Cerium-Catalyzed Reaction of β-Dicarbonyl Compounds with Styrene and Atmospheric Oxygen

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Keywords: Cerium / C−C coupling / Peroxides / Oxidation

The cerium-catalyzed C–C coupling reaction of carbo- and heterocyclic β-dicarbonyl compounds **1** with styrenes **4**, using oxygen (air) as the oxidant, at ambient temperature, is reported. The reaction afforded a mixture of diastereoisomeric hydroperoxides **5** which could be transformed into the unique dioxo compounds **6** by disproportionation of the peroxo function under treatment with acetyl chloride/pyridine.

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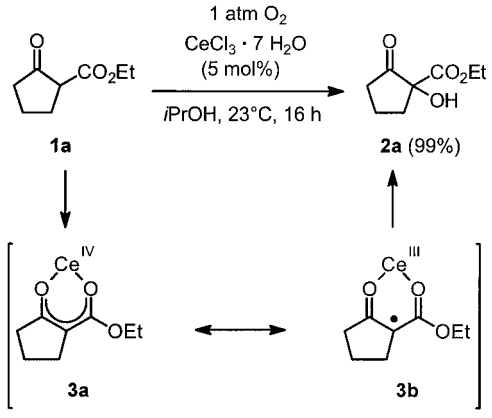
Introduction

Atmospheric oxygen (air) represents the oxidant of choice from an economical and ecological point-of-view, and this makes procedures using oxygen highly attractive. For example, we recently published a novel cerium-catalyzed α-hydroxylation of cyclic β-dicarbonyl compounds **1** with O_2 (Scheme 1).[1] For this reaction we assume a Ce^{IV} diketonate complex **3a** to be an intermediate, which may, in the sense of a ligand-to-metal charge transfer, also be regarded as a Ce^{III} complex **3b** with a radical β-diketon-α-yl ligand. For the system shown in Scheme 1 with catalytic amounts of the cerium salt, a re-oxidation of Ce^{III} to Ce^{IV} by O_2 seems to be reasonable.[2]



Scheme 1. Cerium-catalyzed α-hydroxylation of β-dicarbonyl compound **1a** proceeding via the assumed intermediate **3a/3b**

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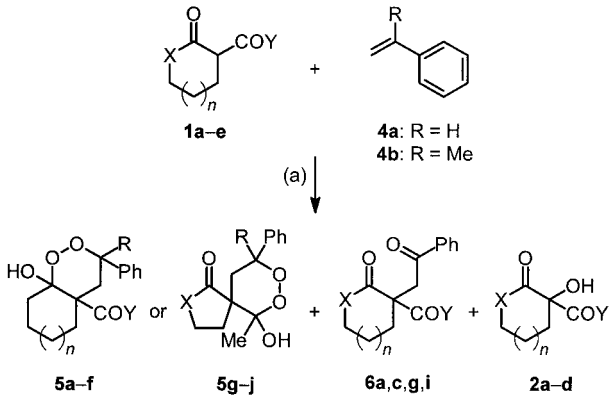
Of course, it has been known for a long time that β-dicarbonyl compounds can be oxidized to their α-radicals with stoichiometric amounts of Ce^{IV} or Mn^{III} reagents such as CAN or $Mn(OAc)_3$, and these radicals have been investigated intensively in C−C bond forming reactions.[3] For example, CAN has been utilized for oxidative dimerizations of malonates,[4] as well as for inter-[5] and intramolecular[6] conversions of β-dicarbonyl compounds with olefins. Analogously, α-radicals generated from β-dicarbonyls and $Mn(OAc)_3$ react with olefins to give lactones and lactams.[7] Intramolecular insertion of these radicals has been applied to the preparation of various β-lactams,[8] higher lactams, and spirolactams.[9] The $Mn(OAc)_3$-mediated reaction of β-oxo esters with enol ethers is of particular interest, since the products bear a 1,4-dicarbonyl motif.[10] This structural motif is commonly accessible only by the application of an umpolung strategy or the transformation of furan derivatives, and is useful in the preparation of annulated cyclopentenone derivatives.[11] All the literature referenced so far has used stoichiometric amounts of Ce^{IV} or Mn^{III} reagents. The re-oxidation of a Mn- or Ce-catalyst with molecular oxygen under the reaction conditions seems to be a highly attractive goal in terms of atom economy. And indeed, the catalytic reaction of β-dicarbonyl compounds with olefins and O_2 in the presence of sub-stoichiometric amounts of $Mn(OAc)_3$ has been reported. Endoperoxidic products (1,2-dioxane derivatives) are obtained in this reaction as the result of a formal [2+2+2]-cycloaddition process.[12] However, the yields of these products only reach an acceptable level in the cases of disubstituted olefins. Optimal results are achieved using 1,1-diaryl-substituted alkenes, whereas simple olefins like styrene give low yields.[13] Applying a $Mn^{II}-Co^{II}$ catalyst system, though, gives satisfying results in the reaction of β-dicarbonyl compounds with simple alkenes and oxygen.[14] In this case, almost no by-products with oxygen incorporation (for example, as hydroxy or peroxo functionalities) are formed. The use of catalytic

amounts of cerium compounds and O_2 as the re-oxidizing agent has been reported so far in only one case, resulting, in the cases of monosubstituted olefins such as styrene, once again, in low yields of dihydrofuran products.[15] Herein, we wish to report our results on C−C coupling reactions of styrenes **4** and cyclic and heterocyclic β-dicarbonyl compounds **1** with air as the oxidant, using only a catalytic amount of the cerium salt $CeCl_3 \cdot 7H_2O$. This reaction gives endoperoxidic 1,2-dioxane derivatives as products, and is analogous to the process using stoichiometric amounts of Mn^{III} and Ce^{IV}.[12,13]

Results and Discussion

Cyclic β-oxo esters **1a**−**c** reacted with styrene (**4a**) and α-methylstyrene (**4b**) in the presence of a cerium-catalyst and atmospheric oxygen, to give the C−C coupling products **5a**−**f** and **6a**,**c** (Scheme 2, Table 1).



