Preparation of Optically Active Cyclic Carbonates and 1,2-Diols *via* Enantioselective Hydrogenation of α-Methylenedioxolanones Catalyzed by Chiral Ruthenium(II) Complexes

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The enantioselective hydrogenation of α-methylene-1,3-dioxolan-2-ones catalyzed by chiral (diphosphine)ruthenium complexes leads to optically active cyclic carbonates with high enantioselectivities. Their hydrolysis in methanol in the presence of potassium carbonate quantitatively affords optically active 1,2-diols.

Optically active carbonates offer selective routes to polyfunctional molecules of interest. The ring-opening of saturated cyclic carbonates by *O*- and *N*-nucleophiles gives access to linear carbonates and urethanes,[1] whereas the cleavage by carbonucleophiles leads to selective transformations into hydroxy esters.[2] Cyclic carbonates are now outstanding monomers for the preparation of polycarbonates *via* ring-opening polymerization,[3] and they have been widely used for the preparation and the protection of polyhydroxylated compounds[4,5] and carbohydrates.[6] The preparation of optically pure cyclic carbonates is based on the cyclization of diols found in natural compounds or resulting from asymmetric dihydroxylation of olefins, with phosgene[1] or activated carbonates.[1,7] The insertion of CO_2 into epoxides and allylic epoxides catalyzed by zinc(II)[8] or palladium(0)[9] also provides optically active cyclic carbonates. The latter have also been prepared *via* diastereoselective cyclization of [(alkenyloxy)carbonyl]oxy radicals,[10] whereas the treatment of *β*,*γ*-epoxycarbamates with various acids[4b,6] has led to the stereoselective formation of hydroxylated cyclic carbonates.

The straightforward synthesis of α-methylene carbonates from tertiary propargylic alcohols and CO_2[11] catalyzed by phosphine has offered a new step toward optically active cyclic carbonates based on the enantioselective hydrogenation of their exocyclic C=C double bond. We report here the first examples of asymmetric hydrogenation of 5-methylene-1,3-dioxolan-2-ones **2a**−**c**, catalyzed by chiral ruthenium complexes and the efficient synthesis of the cyclic carbonates **3a**−**c** of high enantiomeric purity, and we show that their hydrolysis in methanol in the presence of potassium carbonate affords the optically active 1,2-diols **4a**−**c** (Scheme 1).

Results and Discussion

Enantioselective Hydrogenation of 5-Methylene-1,3-dioxolan-2-ones. The starting carbonates **2a**−**c** were prepared in 97% (**2a**),[11] 93% (**2b**), and 80% (**2c**) yields in one step from the reaction of CO_2 (5 MPa) with the tertiary 1,1-disubstituted prop-2-yn-1-ols **1a**−**c** containing two identical substituents at C(1), in the presence of tributylphosphine as catalyst.

The enantioselective hydrogenation of carbonates **2** was attempted with a variety of chiral ruthenium complexes containing an optically active diphosphine ligand. A typical hydrogenation was performed from 0.25 g (2 mmol) of carbonate **2**, 0.01 mmol of ruthenium catalyst, and 10 mL of dichloromethane, which were introduced under inert atmosphere into a 125 mL autoclave. The hydrogenation was then carried out under an initial pressure of hydrogen (2−10 MPa), and the complete conversion of the starting carbonate **2** was determined by gas chromatography. The ^{1}H NMR analyses of the reaction products showed that the saturated cyclic carbonates **3** were the sole products of the reaction, indicating that the hydrogenation was very selective and no cleavage of the cyclic carbonate took place. They were isolated by distillation under reduced pressure in more than 85% yield. The enantiomeric excesses of carbonates **3**, obtained from a variety of optically active ruthenium catalysts[12] and determined by gas chromatography with a chiral Lipodex capillary column, were in the range 84−97% (Table 1).

