonate (1.0 mmol), nucleophile (2.0 mmol), CpRuCl(cod) (0.050 mmol), NH_4PF_6 (0.10 mmol), decane (2.0 mL) at 100 °C for 24 h under an argon atmosphere. [b]Based on the amount of allylic carbonate charged. [c]**3f**/**3f'** = 77/23 by GLC.

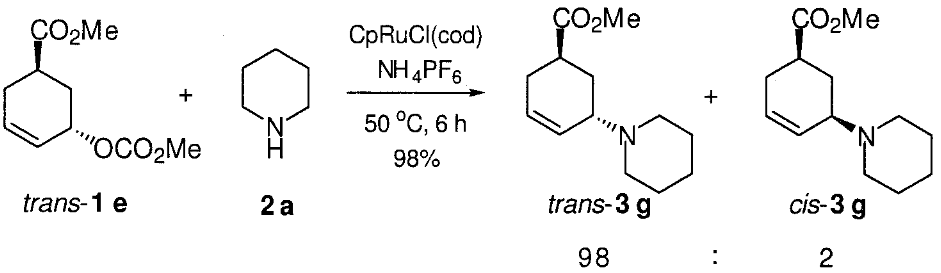
The results obtained from the CpRuCl(cod)/NH_4PF_6-catalyzed allylic substitution of several cyclic allyl carbonates with nucleophiles are summarized in Table 2. Both acyclic primary and secondary amines, represented by benzylamine (**2b**) and dipropylamine (**2c**), were smoothly allylated with **1a** to give the corresponding cyclic allylamines, **3b** and **3c**, in high isolated yields. Five-membered and seven-membered cyclic allyl carbonates, **1b** and **1c**, also reacted with **2a** to give the corresponding cyclic allylamines, **3d** and **3e**, in good yields. In the case of **1d**, substitution predominantly occurred at the less-substituted allylic carbon to give a mixture of regioisomers, **3f** and **3f'**, in a total isolated yield of 88% with a ratio of 77:23. The regiochemistry is quite different from that observed in our previous study on acyclic allyl carbonates,[5,6] probably due to the higher steric hindrance of **1d** and relatively severe reaction conditions. Allylic alkylation of a stabilized *C*-nucleophile, dimethyl sodiomalonate (**4a**), with **1a** also proceeded smoothly to give **5a** in an isolated yield of 92 %.

The development of this new catalyst system enables the first investigation of the stereochemical course of the ruthenium-catalyzed allylic substitution reaction. First, we chose *cis*-5-(methoxycarbonyl)cyclohex-2-enyl methyl carbonate (*cis*-**1e**) as a substrate because it has been extensively used to examine the stereochemical course of palladium-[10] and molybdenum-catalyzed[11] allylic substitution reactions. Treatment of *cis*-**1e** with piperidine (**2a**) in the presence of 5 mol % CpRuCl(cod) and 10 mol % NH_4PF_6 in decane at 100 °C for 20 h predominantly gave *cis*-**3g** (total yield of **3g** 67%, *cis*-**3g**:*trans*-**3g** = 95:5) (eq 2).[12]

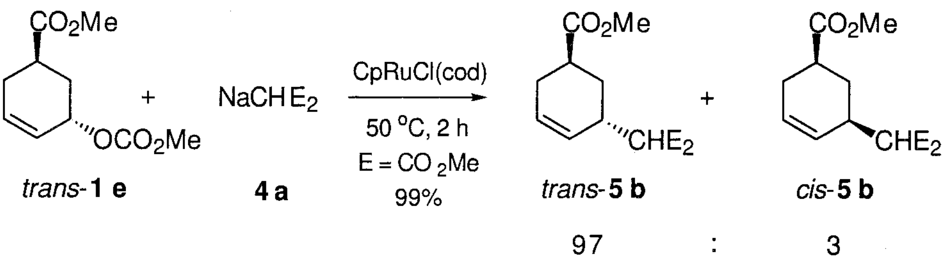


(2)

The reactivity of *trans*-5-(methoxycarbonyl)cyclohex-2-enyl methyl carbonate (*trans*-**1e**) was higher than that of *cis*-**1e**, and the reaction of *trans*-**1e** with **2a** at 50 °C for 6 h gave *trans*-**3g** almost exclusively (total yield of **3g** 98%, *trans*-**3g**:*cis*-**3g** = 98:2) (eq 3). The selective formation of *trans*-**5b** from the reaction of *trans*-**1e** with a stabilized *C*-nucleophile (**4a**) was also observed (total yield of **5b** 99%, *trans*-**5b**:*cis*-**5b** = 97:3), where the addition of NH_4PF_6 as a co-catalyst was not needed (eq 4). Consequently, the ruthenium-catalyzed allylic substitution proceeded with an overall retention of configuration, since interconversion of *cis*-**3g** and *trans*-**3g** was not observed in any of these reactions.

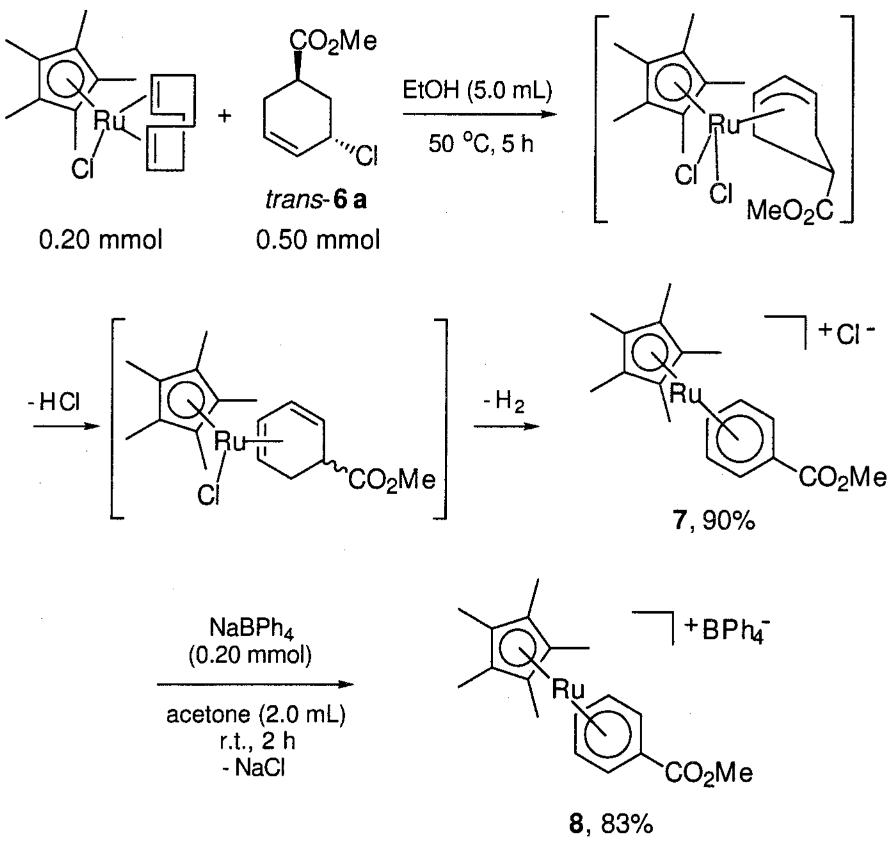


(3)



(4)

To investigate the stereochemistry of the first oxidative addition step of allylic compounds to ruthenium, a stoichiometric reaction of Cp*RuCl(cod) with *trans*-**6a** was examined.[13] The reaction proceeded smoothly in ethanol at 50 °C for 5 h to give an unexpected [Cp*Ru(η^6-$C_6H_5CO_2Me$)]$^+$Cl complex (**7**) as the sole product, which would be obtained by rapid dehydrohalogenation/ dehydrogenation[14] of the desired Cp*RuCl_2(η^3-$C_6H_8CO_2Me$) complex (eq 5). The molecular structure of (**7**) was established by X-ray structure analysis of the anion-exchanged complex [Cp*Ru(η^6-$C_6H_5CO_2Me$)]$^+$[BPh_4]$^-$ (**8**) (Figure 1 and Tables 3-6). A similar reaction sequence has already been reported in the reaction of CpRuBr(cod) with 3-bromocyclohexene by Singleton and co-workers.[15] Thus, our attempt to determine the stereochemistry of the oxidative addition of allylic compounds to ruthenium was in vain.



(5)

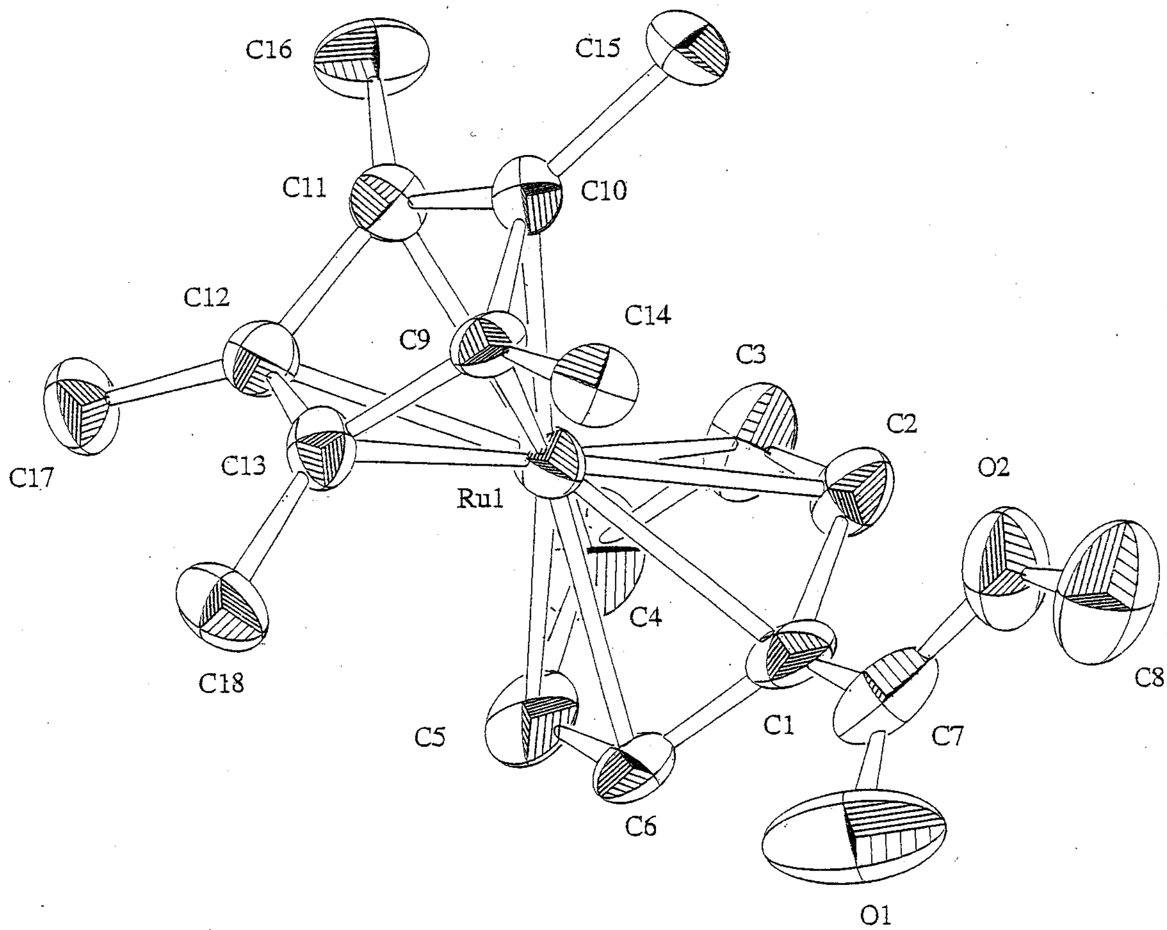


Figure 1. ORTEP drawing of **8** with 30% thermal ellipsoids. Only one of two independent molecules is shown for clarity. Hydrogen atoms and counterion (BPh_4^-) are also omitted for clarity.

Although little work has been done to determine the stereochemical course of the reaction of η^3-allylruthenium complexes with nucleophiles, Harman and co-workers recently reported that the reaction with soft nucleophiles exclusively proceeded via an *anti* mechanism,[16] as in the reaction of most η^3-allylpalladium complexes.[10,17] The observations described here together with information in the literature allow us to suggest that the ruthenium-catalyzed allylic substitution reaction proceeds via a double-inversion (*anti-anti*) mechanism.[18,19] The higher reactivity of *trans*-**1e** compared to that of *cis*-**1e** in the present reaction was explained as follows. *trans*-**1e** should always react faster, since the leaving group is pseudoaxial, so that the alignment of the π-system with the σ^* orbital is easily attained in contrast to *cis*-**1e**, where the leaving group is pseudoequatorial.[20]

In conclusion, we developed a novel ruthenium catalyst system for allylic substitution of *cyclic* allyl carbonates. The development of this new catalyst system provides some insight into the stereochemistry of the ruthenium-catalyzed allylic substitution reaction, and we believe that this finding broadens the applicability of the ruthenium catalyst to organic synthesis using a transition-metal-catalyzed allylic substitution reaction.

Table 3. Experimental Parameters for the X-ray Diffraction Study of **8**

Crystal Data	
Molecular formula	$C_{84}H_{86}O_4B_2Ru_2$
Formula weight	1383.36
Crystal color, habit	yellow, prismatic
Crystal dimensions	0.10×0.10×0.20 mm
Crystal system	orthorhombic
No. of reflections used for unit cell determination	25(28.7-29.9°)
ω Scan peak with at half-hight	0.26
Lattice parameters	a = 14.82(1)Å b = 14.96(1)Å c = 31.85(1)Å V = 7061(7)Å^3
Space group	$P2_12_12_1$ (#19)
Z	8
D_{calc}	2.602 g/cm^3
F_{000}	5760.00
μ(MoKα)	9.57 cm^{-1}
Intensity Measurements	
Diffractometer	Rigaku AFC7R
Radiation	MoKα (λ = 0.71069Å)
Monochromator	graphite
Attenuator	Zr foil
Take-off angle	6.0°
Detector aperture	3.0 mm horizntal 3.0 mm vertical
Crystal to detector distance	235 mm
Voltage, current	50 kV, 200 mA
Temperature	23.0 °C
Scan type	ω
Scan rate	8.0°/min (in ω)
Scan width	(1.15+0.30 tanθ)°
$2\theta_{max}$	55.0°

(continued)

No. of reflection measured	total: 8864
	unique: 8863 (R_{int} = 0.000)

Structure Solution and Refinement

Structure solution	Direct Methods (SHELXS-97)
Refinement	Full-matrix least-squares
Function minimized	$\Sigma w(\mid F_o \mid - \mid F_c \mid)^2$
Least-square weights	$[\sigma_c^2(F_o)+p^2/4F_o^2]^{-1}$
p-factor	0.0020
Anomalous dispersion	All non-hydrogen atoms
No. observation ($I>3.00\sigma(I)$)	4708
No. variables	831
Reflection/Parameter ratio	5.67
R	0.056
Rw	0.060
Goodness of fit indicator	1.04
Max shift/error in final cycle	0.00
Maximum peak in final diff. map	0.35 $e^-/Å^3$
Minimum peak in final diff. map	-0.43 $e^-/Å^3$

Table 4. Positional Parameters and B(eq) Values for **8**

atom	x	y	z	B(eq)
Ru(1)	0.25129(8)	0.56291(6)	0.22595(3)	3.88(2)
O(1)	0.164(1)	0.646(1)	0.3400(5)	13.4(6)
O(2)	0.1007(8)	0.520(1)	0.3226(4)	7.9(3)
C(1)	0.1461(9)	0.6160(9)	0.2677(5)	4.9(3)
C(2)	0.1036(9)	0.558(1)	0.2370(5)	5.2(3)
C(3)	0.1182(10)	0.573(1)	0.1937(5)	6.4(4)
C(4)	0.174(1)	0.646(1)	0.1804(6)	7.9(5)
C(5)	0.215(1)	0.704(1)	0.2119(7)	7.4(4)
C(6)	0.200(1)	0.689(1)	0.2556(6)	6.5(4)
C(7)	0.137(1)	0.596(1)	0.3126(6)	7.3(4)
C(8)	0.090(1)	0.491(2)	0.3671(5)	10.2(6)
C(9)	0.3341(8)	0.4735(7)	0.2640(4)	3.7(2)
C(10)	0.2990(7)	0.4250(8)	0.2304(4)	3.6(2)
C(11)	0.3294(9)	0.4656(8)	0.1919(4)	3.8(2)
C(12)	0.3870(9)	0.5395(9)	0.2029(5)	4.0(2)
C(13)	0.3908(10)	0.545(1)	0.2486(4)	4.1(2)
C(14)	0.3219(10)	0.4511(10)	0.3112(4)	4.7(3)
C(15)	0.237(1)	0.3431(8)	0.2320(5)	5.3(4)
C(16)	0.312(1)	0.430(1)	0.1474(4)	6.1(4)
C(17)	0.443(1)	0.595(1)	0.1723(5)	5.6(4)
C(18)	0.4483(10)	0.6061(9)	0.2739(5)	5.5(4)

Table 5. Intramolecular Bond Distances for **8**

atom	atom	distance (Å)	atom	atom	distance (Å)
Ru(1)	C(1)	2.20(1)	C(1)	C(7)	1.47(2)
Ru(1)	C(2)	2.22(1)	C(2)	C(3)	1.41(2)
Ru(1)	C(3)	2.23(1)	C(3)	C(4)	1.43(3)
Ru(1)	C(4)	2.22(1)	C(4)	C(5)	1.46(3)
Ru(1)	C(5)	2.23(1)	C(5)	C(6)	1.43(2)
Ru(1)	C(6)	2.25(1)	C(9)	C(10)	1.39(2)
Ru(1)	C(9)	2.18(1)	C(9)	C(13)	1.44(2)
Ru(1)	C(10)	2.19(1)	C(9)	C(14)	1.55(2)
Ru(1)	C(11)	2.15(1)	C(10)	C(11)	1.44(2)
Ru(1)	C(12)	2.17(1)	C(10)	C(15)	1.54(2)
Ru(1)	C(13)	2.21(1)	C(11)	C(12)	1.44(2)
O(1)	C(7)	1.21(2)	C(11)	C(16)	1.54(2)
O(2)	C(7)	1.30(2)	C(12)	C(13)	1.46(2)
O(2)	C(8)	1.49(2)	C(12)	C(17)	1.52(2)
C(1)	C(2)	1.45(2)	C(13)	C(18)	1.49(2)
C(1)	C(6)	1.41(2)			

Table 6. Intramolecular Bond Angles for **8**

atom	atom	atom	angle (deg)	atom	atom	atom	angle (deg)
C(1)	Ru(1)	C(2)	38.2(5)	C(5)	Ru(1)	C(6)	37.2(6)
C(1)	Ru(1)	C(3)	68.0(6)	C(5)	Ru(1)	C(9)	146.0(7)
C(1)	Ru(1)	C(4)	80.2(7)	C(5)	Ru(1)	C(10)	170.8(6)
C(1)	Ru(1)	C(5)	66.9(6)	C(5)	Ru(1)	C(11)	132.1(6)
C(1)	Ru(1)	C(6)	37.0(5)	C(5)	Ru(1)	C(12)	107.9(6)
C(1)	Ru(1)	C(9)	106.6(5)	C(5)	Ru(1)	C(13)	113.1(7)
C(1)	Ru(1)	C(10)	122.1(5)	C(6)	Ru(1)	C(9)	118.3(6)
C(1)	Ru(1)	C(11)	158.5(5)	C(6)	Ru(1)	C(10)	151.3(6)
C(1)	Ru(1)	C(12)	157.1(5)	C(6)	Ru(1)	C(11)	164.3(6)
C(1)	Ru(1)	C(13)	120.8(5)	C(6)	Ru(1)	C(12)	126.3(6)
C(2)	Ru(1)	C(3)	37.0(6)	C(6)	Ru(1)	C(13)	106.5(6)
C(2)	Ru(1)	C(4)	67.3(7)	C(9)	Ru(1)	C(10)	37.2(4)
C(2)	Ru(1)	C(5)	79.8(7)	C(9)	Ru(1)	C(11)	64.1(4)
C(2)	Ru(1)	C(6)	68.0(6)	C(9)	Ru(1)	C(12)	64.4(5)
C(2)	Ru(1)	C(9)	116.6(6)	C(9)	Ru(1)	C(13)	38.4(5)
C(2)	Ru(1)	C(10)	106.3(6)	C(10)	Ru(1)	C(11)	38.8(4)
C(2)	Ru(1)	C(11)	126.2(6)	C(10)	Ru(1)	C(12)	64.5(5)
C(2)	Ru(1)	C(12)	164.5(6)	C(10)	Ru(1)	C(13)	63.8(5)
C(2)	Ru(1)	C(13)	150.4(5)	C(11)	Ru(1)	C(12)	38.9(5)
C(3)	Ru(1)	C(4)	37.6(7)	C(11)	Ru(1)	C(13)	65.0(5)
C(3)	Ru(1)	C(5)	68.3(7)	C(12)	Ru(1)	C(13)	38.9(4)
C(3)	Ru(1)	C(6)	80.6(7)	Ru(1)	C(1)	C(2)	71.7(8)
C(3)	Ru(1)	C(9)	142.7(6)	Ru(1)	C(1)	C(6)	73.5(9)
C(3)	Ru(1)	C(10)	112.4(6)	Ru(1)	C(1)	C(7)	125(1)
C(3)	Ru(1)	C(11)	106.9(6)	C(2)	C(1)	C(6)	121(1)
C(3)	Ru(1)	C(12)	164.5(6)	C(2)	C(1)	C(7)	119(1)
C(3)	Ru(1)	C(13)	171.2(6)	C(6)	C(1)	C(7)	118(1)
C(4)	Ru(1)	C(5)	38.4(7)	Ru(1)	C(2)	C(1)	70.1(8)
C(4)	Ru(1)	C(6)	68.3(8)	Ru(1)	C(2)	C(3)	71.9(9)
C(4)	Ru(1)	C(9)	172.9(7)	C(1)	C(2)	C(3)	119(1)
C(4)	Ru(1)	C(10)	137.3(7)	Ru(1)	C(3)	C(2)	71.1(8)
C(4)	Ru(1)	C(11)	108.9(7)	Ru(1)	C(3)	C(4)	71.0(8)
C(4)	Ru(1)	C(12)	110.1(7)	C(2)	C(3)	C(4)	119(1)
C(4)	Ru(1)	C(13)	139.7(7)	Ru(1)	C(4)	C(3)	71.4(8)