1,2	a	b	c	d	e
X	CH_2	CH_2	CH_2	O	NBn
Y	OEt	OEt	OMe	Me	Me
n	0	1	2	0	0

Scheme 2. Cerium-catalyzed C−C coupling reaction of β-dicarbonyl compounds **1a**−**1e** and styrenes **4a**,**b** with oxygen as oxidant; reagents and conditions: (a) **1** (1 equiv.), **4** (2 equiv.), $CeCl_3 \cdot 7H_2O$ (0.05 equiv.), *i*PrOH, 23 °C, 16 h, air; for details see Table 1

The reaction conditions were optimized in the reaction of **1a** with both **4a** and **4b**: to suppress the formation of the α-hydroxylated product **2** in favour of the C−C coupling reaction, the conversion was performed under atmospheric oxygen instead of 1 atm O_2 and a twofold excess of the olefin, while again, 2-propanol was found to be the optimal solvent.

In the same manner, the five-membered heterocyclic β-dicarbonyl compounds **1d**,**e** reacted with styrenes **4a**,**b** to give the addition products **5g**−**5j** and **6g**,**i** (Scheme 2). The results are listed in Table 1.

In nearly all cases, the donors **1** were completely consumed in the reaction. The reaction of **1** and styrene (**4a**) afforded the α-hydroxylation products **2** and the dioxo derivatives **6** as by-products. The reaction of the precursor lactam **1e**, however, gave the dioxo lactam **6i** as the major product in 45 % yield, as well as the C−C coupling product **5i** (5 %) (Table 1).

As depicted in Scheme 2, the hydroperoxides **5** exist in their endoperoxidic hemiketal forms; monocyclic hydroperoxides could not be detected. Four diastereoisomers may be expected for three stereocenters, and indeed, in case of the seven-membered ring product **5f**, four diastereomers were detected. However, with the exceptions of **5e**, **5h** (three diastereoisomers) and **5d**, **5i** (one diastereomer), in general, two diastereoisomers were observed. In case of the lactone-derived hydroperoxides **5g** and **5h**, the two diastereoisomers could be separated by column chromatography on silica gel. While the diastereomers of **5g** were obtained in a 1:1 ratio, two diastereomers of **5h** were isolated in a ratio of 7:1 with a *trans*-configured isomer as the major product, as proved by the X-ray crystal structure. Crystallization of both diastereoisomers of **5g** and **5h** from dichloromethane gave single crystals which were suitable for X-ray crystallographic analysis (Figure 1 and Figure 2).[16]

The relative configuration of both diastereomers of **5g** demonstrates a C−C bond-formation without any stereoselectivity: the lactone and the phenyl group are arranged either in the relative *cis*- (Figure 1, a) or the relative *trans*-configuration (Figure 1, b). In case of **5h**, however, the *trans*-configured isomer (Figure 2, b) dominates the *cis*-iso-

Table 1. Ce^{III}-catalyzed reaction of dicarbonyls **1** and styrenes **4** with atmospheric oxygen as oxidant

Donor	Olefin	Hydroperoxide							Yield (%)			
		5	R	X	Y	*n*	Yield (%)	*dr*	**6**		**2**	
1a	**4a**	**a**	H	CH_2	OEt	0	68	62:38	**a**	4	**a**	3
1a	**4b**	**b**	Me	CH_2	OEt	0	87	64:36	−	−	**a**	5
1b	**4a**	**c**	H	CH_2	OEt	1	50	50:50	**c**	1	**b**	25
1b	**4b**	**d**	Me	CH_2	OEt	1	42	100	−	−	**b**	25
1c	**4a**	**e**	H	CH_2	OMe	2	54	38:35:27	**e**	n. d.[a]	**c**	46
1c	**4b**	**f**	Me	CH_2	OMe	2	53	38:25:23:14	−	−	**c**	17
1d	**4a**	**g**	H	O	Me	−	64	54:46	**g**	8	**d**	18
1d	**4b**	**h**	Me	O	Me	−	73	71:10:19	−	−	**d**	n. d.[a]
1e	**4a**	**i**	H	NBn	Me	−	5	100	**i**	45	**e**	n. d.[a]
1e	**4b**	**j**	Me	NBn	Me	−	52	60:40	−	−	**e**	n. d.[a]

[a] n. d. = not detected.