All the ruthenium catalyst precursors gave very good results in terms of activity and enantioselectivity. For the hydrogenation of **2a**, bis(trifluoroacetate)(diphosphine)ruthenium complexes appeared to be the most efficient catalysts precursors as enantioselectivities lo-

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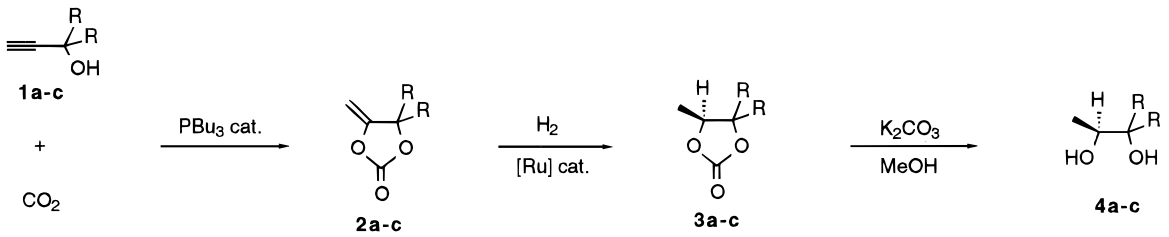
Scheme 1



a: R= Me
b: R-R = spirocyclopentyl
c: R-R= spirocyclohexyl

Table 1. Hydrogenation of Carbonates 2a−c into 3a−c Catalyzed by (Diphosphine)Ru(II) Complexes[a]

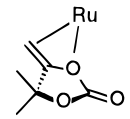
run	catalyst	compd	H_2 (MPa)	*T* (°C)	time (h)	ee[b] (%)
1	((*S*)-Binap)Ru(O_2CCF_3)$_2$[12a]	(+)-**3a**	2	20	72	95
2	((*R*)-Binap)Ru(O_2CCF_3)$_2$[12a]	(−)-**3a**	10	20	18	95
3	((*R*)-Binap)$RuBr_2$[12b]	(−)-**3a**	10	50	20	90
4	[((*R*)-Binap)$RuCl_2$]NEt_3[12c]	(−)-**3a**	10	50	20	93
5	((*R*)-MeO-Biphep)Ru(O_2CCF_3)$_2$[12d]	(−)-**3a**	10	20	17	94
6	((*R*)-Biphemp)Ru(O_2CCF_3)$_2$[12d]	(−)-**3a**	10	20	17	97
7	((*R*)-Binap)Ru(O_2CCF_3)$_2$	(−)-**3a**	10	50	17	83[c]
8	((*S*)-Binap)Ru(O_2CCF_3)$_2$	(+)-**3c**	10	50	20	84
9	((*R*)-Binap)Ru(O_2CCF_3)$_2$	(−)-**3c**	10	50	20	80[c]
10	((*S*)-Binap)Ru(O_2CCF_3)$_2$	(+)-**3c**	5	20	20	88
11	((*R*)-Binap)Ru(O_2CCF_3)$_2$	(−)-**3c**	2	50	68	89
12	((*R*)-Binap)Ru(O_2CCF_3)$_2$	(−)-**3b**	10	50	48	89

[a] Reactions carried out in CH_2Cl_2 with a ratio substrate/catalyst = 200. [b] ee were determined by gas chromatography with a capillary column containing a chiral Lipodex phase (25 m × 0.25 mm). [c] Hydrogenation in methanol.

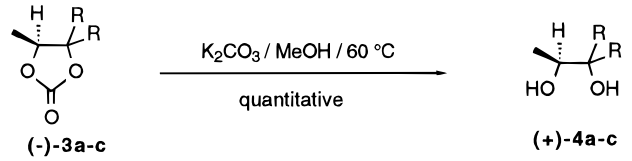
cated in the range 90−97% were obtained with various chiral diphosphines such as Binap, MeO-Biphep, or Biphemp.[13] The results in Table 1 show that the complete conversion of the α-methylene carbonate **2a** (88% isolated yield in run 2) was reached in less than 20 h when the hydrogenation was carried out under 10 MPa of hydrogen, whereas 72 h were required under a 2 MPa initial pressure of hydrogen to obtain **3a** in 95% ee in both cases (Table 1, runs 1 and 2). [(*R*)-Binap)$RuCl_2$]-NEt_3 (Table 1, run 4) and the *in situ* prepared ((*R*)-Binap)$RuBr_2$ (Table 1, run 3) precursors gave similar results as 90 and 93% ee, respectively, were obtained under similar hydrogenation conditions. The best enantioselectivity was obtained with the (Biphemp)Ru(O_2-CCF_3)$_2$ catalyst, which led to 97% ee (Table 1, run 6). The introduction of rigidity and steric hindrance at the sp^3 carbon atom in the α-methylene carbonates **2b** and **2c** did not improve the enantioselectivity of the hydrogenation of the exocyclic double bond. Under our typical conditions the use of (Binap)Ru(O_2CCF_3)$_2$ catalyst precursor led to a complete conversion of the unsaturated carbonates **2b−c** and afforded the saturated cyclic carbonates **3b** and **3c** with 89% ee (Table 1, runs 11 and 12). It is noteworthy that the utilization of methanol as the solvent led to lower enantioselectivities as **3a** and **3c** were obtained with only 83 and 80% ee, respectively, after hydrogenation under 10 MPa of hydrogen at 50 °C (Table 1, runs 7 and 9).