(continued)

Ru(1)	C(4)	C(5)	71.0(9)
C(3)	C(4)	C(5)	119(1)
Ru(1)	C(5)	C(4)	70.7(8)
Ru(1)	C(5)	C(6)	72.2(10)
C(4)	C(5)	C(6)	120(1)
Ru(1)	C(6)	C(1)	69.5(8)
Ru(1)	C(6)	C(5)	70.7(9)
C(1)	C(6)	C(5)	118(1)
O(1)	C(7)	O(2)	119(2)
O(1)	C(7)	C(1)	123(2)
O(2)	C(7)	C(1)	116(1)
Ru(1)	C(9)	C(10)	71.5(7)
Ru(1)	C(9)	C(13)	71.7(8)
Ru(1)	C(9)	C(14)	127.2(9)
C(10)	C(9)	C(13)	109(1)
C(10)	C(9)	C(14)	126(1)
C(13)	C(9)	C(14)	123(1)
Ru(1)	C(10)	C(9)	71.3(7)
Ru(1)	C(10)	C(11)	69.4(7)
Ru(1)	C(10)	C(15)	124.0(9)
C(9)	C(10)	C(11)	108(1)
C(9)	C(10)	C(15)	127(1)
C(11)	C(10)	C(15)	123(1)
Ru(1)	C(11)	C(10)	71.8(7)
Ru(1)	C(11)	C(12)	71.2(7)
Ru(1)	C(11)	C(16)	127.4(10)
C(10)	C(11)	C(12)	107(1)
C(10)	C(11)	C(16)	125(1)
C(12)	C(11)	C(16)	126(1)
Ru(1)	C(12)	C(11)	69.9(7)
Ru(1)	C(12)	C(13)	71.9(9)
Ru(1)	C(12)	C(17)	129.1(10)
C(11)	C(12)	C(13)	107(1)
C(11)	C(12)	C(17)	125(1)
C(13)	C(12)	C(17)	126(1)
Ru(1)	C(13)	C(9)	69.9(8)
Ru(1)	C(13)	C(12)	69.2(8)
Ru(1)	C(13)	C(18)	129(9)
C(9)	C(13)	C(12)	106(1)
C(9)	C(13)	C(18)	127(1)
C(12)	C(13)	C(18)	126(1)

Experimental Section

General. GLC analyses were performed on a Shimadzu GC-8A gas chromatograph with a glass column (3 mm i.d. x 3 m) packed with Silicone SE-30 (5% on Chromosorb W(AW-DMCS), 80-100 mesh) and a Shimadzu GC-14A gas chromatograph with a capillary column [Shimadzu capillary column HiCap-CBP10-M25-025 (polarity similar to OV-1701): 0.22 mm i.d. x 25 m]. The ^{1}H (270, 300, and 400 MHz) and ^{13}C NMR spectra (67.5, 75, and 100 MHz) were obtained on JEOL GSX-270, AL-300, and EX-400 spectrometers, respectively. Samples were analyzed in $CDCl_3$ or CD_2Cl_2 and the chemical shift values are expressed relative to Me_4Si as an internal standard. IR spectra were obtained on a Nicolet Impact 410 spectrometer. High resolution mass spectra (HRMS) were obtained on a JEOL JMS-SX102A spectrometer. Elemental analyses were performed at the Microanalytical Center of Kyoto University.

Materials. The reagents used in this study were dried and purified before use by standard procedures. Cyclic allylic carbonates (**1a-e**) were prepared from the corresponding alcohols and methyl chloroformate according to the reported procedure.[21] *cis*- And *trans*-5-(methoxycarbonyl)cyclohex-2-en-1-ol, and *trans*-5-(methoxycarbonyl)cyclohex-2-enyl chloride (*trans*-**6a**) were prepared as described in the literature.[22] NH_4PF_6 and $Ru_3(CO)_{12}$ were obtained commercially and used without further purification. Ru(cod)(cot),[23] $RuH_2(PPh_3)_4$,[24] $RuCl_2(PPh_3)_3$,[25] Cp*RuCl(cod),[26] CpRuCl(cod),[27] and $CpRuCl(PPh_3)_2$[28] were prepared as described in the literature.

General Procedure. A mixture of cyclic allylic carbonate (**1**) (1.0 mmol), *N*-nucleophile (**2**) or *C*-nucleophile (**4a**) (2.0 mmol), CpRuCl(cod) (15.5 mg, 0.050 mmol), NH_4PF_6 (16.3 mg, 0.10 mmol), and decane (2.0 mL) was placed in a two-necked 20-mL Pyrex flask equipped with a magnetic stirring bar and a reflux condenser under a flow of argon. The mixture was magnetically stirred at 100 °C for 24 h. After the reaction mixture was cooled, the products were analyzed by GLC and isolated by column chromatography [Florisil® (60-100 mesh), eluent: Et_2O], followed by Kugelrohr distillation.

The spectral and analytical data of compounds **3a**,[29] **3c**,[30] **3d**,[31] **5a**,[32] *trans*-**5b**,[10] and *cis*-**5b**[10] have already been reported. All of the new compounds are characterized below.

3-Methylcyclohex-2-enyl methyl carbonate (1d). Colorless liquid, bp 60-65 °C (1.0 mmHg, Kugelrohr); IR (neat) 1672, 1749 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz): δ 1.61-1.64 (m, 1H), 1.71 (s, 3H), 1.75-1.79 (m, 3H), 1.94-1.96 (m, 2H), 3.77 (s, 3H), 5.08 (br, 1H), 5.53 (br, 1H); ^{13}C NMR ($CDCl_3$, 67.5 MHz): δ 18.4, 23.3, 27.6, 29.6, 54.0, 72.2, 119.1, 141.3, 155.2; MS (EI) m/z 170 (M^+). Anal. Calcd for $C_9H_{14}O_3$: C 63.51, H 8.29. Found: C 63.75, H 8.49.

***N*-(Cyclohex-2-enyl)dipropylamine (3b).** Colorless liquid, bp 50-55 °C (1.0 mmHg, Kugelrohr); IR (neat) 724, 1656 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ 0.85 (t, 3H, J = 7.34 Hz), 1.26 (br, 2H), 1.42 (m, 4H), 1.76-1.80 (m, 2H), 1.95 (br, 2H), 2.27-2.46 (m, 4H), 3.34 (br, 1H), 5.59-5.62 (m, 1H), 5.70-5.80 (m, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 11.9, 22.0, 22.4, 23.9, 25.4, 53.0, 57.1, 129.2, 131.3; MS (EI) m/z 181 (M^+). Anal. Calcd for $C_{12}H_{23}N$: C 79.49, H 12.78. Found: C 79.36, H 12.88.

***N*-(Cyclohept-2-eyl)piperidine (3e).** Colorless liquid, bp 60-70 °C (1.0 mmHg, Kugelrohr); IR (neat) 1650 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ 1.24-1.34 (m, 2H), 1.34-1.47 (m, 3H), 1.50-1.63 (m, 4H), 1.63-1.70 (m, 1H), 1.82-1.86 (m, 1H), 1.90-2.20 (m, 3H), 2.42-2.55 (m, 4H), 3.20 (br, 1H), 5.72-5.85 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 24.7, 26.4, 26.6, 28.3, 28.9, 29.2, 49.5, 65.4, 130.4, 135.1; MS (EI) m/z 179 (M^+). Anal. Calcd for $C_{12}H_{21}N$: C 80.38, H 11.80. Found: C 80.10, H 11.65.

***N*-(3-Methylcyclohex-2-enyl)piperidine (3f).** Colorless liquid, bp 60-70 °C (1.0 mmHg, Kugelrohr); IR (neat) 1687 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ 1.35-1.50 (m, 2H), 1.50-1.61 (m, 6H), 1.67 (s, 3H), 1.71-1.82 (m, 2H), 1.82-1.95 (m, 2H), 2.42-2.61 (m, 4H), 3.12 (m, 1H), 5.38 (br, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 22.4, 23.7, 24.8, 25.0, 26.5, 30.1, 49.7, 61.3, 124.3, 136.6; MS (EI) m/z 179 (M^+). Exact mass: calcd for $C_{12}H_{21}N$: 179.1675. Found: 179.1673.

***N*-(1-Methylcyclohex-2-enyl)piperidine (3f').** Colorless liquid, bp 60-70 °C (1.0 mmHg, Kugelrohr); IR (neat) 737, 1673 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ 1.17 (s, 3H), 1.35-1.50 (m, 2H), 1.50-1.61 (m, 6H), 1.71-1.82 (m, 2H), 1.82-1.95 (m, 2H), 2.42-2.61 (m, 4H), 5.50 (d, 1H, J = 10.28 Hz), 5.67 (dt, 1H, J = 10.28, 3.76 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.4, 21.9, 24.9, 25.5, 26.8, 28.0, 46.9, 56.7, 126.7, 135.5; MS (EI) m/z 179 (M^+). These spectral data were obtained for a 77:23 mixture of **3f** and **3f'**.

Methyl *cis*-5-Piperidinylcyclohex-3-enecarboxylate (*cis*-3g). Colorless liquid, bp 100-110 °C (1.0 mmHg, Kugelrohr); IR (neat) 1736 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz); δ 1.41-1.46 (m, 2H), 1.54-1.60 (m, 4H), 1.63 (q, 1H, J = 7.81 Hz), 2.08-2.11 (m, 1H), 2.19-2.23 (m, 2H), 2.47-2.50 (m, 2H), 2.54-2.62 (m, 3H), 3.36 (m, 1H), 3.70 (s, 3H), 5.66-5.69 (m, 1H), 5.75-5.77 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 24.7, 25.0, 26.5, 27.9, 39.4, 49.5, 51.7, 61.3, 127.1, 130.6, 175.9; MS (EI) m/z 223 (M^+). Anal. Calcd for $C_{13}H_{21}NO_2$: C 69.92, H 9.48. Found: C 69.87, H 9.26.

Methyl *trans*-5-Piperidinylcyclohex-3-enecarboxylate (*trans*-3g). Colorless liquid, bp 100-110 °C (1.0 mmHg, Kugelrohr); IR (neat) 1736 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz); δ 1.41-1.46 (m, 2H), 1.51-1.62 (m, 4H), 1.76

(ddd, 1H, J = 5.86, 9.72, 13.67 Hz), 2.06 (td, 1H, J = 4.40, 13.67 Hz), 2.22-2.26 (m, 2H), 2.43-2.50 (m, 2H), 2.54-2.61 (m, 2H), 2.72-2.79 (m, 1H), 3.13-3.14 (m, 1H), 3.69 (s, 3H), 5.68-5.75 (m, 1H), 5.82-5.87 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 24.6, 25.0, 26.4, 27.1, 36.9, 49.2, 50.5, 57.5, 127.5, 128.4, 175.6; MS (EI) m/z 223 (M^+). Anal. Calcd for $C_{13}H_{21}NO_2$: C 69.92, H 9.48. Found: C 69.85, H 9.21.

Preparation of [Cp*Ru(η^6-$C_6H_5CO_2Me$)]$^+$[Cl]$^-$ (7) and [Cp*Ru(η^6-$C_6H_5CO_2Me$)]$^+$[BPh$_4$]$^-$ (8). A mixture of Cp*RuCl(cod) (75.9 mg, 0.20 mmol), *trans*-**6a** (0.50 mmol), and ethanol (5.0 mL) was placed in a two-necked 20-mL Pyrex flask equipped with a magnetic stirring bar under a flow of argon. The mixture was magnetically stirred at 50 °C for 5 h. After the mixture was cooled, the solvent was evaporated and the orange residue was washed with pentane (10 mL x 2), followed by drying in vacuo to give 73.4 mg (0.18 mmol, 90%) of [Cp*Ru(η^6-$C_6H_5CO_2Me$)]$^+$[Cl]$^-$ (**7**) as an orange powder. Mp 277.2-279.5 °C (dec.). IR (KBr) 1726 cm^{-1}; ^{1}H NMR (270 MHz, CD_2Cl_2); δ 2.16 (s, 15H), 4.06 (s, 3H), 6.72 (br, 2H), 7.26-7.31 (br, 2H), 7.70-7.71 (br, 1H).

A mixture of complex **7** (73.4 mg, 0.18 mmol), $NaBPh_4$ (68.4 mg, 0.20 mmol), and acetone (2.0 mL) was placed in a two-necked 20-mL Pyrex flask equipped with a magnetic stirring bar under a flow of argon. The mixture was magnetically stirred at room temperature. After 2 h, the white precipitate (NaCl) was filtered off, and washed with acetone (5 mL x 2). The combined filtrate was evaporated, and the orange residue was recrystallized from CH_2Cl_2/Et_2O to give 103.2 mg (0.15 mmol, 83%) of [Cp*Ru(η^6-$C_6H_5CO_2Me$)]$^+$[BPh$_4$]$^-$ (**8**) as orange crystals. Mp 175.6-179.0 °C (dec.). IR (KBr) 1730 cm^{-1}; ^{1}H NMR (270 MHz, CD_2Cl_2); δ 1.83 (s, 15H), 3.96 (s, 3H), 5.49-5.54 (m, 3H), 6.14 (d, 2H, J = 6.24 Hz), 6.87 (t, 4H, J = 7.16 Hz), 7.02 (t, 8H,

$J = 7.43$ Hz), 7.31 (m, 8 H); ^{13}C NMR (CD_2Cl_2, 67.5 MHz): δ 10.5, 53.9, 87.1, 87.9, 88.6, 98.4, 122.2, 125.9, 126.0, 136.3, 163.3, 164.0, 164.6, 164.7, 165.4.

X-ray Structural Determination of $[Cp^*Ru(\eta^6\text{-}C_6H_5CO_2Me)]^+[BPh_4]^-$ (8). Crystal data, data collection, and refinement parameters for $[Cp^*Ru(\eta^6\text{-}C_6H_5CO_2Me)]^+[BPh_4]^-$ (**8**) are summarized in Tables 3-6. A single crystal of $[Cp^*Ru(\eta^6\text{-}C_6H_5CO_2Me)]^+[BPh_4]^-$ (**8**) was mounted and placed on a Rigaku AFC-7R diffractometer. The unit cell was determined by the automatic indexing of 20 centered reflections and confirmed by the examination of axial photographs. Intensity data were collected using graphite-monochromated MoKα X-radiation (λ = 0.71069 Å). Check reflections were measured every 150 reflections; the data were scaled accordingly and corrected for Lorentz, polarization, and absorption effects. The structure was determined using Patterson and standard difference map techniques on an O2 computer using SHELX97.[33] Systematic absences were uniquely consistent with the space group $P2_12_12_1$ [No. 19].

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Chapter 2

First Ruthenium-Catalyzed Allylation of Thiols Enables the General Synthesis of Allylic Sulfides

Abstract

Cp*RuCl(cod) [Cp* = pentamethylcyclopentadienyl, cod = 1,5-cyclooctadiene] is a highly effective catalyst for the allylation of both aliphatic and aromatic thiols with allylic carbonates. In the presence of a catalytic amount of Cp*RuCl(cod) (5 mol %) at room temperature for 1 h under an argon atmosphere in CH_3CN, general allylic sulfides were readily obtained in high yields. For example, treatment of pentanethiol (**2a**) and benzenethiol (**2b**) with allyl methyl carbonate (**1a**) gave the corresponding allylic sulfides, allyl pentyl sulfide (**3a**) and allyl phenyl sulfide (**3b**), in yields of 96% and 91%, respectively. The regio- and stereochemical courses of the reaction are also examined.

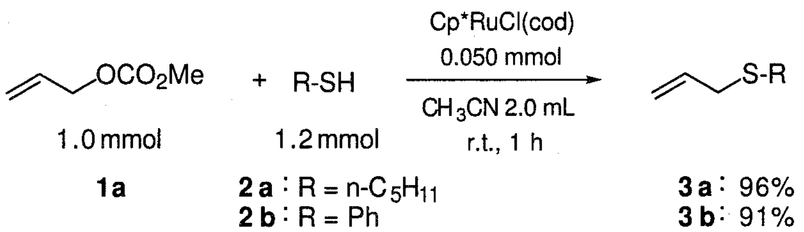
Introduction

The transition-metal complex-catalyzed allylic substitution reaction of nucleophilic reagents with allylic alcohol derivatives is now a well-established methodology in organic synthesis, and is widely used to construct complex organic molecules.[1,2] However, even though a wide range of nucleophiles, such as carbon-, nitrogen-, and oxygen-nucleophiles, and transition-metal catalysts, especially those involving palladium,[2] has been studied,[3] a general method for synthesizing allylic sulfides by the transition-metal complex-catalyzed allylation of sulfur-nucleophiles has not yet been reported, since, in catalytic reactions, sulfur-containing compounds have long been known to act as catalyst poisons because of their strong coordinating properties.[4] Recent progress in the transition-metal complex-catalyzed synthesis of allylic sulfides without poisoning of the catalyst has included (1) rearrangement of *O*-allylphosphoro- or phosphonothionates,[5] (2) conversion of *O*-allyl or *S*-allyl dithiocarbonates with liberation of carbon oxide sulfide (COS),[6] and (3) allylic substitution by silylated thiols,[7] heterocyclic sulfur nucleophiles,[8] sodium thiophenoxides,[9,10c] and aromatic thiols,[10] However, some of these reactions have a serious drawback with regard to substrate preparation. In addition, the catalyst systems reported so far are strictly limited to palladium catalysts,[5-10] and in the simple allylic substitution with thiols, only aromatic and heteroaromatic thiols can be used.[10]

On the other hand, it has been reported that ruthenium complexes, such as Ru(cod)(cot)[11a] [cod = 1,5-cyclooctadiene, cot = 1,3,5-cyclooctatriene] and Cp*RuCl(cod)[11b] [Cp* = pentamethylcyclopentadienyl], facilitate the highly selective catalytic allylation of both carbon- and nitrogen-nucleophiles at the more-substituted allylic termini. In further investigation of the reactivity of several ruthenium complexes toward sulfur-containing compounds,[12] the first example of the transition-metal complex-catalyzed addition of organic disulfides to alkenes was found.[13] Therefore, the ruthenium complex seems to be one of the most promising catalysts for the transformation of sulfur-containing compounds. After many trials, we finally found the first ruthenium-catalyzed allylation of both aliphatic and aromatic thiols with various allylic reagents including allylic alcohols under extremely mild reaction conditions. We report here the development of this new ruthenium-catalyzed reaction which enables a simple and general synthesis of allylic sulfides.

Results and Discussion

Treatment of aliphatic and aromatic thiols, represented by pentanethiol (**2a**) and benzenethiol (**2b**), with allyl methyl carbonate (**1a**) in the presence of 5 mol % Cp*RuCl(cod) in CH_3CN at room temperature for 1 h under an argon atmosphere gave the corresponding allylic sulfides, allyl pentyl sulfide (**3a**) and allyl phenyl sulfide (**3b**), in high yields, respectively (eq 1).



(1)

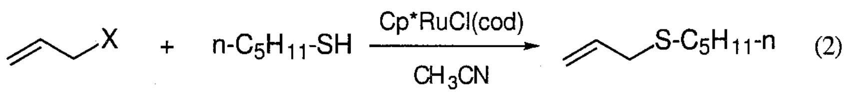
Table 1. Catalytic Activity of Several Ruthenium Complexes on the Synthesis of **3a** by Allylation of **2a** with **1a**[a]

Catalyst	Conv. of **1a** (%)[b]	Yield of **3a** (%)[c]
Cp*RuCl(cod)	100	96 (84)
CpRuCl(cod)	87	86
$CpRuCl(PPh_3)_2$	5	2
(*p*-cymene)$RuCl_2(PPh_3)$	5	trace
$RuCl_2(PPh_3)_3$	34	trace
Ru(cod)(cot)	9	4
$Ru_3(CO)_{12}$[d]	0	0
$RuCl_3 \cdot 3H_2O$	0	0

[a]**1a** (1.0 mmol), **2a** (1.2 mmol), catalyst (0.050 mmol), and CH_3CN (2.0 mL) at room temperature for 1 h under an argon atmosphere. [b]Determined by GLC. [c]Determined by GLC based on the amount of **1a** charged. Figure in the parentheses is an isolated yield. [d]$Ru_3(CO)_{12}$ (0.017 mmol) was used.

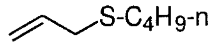
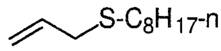
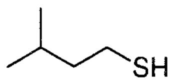
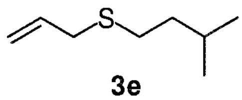
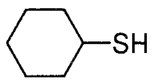
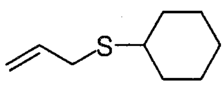
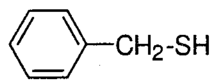
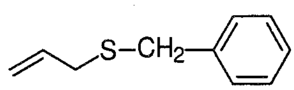
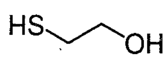
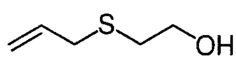
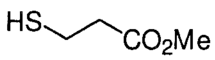
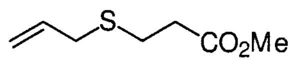
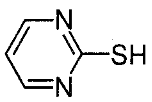
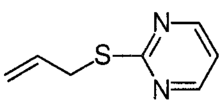
First, the catalytic activity of several ruthenium complexes was examined in the reaction of **1a** with **2a**. The results are summarized in Table 1. Among the catalysts examined, Cp*RuCl(cod) and CpRuCl(cod) showed high catalytic activity. Other di- and zerovalent ruthenium complexes, such as $CpRuCl(PPh_3)_2$, (*p*-cymene)$RuCl_2(PPh_3)$, $RuCl_2(PPh_3)_3$, Ru(cod)(cot), and $Ru_3(CO)_{12}$, were totally ineffective. Almost no reaction occurred with $Pd(PPh_3)_4$, $RhCl(PPh_3)_3$, or $IrCl(CO)(PPh_3)_2$ catalysts, and the present reaction is characteristic of the ruthenium catalysts. The use of an appropriate solvent is also critically important for a successful reaction. Among the solvents examined, CH_3CN gave the best result, which strongly suggests that CH_3CN acts as a suitable ligand to an active ruthenium intermediate as well as a solvent to prevent catalyst poisoning by thiols.