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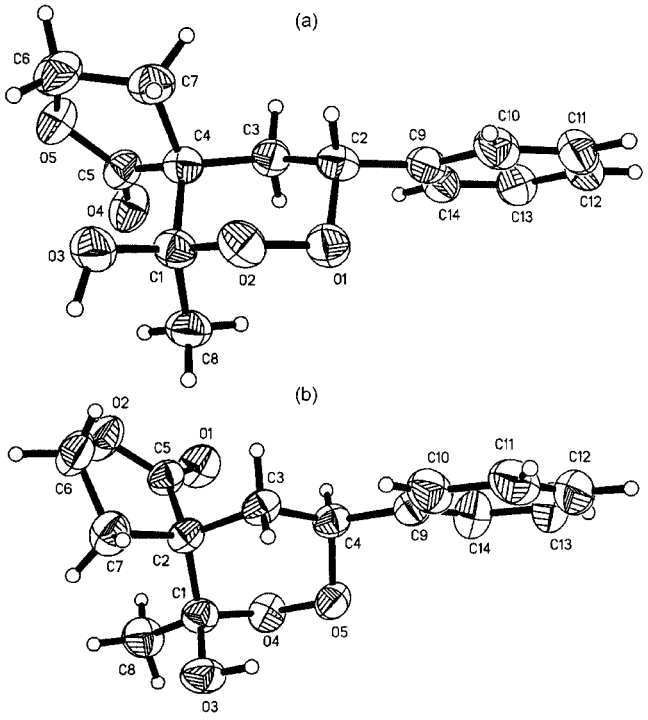


Figure 1. ORTEP view of the diastereoisomers of hydroperoxide **5g**; (a) relative *cis*-configuration and (b) relative *trans*-configuration of the lactone and phenyl group

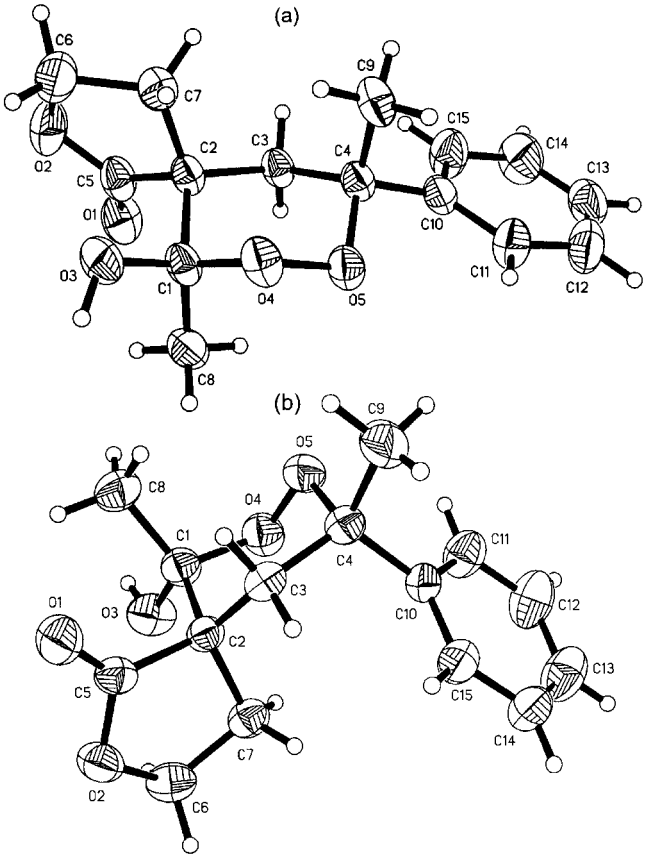
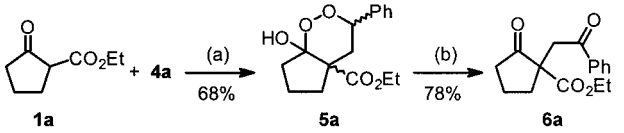


Figure 2. ORTEP view of the diastereoisomers of hydroperoxide **5h**; (a) relative *cis*-configuration and (b) relative *trans*-configuration of the lactone and phenyl group

mer (Figure 2, a) (*trans*:*cis* = 7:1). Also, the crystallographic data of the two diastereomers of **5c** confirm the *cis*/*trans* configuration, but unfortunately, due to low crystal quality in the case of the *cis*-isomer, the data cannot be published. The remarkably high selectivity in the reversible formation of the hemiacetalic, anomeric centers can be explained by stereoelectronic effects, which are common in carbohydrate chemistry, and by the presence of intramolecular hydrogen bonds.

The transformation of the epimeric mixtures of the endoperoxides **5** to unique products is, of course, a fundamental issue. As shown in Scheme 3 for peroxide **5a**, we succeeded in converting the styrene-derived products **5** by treatment with acetyl chloride (AcCl)/pyridine in dichloromethane (path b). An excess of acetyl chloride mediates the disproportionation of the peroxo function in **5a** to give ketone **6a**, which was isolated in 78 % yield.



Scheme 3. Preparation of ketone **6a** from **1a** via the diastereomeric mixture of hydroperoxide **5a**; reagents and conditions: (a) **4a** (2 equiv.), $CeCl_3 \cdot 7H_2O$ (5 mol %), *i*PrOH, 23 °C, air; (b) AcCl (2 equiv.), pyridine (2 equiv.), CH_2Cl_2, 23 °C, 20 h

Conclusion

C−C coupling reactions are fundamental to the construction of carbon skeletons. We report, for the first time, a synthetically applicable oxidative coupling of β-dicarbonyl compounds **1** with olefins **4**. In contrast to other known procedures that require stoichiometric amounts of cerium, manganese or cobalt salts, the presented conversion proceeds under catalysis with the inexpensive and non-toxic cerium salt $CeCl_3 \cdot 7H_2O$, using atmospheric oxygen as oxidant at ambient temperature. The mixtures of diastereoisomeric hydroperoxides **5** obtained disproportionate to give dioxo esters **6**, in a reaction mediated by acetyl chloride/pyridine. Dioxo derivatives **6** are of significant synthetic interest, due to their 1,4-dicarbonyl structural motif, whose synthesis usually requires the application of an umpolung strategy.