The excellent enantioselectivities might be due to the fact that the cyclic carbonates **2a−c** contain an exocyclic C=C double bond and an adjacent oxygen atom, which make possible the double chelation to the ruthenium center and leads to high enantioface differentiation (Chart 1). This chelation does not seem to be very affected by the bulk and the rigidity of the substituents at the other cyclic carbon of the dioxolanone ring; nevertheless, the best enantioselectivities are obtained from carbonate **2a**.

Chart 1



Scheme 2



This explanation corresponds to that given by Takaya *et al.*[14] for the enantioselective hydrogenation of cyclic enol esters and ethers. When methanol is used as the solvent, the possible competition between the coordination of the carbonate oxygen and methanol, which only allows the coordination of the C=C bond, might explain the lower enantioselectivities obtained in this solvent.

Carbonate Opening: Synthesis of Optically Active Diols. The treatment of 1.34 mmol of carbonate **3a** with 2.00 mmol of potassium carbonate in 10 mL of anhydrous methanol at 60 °C for 2.5 h led to the quantitative conversion of the carbonate into the corresponding diol (Scheme 2). After evaporation of the solvent and dissolution of the salt in saturated NH_4Cl, the diol was extracted with diethyl ether and distilled under reduced pressure. This procedure allowed the isolation of the optically active diols (+)-**4a−c** from

(13) Binap: (1,1′-binaphthyl-2,2′-diyl)bis(diphenylphosphine). Biphemp: (6,6′-dimethylbiphenyl-2,2′-diyl)bis(diphenylphosphine). MeO-Biphep: (6,6′-dimethoxybiphenyl-2,2′-diyl)bis(diphenylphosphine).

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carbonates (−)-**3a**−**c** in 87, 85 and 85% yield, respectively. Carbonate **3a** led to the diol (+)-**4a** ($[\alpha]_D$= +9 (*c* 1.5, Et_2O) corresponding to the diol with the (*S*) configuration previously prepared by deamination of 3-amino-2-methylbutan-2-ol.[15]

As the ring opening of cyclic carbonates is known to proceed with retention of configuration, this indicated that the utilization of ((*R*)-diphosphine)ruthenium(O_2CCF_3)$_2$ catalysts led to carbonate (−)-**3a** with the (*S*) configuration. This method makes possible the preparation of 1-methyl-2,2-disubstituted diols containing two identical substituents at C(2) in three steps from the easily available corresponding prop-2-yn-1-ols[16] and involves the participation of CO_2 as an essential synthetic tool. It is noteworthy that the diol (*S*)-**4a** has already been used as ligand in the molybdenum-mediated kinetic resolution of oxiranes.[17]

The above convenient syntheses of optically active cyclic carbonates and 1,2-diols in two and three steps, respectively, from carbon dioxide and prop-2-yn-1-ols offer a potential for the synthesis of optically active molecules and ligands without the utilization of phosgene derivatives.