Various allylic compounds, such as allyl ethyl carbonate (**1b**), allyl trifluoroacetate (**1c**), and allyl acetate (**1d**), can be used in the present allylation reaction of pentanethiol (**2a**) to give allyl pentyl sulfide (**3a**) in high yield (eq 2). On the other hand, the yield of **3a** decreased to 38% with allyl phenyl ether (**1e**). Furthermore, under the present reaction conditions, it is difficult to cleave the allylic carbon-sulfur bond with the ruthenium catalyst,[14] as shown in the reaction of allyl phenyl sulfide (**3b**) with **2a**. Note that allyl alcohol *itself* (**1f**), which is considered to be a poor substrate for the formation of η^3-allyl transition-metal complexes, gave **3a** in high yield (88%). The direct use of allylic alcohols as an effective allylating reagent is an important theme in transition-metal complex-catalyzed allylation reactions and is highly economical in terms of atoms used.[15]



1b : X = OCO_2Et	**2a**		**3a** : > 99% (1 h)
1c : X = $OCOCF_3$			> 99% (1 h)
1d : X = OAc			88% (5 h)
1e : X = OPh			38% (24 h)
1f : X = OH			88% (40 °C, 7 h)
3b : X = SPh			8% (24 h)

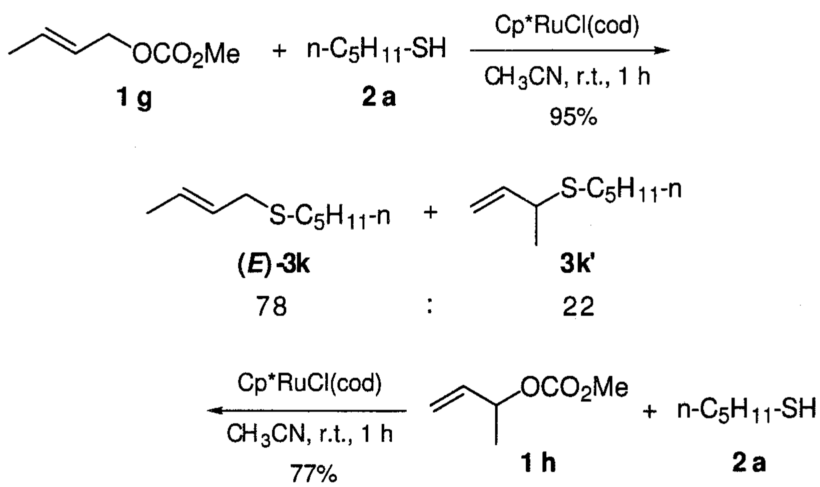
Table 2. Cp*RuCl(cod)-Catalyzed Allylation of Thiols with Allyl Methyl Carbonate (**1a**)[a]

Run	Thiol	Product	Isolated Yield (%)[b]
1	n-C_4H_9-SH **2c**	 **3c**	(97)[c]
2	n-C_8H_{17}-SH **2d**	 **3d**	93
3	 **2e**	 **3e**	72
4	 **2f**	 **3f**	77
5	 **2g**	 **3g**	97
6	 **2h**	 **3h**	90
7	 **2i**	 **3i**	87
8[d]	 **2j**	 **3j**	70

[a]**1a** (1.0 mmol), **2** (1.2 mmol), Cp*RuCl(cod) (0.050 mmol), and CH_3CN (2.0 mL) at room temperature for 1 h under an argon atmosphere. [b]Based on the amount of **1a** charged. [c]GLC yield. [d]For 10 h.

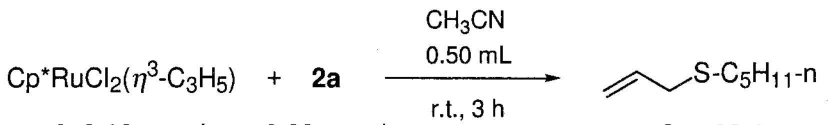
The allylation of several aliphatic and heteroaromatic thiols (**2c-j**) with allyl methyl carbonate (**1a**) also proceeded smoothly with a Cp*RuCl(cod) catalyst, and the results are listed in Table 2.[16] In all cases, **1a** was completely consumed, and the corresponding allylic sulfides were obtained in high isolated yields. No byproducts could be detected by GLC. Some functional groups, such as hydroxyl (**2h**) and methoxycarbonyl groups (**2i**), did not affect the reaction.

Allylic rearrangements consistent with the formation of an η^3-allylruthenium intermediate were observed. The two regioisomeric allylic carbonates, (*E*)-crotyl methyl carbonate (**1g**) and 3-buten-2-yl methyl carbonate (**1h**), reacted with **2a** to give identical mixtures of regioisomeric sulfides ((*E*)-**3k** + **3k'**) (eq 3). Interestingly, the regioselectivity is totally different from those observed in the ruthenium-catalyzed allylation of carbon-[11a] and nitrogen-nucleophiles.[11b] In the present reaction, the attack of sulfur-nucleophiles predominantly occurred at the less-substituted allylic termini of an η^3-allylruthenium intermediate.



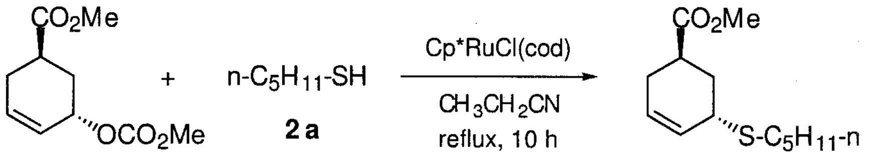
(3)

To further clarify the intermediacy of an η^3-allylruthenium complex, the stoichiometric reaction of $Cp^*RuCl_2(\eta^3\text{-}C_3H_5)$ (**4**) with **2a** was examined, and the corresponding allyl pentyl sulfide (**3a**) was obtained in an isolated yield of 66% (eq 4).



4 0.10 mmol 0.20 mmol **3a**, 66% (4)

The stereochemical course of the reaction was also investigated (eq 5). Since the reactivity of cyclic allylic carbonate, *trans*-5-(methoxycarbonyl)-2-cyclohexen-1-yl methyl carbonate (**1i**), was lower than those of acyclic allylic carbonates, relatively severe reaction conditions (i.e., reflux (97 ^oC) in CH_3CH_2CN for 10 h) were required for completion of the reaction, in which the product (**3l**), with a net retention of configuration, was obtained exclusively in an isolated yield of 70% by the reaction of **1i** with **2a**. This result suggests that the reaction proceeds with a double inversion mechanism,[17] considering that nucleophilic attack of soft nucleophiles to η^3-allylruthenium complexes proceeded via an inversion of configuration.[18]



1i **3l**, 70% (*trans* 100%) (5)

In conclusion, a ruthenium complex was found to be a new and highly efficient catalyst for the allylation of both aliphatic and aromatic thiols under extremely mild reaction conditions, which enables the general and practical synthesis of allylic sulfides. This reaction should open up new opportunities in transition-metal complex-catalyzed sulfur chemistry, since organosulfur compounds are quite useful intermediates in organic synthesis.[19] The development of a catalyst system which gives the opposite regioselectivity, leading to development of the enantioselective version of this reaction, is currently under investigation.

Experimental Section

General. GLC analyses were carried out on a gas chromatograph equipped with a glass column (3 mm i.d. x 3 m) packed with Silicone SE-30 (5% on Chromosorb W(AW-DMCS), 80-100 mesh). The ^{1}H-NMR spectra were recorded at 300 MHz, and the ^{13}C-NMR spectra were recorded at 75 MHz. Samples were analyzed in $CDCl_3$, and the chemical shift values are expressed relative to Me_4Si as an internal standard. High resolution mass spectra (HRMS) were obtained on a JEOL JMS-SX102A spectrometer. Elemental analyses were performed at the Microanalytical Center of Kyoto University.

Materials. The reagents used in this study were dried and purified before use by standard procedures. Allylic carbonates (**1a**, **1b**, **1g**, **1h**, and **1i**) were prepared from the corresponding alcohols and methyl or ethyl chloroformate according to the reported procedure.[20,21] Other allylic compounds (**1c**-**f**, and **3b**) were obtained commercially, and used after distillation. $Ru_3(CO)_{12}$, $RuCl_3{\cdot}3H_2O$, $RhCl(PPh_3)_3$, $IrCl(CO)(PPh_3)_2$, and $Pd_2(dba)_3$ were obtained commercially, and used without further purification. Cp*RuCl(cod),[22] CpRuCl(cod),[23] $CpRuCl(PPh_3)_2$,[24] (*p*-cymene)$RuCl_2(PPh_3)$,[25] $RuCl_2(PPh_3)_3$,[26] Ru(cod)(cot),[27] $Pd(PPh_3)_4$,[28] and Cp*$RuCl_2(\eta^3\text{-}C_3H_5)$[29] were prepared as described in the literature.

Allylation of Thiols (2a-j) with Allylic Carbonates (1a, 1b, 1g, and 1h). A mixture of allylic carbonate (1.0 mmol), thiol (1.2 mmol), Cp*RuCl(cod) (0.050 mmol), and CH_3CN (2.0 mL) was placed in a two-necked 20-mL Pyrex flask equipped with a magnetic stirring bar under a flow of argon. The reaction was carried out at room temperature for 1 h with stirring. The products were isolated by Kugelrohr distillation.

Stoichiometric Reaction of $Cp^*RuCl_2(\eta^3\text{-}C_3H_5)$ (4) with Pentanethiol (2a). A mixture of $Cp^*RuCl_2(\eta^3\text{-}C_3H_5)$ (**4**) (0.10 mmol), pentanethiol (**2a**) (0.20 mmol), and CH_3CN (0.50 mL) was placed in a two-necked 20-mL Pyrex flask equipped with a magnetic stirring bar under a flow of argon. The reaction was carried out at room temperature for 3 h with stirring. The product (**3a**) was isolated by Kugelrohr distillation.

Allylation of Pentanethiol (2a) with Cyclic Allyl Carbonate (1i). A mixture of cyclic allyl carbonate (**1i**) (1.0 mmol), pentanethiol (**2a**) (1.2 mmol), Cp*RuCl(cod) (0.050 mmol), and CH_3CH_2CN (2.0 mL) was placed in a two-necked 20-mL Pyrex flask equipped with a magnetic stirring bar and a reflux condenser under a flow of argon. The reaction was carried out under reflux (bath temp. 100 °C) for 10 h with stirring. After the reaction mixture was cooled, the product (**3l**) was isolated by column chromatography [Florisil® (60-100 mesh), eluent: Et_2O], followed by Kugelrohr distillation.

The spectral and analytical data of **3b** were fully consistent with those of an authentic sample. Compounds, **3c**,[30] **3d**,[31] and **3g**,[31] have already been reported. All of the new compounds are characterized below.

Allyl pentyl sulfide (3a). Colorless liquid, bp 50-55 °C (5.0 mmHg, Kugelrohr); IR (neat) 914, 989, 1634 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ 0.90 (t, 3H, J = 6.98 Hz), 1.34 (m, 4H), 1.57 (m, 2H), 2.45 (t, 2H, J = 7.44 Hz), 3.12 (d, 2H, J = 7.34 Hz), 5.07 (d, 1H, J = 10.65 Hz), 5.08 (d, 1H, J = 16.16 Hz), 5.79 (tdd, 1H, J = 7.34, 10.65, 16.16 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 13.9, 22.3, 29.0, 30.6, 31.0, 34.7, 116.6, 134.6; MS (EI) m/z 144 (M^+). Anal. Calcd for $C_8H_{16}S$: C 66.60, H 11.18. Found: C 66.32, H 11.09.

Allyl isopentyl sulfide (3e). Colorless liquid, bp 50-55 °C (5.0 mmHg, Kugelrohr); IR (neat) 914, 989, 1634 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ 0.89 (d, 6H, J = 6.61 Hz), 1.45 (m, 2H), 1.66 (m, 1H), 2.45 (t, 2H, J = 7.71 Hz), 3.12 (d, 2H, J = 7.16 Hz), 5.07 (d, 1H, J = 11.35 Hz), 5.08 (d, 1H, J = 15.78 Hz), 5.78 (tdd, 1H, J = 7.16, 11.35, 15.78 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 22.3, 27.5, 28.6, 34.7, 38.3, 116.6, 134.5; MS (EI) m/z 144 (M^+). Anal. Calcd for $C_8H_{16}S$: C 66.60, H 11.18. Found: C 66.36, H 11.10.

Allyl cyclohexyl sulfide (3f). Colorless liquid, bp 80-85 °C (3.0 mmHg, Kugelrohr); IR (neat) 913, 998, 1634 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.24-1.31 (m, 5H), 1.61 (br, 1H), 1.75 (m, 2H), 1.93 (m, 2H), 2.62 (m, 1H), 3.28 (d, 2H, J = 7.16 Hz), 5.05 (d, 1H, J = 10.46 Hz), 5.10 (d, 1H, J = 17.62 Hz), 5.82 (tdd, 1H, J = 7.16, 10.46, 17.62 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 25.81, 25.98, 33.13, 33.36, 42.20, 116.3, 135.0; MS (EI) m/z 156 (M^+). Anal. Calcd for $C_9H_{16}S$: C 69.17, H 10.32. Found: C 69.37, H 10.58.

2-Prop-2-enylthioethan-1-ol (3h). Colorless liquid, bp 100-105 °C (3.0 mmHg, Kugelrohr); IR (neat) 919, 991, 1634, 3364 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz): δ 2.34 (br, 1H), 2.67 (t, 2H, J = 6.15 Hz), 3.14 (d, 2H, J = 7.16 Hz), 3.70 (t, 2H, J = 6.15 Hz), 5.09 (d, 1H, J = 11.12 Hz), 5.10 (d, 1H, J = 15.42 Hz), 5.72 (tdd, 1H, J = 7.16, 11.12, 15.42 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 33.6, 34.1, 60.14, 117.4, 134.1; MS (EI) m/z 118 (M^+). Anal. Calcd for $C_5H_{10}OS$: C 50.81, H 8.53. Found: C 50.89, H 8.64.

Methyl 3-prop-2-enylthiopropanoate (3i). Colorless liquid, bp 80-85 °C (3.0 mmHg, Kugelrohr); IR (neat) 913, 998, 1634, 1739 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz): δ 2.54 (t, 2H, J=7.20 Hz), 2.68 (t, 2H, J=7.20 Hz), 3.10 (d, 2H, J=7.16 Hz), 3.65 (s, 3H) 5.06 (d, 1H, J=9.91 Hz), 5.07 (d, 1H, J=16.88 Hz), 5.73 (tdd, 1H, J=7.16, 9.91, 16.88 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 25.3, 34.2, 34.6, 51.6, 117.1, 134.0, 172.2; MS (EI) m/z 160 (M^+). Anal. Calcd for $C_7H_{12}O_2S$: C 52.47, H 7.55. Found: C 52.73, H 7.63.

Allyl pyrimidyl sulfide (3j). Colorless liquid, bp 145-150 °C (2.0 mmHg, Kugelrohr); IR (neat) 921, 990, 1636 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz):

δ 3.80 (d, 2H, *J* = 6.79 Hz), 5.11 (dd, 1H, *J* = 1.10, 10.09 Hz), 5.33 (dd, 1H, *J* = 1.10, 16.88 Hz), 5.97 (tdd, 1H, *J* = 6.79, 10.09, 16.88 Hz) 6.94 (t, 1H, *J* = 4.77 Hz) 8.49 (d, 2H, *J* = 4.77 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 33.6, 116.4, 117.7, 133.3, 157.1, 171.9; MS (EI) m/z 152 (M^+). Anal. Calcd for $C_7H_8N_2S$: C 55.24, H 5.30. Found: C 55.65, H 5.34.

(*E*)-2-Buten-1-yl pentyl sulfide (3k). Colorless liquid, bp 70-75 ^oC (5.0 mmHg, Kugelrohr); IR (neat) 925, 964, 1666 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz): δ 0.89 (t, 3H, *J* = 7.07 Hz), 1.31 (m, 4H), 1.55 (m, 2H), 1.68 (d, 3H, *J* = 5.87 Hz), 2.43 (t, 2H, *J* = 7.43 Hz), 3.58 (d, 2H, *J* = 6.06 Hz), 5.46 (qd, 1H, *J* = 16.15, 5.87 Hz), 5.48 (td, 1H, *J* = 16.15, 6.06 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 13.9, 17.6, 22.3, 29.3, 30.7, 31.1, 33.9, 127.3, 127.7; MS (EI) m/z 158 (M^+). Anal. Calcd for $C_9H_{18}S$: C 68.29, H 11.46. Found (for a 78:22 mixture of **3k** and **3k'**): C 68.38, H 11.19.

3-Buten-2-yl pentyl sulfide (3k'). Colorless liquid, bp 70-75 ^oC (5.0 mmHg, Kugelrohr); IR (neat) 925, 964, 1634 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz): δ 0.89 (t, 3H, *J* = 7.07 Hz), 1.29 (d, 3H, *J* = 7.80 Hz), 1.31 (m, 4H), 1.55 (m, 2H), 2.43 (t, 2H, *J* = 7.43 Hz), 3.29 (qd, 1H, *J* = 8.81, 7.80 Hz), 4.96 (dd, 1H, *J* = 17.10, 1.50 Hz), 4.97 (dd, 1H, *J* = 10.50, 1.50 Hz), 5.69 (ddd, 1H, *J* = 17.10, 10.50, 8.81 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 20.2, 22.3, 29.3, 30.5, 30.7, 31.2, 42.8, 113.7, 140.7; MS (EI) m/z 158 (M^+). Exact mass: calcd for $C_9H_{18}S$: 158.1130. Found: 158.1122.

Methyl *trans*-5-pentylthiocyclohex-3-enecarboxylate (3l). Colorless liquid, bp 120-125 ^oC (1.0 mmHg, Kugelrohr); IR (neat) 1436, 1738 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz): δ 0.89 (t, 3H, *J* = 6.88 Hz), 1.25-1.42 (m, 4H), 1.57-1.62 (m, 2H), 1.96 (ddd, 1H, *J* = 11.74, 11.74, 4.59 Hz), 2.13-2.36 (m, 3H), 2.50-2.58 (m, 2H), 2.93-3.00 (m, 1H), 3.45 (br, 1H), 3.69 (s, 3H), 5.70-5.74 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 13.9, 22.3, 27.6, 29.5, 30.9, 31.1, 31.9, 35.1, 40.1, 51.7, 126.9, 127.4, 176.0 ; MS (EI) m/z 242 (M^+). Exact mass: calcd for $C_{13}H_{22}O_2S$: 242.1340. Found: 242.1340.

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Chapter 3

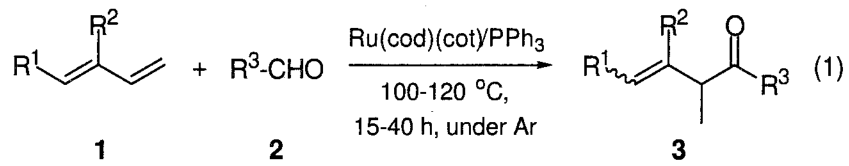
First Intermolecular Hydroacylation of 1,3-Dienes with Aldehydes Catalyzed by Ruthenium

Abstract

Ru(cod)(cot)/PPh_3 [cod = 1,5-cyclooctadiene, cot = 1,3,5-cyclooctatriene] is an effective catalyst system for the first intermolecular hydroacylation of 1,3-dienes with aromatic and heteroaromatic aldehydes to give the corresponding β,γ-unsaturated ketones in reasonable yields. In this reaction, carbon monoxide is not needed to suppress decarbonylation of aldehydes as well as to maintain the catalytic activity. The key intermediate is an (acyl)(η^3-allyl)ruthenium complex which undergoes reductive elimination to give the corresponding ketones.

Introduction

Hydroacylation is an intriguing catalytic process because of its potential usefulness in the general synthesis of ketones from alkenes and aldehydes. Although activation of the formyl C-H bond by transition-metal complexes often leads to decarbonylation,[1] a hydrido-acyl intermediate could hydroacylate an unsaturated bond if the rate of hydroacylation is faster than the rate of decarbonylation. With rhodium-based catalysts, conversion of 4-pentenals to cyclopentanones via intramolecular hydroacylation has been extensively studied,[2,3] and has been extended to asymmetric cyclization of substituted 4-pentenals into chiral cyclopentanones.[4,5] Recently, several examples of rhodium-catalyzed hydroiminoacylation were also reported as analogues of hydroacylation.[6] However, the catalytic systems reported so far are strictly limited to rhodium, and there are still only a few examples of a transition-metal-catalyzed *intermolecular* hydroacylation reactions,[7,8] each of which has some limitations. Recently, the reactivity of η^3-allylruthenium complexes[9] as well as ruthenium-catalyzed activation of the formyl C-H bond have been reported.[10] In this chapter, we report the first example of ruthenium-catalyzed intermolecular hydroacylation of 1,3-dienes with aldehydes (eq 1).[11]



The reaction of 1,3-dienes with aldehydes catalyzed by transition-metal complexes, especially those involving palladium, generally yields tetrahydropyran derivatives and/or open-chain homoallyl alcohols.[12] Therefore, the present reaction represents the first method for preparing β,γ-unsaturated ketones from readily available 1,3-dienes and aldehydes.