Experimental Section

General: The following compound was prepared according to literature procedures: **1e**.[1b] All other starting materials are commercially available. Column chromatography was carried out using Merck SiO_2 60 with hexanes (PE, b.p. 40−60 °C), and EtOAc (EA) as eluents. ^{13}C NMR multiplicities were determined with DEPT experiments.

General Procedure for the Cerium-Catalyzed Hydroperoxide Formation: The respective substrate **1** (1 equiv.) was added to a mixture of $CeCl_3 \cdot 7H_2O$ (0.05 equiv.) and the respective olefin **4** (2 equiv.) in *i*PrOH (ca. 0.5 mL/1.6 mmol **1**), and the reaction mixture was

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stirred at 23 °C for 16 h under atmospheric oxygen. After removal of all volatile materials under vacuum, the residue was filtered through or chromatographed on SiO_2 (PE/EA) to yield the products **5**.

Ethyl 1-Hydroxy-4-phenyl-2,3-dioxabicyclo[4.3.0]nonane-6-carboxylate (5a): According to the General Procedure, **1a** (249 mg, 1.59 mmol), $CeCl_3 \cdot 7H_2O$ (30 mg, 0.081 mmol), and **4a** (334 mg, 3.21 mmol) in *i*PrOH (0.5 mL) were converted. Filtration through a short column of SiO_2 (PE:EA, 10:1) gave a crude fraction consisting of diastereomers A and B of **5a** in a ratio of 62:38 (315 mg, 1.08 mmol, 68 %), alcohol **2a** (7 mg, 0.04 mmol, 3 %), and ketone **6a** (17 mg, 0.062 mmol, 4 %). By repeated chromatography (SiO_2, PE:EA, 5:1), by-products **2a** (R_f = 0.25) and **6a** (R_f = 0.22), and diastereomer A (R_f = 0.19) and B (R_f = 0.26) were completely separated. **Diastereomer A:** ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.29 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.75−1.86 (m, 1 H, CH_2), 1.88−2.02 (m, 3 H, CH_2), 2.17−2.27 (m, 2 H, CH_2), 2.30−2.37 (m, 1 H, CH_2), 2.67 (dd, *J* = 11.9, *J* = 14.3 Hz, 1 H, CH_2), 4.15 (br. s, 1 H, OH), 4.18−4.25 (m, 2 H, CH_2), 5.26 (dd, *J* = 2.5, *J* = 11.9 Hz, 1 H, CH), 7.32−7.40 (m, 5 H, CH) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 14.06 (CH_3), 19.30 (CH_2), 31.61 (CH_2), 32.50 (CH_2), 35.13 (CH_2), 52.69 (C), 61.43 (CH_2), 78.58 (CH), 108.37 (C), 127.08 (CH), 128.60 (CH), 128.85 (CH), 137.43 (C), 174.57 (C) ppm. IR (film): $\tilde{\nu}$ = 3352 (br. s), 1708 (s), 1255 (m), 1177 (m), 1160 (m), 1154 (m), 1102 (m), 1044 (m) cm^{-1}. MS (FAB, glycerol): *m*/*z* (%) = 293 (75) [MH^+], 275 (74) [$M^+ - H_2O$], 259 (82) [$M^+ - H_2O_2$], 229 (40), 201 (100), 153 (64), 105 (15). $C_{16}H_{20}O_5$ (292.33): calcd. C 65.74, H 6.90; found C 65.52, H 6.90. **Diastereomer B:** ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.38 (t, *J* = 7.3 Hz, 3 H, CH_3), 1.74−1.89 (m, 3 H, CH_2), 1.97−2.01 (m, 1 H, CH_2), 1.97 (dd, *J* = 10.7, *J* = 14.1 Hz, 1 H, CH_2), 2.24−2.36 (m, 2 H, CH_2), 2.55 (dd, *J* = 5.2, *J* = 14.1 Hz, 1 H, CH_2), 4.20−4.35 (m, 2 H, CH_2), 5.15 (dd, *J* = 5.2, *J* = 10.7 Hz, 1 H, CH), 6.20 (s, 1 H, OH), 7.29−7.40 (m, 5 H, CH) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 14.23 (CH_3), 20.01 (CH_2), 34.95 (CH_2), 35.54 (CH_2), 37.18 (CH_2), 51.74 (C), 61.77 (CH_2), 79.50 (CH), 111.07 (C), 125.98 (CH), 128.19 (CH), 128.67 (CH), 140.38 (C), 175.72 (C) ppm. $C_{16}H_{20}O_5$ (292.33): calcd. C 65.74, H 6.90; found C 65.59, H 6.94. **Ketone 6a:** ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.24 (t, *J* = 7.1 Hz, 3 H), 2.03−2.17 (m, 3 H), 2.53−2.69 (m, 3 H), 3.48 (d, *J* = 18.6 Hz, 1 H), 3.86 (d, *J* = 18.6 Hz, 1 H), 4.17 (q, *J* = 7.1 Hz, 2 H), 7.43−7.49 (m, 2 H), 7.55−7.60 (m, 1 H), 7.93−7.97 (m, 2 H) ppm. $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$): δ = 14.00 (CH_3), 19.86 (CH_2), 33.40 (CH_2), 37.76 (CH_2), 43.48 (CH_2), 57.47 (C), 61.66 (CH_2), 128.11 (CH), 128.65 (CH), 133.47 (CH), 136.31 (C), 170.71 (C), 196.74 (C), 215.11 (C) ppm. IR (film): $\tilde{\nu}$ = 2980 (m), 1755 (s), 1721 (s), 1684 (s), 1451 (m), 1401 (m), 1359 (m), 1285 (m), 1224 (s), 1186 (m), 1153 (m), 1105 (m), 1039 (m), 1001 (m) cm^{-1}. MS (CI, CH_4): *m*/*z* (%) = 274 (34) [M^+], 257 (21), 229 [$M^+ - OEt$], 201 [$M^+ - CO_2Et$], 183 (5), 155 (17), 105 (53), 91 (7), 77 (8). HRMS calcd. for $C_{16}H_{18}O_4$: 274.1205; found 274.1205 [M^+]. $C_{16}H_{18}O_4$ (274.31): calcd. C 70.06, H 6.61; found C 69.57, H 6.62. The data of **2a** were in accordance with the literature.[1b]