Experimental Section

Cyclopentanespiro-4′-5′-Methylene-1′,3′-dioxolan-2′-one (2b). Ten mmol of the propargylic alcohol **1b** and 0.2 mL (0.8 mmol) of tributylphosphine were stirred for 20 h at 100 °C under CO_2 pressure (5 MPa). The carbonate **2b** (93%) was isolated by chromatography over a silica gel column eluted with a dichloromethane/pentane (3:1) mixture: IR (neat) ν 1823, 1683 cm^{-1}; ^{1}H NMR (300.133 MHz, $CDCl_3$) δ 4.73 (d, 1H, J = 4.0 Hz), 4.31 (d, 1H, J = 4.0 Hz), 2.18 (m, 8H); ^{13}C {^{1}H} NMR (75.469 MHz, $CDCl_3$) δ 155.68, 151.49, 94.27, 85.40, 40.63, 24.23. Anal. Calcd for $C_8H_{10}O_3$: C, 62.33; H, 6.54. Found: C, 62.71; H, 7.00.

General Procedure for the Hydrogenation of Cyclic α-methylene carbonates. 5-Methylene-1,3-dioxolan-2-one (0.250 g) and the ruthenium catalyst (0.5 mol %) were placed in a 125 mL stainless steel autoclave. After addition of 10 mL of solvent under nitrogen atmosphere, the autoclave was pressurized with hydrogen (2−10 MPa) and heated (see Table 1). The solvent was evaporated, and the hydrogenated carbonate was recovered by distillation under reduced pressure. The enantiomeric excess was determined by GC using a chiral Lipodex capillary column (25 m × 0.25 mm). The optical rotation was measured on a Perkin-Elmer-241 polarimeter.

4,4,5-Trimethyl-1,3-dioxolan-2-one (3a). Isolated as a white solid (85%) from the hydrogenation of 0.250 g of carbonate **2a** in CH_2Cl_2 under 10 MPa of hydrogen at 20 °C for 17 h, in the presence of ((*R*)-Biphemp)Ru(O_2CCF_3)$_2$ as catalyst: mp = 64 °C; IR (KBr) ν 1795 cm^{-1}; ^{1}H NMR (300.133 MHz, $CDCl_3$) δ 4.43 (q, 1H, J = 6.5 Hz), 1.47, 1.35 (2 s, 6H), 1.34 (d, 3H, J = 6.5 Hz); ^{13}C {1H} NMR (75.469 MHz, $CDCl_3$) δ 154.20, 84.18, 81.52, 25.78, 21.03, 14.53; $[\alpha]^{18}_D$ −24 (*c* = 2, EtOH) (ee = 97%). Anal. Calcd for $C_6H_{10}O_3$: C, 55.37; H, 7.74. Found: C, 55.08; H, 8.01.

Cyclopentanespiro-4′-5′-methyl-1′,3′-dioxolan-2′-one (3b) was isolated as a colorless liquid (82%) from the hydrogenation of 0.250 g of carbonate **2b** in CH_2Cl_2 under 10 MPa of hydrogen at 50 °C for 19 h, in the presence of ((*R*)-Binap)Ru(O_2CCF_3)$_2$ as catalyst: bp 110 °C (1.5 mmHg); IR (neat) ν 1790 cm^{-1}; ^{1}H NMR (300.133 MHz, $CDCl_3$) δ 4.59 (q, 1H, J = 6.5 Hz), 2.03−1.64 (m, 8H), 1.32 (d, 3H, J = 6.5 Hz); ^{13}C {^{1}H} NMR (75.469 MHz, $CDCl_3$) δ 154.31, 95.10, 79.06, 37.06, 32.09, 23.37, 22.61, 15.68; $[\alpha]^{18}_D$ −23 (*c* = 2, EtOH) (ee = 89%). Anal. Calcd for $C_8H_{12}O_3$: C, 61.52; H, 7.74. Found: C, 61.50; H, 7.91.