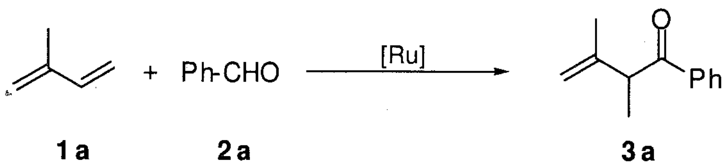
Results and Discussion

We initially examined the reaction of isoprene (**1a**) with benzaldehyde (**2a**) in the presence of several ruthenium complexes. The results are summarized in Table 1. The reaction of **2a** (5.0 mmol) with **1a** (4.0 mL) in the presence of a catalytic amount of Ru(cod)(cot) and PPh_3 (4.0 mol % each) at 120 °C for 15 h under an argon atmosphere gave the corresponding β,γ-unsaturated ketone (**3a**) in 40% yield. Conversion of benzaldehyde was 80% and the only byproduct derived from benzaldehyde was benzene. Other catalyst systems, such as $RuH_2(PPh_3)_4$, $Ru_3(CO)_{12}/PPh_3$, and $Cp^*RuCl(cod)/PPh_3$, were totally ineffective.

The effect of the molar ratio of PPh_3 to Ru(cod)(cot) was examined in the hydroacylation of **1a** with **2a** at 120 °C for 15 h under an argon atmosphere. As can be readily seen from Figure 1, the catalytic activity of Ru(cod)(cot) was greatly affected by the amount of PPh_3 ligand added. The best result was obtained when the PPh_3/Ru(cod)(cot) ratio was 1.0. Ratios higher and lower than 1.0 both led to a low conversion of aldehyde **2a** and a low yield of the product **3a**. The combination of Ru(cod)(cot) with suitable tertiary phosphine ligands can provide several useful catalytic systems,[13] but there is no information available regarding the reaction of Ru(cod)(cot) with bulky phosphines such as PPh_3. In the early stage of the present catalytic process, PPh_3 could react with

Ru(cod)(cot) to give Ru(η^4-cod)(η^4-cot)(PPh_3) in a manner similar to the reaction with PMe_3 and $P(OMe)_3$.[14,15]

Table 1. Catalytic Activity of Several Ruthenium Complexes in the Hydroacylation of Isoprene (**1a**) with Benzaldehydes (**2a**)[a]



Run	Ru Complex	Ligand	Conv. of **2a**[b]	Yield of **3a** (%)[b]
1	-	PPh_3	7	0
2	Ru(cod)(cot)	-	33	7
3	Ru(cod)(cot)	PPh_3	80	40
4	$RuH_2(PPh_3)_4$	-	32	6
5[c]	$Ru_3(CO)_{12}$	PPh_3	13	2
6	Cp*RuCl(cod)	PPh_3	0	0

[a]A mixture of isoprene (**1a**) (4.0 mL), benzaldehyde (**2a**) (5.0 mmol), Ru(cod)(cot) (0.20 mmol) and PPh_3 (0.20 mmol) in a 50-mL stainless steel autoclave was heated at 120 °C for 15 h under an argon atmosphere. [b]Determined by GLC based on the amoumt of **2a** charged. [c]$Ru_3(CO)_{12}$ (0.066 mmol) was used.

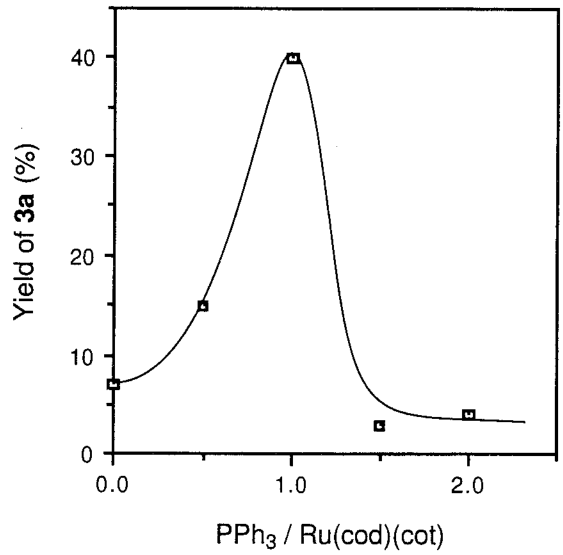


Figure 1. Effect of the molar ratio of PPh_3/Ru(cod)(cot) on the hydroacylation of **1a** with **2a**. Reaction conditions: **1a** (4.0 mL), **2a** (5.0 mmol), and Ru(cod)(cot) (0.20 mmol) at 120 °C for 15 h under an argon atmosphere.

As for phosphorus ligands, with the use of more electron-donating ligands, such as PCy_3 and P(*o*-Tol)$_3$ instead of PPh_3, Tishchenko-type dimerization of **2a** mainly proceeded to give the corresponding ester, benzyl benzoate, as the main product (Runs 2 and 3 in Table 2).[16] In addition, although the combination of Ru(cod)(cot) with electron-withdrawing ligands, such as P(*p*-FC_6H_4)$_3$, showed good catalytic activity (Run 4), combination with triaryl or trialkylphosphite, such as P(OPh)$_3$ and P(OBu)$_3$, resulted in vain (Runs 5 and 6).

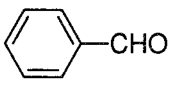
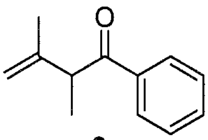
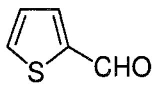
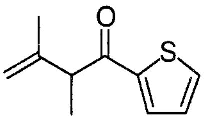
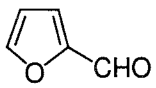
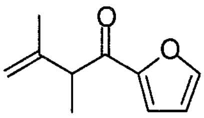
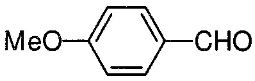
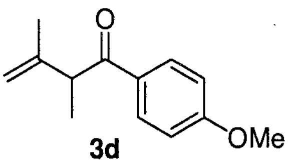
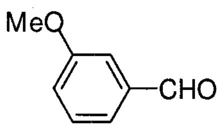
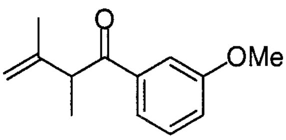
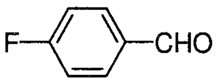
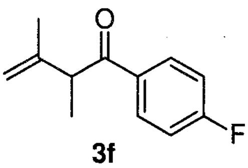
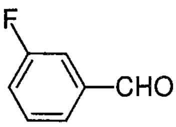
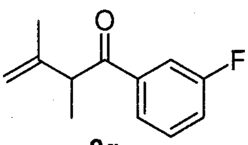
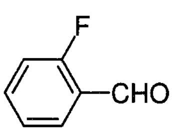
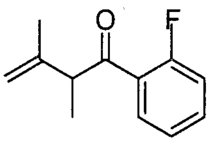
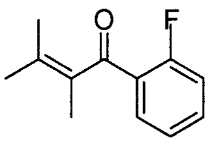
Table 2. Ligand Effects on Ru(cod)(cot)-Catalyzed Intermolecular Hydroacylation of Isoprene (**1a**) with Benzaldehyde (**2a**)[a]

Run	Ligand	Conv. of **2a**[b]	Yield (%)[b]	
			3a	$PhCO_2CH_2Ph$
1	PPh_3	80	40	trace
2	PCy_3	85	0	18
3	P(*o*-Tol)$_3$	89	13	31
4	P(*p*-FC_6H_4)$_3$	75	40	trace
5	$P(OPh)_3$	-	0	0
6	$P(OBu)_3$	75	40	trace

[a]A mixture of isoprene (**1a**) (4.0 mL), benzaldehyde (**2a**) (5.0 mmol), Ru(cod)(cot) (0.20 mmol), and ligand (0.20 mmol) in a 50-mL stainless steel autoclave was heated at 120 °C for 15 h under an argon atmosphere. [b]Determined by GLC based on the amount of **2a** charged.

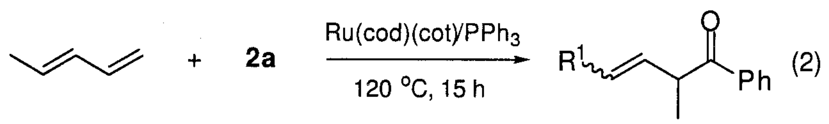
The results obtained from the reactions of isoprene (**1a**) with aromatic and heteroaromatic aldehydes are summarized in Table 3. In all cases, the starting aldehydes were almost completely consumed to give the corresponding β,γ-unsaturated ketones (**3a-i**) in reasonable yields. Heteroaromatic aldehydes such as thiophene-2-carbaldehyde and furan-2-carbaldehyde were also useful (Runs 2 and 3). Only the reaction with *o*-fluorobenzaldehyde afforded a mixture of α,β- and β,γ-unsaturated ketones (Run 8). Unfortunately, the reactions with aliphatic aldehydes were unsuccessful. For example, the reaction of **1a** with dodecanal gave the corresponding ketone in only 10% yield together with various byproducts,[17] while the conversion of dodecanal was 70%.

Table 3. Ru(cod)(cot)/PPh_3-Catalyzed Hydroacylation of Isoprene (**1a**) with Several Aldehydes[a]

Run	Aldehyde	Product	Yield (%)[b]
1[c]		 **3a**	54
2		 **3b**	(43)
3		 **3c**	(40)
4		 **3d**	13
5		 **3e**	17
6		 **3f**	16
7		 **3g**	38
8		 **3h**, 14  **3i**, 8	

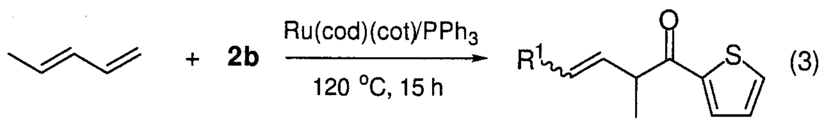
[a]A mixture of isoprene (**1a**) (4.0 mL), aldehyde (5.0 mmol), Ru(cod)(cot) (0.20 mmol), and PPh_3 (0.20 mmol) in a 50-mL stainless steel autoclave was heated at 120 °C for 15 h under an argon atmosphere. [b]GLC yield (isolated yield) based on the amount of aldehyde charged. [c]At 100 °C for 40 h.

The reaction of *trans*-1,3-pentadiene (**1b**) with benzaldehyde (**2a**) and thiophene-2-carbaldehyde (**2b**) gave the corresponding *β,γ*-unsaturated ketones, **3j** and **3k**, in isolated yields of 60% and 43%, respectively (eqs 2 and 3).



1b **3j**

60% (*E*:*Z* = 61:39)

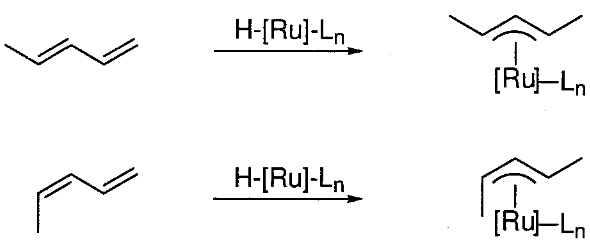


1b **3k**

43% (*E*:*Z* = 56:44)

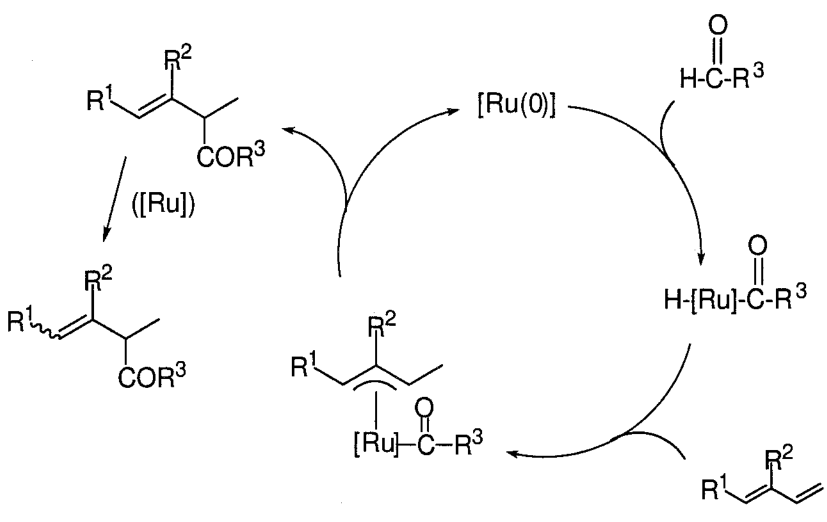
It is noteworthy that the hydroacylation of *trans*-1,3-pentadiene (**1b**) with benzaldehyde (**2a**) gave the corresponding *β,γ*-unsaturated ketone (**3j**) in 60% yield (eq 2), while no reaction occurred with *cis-1,3-pentadiene*. This result strongly suggests that an η^3-allylruthenium species is a key intermediate in the present reaction. A stable *syn,syn*-η^3-allylruthenium intermediate could be obtained from the reaction of *trans*-1,3-pentadiene with a (hydrido)ruthenium(II) species, while *cis*-1,3-pentadiene would give an unstable *anti,syn*-η^3-allylruthenium intermediate (Scheme 1).

Scheme 1



Considering all of our findings, the most plausible mechanism is illustrated in Scheme 2. First, an (acyl)(hydrido)ruthenium(II) species is generated by the oxidative addition of aldehyde to an active ruthenium(0) species. Next, insertion of the less-substituted double bond in 1,3-diene into a hydrido-ruthenium bond occurs to give an (acyl)(η^3-allyl)ruthenium(II) intermediate. Successive regioselective reductive elimination between the acyl and η^3-allyl ligands[18,19] gives the β,γ-unsaturated ketone with regeneration of an active ruthenium(0) species.

Scheme 2



In conclusion, we have developed a novel method for preparing *β,γ*-unsaturated ketones by the ruthenium-catalyzed intermolecular hydroacylation of 1,3-dienes with aldehydes. This reaction does not require ethylene,[2b,d,e,3a] hydrogen,[2f,4f,g,5b] or carbon monoxide[8] to activate the catalyst or to suppress the decarbonylation of aldehydes as well as to maintain the catalytic activity. Since hydroacylation is now a powerful tool in organic synthesis,[20] the present reaction should open new opportunities in this field.

Experimental Section

Materials. The reagents used in this study were dried and purified before use by standard procedures. $Ru_3(CO)_{12}$ was obtained commercially and used without further purification. Ru(cod)(cot),[21] $RuH_2(PPh_3)_4$,[22] and Cp*RuCl(cod),[23] were prepared as described in the literature.

Analytical Procedures. GLC analyses were carried out on gas chromatographs equipped with a glass column (3 mm i.d. x 3 m) packed with Silicone OV-17 (2% on Chromosorb W(AW-DMCS), 80-100 mesh) and a capillary column [Shimadzu capillary column HiCap-CBP10-M25-025 (polarity similar to that of OV-1701): 0.22 mm i.d. x 25 m]. The ^{1}H-NMR spectra were recorded at 400 MHz, and ^{13}C-NMR spectra were recorded at 100 MHz. Samples were analyzed in $CDCl_3$, and the chemical shift values are expressed relative to Me_4Si as an internal standard. High resolution mass spectra (HRMS) were obtained on a JEOL JMS-SX102A spectrometer. Elemental analyses were performed at the Microanalytical Center of Kyoto University.

General Procedures. A mixture of 1,3-diene (**1**) (4.0 mL), aldehyde (**2**) (5.0 mmol), Ru(cod)(cot) (63.0 mg, 0.20 mmol) and PPh_3 (52.5 mg, 0.20 mmol) was placed in a 50-mL stainless steel autoclave under an argon atmosphere. The mixture was magnetically stirred at 120 °C for 15 h. After cooling, the products were isolated by Kugelrohr distillation and/or recycling preparative HPLC. All of the new products are characterized below.

2,3-Dimethyl-1-phenylbut-3-en-1-one (3a).[18] Colorless oil, bp 70 °C (5.0 mmHg, Kugelrohr); IR (neat) 1684 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.34 (d, 3H, J = 6.83 Hz), 1.74 (s, 3H), 4.13 (q, 1H, J = 6.83 Hz), 4.89 (s, 1H), 4.90 (s, 1H), 7.42-7.46 (m, 2H), 7.51-7.56 (m, 1H), 7.96-7.99 (m, 2H); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 16.0, 20.5, 49.1, 113.6, 128.4 (two overlapping signals), 132.8, 136.7, 145.3, 200.9; Anal. Calcd for $C_{12}H_{14}O$: C 82.72, H 8.10. Found: C 82.65, H 8.24.

1-(2-Thienyl)-2,3-dimethylbut-3-en-1-one (3b). Pale yellow oil, bp 80 °C (5.0 mmHg, Kugelrohr); IR (neat) 1660 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.34 (d, 3H, *J* = 6.84 Hz), 1.75 (d, 3H, *J* = 0.98 Hz), 3.99 (q, 1H, *J* = 6.84 Hz), 4.93 (s, 1H), 4.97 (s, 1H), 7.11 (dd, 1H, *J* = 5.13, 3.90 Hz), 7.61 (dd, 1H, *J* = 5.13, 0.97 Hz), 7.78 (dd, 1H, *J* = 3.90, 0.97 Hz); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 15.9, 20.2, 50.8, 113.6, 128.0, 132.0, 133.4, 143.8, 145.1, 193.7; Anal. Calcd for $C_{10}H_{12}OS$: C 66.63, H 6.71, O 8.88. Found: C 66.83, H 6.92, O 9.18.

1-(2-Furyl)-2,3-dimethylbut-3-en-1-one (3c).[18] Colorless oil, bp 70 °C (5.0 mmHg, Kugelrohr); IR (neat) 1673 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.31 (d, *J* = 6.84 Hz, 3H), 1.76 (s, 3H), 3.94 (q, *J* = 6.84 Hz, 1H), 4.90 (s, 1H), 4.92 (s, 1H), 6.52 (dd, *J* = 3.42, 1.47 Hz, 1H), 7.23 (d, *J* = 3.42 Hz, 1H), 7.58 (d, *J* = 1.47 Hz, 1H); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 15.3, 20.5, 49.2, 112.1, 113.3, 117.5, 144.6, 146.2, 152.3, 189.8; Anal. Calcd for $C_{10}H_{12}O_2$: C 73.15, H 7.37. Found: C 72.85, H 7.64.

1-(4'-Methoxyphenyl)-2,3-dimethylbut-3-en-1-one (3d). Pale yellow oil, bp 120 °C (5.0 mmHg, Kugelrohr); IR (neat) 1684 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 270 MHz): δ 1.24 (d, *J* = 6.92 Hz, 3H), 1.65 (s, 3H), 3.77 (s, 3H), 4.01 (q, 1H, *J* = 6.92 Hz), 4.81 (s, 2H), 6.83 (d, 2H, *J* = 8.90 Hz), 7.99 (d, 2H, *J* = 8.90 Hz); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 16.1, 20.4, 48.7, 55.4, 113.2, 113.5, 130.4, 130.7, 145.2, 163.2, 199.4; Exact mass: calcd for $C_{13}H_{16}O_2$: 204.1150; found: 204.1153.

1-(3'-Methoxyphenyl)-2,3-dimethylbut-3-en-1-one (3e). Pale yellow oil, bp 150 °C (5.0 mmHg, Kugelrohr); IR (neat) 1684 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.33 (d, 3H, *J* = 6.83 Hz), 1.74 (s, 3H), 3.84 (s, 3H), 4.09 (q, 1H, *J* = 6.84 Hz), 4.88-4.90 (m, 2H), 7.06-7.57 (m, 4H); ^{13}C-NMR ($CDCl_3$, 100

MHz): δ 16.0, 20.4, 49.1, 55.4, 112.8, 113.4, 119.1, 120.9, 129.3, 138.0, 145.2, 159.7, 200.9; Exact mass: calcd for $C_{13}H_{16}O_2$: 204.1150; found: 204.1160.

1-(4'-Fuluorophenyl)-2,3-dimethylbut-3-en-1-one (3f). Pale yellow oil, bp 150 °C (5.0 mmHg, Kugelrohr); IR (neat) 1684 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 270 MHz): δ 1.33 (d, 3H, J = 6.92 Hz), 1.72 (s, 3H), 4.06 (q, 1H, J = 6.92 Hz), 4.89 (s, 2H), 7.09 (d, 2H, J = 8.41 Hz), 8.04 (d, 2H, J = 8.41 Hz); ^{13}C-NMR ($CDCl_3$, 67.8 MHz): δ 15.8, 20.1, 49.0, 113.5, 115.1, 115.5, 130.8, 131.0, 145.0, 163.5, 167.3, 199.0; Exact mass: calcd for $C_{12}H_{13}OF$: 192.0864; found: 192.0907.

1-(3'-Fuluorophenyl)-2,3-dimethylbut-3-en-1-one (3g). Pale yellow oil, bp 150 °C (5.0 mmHg, Kugelrohr); IR (neat) 1690 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 270 MHz): δ 1.34 (d, 3H, J = 6.83 Hz), 1.74 (s, 3H), 4.06 (q, 1H, J = 6.83 Hz), 4.87-4.91 (m, 2H), 7.20-7.70 (m, 4H); ^{13}C-NMR ($CDCl_3$, 67.8 MHz): δ 15.9, 20.4, 49.4, 113.9, 115.3, 119.6, 124.1, 130.0, 144.9, 161.5, 164.0, 199.6; Exact mass: calcd for $C_{12}H_{13}OF$: 192.0951; found: 192.0955.