Ethyl 1-Hydroxy-4-methyl-4-phenyl-2,3-dioxabicyclo[4.3.0]nonane-6-carboxylate (5b): According to the General Procedure, **1a** (254 mg, 1.63 mmol), $CeCl_3 \cdot 7H_2O$ (30 mg, 0.081 mmol), and **4b** (386 mg, 3.27 mmol) in *i*PrOH (0.5 mL) were converted. Filtration through SiO_2 and subsequent chromatography (SiO_2, PE:EA, 5:1) gave three fractions. The first fraction contained diastereomer A of **5b** (R_f = 0.38, 281 mg, 0.917 mmol, 56 %) as colorless crystals, m.p. 66 °C. The second fraction contained diastereomer B of **5b** (R_f = 0.23, 153 mg, 0.499 mmol, 31 %) as a colorless oil. In the third fraction, alcohol **2a** was obtained (R_f = 0.17, 14 mg, 0.081 mmol, 5 %). **Diastereomer A:** ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.91 (t, *J* = 7.2 Hz, 3 H, CH_3), 1.57 (s, 3 H, CH_3), 1.77−1.92 (m, 3 H), 1.95−2.13 (m, 2 H), 2.11 (d, *J* = 14.0 Hz, 1 H), 2.20−2.30 (m, 1 H), 2.81 (d, *J* = 14.0 Hz, 1 H), 3.19 (dq, *J* = 10.8, *J* = 7.2 Hz, 1 H), 3.70 (dq, *J* = 10.7, *J* = 7.2 Hz, 1 H), 7.18−7.23 (m, 1 H, Ph), 7.25−7.35 (m, 5 H, Ph and OH) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 13.50 (CH_3), 20.08 (CH_2), 30.03 (CH_3), 35.50 (CH_2), 36.10 (CH_2), 42.80 (CH_2), 49.61 (C), 61.00 (CH_2), 81.36 (C), 111.56 (C), 124.93 (CH), 126.95 (CH), 127.98 (CH), 143.53 (C), 176.33 (C) ppm. IR (ATR): $\tilde{\nu}$ = 3328 (br. s), 2968 (m), 1692 (s), 1443 (s), 1369 (m), 1339 (m), 1300 (m), 1203 (m), 1113 (m) cm^{-1}. MS (FAB, glycerol): *m*/*z* (%) = 307 (61) [MH^+], 289 (25) [$MH^+ - H_2O$], 271 (38), 243 (31), 215 (100) [$MH^+ - H_2O - CO_2Et$], 195 (10), 147 (5), 121 (14), 73 (22). $C_{17}H_{22}O_5$ (306.35): calcd. C 66.65, H 7.24; found C 66.63, H 7.24. **Diastereomer B:** ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.36 (t, *J* = 7.0 Hz, 3 H, CH_3), 1.40 (s, 3 H, CH_3), 1.44−1.55 (m, 1 H), 1.65−1.77 (m, 2 H), 1.85−1.92 (m, 1 H), 1.97−2.03 (m, 1 H), 2.06−2.13 (m, 1 H), 2.39 (d, *J* = 14.0 Hz, 1 H), 2.70 (d, *J* = 14.0 Hz, 1 H), 4.24−4.34 (m, 2 H), 6.06 (br. s, 1 H), 7.26−7.30 (m, 1 H), 7.36−7.39 (m, 2 H), 7.46−7.47 (m, 2 H) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 14.14 (CH_3), 19.95 (CH_2), 29.19 (CH_3), 34.59 (CH_2), 36.15 (CH_2), 38.90 (CH_2), 51.18 (C), 61.52 (CH_2), 81.03 (C), 109.89 (C), 124.69 (CH), 126.87 (CH), 128.32 (CH), 146.41 (C), 176.47 (C) ppm. $C_{17}H_{22}O_5$ (306.35): calcd. C 66.65, H 7.24; found C 66.50, H 7.19. The data of **2a** were in accordance with the literature.[1b]