Cyclohexanespiro-4′-5′-methyl-1′,3′-dioxolan-2′-one (3c) was isolated as a colorless liquid (80%) from the hydrogenation of 0.250 g of carbonate **2c** in CH_2Cl_2 under 2 MPa of hydrogen at 20 °C for 68 h, in the presence of ((*R*)-Binap)Ru(O_2CCF_3)$_2$ as catalyst: bp 140 °C (1.5 mmHg); IR (neat) ν 1798 cm^{-1}; ^{1}H NMR (300.133 MHz, $CDCl_3$) δ 4.30 (q, 1H, J = 6.6 Hz), 2.03−1.15 (m, 10H), 1.24 (d, 3H, J = 6.6 Hz); ^{13}C {^{1}H} NMR (75.469 MHz, $CDCl_3$) δ 154.25, 85.16, 81.51, 35.16, 30.06, 24.81, 22.01, 21.64, 14.43; $[\alpha]^{18}_D$ −30 (*c* = 2, EtOH) (ee = 89%). Anal. Calcd for $C_9H_{14}O_3$: C, 63.51; H, 8.29. Found: C, 63.63; H, 8.40.

General Procedure for the Preparation of Diols. Carbonate **3a**−**c** (1.34 mmol) and 2.0 mmol of potassium carbonate were heated at 60 °C for 2.5 h in 10 mL of anhydrous methanol. The solvent was then evaporated, and the reaction mixture was dissolved in a saturated solution of NH_4Cl and extracted with diethyl ether. After the solution was dried with $MgSO_4$, the diols were collected by distillation under reduced pressure as colorless liquids.

(*S*)-2-Methyl-2,3-butanediol (4a): 87%; IR (neat) ν 3395 cm^{-1}; ^{1}H NMR (300.133 MHz, $CDCl_3$) δ 3.54 (q, 1H, J = 6.5 Hz), 2.70−2.46 (2s, broad signals, 2H), 1.16 (s, 3H,), 1.12 (s, 3H), 1.11 (d, 3H, J = 6.4 Hz); ^{13}C {^{1}H} NMR (75.469 MHz, $CDCl_3$) δ 74.27, 73.32, 26.54−22. 65, 17.69; $[\alpha]^{18}_D$ +9 (*c* = 1.5, diethyl ether) ($[\alpha]_D$ neat −5.15 for (*R*)-(**4a**)).[15] Anal. Calcd for $C_5H_{12}O_2$: C, 57.66; H, 11.61. Found: C, 57.02; H, 11.69.

1-(1-Hydroxyethyl)cyclopentan-1-ol (4b): 85%; IR (neat) ν 3405 cm^{-1}; ^{1}H NMR (300.133 MHz, $CDCl_3$) δ 3.64 (q, 1H, J = 6.4 Hz), 2.65 (s, 1H), 2.35 (s, 1H), 1.48−1.81 (m, 10H), 1.16 (d, 3H, J = 6.4 Hz); ^{13}C NMR (75.469 MHz, $CDCl_3$) δ 84.95 (s), 73.54 (d, J = 141.9 Hz), 38.15 (t, J = 129.0 Hz), 35.39 (t, J = 127.6 Hz), 24.30 (t, J = 128.3 Hz), 24.20 (t, J = 128.3 Hz), 18.05 (q, J = 126.0 Hz); $[\alpha]^{18}_D$ +6 (*c* = 1.5, diethyl ether). Anal. Calcd for $C_7H_{14}O_2$: C, 64.58; H, 10.84. Found: C, 64.29; H, 11.00.

1-(1-Hydroxyethyl)cyclohexan-1-ol (4c): 85%; IR (neat) ν 3402 cm^{-1}; ^{1}H NMR (300.133 MHz, $CDCl_3$) δ 3.43 (q, 1H, J = 6.5 Hz), 2.85 (s, 1H), 2.32 (s, 1H,), 1.10−1.58 (m, 10H), 1.08 (d, 3H, J = 6.5 Hz); ^{13}C NMR (75.469 MHz, $CDCl_3$) δ 73.77 (d, J = 142.4 Hz), 73.52 (s), 34.18 (t, J = 124.6 Hz), 31.28 (t, J = 122.1 Hz), 25.90 (t, J = 123.3 Hz), 21.67 (t, J = 132.2 Hz), 21.47 (t, J = 147.5 Hz), 17.02 (q, J = 125.9 Hz); $[\alpha]^{18}_D$ +5 (*c* = 1, diethyl ether). Anal. Calcd for $C_8H_{16}O_2$: C, 66.63; H, 11.18. Found: C, 65.76; H, 11.18.

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