1-(2'-Fuluorophenyl)-2,3-dimethylbut-3-en-1-one (3h). Pale yellow oil, bp 120 °C (5.0 mmHg, Kugelrohr); IR (neat) 1687 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.24 (d, 3H, J = 6.84 Hz), 1.64 (s, 3H), 3.94 (q, 1H, J = 6.84 Hz), 4.70-4.75 (m, 2H), 6.97-7.69 (m, 4H); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 15.3, 20.7, 53.0, 113.4, 116.5, 124.3, 130.7, 133.8, 144.3, 159.7, 162.2, 199.9; Exact mass: calcd for $C_{12}H_{13}OF$: 192.0951; found: 192.0956.

1-(2'-Fuluorophenyl)-2,3-dimethylbut-2-en-1-one (3i). Pale yellow oil, bp 120 °C (5.0 mmHg, Kugelrohr); IR (neat) 1674 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.74 (s, 3H), 1.82 (s, 3H), 1.87 (s, 3H), 7.07-7.70 (m, 4H); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 15.9, 21.3, 22.3, 116.6, 124.3, 131.0, 131.4, 133.7, 137.8, 159.7, 162.2, 197.3; Exact mass: calcd for $C_{12}H_{13}OF$: 192.0951; found: 192.0955.

(*E*)-2-Methyl-1-phenylpent-3-en-1-one (*E*-3j). Pale yellow oil, bp 120 °C (5.0 mmHg, Kugelrohr); IR (neat) 1688 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.21 (d, 3H, *J* = 6.83 Hz), 1.58 (d, 3H, *J* = 4.88 Hz), 4.03 (dq, 1H, *J* = 4.88, 6.35 Hz), 5.44 (dd, 1H, *J* = 17.09, 6.35 Hz), 5.48 (dq, 1H, *J* = 17.09, 6.83 Hz), 7.33-7.46 and 7.85-7.90 (m, 5H); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 13.1, 17.5, 44.5, 125.4, 128.3, 128.4, 128.5, 132.8, 136.5, 201.6; Anal. Calcd for $C_{12}H_{14}O$: C 82.72, H 8.10. Found (for a 61:39 mixture of ***E*-3j** and ***Z*-3j**): C 82.46, H 8.13.

(*Z*)-2-Methyl-1-phenylpent-3-en-1-one (*Z*-3j). Pale yellow oil, bp 120 °C (5.0 mmHg, Kugelrohr); IR (neat) 1684 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.20 (d, 3H, *J* = 6.84 Hz), 1.68 (dd, 3H, *J* = 6.83, 1.46 Hz), 4.31 (dq, 1H, *J* = 9.03, 6.84 Hz), 5.36-5.50 (m, 2H), 7.26-7.48 and 7.81-7.90 (m, 5H); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 11.7, 18.0, 40.2, 117.5, 129.7, 130.6, 130.9, 132.9, 137.0, 201.9.

(*E*)-1-(2-Thienyl)-2-methylpent-3-en-1-one (*E*-3k). Pale yellow oil, bp 80 °C (5.0 mmHg, Kugelrohr); IR (neat) 1660 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.31 (d, 3H, *J* = 6.84 Hz), 1.67 (d, 3H, *J* = 5.37 Hz), 3.92 (dq, 1H, *J* = 7.32, 6.84 Hz), 5.59 (dd, 1H, *J* = 16.85, 7.32 Hz), 5.65 (dq, 1H, *J* = 16.85, 5.37 Hz), 7.11-7.13 (m, 1H), 7.61-7.62 (m, 1H), 7.73-7.76 (m, 1H); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 13.1, 17.5, 46.4, 125.5, 128.0, 131.8, 132.0, 133.5, 143.7, 194.5; Exact mass: calcd for $C_{10}H_{12}OS$: 180.0609; found: 180.0608; Anal. Calcd for $C_{10}H_{12}OS$: C 66.63, H 6.71. Found (for a 56:44 mixture of ***E*-3k** and ***Z*-3k**): C 66.69, H 6.75.

(*Z*)-1-(2-Thienyl)-2-methylpent-3-en-1-one (*Z*-3k). Pale yellow oil, bp 80 °C (5.0 mmHg, Kugelrohr); IR (neat) 1660 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 400 MHz): δ 1.29 (d, 3H, *J* = 6.84 Hz), 1.77 (d, 3H, *J* = 5.37 Hz), 4.14 (dq, 1H, *J* = 8.79, 6.84 Hz), 5.56 (dd, 1H, *J* = 9.28, 8.79 Hz), 5.57 (dq, 1H, *J* =

9.28, 5.37), 7.11-7.13 (m, 1H), 7.61-7.62 (m, 1H), 7.73-7.76 (m, 1H); ^{13}C-NMR ($CDCl_3$, 100 MHz): δ 11.7, 17.9, 41.6, 117.6, 127.5, 130.5, 130.8, 133.5, 143.6, 194.7.

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Chapter 4

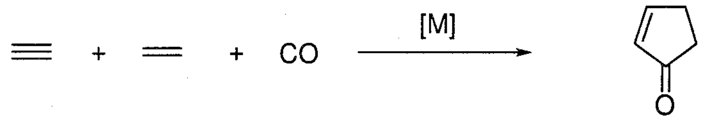
A New Route to Cyclopentenones via Ruthenium-Catalyzed Carbonylative Cyclization of Allylic Carbonates with Alkenes

Abstract

$[RuCl_2(CO)_3]_2/Et_3N$ and $(\eta^3\text{-}C_3H_5)RuBr(CO)_3/Et_3N$ are highly effective catalyst systems for carbonylative cyclization of allylic carbonates with alkenes to give the corresponding cyclopentenones in high yields. For example, treatment of allyl methyl carbonate (**1a**) with 2-norbornene (**2a**) in the presence of a catalytic amount of $[RuCl_2(CO)_3]_2$ (2.5 mol %) and Et_3N (10 mol %) at 120 °C for 5 h under 3 atm of carbon monoxide gave the corresponding cyclopentenone, *exo*-4-methyltricyclo[5.2.1.0^{2,6}]dec-4-en-3-one (**3a**), in 80% yield with high stereoselectivity (*exo* 100%). This catalyst system is also effective for intramolecular carbonylative cyclization of methyl 2,7-octadienyl carbonate (**1h**) to give the corresponding bicyclic cyclopentanone (**6b**) in good yield.

Introduction

The development of simple and general methods for the synthesis of cyclopentenones from readily available substrates continues to be one of the most active and challenging areas of synthetic research,[1,2] owing to the wide abundance of this structural unit in a large number of natural products. Cocyclization of alkynes, alkenes and carbon monoxide by transition-metal complexes leading to cyclopentenones, known as the Pauson-Khand reaction,[2] has been accepted as a powerful and convergent method for the construction of cyclopentenones (eq 1), and has been used successfully as the key step in the synthesis of a variety of natural products.[3] Considerable advance relating to this methodology has been reported recently, including the development of catalytic versions of this reaction.[4]

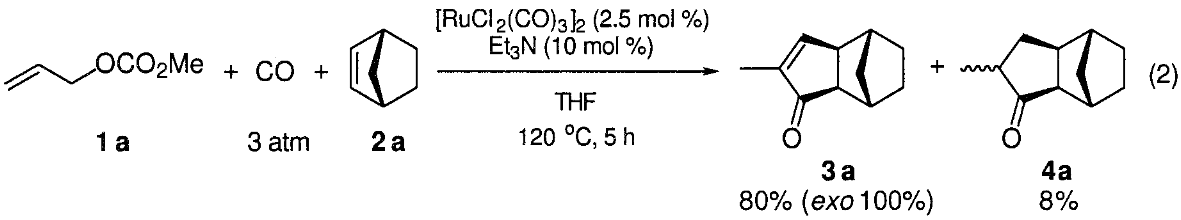


(1)

Another formally related process, the carbonylative cyclization of allylic halides with alkynes promoted by nickel[5] and palladium[6] complexes via η^3-allyl intermediates, has recently been reported. However, the use of alkyne substrates is essential for both the Pauson-Khand reaction and the carbonylative cyclization reactions.[7] During the investigation of the allylruthenium chemistry[8] as well as ruthenium-catalyzed Pauson-Khand reaction,[4i] we found the first example of ruthenium-catalyzed carbonylative cyclization of allylic carbonates with *alkenes*, which offers a new route to cyclopentenones. We report here the development of this new catalyst system for the synthesis of cyclopentenones via an η^3-allylruthenium intermediate.

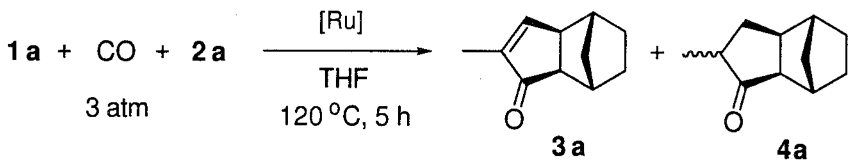
Results and Discussion

Treatment of allyl methyl carbonate (**1a**) with 2-norbornene (**2a**) in the presence of 2.5 mol % $[RuCl_2(CO)_3]_2$ and 10 mol % Et_3N in THF at 120 °C for 5 h under 3 atm of carbon monoxide gave the corresponding cyclopentenone, *exo*-4-methyltricyclo[5.2.1.0^{2,6}]dec-4-en-3-one (**3a**), in 80% yield with high stereoselectivity (*exo* 100%), together with a small amount of the hydrogeneted cyclopentanone, *exo*-4-methyltricyclo[5.2.1.0^{2,6}]decan-3-one (**4a**), as a byproduct (eq 2).



First, effect of the catalysts was examined in the reaction of **1a** with **2a**, and the results are summarized in Table 1. An appropriate catalyst combined with an amine ligand was critically important for the success of the reaction. For example, no catalytic activity of $[RuCl_2(CO)_3]_2$ was observed in the absence of Et_3N, but the concomitant use of $[RuCl_2(CO)_3]_2$ with Et_3N dramatically increased the catalytic activity to give **3a** in the best yield of 80%. A small amount of the saturated cyclopentanone (**4a**) was obtained as a byproduct. $[(p\text{-cymene})RuCl_2]_2/Et_3N$, which would give the same active species as that from $[RuCl_2(CO)_3]_2/Et_3N$ under CO pressure, also showed good catalytic activity (yield of **3a**, 60%). However, other ruthenium complexes, such as Cp*RuCl(cod) [Cp* = pentamethylcyclopentadienyl; cod = 1,5-cyclooctadiene], $RuCl_2(PPh_3)_3$, $Ru_3(CO)_{12}$, and $Ru(CO)_3(PPh_3)_2$ were almost ineffective even in the presence of Et_3N.

Table 1. Effect of the Catalysts on the Carbonylative Cyclization of **1a** with **2a**[a]



Run	Catalyst	Additive[b]	Yield of **3a** (%)[c]	Yield of **4a** (%)[c]
1	$[RuCl_2(CO)_3]_2$	-	0	0
2	$[RuCl_2(CO)_3]_2$	Et_3N	80	8
3	$[(p\text{-cymene})RuCl_2]_2$	Et_3N	60	6
4	Cp*RuCl(cod)	-	0	0
5	Cp*RuCl(cod)	Et_3N	13	0
6	CpRuCl(cod)	-	0	0
7	$RuCl_2(PPh_3)_3$	-	0	0
8	$Ru_3(CO)_{12}$	-	0	0
9	$Ru_3(CO)_{12}$	Et_3N	0	0
10	$Ru(CO)_3(PPh_3)_2$	Et_3N	0	0

[a] **1a** (1.0 mmol), **2a** (2.0 mmol), catalyst (0.050 mmol as Ru atom), and THF (8.0 mL) at 120 °C for 5 h under 3 atm of carbon monoxide. [b] Et_3N (0.10 mmol) was added. [c] Determined by GLC based on the amount of **1a** charged.

Since the catalytic activity of $[RuCl_2(CO)_3]_2$ was strongly affected by the amine ligand, effect of the several amine ligands was also examined (Table 2). Tertiary alkyl amines, such as quinuclidine and *N*-methylpiperidine, generally enhanced the catalytic activity (yields of **3a**, 68% and 50%, respectively), and Et_3N gave the best result. Almost no promoting effect was observed with aromatic amines, such as *N,N*-dimethylaniline and pyridine, and bidentate amines, such as *N,N,N',N'*-tetramethylethylenediamine (TMEDA) and 1,10-phenanthroline.

Table 2. Effect of the Amine Ligands on $[RuCl_2(CO)_3]_2$-Catalyzed Carbonylative Cyclization of **1a** with **2a**[a]

Run	Ligand	Yield of **3a** (%)[b]	Yield of **4a** (%)[b]
1	none	0	0
2	Et_3N	80	8
3	Quinuclidine	68	3
4	*N*-Methylpiperidine	50	4
5	*N,N*-Dimethylaniline	17	4
6	Pyridine	0	0
7	TMEDA[c]	0	0
8	1,10-Phenanthroline[c]	0	0

[a] **1a** (1.0 mmol), **2a** (2.0 mmol), $[RuCl_2(CO)_3]_2$ (0.025 mmol), ligand (0.10 mmol), and THF (8.0 mL) at 120 °C for 5 h under 3 atm of carbon monoxide. [b] Determined by GLC based on the amount of **1a** charged. [c] Ligands (0.050 mmol) were used.

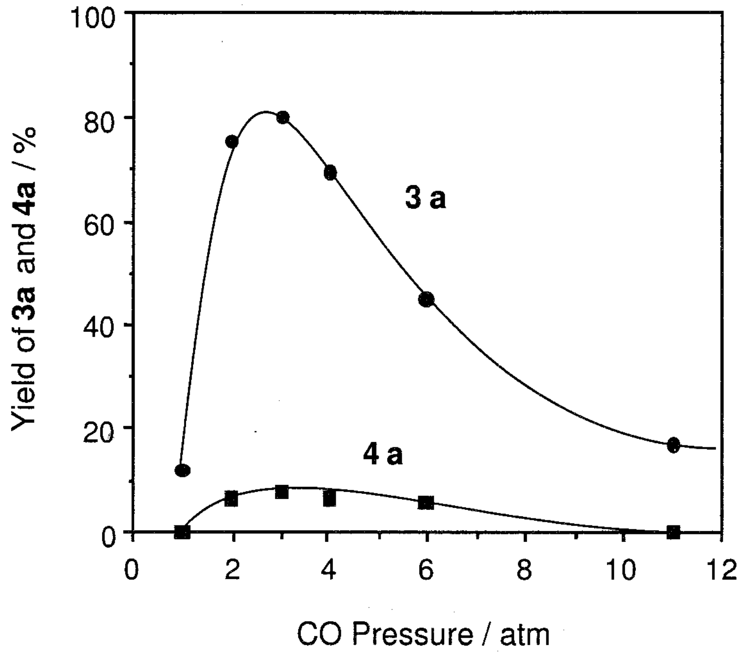
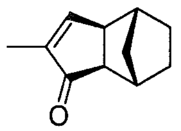


Figure 1. Effect of CO pressure on the formation of **3a** and **4a** by the carbonylative cyclization of **1a** with **2a**. Reaction conditions: **1a** (1.0 mmol), **2a** (2.0 mmol), $[RuCl_2(CO)_3]_2$ (0.025 mmol), Et_3N (0.10 mmol), and THF (8.0 mL) at 120 °C for 5 h.

A dramatic effect of carbon monoxide pressure on the carbonylative cyclization of **1a** with **2a** was also observed, and the result is shown in Figure 1. The best result was obtained under 3 atm of carbon monoxide, and either increase or decrease of carbon monoxide pressure caused a rapid decrease of the yield of **3a**.

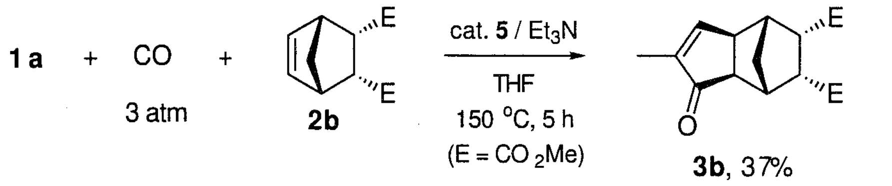
To clarify the intermediacy of an η^3-allylruthenium complex, the stoichiometric reaction of $(\eta^3\text{-}C_3H_5)RuBr(CO)_3$ (**5**) with an equimolar amount of **2a** was examined, and the corresponding cyclopentenone (**3a**) was obtained in an isolated yield of 47% (eq 3). Complex **5** also showed high catalytic activity in the presence of Et_3N for the carbonylative cyclization of **1a** with **2a** to give **3a** in 65% yield. Consequently, an η^3-allylruthenium complex, an analogue of complex **5**, appears to be the key intermediate as well as an active catalyst precursor in the present reaction.

$(\eta^3\text{-}C_3H_5)RuBr(CO)_3$ **5** + CO (3 atm) + **2a** —(THF, 120 °C, 12 h)→

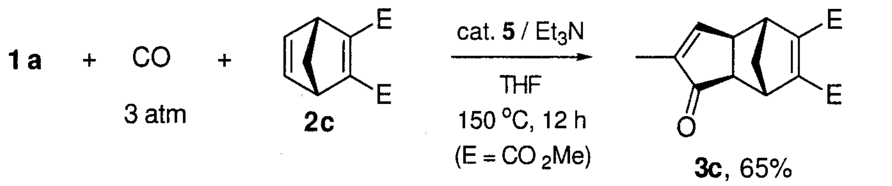


3a , 47% (3)

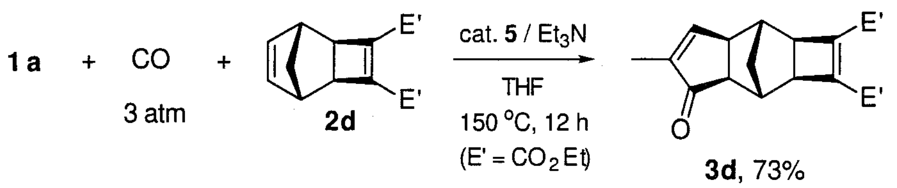
The carbonylative cyclization of **1a** with norbornene derivatives, **2b**, **2c**, and **2d**, also gave the corresponding cyclopentenones, **3b**, **3c**,and **3d**, in the isolated yields of 37%, 65% and 73%, respectively (eqs 4-6). The scope of the present carbonylative cyclization with respect to the alkene is restricted, and the norbornene skeleton is now essential for the present reaction. At this stage, attempts to obtain cyclopentenones with less strained or less reactive alkenes, e.g. ethylene (**2e**) (*vide infra*), 2,3-dimethyl-2-butene, 1-octene, 4-octene, and styrene, were not successful.



(4)



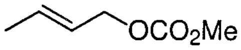
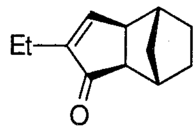
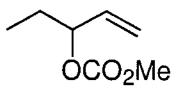
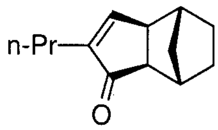
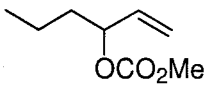
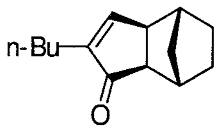
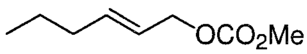
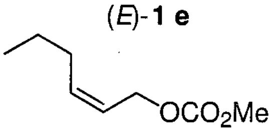
(5)



(6)

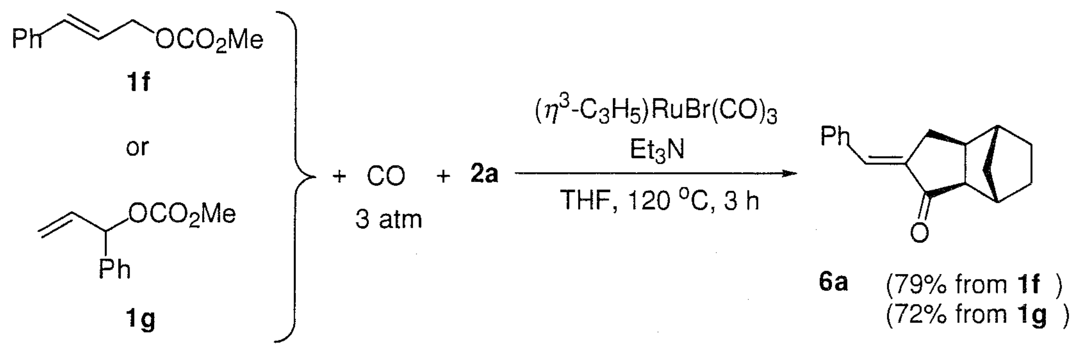
The results obtained from the reactions of several substituted allylic carbonates (**1b**-**e**) with 2-norbornene (**2a**) by the catalyst system of (η^3-allyl)RuBr$(CO)_3$/Et_3N[9] are summarized in Table 3. In all cases, allylic carbonates were completely consumed, and the corresponding cyclopentenones were obtained in high yields. The regioisomeric allylic carbonates, e.g., 1-hexene-3-yl methyl carbonate (**1d**) and (*E*)-2-hexenyl methyl carbonate ((*E*)-**1e**), gave the same product (**3g**) in high yields, respectively, which suggests that the present reaction proceeds via an η^3-allylruthenium intermediate. In addition, the result that cyclopentenone (**3g**) was also obtained from the carbonylative cyclization of either (*Z*)-**1e** and (*E*)-**1e** with **2a** indicates the rapid isomerization between *anti*- and *syn*-η^3-allylruthenium intermediates.

Table 3. (η^3-C_3H_5)RuBr(CO)$_3$/Et_3N-Catalyzed Carbonylative Cyclization of Several Allylic Carbonates with **2a**[a]

Run	Allylic Carbonate	Products (%)[b]	
1	 **1 b**		**3e** (73)
2	 **1 c**		**3f** (91)
3	 **1 d**		**3g** (73)
4	 (*E*)-**1 e**	**3g** (75)	
5	 (*Z*)-**1 e**	**3g** (95)	

[a]Allylic carbonate (**1**) (1.0 mmol), **2a** (1.1 mmol), (η^3-C_3H_5)Ru-Br(CO)$_3$ (0.050 mmol), Et_3N (0.10 mmol), and THF (2.0 mL) at 120 ^oC for 3 h under 3 atm of carbon monoxide. [b]Determined by GLC based on the amount of **1** charged.