Ethyl 1-Hydroxy-4-phenyl-2,3-dioxabicyclo[4.4.0]decane-6-carboxylate (5c): According to the General Procedure, **1b** (267 mg, 1.57 mmol), $CeCl_3 \cdot 7H_2O$ (30 mg, 0.081 mmol), and **4a** (331 mg, 3.18 mmol) in *i*PrOH (0.5 mL) were converted. Filtration through a short column of SiO_2 (PE:EA, 10:1) gave a crude fraction consisting of diastereomers A and B of **5c** in a ratio 1:1 (240 mg, 0.785 mmol, 50 %), alcohol **2b** (68 mg, 0.39 mmol, 25 %) and ketone **6c** (5 mg, 0.02 mmol, 1 %). By chromatography (SiO_2, PE:EA, 5:1), by-products **2b** (R_f = 0.19) and **6c** (R_f = 0.23) were removed, and diastereomer A (R_f = 0.32) and B (R_f = 0.15) were separated completely and obtained as colorless solids. **Diastereomer A:** M.p. 118 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.35 (t, *J* = 7.0 Hz, 3 H, CH_3), 1.51−1.65 (m, 2 H, CH_2), 1.71−1.82 (m, 4 H, CH_2), 2.03 (dt, *J* = 13.4, *J* = 4.8 Hz, 1 H, CH_2), 2.43 (dd, *J* = 2.4, *J* = 14.2 Hz, 1 H, CH_2), 2.45−2.55 (m, 1 H, CH_2), 2.55 (dd, *J* = 11.7, *J* = 14.2 Hz, 1 H, CH_2), 4.24−4.31 (m, 1 H, CH_2), 4.34−4.40 (m, 1 H, CH_2), 5.13 (dd, *J* = 2.4, *J* = 11.6 Hz, 1 H, CH), 7.25−7.26 (m, 1 H, CH), 7.32−7.39 (m, 5 H, CH, OH) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 14.10 (CH_3), 20.18 (CH_2), 22.57 (CH_2), 30.45 (CH_2), 33.46 (CH_2), 35.76 (CH_2), 48.44 (C), 61.99 (CH_2), 81.51 (CH), 102.79 (C), 126.68 (CH), 128.63 (CH), 128.72 (CH), 137.54 (C), 177.71 (C) ppm. IR (ATR): $\tilde{\nu}$ = 3361 (br. s), 2931 (m), 1706 (s), 1446 (m), 1278 (m), 1238 (s), 1174 (s), 1085 (m), 1025 (m), 1001 (m) cm^{-1}. MS (FAB, glycerol): *m*/*z* (%) = 307 (16) [M^+], 289 (57) [$M^+ - H_2O$], 273 (100), 243 (6), 215 (16), 199 (22), 195 (48), 170 (6), 123 (12), 105 (15), 75 (5). $C_{17}H_{22}O_5$ (306.15): calcd. C 66.65, H 7.24; found C 66.79, H 7.15. **Diastereomer B:** ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.28 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.47−1.57 (m, 2 H, CH_2), 1.63−1.69 (m, 2 H, CH_2), 1.82−1.93 (m, 3 H, CH_2), 2.23−2.31 (m, 2 H, CH_2), 2.65 (dd, *J* = 11.9, *J* = 14.0 Hz, 1 H, CH_2), 4.15−4.25 (m, 3 H, CH_2, OH), 5.40 (dd, *J* = 2.4, *J* = 11.9 Hz, 1 H, CH), 7.31−7.39 (m, 5 H, CH) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 14.11 (CH_3), 22.02 (CH_2), 22.54 (CH_2), 31.11 (CH_2), 34.06 (CH_2), 35.82 (CH_2), 48.31 (C), 61.22 (CH_2), 78.53 (CH), 99.30 (C), 127.12 (CH), 128.59 (CH), 128.88 (CH), 137.58 (C), 174.71 (C) ppm. $C_{17}H_{22}O_5$ (306.15): calcd. C 66.65, H

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7.24; found C 66.47, H 7.18. **Ketone 6c:** M.p. 92 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.27 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.74−1.88 (m, 4 H, CH_2), 2.03−2.11 (m, 1 H, CH_2), 2.44−2.49 (m, 1 H, CH_2), 2.51−2.56 (m, 1 H, CH_2), 2.81−2.88 (m, 1 H, CH_2), 3.39 (d, *J* = 17.4 Hz, 1 H, C*H*H), 3.57 (d, *J* = 17.4 Hz, 1 H, CH*H*), 4.19−4.29 (m, 2 H, CH_2), 7.43−7.47 (m, 2 H, CH), 7.54−7.58 (m, 1 H, CH), 7.94−7.97 (m, 2 H, CH) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 14.05 (CH_3), 22.03 (CH_2), 26.82 (CH_2), 36.74 (CH_2), 40.55 (CH_2), 44.03 (CH_2), 58.92 (C), 61.55 (CH_2), 128.06 (CH), 128.54 (CH), 133.12 (CH), 136.83 (C), 172.05 (C), 196.99 (C), 207.34 (C) ppm. IR (KBr): $\tilde{\nu}$ = 2968 (m), 2958 (m), 2933 (m), 2866 (m), 1720 (s), 1677 (s), 1455 (m), 1387 (m), 1369 (m), 1313 (m), 1225 (m), 1183 (s), 1137 (m), 1071 (m), 1034 (m) cm^{-1}. MS (EI, 70 eV): *m*/*z* (%) = 288 (5) [M^+], 270 (2) [$M^+ - H_2O$], 243 (23) [$M^+ - OEt$], 215 (45) [$M^+ - CO_2Et$], 169 (100), 137 (21), 123 (40), 109 (15), 81 (18), 77 (80). HRMS calcd. for $C_{17}H_{20}O_4$: 289.1435 [MH^+]; found 289.1440. The data of **2b** were in accordance with the literature.[1b]

Ethyl 1-Hydroxy-4-methyl-4-phenyl-2,3-dioxabicyclo[4.4.0]decane-6-carboxylate (5d): According to the General Procedure, **1b** (90 mg, 0.53 mmol), $CeCl_3 \cdot 7H_2O$ (10 mg, 0.027 mmol), and **4b** (125 mg, 1.06 mmol) in *i*PrOH (0.2 mL) were converted. By chromatography (SiO_2, PE:EA, 5:1), alcohol **2b** (R_f = 0.19, 25 %) was separated, and **5d** was obtained as colorless crystals (R_f = 0.36, 69 mg, 0.22 mmol, 42 %), m.p. 121 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.07 (br. t, *J* = 6.4 Hz, 3 H, CH_3), 1.41 (br. s, 3 H, CH_3), 1.57−1.64 (m, 2 H), 1.66−1.82 (m, 5 H), 2.36−2.51 (m, 1 H), 2.56 (br. d, *J* = 14.1 Hz, 1 H), 2.83 (d, *J* = 14.3 Hz, 1 H), 3.09−3.16 (m, 1 H), 3.66−3.73 (m, 1 H), 6.98 (br. s, 1 H, OH), 7.18−7.22 (m, 1 H), 7.29−7.32 (m, 2 H), 7.46−7.48 (m, 2 H) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 13.42 (CH_3), 20.37 (CH_2), 22.34 (CH_2), 30.39 (CH_3), 30.65 (CH_2), 33.48 (CH_2), 39.73 (CH_2), 45.82 (C), 60.83 (CH_2), 82.30 (C), 102.24 (C), 126.10 (CH), 126.73 (CH), 127.56 (CH), 142.69 (C), 177.03 (C) ppm. IR (ATR): $\tilde{\nu}$ = 3316 (br. s), 2937 (m), 1688 (s), 1456 (s), 1444 (s), 1370 (m), 1324 (m), 1265 (m), 1204 (s), 1186 (s), 1172 (s), 1095 (m) cm^{-1}. MS (FAB, glycerol): *m*/*z* (%) = 321 (58) [MH^+], 303 (18) [$MH^+ - H_2O$], 287 (67), 269 (7), 229 (9), 209 (100), 185 (25), 170 (14), 132 (17), 105 (24). $C_{18}H_{24}O_5$ (320.38): calcd. C 67.48, H 7.55; found C 67.54, H 7.52.