On the other hand, aryl-substituted allylic carbonates, such as cinnamyl methyl carbonate (**1f**) and 1-phenylallyl methyl carbonate (**1g**), gave 2-benzylidenecyclopentanone (**6a**) even by the use of the (η^3-C_3H_5)RuBr(CO)$_3$/Et_3N catalyst,[9] probably due to the strong π-conjugation of an olefinic moiety with the phenyl group (eq 7). The structure of **6a** was confirmed by X-ray crystallography (Tables 4-7), which indicates that the conformation of **6a** is exclusively *exo*, and the phenyl group in **6a** stays at the opposite side of the carbonyl group (Figure 2).



(7)

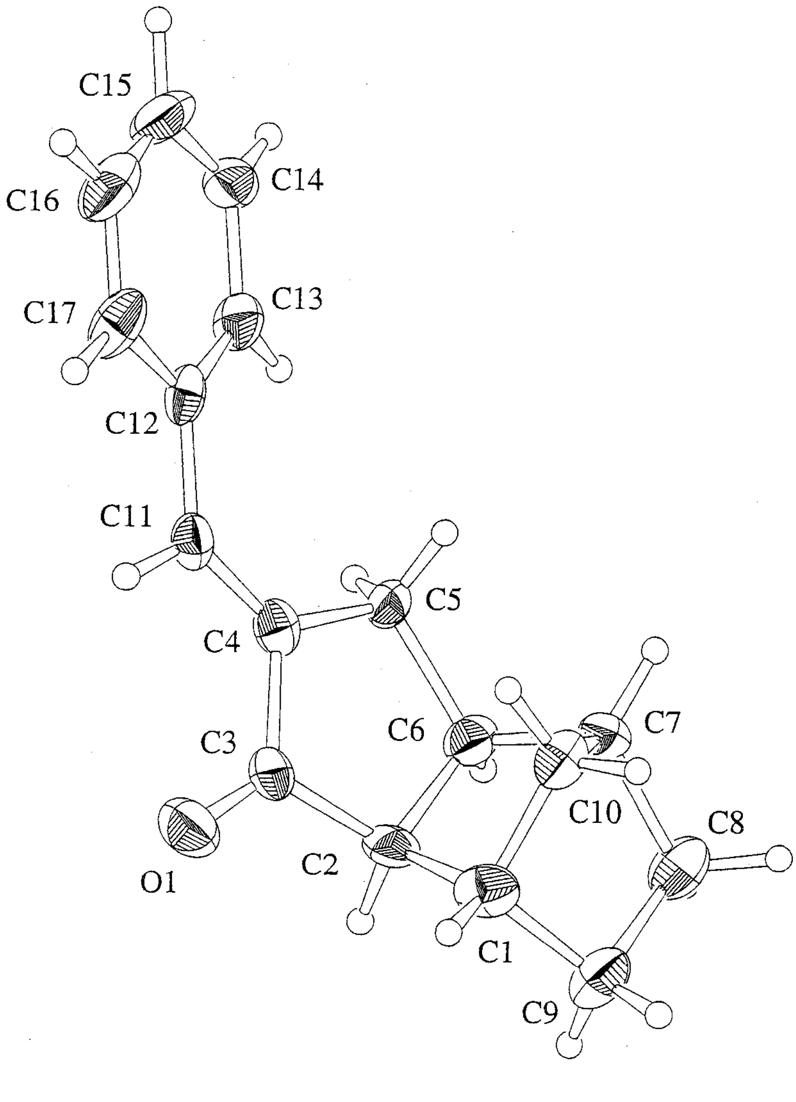


Figure 2. ORTEP drawing of **6a** with 30% thermal ellipsoids.

Table 4. Experimental Parameters for the X-ray Diffraction Study of **6a**

Crystal Data	
Molecular formula	$C_{17}H_{18}O$
Formula weight	238.33
Crystal color, habit	colorless, prismatic
Crystal dimensions	0.20×0.20×0.10 mm
Crystal system	orthorhombic
No. of reflections used for unit cell determination	18(20.0-28.6°)
ω Scan peak with at half-hight	0.31
Lattice parameters	a = 11.51(1)Å b = 11.42(1)Å c = 9.90(1)Å V = 1300(2)Å^3
Space group	$P2_12_12_1$ (#19)
Z	4
D_{calc}	1.217 g/cm^3
F_{000}	512
μ(MoKα)	9.57 cm^{-1}
Intensity Measurements	
Diffractometer	Rigaku AFC7R
Radiation	MoKα (λ = 0.71069Å)
Monochromator	graphite
Attenuator	Zr foil
Take-off angle	6.0°
Detector aperture	3.0 mm horiznta l 3.5 mm vertical
Crystal to detector distance	235 mm
Voltage, current	50 kV, 200 mA
Temperature	23.0 °C
Scan type	ω-2θ
Scan rate	16.0°/min (in ω)
Scan width	(1.10+0.30 tanθ)°
$2\theta_{max}$	55.1°

(continued)

No. of reflection measured	total: 2819
	unique:1489 (R_{int} = 0.119)

Structure Solution and Refinement

Structure solution	Direct Methods (SIR92)
Refinement	Full-matrix least-squares
Function minimized	$\Sigma w(\mid F_o \mid - \mid F_c \mid)^2$
Least-square weights	$[\sigma_c^2(F_o)+p^2/4F_o^2]^{-1}$
p-factor	0.0060
Anomalous dispersion	All non-hydrogen atoms
No. observation (I>3.00σ(I))	572
No. variables	182
Reflection/Parameter ratio	3.14
R	0.068
Rw	0.070
Goodness of fit indicator	1.12
Max shift/error in final cycle	0.00
Maximum peak in final diff. map	0.16 $e^-/Å^3$
Minimum peak in final diff. map	-0.18 $e^-/Å^3$

Table 5. Positional Parameters and B(eq) Values for **6a**

atom	x	y	z	B(eq)
O(1)	0.0458(8)	0.0764(8)	0.7080(8)	5.4(2)
C(1)	-0.032(1)	0.217(1)	0.461(1)	4.5(3)
C(2)	0.091(1)	0.193(1)	0.508(1)	4.3(3)
C(3)	0.093(1)	0.084(1)	0.598(1)	4.1(3)
C(4)	0.159(1)	-0.011(1)	0.527(1)	3.6(3)
C(5)	0.210(1)	0.0352(9)	0.398(1)	3.5(3)
C(6)	0.159(1)	0.163(1)	0.379(1)	4.0(3)
C(7)	0.065(1)	0.171(1)	0.269(1)	3.8(3)
C(8)	0.036(1)	0.3018(10)	0.250(1)	5.2(3)
C(9)	-0.034(1)	0.336(1)	0.382(1)	5.5(3)
C(10)	-0.043(1)	0.1289(10)	0.346(1)	4.3(3)
C(11)	0.158(1)	-0.120(1)	0.578(1)	3.7(3)
C(12)	0.206(1)	-0.228(1)	0.523(1)	3.6(39
C(13)	0.290(1)	-.234(1)	0.426(1)	4.0(3)
C(14)	0.331(1)	-0.340(1)	0.375(1)	4.4(3)
C(15)	0.287(1)	-0.441(1)	0.428(2)	5.8(4)
C(16)	0.202(1)	-0.439(1)	0.523(2)	6.0(4)
C(17)	0.161(1)	-0.336(1)	0.574(1)	5.2(3)

Table 6. Intramolecular Bond Distances for **6a**

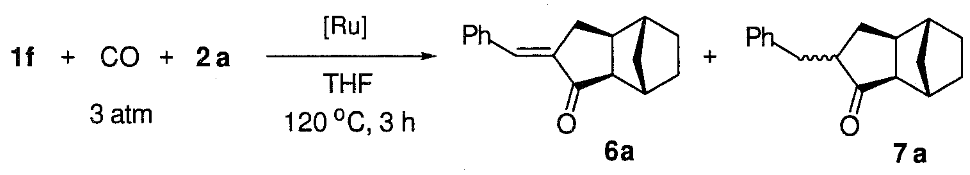
atom	atom	distance (Å)	atom	atom	distance (Å)
O(1)	C(3)	1.22(1)	C(7)	C(8)	1.54(2)
C(1)	C(2)	1.52(2)	C(7)	C(10)	1.53(2)
C(1)	C(9)	1.57(2)	C(8)	C(9)	1.59(2)
C(1)	C(10)	1.52(2)	C(11)	C(12)	1.47(2)
C(2)	C(3)	1.53(2)	C(12)	C(13)	1.36(2)
C(2)	C(6)	1.54(2)	C(12)	C(17)	1.43(2)
C(3)	C(4)	1.50(2)	C(13)	C(14)	1.39(2)
C(4)	C(5)	1.50(2)	C(14)	C(15)	1.36(2)
C(4)	C(11)	1.34(2)	C(15)	C(16)	1.37(2)
C(5)	C(6)	1.58(2)	C(16)	C(17)	1.37(2)
C(6)	C(7)	1.54(2)			

Table 7. Intramolecular Bond Angles for **6a**

atom	atom	atom	angle (deg)	atom	atom	atom	angle (deg)
C(2)	C(1)	C(9)	109(1)	C(6)	C(7)	C(8)	107(1)
C(2)	C(1)	C(10)	101(1)	C(6)	C(7)	C(10)	101(1)
C(9)	C(1)	C(10)	101(1)	C(8)	C(7)	C(10)	101(1)
C(1)	C(2)	C(3)	109(1)	C(7)	C(8)	C(9)	104(1)
C(1)	C(2)	C(6)	104(1)	C(1)	C(9)	C(8)	100.8(10)
C(3)	C(2)	C(6)	107(1)	C(1)	C(10)	C(7)	95(1)
O(1)	C(3)	C(2)	124(1)	C(4)	C(11)	C(12)	129(1)
O(1)	C(3)	C(4)	126(1)	C(11)	C(12)	C(13)	125(1)
C(2)	C(3)	C(4)	108(1)	C(11)	C(12)	C(17)	117(1)
C(3)	C(4)	C(5)	110(1)	C(13)	C(12)	C(17)	117(1)
C(3)	C(4)	C(11)	118(1)	C(12)	C(13)	C(14)	122(1)
C(5)	C(4)	C(11)	130(1)	C(13)	C(14)	C(15)	118(1)
C(4)	C(5)	C(6)	106(1)	C(14)	C(15)	C(16)	120(1)
C(2)	C(6)	C(5)	106(1)	C(15)	C(16)	C(17)	121(1)
C(2)	C(6)	C(7)	102.7(10)	C(12)	C(17)	C(16)	119(1)
C(5)	C(6)	C(7)	114(1)				

Effects of the catalysts and the amine ligands were also examined in the reaction of **1f** with **2a**, and the results are summarized in Tables 8 and 9. Among the catalyst system examined, $[RuCl_2(CO)_3]_2/Et_3N$ also gave the best results.

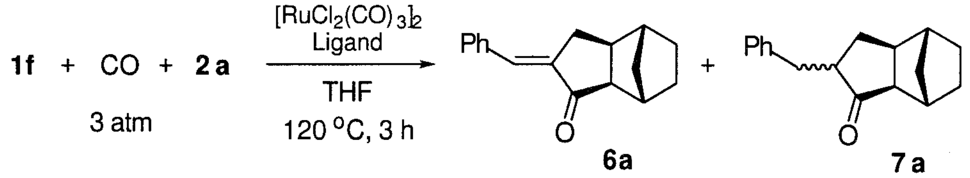
Table 8. The Effect of the Catalysts on the Carbonylative Cyclization of **1f** with **2a**[a]



Run	Catalyst	Additive[b]	Yield of **6a** (%)[c]	Yield of **7a** (%)[c]
1	$[RuCl_2(CO)_3]_2$	-	8	1
2	$[RuCl_2(CO)_3]_2$	Et_3N	91	9
3	$[(p\text{-cymene})RuCl_2]_2$	-	4	0
4	$[(p\text{-cymene})RuCl_2]_2$	Et_3N	88	5
5	$(\eta^3\text{-}C_3H_5)BrRu(CO)_3$	Et_3N	79	20
6	Cp*RuCl(cod)	-	0	0
7	CpRuCl(cod)	-	0	0
8	$RuCl_2(PPh_3)_3$	-	0	0
9	$Ru_3(CO)_{12}$	-	1	0

[a]**1f** (1.0 mmol), **2a** (1.1 mmol), catalyst (0.040 mmol as Ru atom), and THF (2.0 mL) at 120 °C for 3 h under 3 atm of carbon monoxide. [b]Et_3N (0.060 mmol) was added. [c]Determined by GLC based on the amount of **1f** charged.

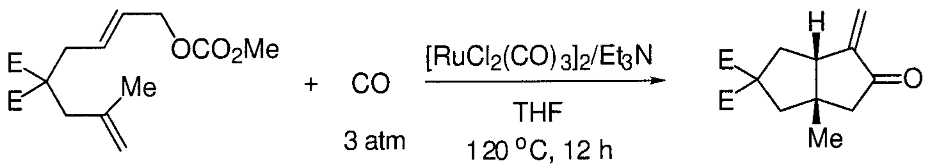
Table 9. Effect of the Amine Ligands on $[RuCl_2(CO)_3]_2$-Catalyzed Carbonylative Cyclization of **1f** with **2a**[a]



Run	Ligand	Yield of **6a** (%)[b]	Yield of **6a** (%)[b]
1	none	0	0
2	Et_3N	91	9
3	$(n\text{-}Bu)_3N$	68	8
4	Quinuclidine	35	3
5	*N*-Methylpiperidine	74	6
6	*N*,*N*-Dimethylaniline	4	3
7	Pyridine	0	0
8	TMEDA[c]	2	0
9	1,10-Phenanthroline[c]	0	0

[a]**1f** (1.0 mmol), **2a** (1.1 mmol), $[RuCl_2(CO)_3]_2$ (0.020 mmol), ligand (0.060 mmol), and THF (2.0 mL) at 120 °C for 3 h under 3 atm of carbon monoxide. [b]Determined by GLC based on the amount of **1f** charged. [c]Ligands (0.030 mmol) were used.

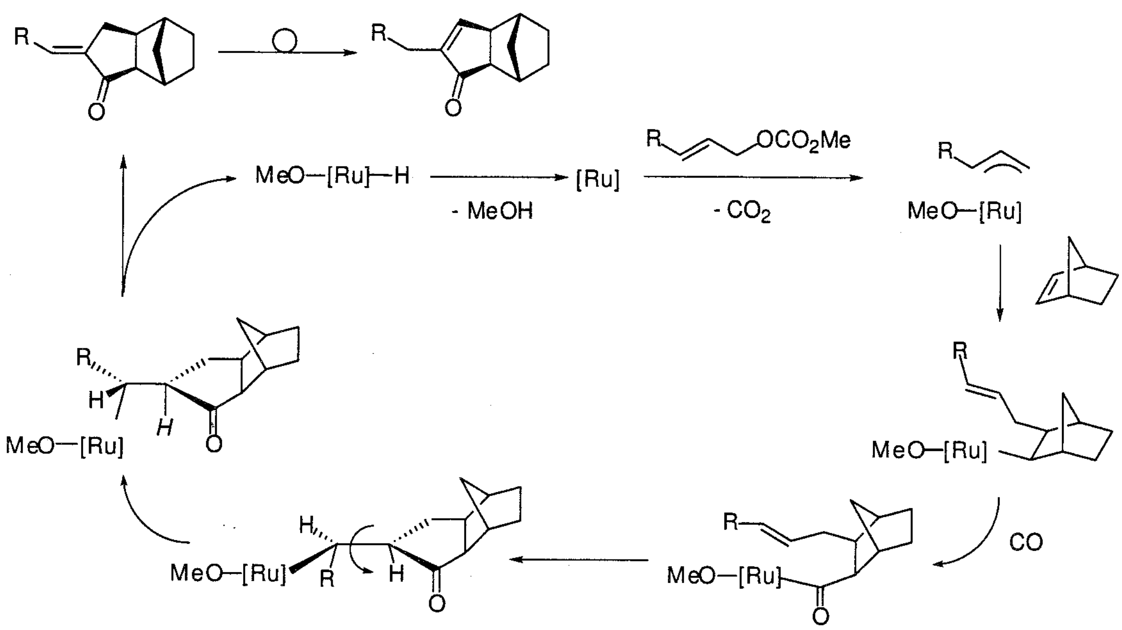
A synthetic application of the present reaction is demonstrated in the following *intramolecular* carbonylative cyclization of **1h** (eq 8). Treatment of methyl 2,7-octadienyl carbonate (**1h**) under the present reaction conditions gave the bicyclic cyclopentanone **6b** in 60% yield.[6b,c,10]



1h **6b**, 60% (8)

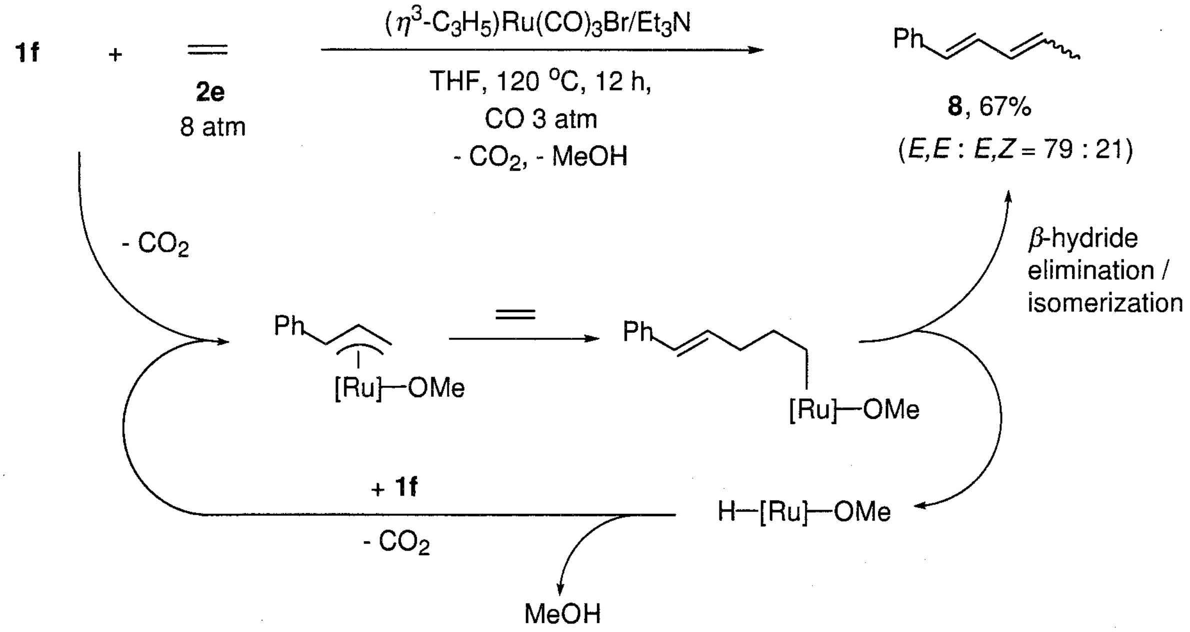
The most plausible mechanism of the intermolecular carbonylative cyclization is illustrated in Scheme 1. Invariable *exo*-coordination of 2-norbornene derivatives to an active η^3-allylruthenium intermediate, stereoselective *cis*-carbo-ruthenation, and successive insertion of CO would give an (acyl)ruthenium intermediate. Subsequent intramolecular insertion of a C=C bond into an acyl-ruthenium bond, followed by β-hydride elimination/isomerization would give the corresponding cyclopentenones exclusively in an *exo* form.

Scheme 1



On the other hand, treatment of cinnamyl methyl carbonate (**1f**) with ethylene (**2e**) instead of 2-norbornene (**2a**) by the present catalyst system, a mixture of (*1E, 3E*)- and (*1E, 3Z*)-1-phenyl-1,3-pentadiene (**8**) was obtained in total isolated yield of 67 % with a ratio of 79 : 21. As for the mechanism, ethylene (**2e**) would also insert into an η^3-allylruthenium intermediate, but β-hydride elimination would occur prior to CO insertion, followed by isomerization to give **8** (Scheme 2). A similar ruthenium-catalyzed linear co-dimerization of allylic carbonates or 1,3-dienes with alkenes via an η^3-allylruthenium intermediate has been reported, in which only electron-deficient alkenes, e.g. *N,N*-dimethylacrylamide, could be used.[11] The present reaction suggests the possibility that it may lead to a general method for ruthenium-catalyzed co-dimerization of allylic compounds with unactivated alkenes.

Scheme 2



In conclusion, we have found the first practically useful ruthenium catalyst for the rapid construction of cyclopentenones *without the use of an alkyne substrate.* This catalytic processs, which is an alternative to the Pauson-Khand reaction, could become a valuable tool in the field of organic and natural product synthesis.

Experimental Section

General. GLC analyses were carried out on a gas chromatograph equipped with a glass column (3 mm i.d. x 3 m) packed with Silicone SE-30 (5% on Chromosorb W(AW-DMCS), 80-100 mesh). The products were isolated by Kugelrohr distillation, and purified on a recycling preparative HPLC (Japan Analytical Industry Co. Ltd., Model 908) equipped with JAIGEL-1H and 2H columns (GPC) using $CHCl_3$ as an eluent. The ^1H-NMR spectra were recorded at 300 and/or 400 MHz. ^{13}C-NMR spectra were recorded at 75 and/or 100 MHz. Samples were analyzed in $CDCl_3$, and the chemical shift values are expressed relative to Me_4Si as an internal standard. IR spectra were obtained on a Nicolet Impact 410 spectrometer. Elemental analyses were performed at the Microanalytical Center of Kyoto University.

Materials. The reagents used in this study were dried and purified before use by standard procedures. Carbon monoxide (>99.9%) was used without purification. Allylic carbonates (**1a-g**,[12] **and 1h**[10c]) were prepared from the corresponding alcohols and methyl or phenyl chloroformate according to the reported procedure. The norbornene derivatives, **2b**,[13] **2c**,[14] and **2d**,[15] were prepared by the methods in the literature. $[RuCl_2(CO)_3]_2$ and $Ru_3(CO)_{12}$ were obtained commercially, and used without further purification. $[(p\text{-cymene})RuCl_2]_2$,[16] Cp*RuCl(cod),[17] $RuCl_2(PPh_3)_3$,[18] $Ru(CO)_3(PPh_3)_2$,[19] and $(\eta^3\text{-}C_3H_5)Ru(CO)_3Br$ (**5**),[20] were prepared as described in the literature.

Carbonylative Cyclization of Allylic Carbonates (1a-g) with 2-Norbornene Derivatives (2a-c). A mixture of allylic carbonate (1.0 mmol), 2-norbornene derivative (2.0 mmol), $[RuCl_2(CO)_3]_2$ (12.8 mg, 0.025 mmol) or $(\eta^3\text{-}C_3H_5)Ru(CO)_3Br$ (15.3 mg, 0.050 mol), Et_3N (10.1 mg, 0.10

mmol), and THF (2.0-8.0 mL) was placed in a 50-mL stainless steel autoclave under a flow of argon. Carbon monoxide was then pressured to 3 atm at room temperature, and the mixture was magnetically stirred at 120-150 °C for 5-12 h. After cooling, the products were isolated by Kugelrohr distillation, and purified by recycling preparative HPLC.

Carbonylative Cyclization of Cinnamyl Methyl Carbonate (1f) and Methyl 1-Phenylallyl Carbonate (1g) with 2a. A mixture of carbonate (**1f** or **1g**) (1.0 mmol), 2-norbornene (**2a**) (103 mg, 1.1 mmol), $[RuCl_2(CO)_3]_2$ (10.2 mg, 0.020 mmol), Et_3N (6.0 mg, 0.060 mmol), and THF (2.0 mL) was placed in a 50-mL stainless steel autoclave under a flow of argon. Carbon monoxide was then pressured to 3 atm at room temperature, and the mixture was magnetically stirred at 120 °C for 3 h. After cooling, the products were isolated by Kugelrohr distillation, and purified by recycling preparative HPLC.

Stoichiometric Reaction of (η^3-C_3H_5)$RuBr(CO)_3$ (5) with 2-Norbornene (2a). A mixture of (η^3-C_3H_5)$RuBr(CO)_3$ (**5**) (30.6 mg, 0.10 mmol), 2-norbornene (**2a**) (18.8 mg, 0.20 mmol), and THF (2.0 mL) was placed in a 50-mL stainless steel autoclave under a flow of argon. Carbon monoxide was then pressured to 3 atm at room temperature, and the mixture was magnetically stirred at 120 °C for 12 h. After cooling, the product was isolated by Kugelrohr distillation.

Intramolecular Carbonylative Cyclization of 5,5-Dicarbomethoxy-7-methyl-2,7-octadienyl Methyl Carbonate (1h). A mixture of 5,5-dicarbomethoxy-7-methyl-2,7-octadienyl methyl carbonate (**1h**) (314 mg, 1.0 mmol), $[RuCl_2(CO)_3]_2$ (12.8 mg, 0.025 mmol), Et_3N (10.1 mg, 0.10 mmol), and THF (5.0 mL) was placed in a 50-mL stainless steel autoclave under a flow of argon. Carbon monoxide was then pressured to 3 atm at room temperature, and the mixture was magnetically stirred at 120 °C for 12 h. After cooling, the product was isolated by Kugelrohr distillation, and purified by recycling preparative HPLC.

Compounds **3a**,[7b] **3c**,[21] **3e**,[7b] **3f**,[22] **3g**,[23] **4a**,[7b] and **8**[24] have already been reported. All of the new compounds are characterized below.

5,5-Dicarbomethoxy-7-methyl-2,7-octadienyl methyl carbonate (1h). Colorless oil, bp 120 °C (1.0 mmHg, Kugelrohr); IR (neat): 1740 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ 1.58 (s, 3H), 2.59 (d, 2H, J = 6.06 Hz), 2.62 (s, 2H), 3.64 (s, 6H), 3.70 (s, 3H), 4.47 (d, 2H, J = 5.14 Hz), 4.69 (s, 1H), 4.81 (s, 1H), 5.55-5.67 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 22.9, 35.4, 40.4, 52.3, 54.6, 57.1, 67.8, 115.8, 127.7, 130.5, 140.1, 155.4, 171.2; Mass (EI) m/z 314 (M^+). Anal. Calcd for $C_{15}H_{22}O_7$: C 57.32; H 7.05. Found: C 57.45; H 7.30.

Diethyl *exo*-tricyclo[4.2.1.0^{2,5}]nona-3,7-diene-3,4-dicarboxylate (2c). Pale yellow oil, bp 110-115 °C (1.0 mmHg, Kugelrohr); IR (neat): 1721 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz): δ 1.25-1.38 (m, 2H), 1.29 (t, 6H, J = 7.08 Hz), 2.52 (s, 2H), 2.67 (s, 2H), 4.21 (q, 4H, J = 7.08 Hz), 6.14 (s, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 14.1, 38.2, 39.5, 44.1, 60.7, 135.9, 144.9, 161.5; Mass (EI) m/z 262 (M^+). Anal. Calcd for $C_{15}H_{18}O_4$: C 68.68; H 6.92. Found: C 68.81; H 7.01.

Dimethyl *exo*-4-Methyltricyclo[5.2.1.0^{2,6}]dec-4-en-3-one-*endo*-8,9-dicarboxylate (3b). White solid, mp 97.5-98.8 °C; IR (KBr): 1731, 1692 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz): δ 1.06 (d, 1H, J = 11.01 Hz), 1.17 (d, 1H, J = 11.01 Hz), 1.73 (s, 3H), 2.44 (br, 1H), 2.59 (d, 1H, J = 3.85 Hz), 2.68 (d, 1H, J = 3.85 Hz), 3.01 (dd, 1H, J = 3.85, 11.74 Hz), 3.12 (dd, 1H, J = 3.85, 11.74 Hz), 3.36 (br, 1H), 3.61 (s, 3H), 3.62 (s, 3H), 7.16 (s, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 10.1, 32.3, 41.3, 41.6, 42.4, 45.8, 46.5, 48.1, 51.4, 51.7, 145.5, 159.2, 172.1, 172.1, 210.8; Mass (EI) m/z 278 (M^+). Anal. Calcd for $C_{15}H_{18}O_5$: C 64.74; H 6.52. Found: C 64.70; H 6.67.

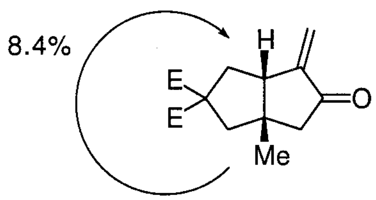
Diethyl *exo,exo*-4-methyltetracyclo[5.4.1.0^{2,6}.0^{8,11}]dodeca-4,9-dien-3-one-9,10-dicarboxylate (3d). Pale yellow oil, bp 160-170 °C (1.0 mmHg, Kugelrohr); IR (neat): 1731, 1705 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz): δ 0.86 (d, 1H, J = 11.72 Hz), 1.12 (d, 1H, J = 11.72 Hz), 1.24 (t, 3H, J = 7.08 Hz), 1.25 (t, 3H, J = 7.08 Hz), 1.71 (s, 3H), 2.11 (d, 1H, J = 4.89 Hz), 2.19 (s, 1H), 2.43 (s, 1H), 2.53 (br, 1H), 2.76 (s, 1H), 2.78 (s, 1H), 4.15 (q, 2H, J = 7.08 Hz), 4.16 (q, 2H, J = 7.08 Hz), 7.09 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 10.0, 14.0, 14.1, 23.7, 35.9, 36.1, 46.6, 46.7, 47.2, 51.9, 60.8, 60.9, 142.2 (two overlapping signals), 145.0, 158.5, 160.7, 161.0, 209.9; Mass (EI) m/z 330 (M^+). Anal. Calcd for $C_{19}H_{22}O_5$: C 69.07; H 6.71. Found: C 68.98; H 6.98.

4-Benzylidenetricyclo[5.2.1.0^{2,6}]decan-3-one (6a). White solid, mp 99.0-100.3 °C; IR (KBr): 1696 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.07 (d, 1H, J = 10.28 Hz), 1.14 (d, 1H, J = 10.28 Hz), 1.17-1.34 (m, 2H), 1.50-1.59 (m, 2H), 2.21 (s, 1H), 2.33 (s, 1H), 2.34 (s, 1H), 2.53-2.61 (m, 2H), 3.17-3.28 (m, 1H), 7.29 (s, 1H), 7.34-7.55 (m, 5H); ^{13}C NMR ($CDCl_3$, 75 MHz): δ 28.4, 28.7, 33.6, 34.8, 40.4, 42.4, 44.4, 56.0, 128.4, 129.2, 130.8, 132.1, 135.6, 137.2, 211.2; Mass (EI) m/z 238 (M^+). Anal. Calcd for $C_{17}H_{18}O$: C 85.67; H 7.61. Found: C 85.40; H 7.68.

X-ray Structural Determination of 6a. Crystal data, data collection, and refinement parameters for **6a** are summarized in Tables 4-7. A single crystal of **6a** was mounted and placed on a Rigaku AFC-7R diffractometer. The unit cell was determined by the automatic indexing of 20 centered reflections and confirmed by examination of axial photographs. Intensity data were collected using graphite monochromated MoKα X-radiation

(λ = 0.71069 Å). Check reflections were measured every 150 reflections; the data were scaled accordingly and corrected for Lorentz, polarization, and absorption effects. The structure was determined using Patterson and standard difference map techniques on an O2 computer using SHELX97.[25] Systematic absences were uniquely consistent with the space group $P2_12_12_1$ [No. 19].

Dimethyl 4-vinylidene-3-oxobicyclo[3.3.0^{1,5}]octane-7,7-dicarboxylate (6b). Colorless oil, bp 130-135 ^{o}C (1.0 mmHg, Kugelrohr); IR (neat): 1731 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.12 (s, 3H), 2.21 (d, 1H, *J* = 18.55 Hz), 2.22 (dd, 1H, *J* = 6.84, 13.67 Hz), 2.25 (d, 1H, *J* = 14.16 Hz), 2.36 (d, 1H, *J* = 14.16 Hz), 2.44 (d, 1H, *J* = 18.55 Hz), 2.77 (dd, 1H, *J* = 7.81, 13.67 Hz), 2.85 (dd, 1H, *J* = 6.84, 7.81 Hz), 3.60 (s, 3H), 3.69 (s, 3H), 5.26 (d, 1H, *J* = 2.20 Hz), 5.98 (d, 1H, *J* = 2.20 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 27.5, 40.4, 44.8, 46.7, 51.4, 52.8, 52.9, 53.0, 61.1, 119.2, 147.9, 172.4, 172.5, 205.9; Mass (EI) m/z 266 (M^+). Anal. Calcd for $C_{14}H_{18}O_5$: C 63.15; H 6.81. Found: C 63.44; H 7.08. Irradiation of the methyl protons at δ 1.12 gave a 8.4% NOE of the C-5 hydrogen at δ 2.85. The stereochemistry of the major isomer was therefore assigned as shown:



6b

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Chapter 5

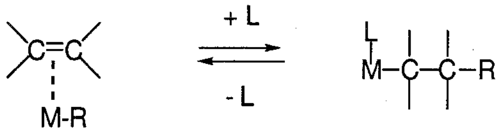
Ruthenium-Catalyzed β-Allyl Elimination Leading to Selective Cleavage of a Carbon-Carbon Bond in Homoallyl Alcohols

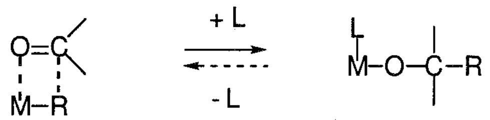
Abstract

$RuCl_2(PPh_3)_3$ is a highly effective catalyst for the deallylation of tertiary homoallyl alcohols. Under 10 atm of carbon monoxide at 180 °C in the presence of 5 mol % $RuCl_2(PPh_3)_3$ catalyst and an excess amount of allyl acetate in THF, various tertiary homoallyl alcohols were converted into the corresponding ketones and alkenes in high yields via selective cleavage of a carbon-carbon bond. For example, deallylation of 2-phenylpent-4-en-2-ol (**1a**) gave acetophenone (**2a**) in an isolated yield of 91% together with propene in 54% yield.

Introduction

The development of efficient methods for the selective formation[1] and cleavage[2,3] of carbon-carbon bonds catalyzed by transition-metal complexes is a central and challenging subject of modern organic synthesis. Among various processes catalyzed by transition-metal complexes, alkene insertion into metal-alkyl bonds is recognized as a fundamental model reaction of alkene polymerization (eq 1 forward). The reverse reaction, i.e., carbon-carbon bond cleavage via β-alkyl elimination (eq 1 reverse), has recently received growing attention, especially in the field of polymer chemistry.[4] Since Watson and Roe reported the first example of β-methyl elimination in the decomposition of $(C_5Me_5)_2LuCH_2CHMe_2$,[5] several examples of reversible β-alkyl insertion-elimination at both early and late transition-metal centers have been reported.[6]

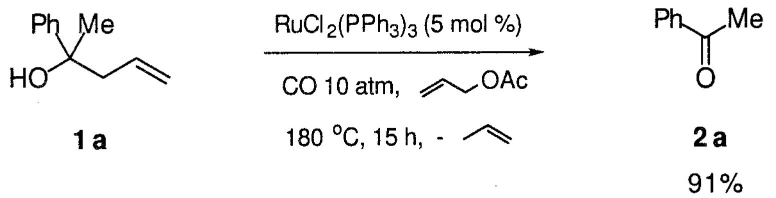

(1)


(2)

On the other hand, the addition of metal-alkyls to carbonyl compounds is another excellent method for the selective formation of carbon-carbon bonds (eq 2 forward).[7] However, since this reaction is generally irreversible, neither stoichiometric nor catalytic carbon-carbon bond cleavage via β-alkyl elimination from an (alkoxy)metal intermediate has yet been reported (eq 2 reverse). On the basis of recent studies of ruthenium-catalyzed carbon-carbon bond activation[3g,n] as well as η^3-allylruthenium chemistry,[8] we assume that successful catalytic carbon-carbon bond cleavage via β-alkyl elimination from an (alkoxy)metal intermediate can be attained by using tertiary homoallyl alcohols as a substrate, since the formation of a stable η^3-allylruthenium species by β-allyl elimination should contribute significantly to the driving force of this catalytic reaction. After many trials, we finally found the first example of catalytic deallylation of tertiary homoallyl alcohols via selective cleavage of a carbon-carbon bond. We report here the development of this new catalyst system and a synthetic application of β-allyl elimination.

Results and Discussion

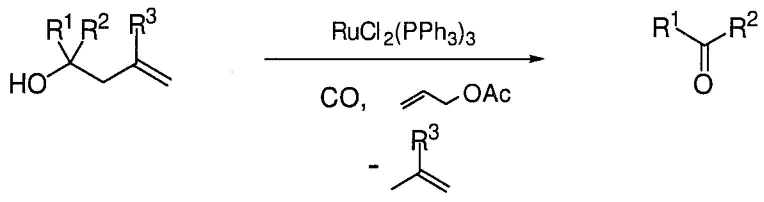
Treatment of tertiary homoallyl alcohol **1a** with an excess of allyl acetate in the presence of 5 mol % $RuCl_2(PPh_3)_3$ in THF under 10 atm of carbon monoxide at 180 °C for 15 h gave a deallylated product, acetophenone **2a**, in an isolated yield of 91% (eq 3).

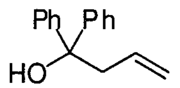
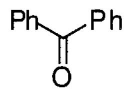
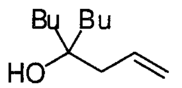
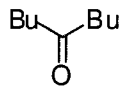
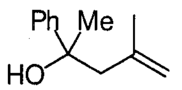
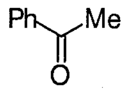


(3)

General tertiary homoallyl alcohols bearing either an aryl or alkyl substituent (**1b-d**) were smoothly deallylated by the present catalyst system to give the corresponding ketones (**2b-d**) in high isolated yields (Table 1).

Table 1. Ruthenium-Catalyzed Deallylation of Tertiary Homoallyl Alcohols[a]



Run	Homoallyl alcohol	Product	Isolated yield (%)
1	 **1b**	 **2b**	87
2	 **1c**	 **2c**	71
3	 **1d**	 **2d**	85

[a]Homoallyl alcohol (**1**) (4.0 mmol), allyl acetate (30 mmol), $RuCl_2(PPh_3)_3$ (0.20 mmol), and THF (8.0 mL) under CO (10 atm) at 180 °C for 15 h.

Gas analysis showed the generation of propene (54% yield) in the reaction of **1a**, and of isobutene (42% yield) in the reaction of **1d**.[9] The presence of both carbon monoxide and allyl acetate was crucial (Table 2). Carbon monoxide operates as an effective π-acid.[10] While the role of allyl acetate is not yet clear, we believe that it is required for the generation and stabilization of a catalytically active ruthenium species.[11] Attempts to effect the reaction at temperatures lower than 150 °C resulted in drastically diminished yield (Run 4 in Table 2).

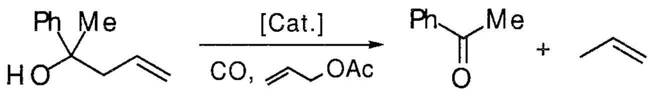
Table 2. Effect of the Reaction Conditions on Deallylation of **1a** to **2a**[a]

Run	Allyl acetate (mmol)	Temp. (°C)	CO Press. (atm)	Yield of **2a** (%)[b]
1	30	180	10	91
2	10	180	10	43
3	0	180	10	32
4	30	150	10	0
5	30	180	0[c]	0

[a]**1a** (4.0 mmol), $RuCl_2(PPh_3)_3$ (0.20 mmol), and THF (8.0 mL) for 15 h. [b]Determined by GLC. [c]Under an argon atmosphere.

Several transition-metal complexes as well as ruthenium complexes were examined with regard to their ability to catalyze the deallylation of **1a** to **2a**. The results are summarized in Table 3. All of the ruthenium complexes showed catalytic activity, and among them, $RuCl_2(PPh_3)_3$ showed the highest activity. Besides ruthenium complexes, only $RhCl(PPh_3)_3$ showed a moderate catalytic activity, while complexes, such as $NiBr_2(PPh_3)_2$, $PdCl_2(PPh_3)_2$, and *cis*-$PtCl_2(PPh_3)_2$, were totally ineffective in the present deallylation reaction.

Table 3. Catalytic Activity of Several Transition-Metal Complexes in Deallylation of **1a** to **2a**[a]

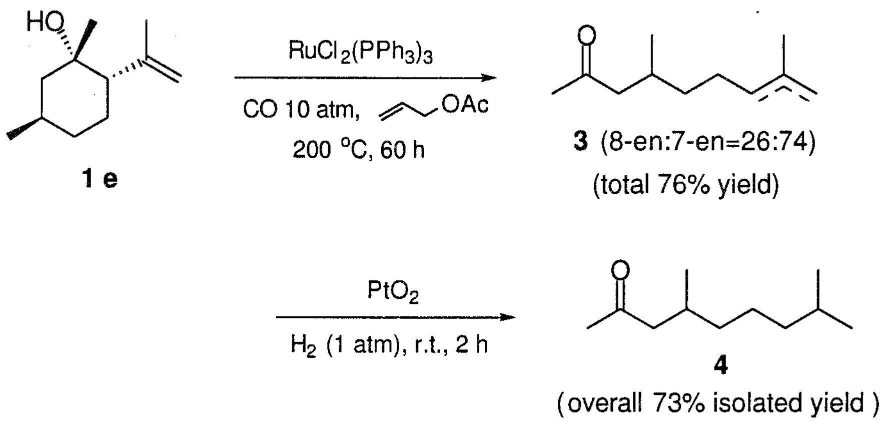


1a **2a**

Run	Catalyst	Yield of **2a** (%)[b]
1	$RuCl_2(PPh_3)_3$	(91)
2	*cis*-$RuCl_2(CO)_2(PPh_3)_2$	65
3	Cp*RuCl(cod)	64
4	$Ru_3(CO)_{12}$[c]	45
5	$RhCl(PPh_3)_3$	53
6	$NiBr_2(PPh_3)_2$	0
7	$PdCl_2(PPh_3)_2$	0
8	*cis*-$PtCl_2(PPh_3)_2$	0

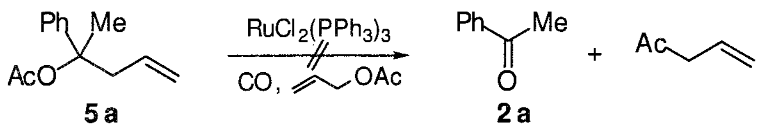
[a] **1a** (4.0 mmol), catalyst (0.20 mmol), allyl acetate (30 mmol), THF (8.0 mL), CO (10 atm), 180 °C, 15 h. [b] GLC yield (Isolated yield). [c] $Ru_3(CO)_{12}$ (0.067 mmol) was used.

A synthetic application of the present reaction is demonstrated in the following ring-opening reaction of cyclic homoallyl alcohols (eq 4). The treatment of **1e** under the present reaction conditions gave the ring-opening product, unsaturated ketone **3**, as a mixture of olefinic isomers (8-en:7-en = 26:74, total 76% yield). Hydrogenation of **3** by PtO_2 catalyst gave the saturated ketone **4** in an overall isolated yield of 73%. Thus, the present reaction may offer a novel method for the catalytic ring-opening reaction of general 2-vinylcycloalkanols.[12]

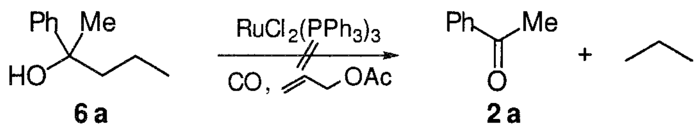


(4)

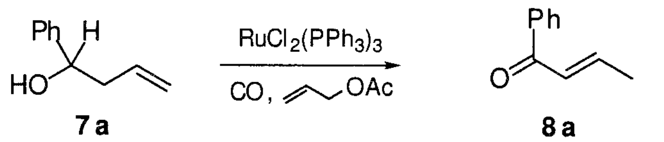
The following reactions using **5a**, **6a**, and **7a**, illustrated in eqs 5-7, provided insight into the mechanism. First, treatment of **5a** did not give **2a** at all, which indicates that the first step of the reaction is oxidative addition of a hydroxyl group of **1a** to ruthenium. Second, the failure of the depropylation of **6a** to **2a** suggests that the driving force of this reaction is the formation of an allylruthenium species. Furthermore, substrate **7a**, which has both a β-hydrogen and a β-allyl group, gave the α,β-unsaturated ketone **8a** exclusively via β-hydrogen elimination.



(5)



(6)

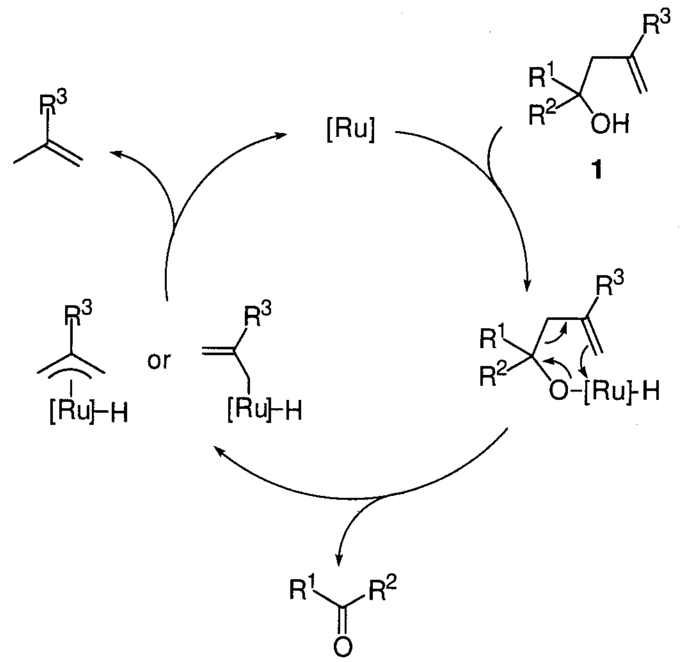


7a 8a
65%(*E* 100%)

(7)

Considering all of our findings, the most plausible mechanism is illustrated in Scheme 1. The initial step might consist of oxidative addition of the hydroxyl group in **1** to an active ruthenium center. Subsequent β-allyl elimination from an (alkoxy)ruthenium intermediate gives a ketone **2** together with a (hydrido)(allyl)ruthenium intermediate, which undergoes reductive elimination to give an alkene. Carbon monoxide may promote the final reductive elimination of an alkene as an effective π-acid (*vide supra*).

Scheme 1



In summary, we have developed the first and practical ruthenium-catalyzed deallylation of tertiary homoallyl alcohols via selective cleavage of a carbon-carbon bond. The mechanistic aspects and scope of the transfer-allylation reaction[13] are currently under investigation, but we believe that this carbon-carbon bond cleavage involves the first β-alkyl (β-allyl) elimination from an (alkoxy)ruthenium intermediate in its catalytic cycle.

Experimental Section

General. GLC analyses were carried out on gas chromatographs equipped with a glass column (3 mm i.d. x 3 m) packed with Silicone OV-17 (2% on Chromosorb W(AW-DMCS), 80-100 mesh), a stainless column (3 mm i.d. x 3 m) packed with Porapak-Q (80-100 mesh), and a capillary column [Shimadzu capillary column HiCap-CBP10-M25-025 (polarity similar to OV-1701): 0.22 mm i.d. x 25 m]. The products were isolated by Kugelrohr distillation. Compound **4** was purified on a recycling preparative HPLC (Japan Analytical Industry Co. Ltd., Model LC-908) equipped with JAIGEL-1H and 2H columns (GPC) using $CHCl_3$ as an eluent. The ^1H-NMR spectra were recorded at 400 MHz, and ^{13}C-NMR spectra were recorded at 100 MHz. Samples were analyzed in $CDCl_3$, and the chemical shift values are expressed relative to Me_4Si as an internal standard. Elemental analyses were performed at the Microanalytical Center of Kyoto University.

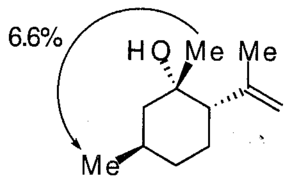
Materials. The reagents used in this study were dried and purified before use by standard procedures. Carbon monoxide (>99.9%) was used without further purification. $Ru_3(CO)_{12}$ was obtained commercially, and used without further purification. $RuCl_2(PPh_3)_3$,[14] *cis*-$RuCl_2(CO)_2(PPh_3)_2$,[10] $Cp^*RuCl(cod)$,[15] $RhCl(PPh_3)_3$,[16] $NiBr_2(PPh_3)_2$,[17] $PdCl_2(PPh_3)_2$,[18] and *cis*-$PtCl_2(PPh_3)_2$[19] were prepared as described in the literature. Homoallyl alcohols (**1a-d**) were also prepared by the reaction of ketones with allylic Grignard reagents.[20] Acetylation of **1a** by acetic anhydride was carried out in the presence of triethylamine and a catalytic amount of DMAP (4-dimethylaminopyridine) to give **5a** in 85% yield.[21] The reaction of acetophenone with n-PrMgBr, and the reaction of benzaldehyde with allylmagnesium bromide gave **6a** and **7a**, respectively. Hydrogenation of **3** to

4 by PtO_2 catalyst was carried out as described in the literature.[22] The characteristics of **1e** and **4** are shown below. The spectral and analytical data of **2a-d** were fully consistent with those of authentic samples. Compounds **8a** and **9a** have already been reported.[23]

Preparation of *rel*-(1*S*,2*S*,5*R*)-1,5-dimethyl-2-isopropenyl-cyclohexanol (1e). Swern oxidation[24] of *rel*-(1*R*,2*S*,5*R*)-2-isopropenyl-5-methylcyclohexanol (94% *de*, 60 mmol) by a mixture of oxalyl chloride (62 mmol) and DMSO (65 mmol) in the presence of triethylamine (298 mmol) gave *rel*-(2*S*,5*R*)-2-isopropenyl-5-methylcyclohexanone in an isolated yield of 83% (93% *de*). Colorless liquid, bp 130 °C (15 mmHg, Kugelrohr); IR (neat) 1712 cm^{-1}; ^1H NMR($CDCl_3$, 400 MHz): δ 1.04 (d, 3H, *J* = 6.40 Hz, CH_3), 1.42 (tdd, 1H, *J* = 12.95, 13.30, 3.42 Hz, C*H*H(3)), 1.76 (tdd, 1H, *J* = 13.8, 12.95, 3.42 Hz, C*H*H(4)), 1.78 (s, 3H, CH_3), 1.84-1.98 (m, 2H, CH*H*(3), CH(5)), 2.02-2.08 (m, 2H, CH*H*(4), C*H*H(6)), 2.40 (ddd, 1H, *J* = 13.30, 3.67, 1.95 Hz, CH*H*(6)), 2.96 (dd, 1H, *J* = 13.18, 5.37 Hz, CH(2)), 4.72 (s, 1H, =C*H*H), 4.93 (s, 1H, =CH*H*); ^{13}C NMR($CDCl_3$, 100 MHz): δ 21.22, 22.14, 31.08, 33.73, 35.21, 50.45, 57.58, 112.72, 143.39, 220.12; MS m/z 152 (M^+).

The reaction of *rel*-(2*S*,5*R*)-2-isopropenyl-5-methylcyclohexanone (4.0 g, 26 mmol) in THF (20 mL) with MeMgBr in THF (0.91 M, 45 mL, 41 mmol) at 0 °C under an argon atmosphere gave **1e** in an isolated yield of 70% (93% *de*).

***rel*-(1*S*,2*S*,5*R*)-1,5-Dimethyl-2-isopropenylcyclohexanol (1e).** Colorless liquid, bp 110 °C (24 mmHg, Kugelrohr); ^1H NMR($CDCl_3$, 400 MHz): δ 0.78-0.81 (m, 1H, C*H*H(3)), 0.80 (d, 3H, *J* = 6.34 Hz, CH_3), 0.94 (t, 1H, *J* = 12.94 Hz, C*H*H(6)), 1.13 (s, 3H, CH_3), 1.38 (dt, 1H, *J* = 13.19, 3.42 Hz, C*H*H(4)), 1.48 (s, 1H, OH), 1.60-1.74 (m, 4H, CH*H*(3), CH*H*(4), CH(5), CH*H*(6)), 1.75 (s, 3H, CH_3), 1.78 (dd, 1H, *J* = 12.94, 3.42 Hz, CH(2)), 4.68 (s, 1H, =C*H*H), 4.81 (s, 1H, =CH*H*); ^{13}C NMR($CDCl_3$, 100 MHz): δ 22.10, 24.39, 27.60, 27.64, 29.75, 34.86, 48.73, 53.05, 70.62, 111.77, 148.02; MS m/z 168 (M^+). Anal. Calcd for $C_{11}H_{20}O$: C 78.51, H 11.98. Found: C 78.59, H 12.06. A nuclear Overhauser enhancement study was undertaken to determine the relative configuration of the major isomer. Irradiation of the methyl group at δ 1.13 gave a 6.6% NOE of the methyl group at δ 0.80. The stereochemistry of the major isomer was therefore assigned as shown:



1e

Ruthenium-Catalyzed Deallylation of Tertiary Homoallyl Alcohols 1. A mixture of tertiary homoallyl alcohol **1** (4.0 mmol), $RuCl_2(PPh_3)_3$ (0.20 mmol), allyl acetate (30 mmol), and THF (8.0 mL) was placed in a 50-mL stainless steel autoclave under a flow of argon. Carbon monoxide was then pressurized to 10 atm at room temperature, and the mixture was magnetically stirred at 180 °C for 15 h. After cooling, the gaseous products were collected in a gas burette, and analyzed by GC. The resulting red-brown solution was analyzed by GLC, and the products **2** were isolated by Kugelrohr distillation.

Ruthenium-Catalyzed Deallylation of 1a Using Maleic Anhydride. A mixture of **1a** (4.0 mmol), $RuCl_2(PPh_3)_3$ (0.20 mmol), maleic anhydride (10 mmol), allyl acetate (30 mmol), and THF (8.0 mL) was placed in a 50-mL stainless steel autoclave *under an argon atmosphere.* The reaction performed at 180 °C for 15 h gave **2a** in 65% yield.

Ruthenium-Catalyzed Transfer-Allylation of Benzaldehyde with Tertiary Homoallyl Alcohols 1a or 1d. A mixture of tertiary homoallyl alcohol (**1a** or **1d**) (4.0 mmol), benzaldehyde (4.0 mmol), $RuCl_2(PPh_3)_3$ (0.20 mmol), allyl acetate (30 mmol), and THF (8.0 mL) was placed in a 50-mL stainless steel autoclave. Carbon monoxide was then pressurized to 10 atm at room temperature, and the mixture was magnetically stirred at 200 °C for 40 h. After cooling, the products were isolated by Kugelrohr distillation and/or recycling preparative HPLC.

4,8-Dimethyl-2-nonanone (4). Colorless liquid, bp 90 °C (1.0 mmHg); IR (neat) 1733 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz): δ 0.86 (d, 6H, *J* = 6.84 Hz, $2CH_3$), 0.89 (d, 3H, *J* = 6.84 Hz, CH_3), 1.14 (dt, 2H, *J* = 7.32, 6.84, CH_2(7)), 1.19-1.36 (m, 4H, $2CH_2$(5,6)), 1.52 (septet, 1H, *J* = 6.84 Hz, CH(8)), 1.92-2.07 (m, 1H, CH(4)), 2.13 (s, 3H, CH_3), 2.22 (dd, 1H, *J* = 15.80, 8.30 Hz, C*H*H(3)), 2.41 (dd, 1H, *J* = 15.60, 5.86 Hz, CH*H*(3)), ; ^{13}C NMR($CDCl_3$, 100 MHz): δ 19.57, 22.32, 22.43, 24.49, 27.70, 29.05, 30.12, 36.92, 38.84, 51.04, 208.96; MS m/z 168 (M^+).

Satisfactory elemental analysis data were obtained for semicarbazone[25] of **4**. Anal. Calcd for $C_{12}H_{25}N_3O$: C 63.40, H 11.08, N 18.48. Found: C 63.16, H 10.87, N 18.16.

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(7) Addition of allylorganometallics to carbonyl compounds, see: Roush, W. R. In *Comprehensive Organic Synthesis*: Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, U.K., 1991; Vol. 2, pp 1-53.

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(9) In the reaction of **1d**, a small amount (0.36 mmol) of propene was generated from allyl acetate (30 mmol) together with isobutene (1.68 mmol, 42%) from **1d**.

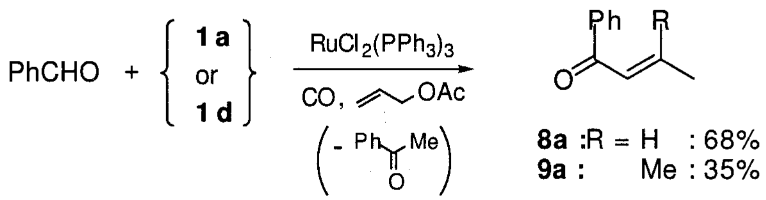
(10) After the reaction, $RuCl_2(PPh_3)_3$ was quantitatively converted into *cis*-$RuCl_2(CO)_2(PPh_3)_2$ (Stephenson, T. A.; Wilkinson, G. *J. Inorg. Nucl. Chem.* **1966**, *28*, 945). In addition, carbon monoxide can be replaced by maleic anhydride (yield of **1a**, 65%; see Experimental Section). These results indicate that carbon monoxide and maleic anhydride may coordinate to an active ruthenium center and promote the reductive elimination of propene from a

(hydrido)(allyl)ruthenium intermediate, as well as control the electronic condition of an active ruthenium center.

(11) Oxidative addition of allyl trifluoroacetate to Ru(0) has already been reported, see: Komiya, S.; Kabasawa, T.; Yamashita, K.; Hirano, M.; Fukuoka, A. *J. Organomet. Chem.* **1994**, *471*, C6.

(12) The thermal ring-opening reaction (retro-ene reaction) of 2-vinylcyclohexanols is generally carried out in the vapor phase at *ca.* 500 °C. Marvell, E. N.; Rusay, R. *J. Org. Chem.* **1977**, *42*, 3336.

(13) The following novel ruthenium-catalyzed transfer-allylation of aldehydes with **1a** or **1d** also supports the formation of an allylruthenium intermediate. For example, the treatment of benzaldehyde with an equimolar amount of **1a** or **1d** in the presence of $RuCl_2(PPh_3)_3$ catalyst and an excess amount of allyl acetate in THF gave the transfer-allylated product, (*E*)-1-phenyl-2-buten-1-one (**8a**) and 3-methyl-1-phenylbut-2-en-1-one (**9a**) in yields of 68% and 35%, respectively (eq 8). Of course, no reaction occurred in the absence of **1a** or **1d**, even in the presence of allyl acetate.



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General Conclusion

This thesis is a summary of studies on the development of novel catalytic reactions via η^3-allylruthenium intermediates and consists of Chapters 1 to 5.

In Chapter 1, a novel ruthenium catalyst system of CpRuCl(cod)/NH_4PF_6 for allylic substitution of *cyclic* allyl carbonates was developed, while Cp*RuCl(cod) and Ru(cod)(cot) are highly active catalyst systems for allylic substitution of *acyclic* allyl carbonates. The development of this new catalyst system provided some insight into the stereochemistry and scope of the ruthenium-catalyzed allylic substitution reaction. Consequently, the ruthenium-catalyzed allylation of carbon- and nitrogen-nucleophiles proceeded with overall retention of configuration.

In Chapter 2, the first ruthenium-catalyzed allylation of thiols with various allylic compounds was investigated. In the presence of a catalytic amount of Cp*RuCl(cod) at room temperature for 1 h in CH_3CN, synthesis of general allylic sulfides from both aliphatic and aromatic thiols has been attained. In the present reaction, allylic alcohols can be used as an effective allylating reagent, which is highly economical in terms of atoms used. This reaction should open up new opportunities in transition-metal complex-catalyzed sulfur chemistry. The regio- and stereochemical courses of the reaction were also disclosed, and overall retention of the configuration was also observed.

In Chapter 3, the first intermolecular hydroacylation of 1,3-dienes with aldehydes catalyzed by a ruthenium complex was developed. Ru(cod)(cot)/PPh_3 was an effective catalyst system for this reaction to give the corresponding β,γ-unsaturated ketones in reasonable yields. In this reaction, carbon monoxide was not needed to suppress decarbonylation of aldehydes, and to maintain the catalytic activity.

In Chapter 4, a novel synthesis of cyclopentenones via ruthenium-catalyzed intermolecular carbonylative cyclization of allylic carbonates with alkenes was described. In the presence of a catalytic amount of $[RuCl_2(CO)_3]_2$ or $(\eta^3\text{-}C_3H_5)RuBr(CO)_3$ and Et_3N at 120 °C for 5 h under 3 atm of carbon monoxide, the reaction of allyl methyl carbonate with 2-norbornene gave the corresponding cyclopentenone, *exo*-4-methyltricyclo[5.2.1.0^{2,6}]dec-4-ene-3-one, in high yield with high stereoselectivity (*exo* 100%). On the other hand, aryl-substituted allylic carbonates, such as cinnamyl methyl carbonate, gave 2-benzylidenecyclopentanone in high yield instead of the corresponding cyclopentenone, due to the strong π-conjugation of an olefinic moiety with the phenyl group. The geometry of the olefinic moiety was confirmed by X-ray crystallography, which indicates that the phenyl group stays at the opposite side of the carbonyl group. This catalyst system was also effective for *intramolecular* carbonylative cyclization of methyl 2,7-octadienyl carbonate to give the corresponding bicyclic cyclopentanone in good yield. This catalyst process, which is an alternative to the Pauson-Khand reaction, could become a valuable tool in the field of organic and natural product synthesis.

In Chapter 5, ruthenium-catalyzed *β*-allyl elimination leading to selective cleavage of a carbon-carbon bond in tertiary homoallyl alcohols was disclosed. Under 10 atm of carbon monoxide at 180 °C in the presence of 5 mol % $RuCl_2(PPh_3)_3$ catalyst and an excess amount of allyl acetate in THF, deallylation of various tertiary homoallyl alcohols proceeded to give the corresponding ketones and alkenes in high yields. This carbon-carbon bond cleavage involved the first *β*-alkyl (*β*-allyl) elimination from an (alkoxy)ruthenium intermediate in its catalytic cycle, in which the formation of a stable allylruthenium species should contribute significantly to the driving force of this process. A synthetic application of the present reaction was demonstrated in the deallylation of cyclic homoallyl alcohols, which may offer a novel method for the catalytic ring-opening reaction of general 2-vinylcycloalkanols.

As described above, several novel catalytic reactions via η^3-allylruthenium intermediate have been developed in this thesis. The purpose of this study is to establish the novel reactivity of η^3-allylruthenium complexes, as well as to provide novel synthetic methods via η^3-allylruthenium intermediates. We believe that these findings revealed here attain the initial object and open up new opportunities in organometallic chemistry, especially in the chemistry of ruthenium complexes. Hopefully, these reactions developed in this thesis will be widely used as convenient, versatile and general methods in both synthetic organic chemistry and the chemical industry.

List of Publications

Chapter 1

Ruthenium-Catalyzed Allylic Substitution of Cyclic Allyl Carbonates with Nucleophiles. Stereoselectivity and Scope of the Reaction

Yasuhiro Morisaki, Teruyuki Kondo, and Take-aki Mitsudo

Organometallics **1999**, *18*, 4742-4746.

Chapter 2

First Ruthenium-Catalyzed Allylation of Thiols Enables the General Synthesis of Allylic Sulfides

Teruyuki Kondo, Yasuhiro Morisaki, Shin-ya Uenoyama, Kenji Wada, and Take-aki Mitsudo

J. Am. Chem. Soc. **1999**, *121*, 8657-8658.

Chapter 3

First Intermolecular Hydroacylation of 1,3-Dienes with Aldehydes Catalyzed by Ruthenium

Teruyuki Kondo, Naotaka Hiraishi, Yasuhiro Morisaki, Kenji Wada, Yoshihisa Watanabe, and Take-aki Mitsudo

Organometallics **1998**, *17*, 2131-2134.

Chapter 4

A New Route to Cyclopentenones via Ruthenium-Catalyzed Carbonylative Cyclization of Allylic Carbonates with Alkenes

Yasuhiro Morisaki, Teruyuki Kondo, and Take-aki Mitsudo

J. Am. Chem. Soc., submitted for publication.

Chapter 5

Ruthenium-Catalyzed *β*-Allyl Elimination Leading to Selective Cleavage of a Carbon-Carbon Bond in Homoallyl Alcohols

Teruyuki Kondo, Kouichi Kodoi, Eiji Nishinaga, Takumi Okada, Yasuhiro Morisaki, Yoshihisa Watanabe, and Take-aki Mitsudo

J. Am. Chem. Soc. **1998**, *120*, 5587-5588.

Other Publication

The following publication is not included in this thesis:

Ruthenium Complex-Controlled Catalytic *N*-Mono- or *N,N*-Dialkylation of Heteroaromatic Amines with Alcohols

Yoshihisa Watanabe, Yasuhiro Morisaki, Teruyuki Kondo, and Take-aki Mitsudo

J. Org. Chem. **1996**, *61*, 4214-4218.

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