Methyl 7-Hydroxy-10-phenyl-8,9-dioxabicyclo[5.4.0]undecane-1-carboxylate (5e): According to the General Procedure, **1c** (272 mg, 1.60 mmol), $CeCl_3 \cdot 7H_2O$ (30 mg, 0.081 mmol), and **4a** (336 mg, 3.23 mmol) in *i*PrOH (0.5 mL) were converted. Chromatography (SiO_2, PE:EA, 10:1) gave a crude fraction consisting of diastereomers A, B and C of **5e** in a ratio of 38:35:27 (264 mg, 0.862 mmol, 54 %) and alcohol **2c** (137 mg, 0.735 mmol, 46 %). By repeated chromatography (SiO_2, PE:EA, 10:1) **2c** was separated, and two product-containing fractions were obtained. The first fraction contained diastereomers A and B [R_f (SiO_2, PE:EA, 5:1) = 0.32] as a colorless oil. The second fraction contained diastereomer C [R_f (SiO_2, PE:EA, 5:1) = 0.16] as a colorless oil. **Diastereomers A and B:** ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.43−1.58 (m, 5 H, CH_2), 1.59−1.69 (m, 4 H, CH_2), 1.70−1.86 (m, 5 H, CH_2), 1.88−1.97 (m, 2 H, CH_2), 2.03 (ddd, *J* = 12.4, *J* = 5.3, *J* = 14.3 Hz, 1 H, CH_2, isomer B), 2.11−2.16 (m, 2 H, CH_2), 2.21−2.30 (m, 2 H, CH_2), 2.36 (dd, *J* = 12.2, *J* = 14.0 Hz, 1 H, CH_2, isomer B), 2.40−2.44 (m, 1 H, CH_2, isomer B), 2.56 (dd, *J* = 4.0, *J* = 14.0 Hz, 1 H, CH_2, isomer A), 3.26 (br. s, 1 H, OH, isomer B), 3.79 (s, 3 H, CH_3, isomer B), 3.84 (s, 3 H, CH_3, isomer A), 5.08 (dd, *J* = 2.1, *J* = 12.2 Hz, 1 H, CH, isomer B), 5.09 (dd, *J* = 4.0, *J* = 10.9 Hz, 1 H, CH, isomer A), 7.29−7.40 (m, 10 H, CH), 7.70 (br. s, 1 H, OH, isomer A) ppm. IR (ATR): $\tilde{\nu}$ = 3338 (br. s), 2930 (s), 2862 (m), 1734 (s), 1699 (s), 1453 (s), 1212 (s), 1110 (m), 1017 (s) cm^{-1}. MS (FAB, glycerol): *m*/*z* (%) = 307 (18) [MH^+], 289 (64) [$MH^+ - H_2O$], 273 (100), 229 (2), 213 (25), 195 (14), 170 (2), 105 (24). $C_{17}H_{22}O_5$ (306.15): calcd. C 66.65, H 7.24; found C 66.57, H 7.20. **Diastereomer A:** $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$): δ = 21.98 (CH_2), 23.04 (CH_2), 24.94 (CH_2), 25.97 (CH_2), 38.13 (CH_2), 38.97 (CH_2), 51.60 (C), 52.97 (CH_3), 80.80 (CH), 102.88 (C), 126.39 (CH), 128.35 (CH), 128.57 (CH), 136.97 (C), 178.36 (C) ppm. **Diastereomer B:** $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$): δ = 23.04 (CH_2), 24.94 (CH_2), 25.97 (CH_2), 34.30 (CH_2), 37.56 (CH_2), 38.97 (CH_2), 51.60 (C), 51.92 (CH_3), 79.68 (CH), 102.88 (C), 127.17 (CH), 128.60 (CH), 128.95 (CH), 140.68 (C), 173.82 (C) ppm. **Diastereomer C:** ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.45−1.68 (m, 4 H, CH_2), 1.69−1.82 (m, 2 H, CH_2), 1.86 (ddd, *J* = 2.1, *J* = 6.8, *J* = 14.4 Hz, 1 H, CH_2), 1.94−1.98 (m, 1 H, CH_2), 2.01 (dd, *J* = 2.6, *J* = 13.8 Hz, 1 H, CH_2), 2.35−2.40 (m, 1 H, CH_2), 2.45−2.51 (m, 1 H, CH_2), 2.64 (dd, *J* = 11.4, *J* = 13.8 Hz, 1 H, CH_2), 3.68 (s, 3 H, CH_3), 4.24 (br. s, 1 H, OH), 5.37 (dd, *J* = 2.6, *J* = 11.4 Hz, 1 H, CH), 7.29−7.42 (m, 5 H, CH) ppm. $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$): δ = 19.40 (CH_2), 22.33 (CH_2), 25.48 (CH_2), 26.91 (CH_2), 37.87 (CH_2), 38.70 (CH_2), 51.85 (CH_3), 52.00 (C), 78.55 (CH), 101.93 (C), 126.94 (CH), 128.56 (CH), 128.77 (CH), 137.69 (C), 175.39 (C) ppm. The data of **2c** were in accordance with the literature.[1b]

Methyl 7-Hydroxy-10-methyl-10-phenyl-8,9-dioxabicyclo[5.4.0]undecane-1-carboxylate (5f): According to the General Procedure, **1c** (291 mg, 1.71 mmol), $CeCl_3 \cdot 7H_2O$ (30 mg, 0.081 mmol), and **4b** (393 mg, 3.33 mmol) in *i*PrOH (0.5 mL) were converted. Filtration through a short column of SiO_2 (PE:EA, 10:1) gave a crude fraction consisting of diastereomers A, B, C and D of **5f** in a ratio 38:25:23:14 (288 mg, 0.899 mmol, 53 %) and alcohol **2c** (54 mg, 0.290 mmol, 17 %). Alcohol **2c** was separated by repeated chromatography (SiO_2, PE:EA, 10:1), and two product-containing fractions were obtained. The first fraction contained diastereomers A and D [R_f (PE/EA, 5:1) = 0.28, A:D, 80:20] as a colorless oil, and the second fraction contained diastereomers B and C [R_f (PE/EA, 5:1)= 0.34−0.44, B:C, 40:60] as a colorless solid. **Diastereomers A and D:** ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.16−1.28 (m, 2 H), 1.31 (s, 3 H, CH_3, isomer A), 1.43−1.60 (m, 5 H), 1.61 (s, 3 H, CH_3, isomer D), 1.63−1.70 (m, 1 H), 1.70−1.87 (m, 8 H), 1.87−2.00 (m, 2 H), 2.12 (dd, *J* = 14.6, *J* = 8.9 Hz, 1 H, isomer A), 2.23 (d, *J* = 14.0 Hz, 1 H, isomer D), 2.24 (d, *J* = 14.0 Hz, 1 H, isomer A), 2.43 (d, *J* = 14.6 Hz, 1 H, isomer D), 2.68−2.70 (m, 1 H, isomer D), 2.70 (d, *J* = 14.0 Hz, 1 H, isomer A), 3.39 (s, 1 H, OH, isomer D), 3.79 (s, 3 H, CH_3, isomer D), 3.79 (s, 3 H, CH_3, isomer A), 7.23−7.25 (m, 3 H, CH, isomer D), 7.28−7.30 (m, 2 H, CH, isomer D), 7.33−7.36 (m, 3 H, CH, isomer A), 7.40−7.41 (m, 2 H, CH, isomer A), 7.46 (br. s, 1 H, OH, isomer A) ppm. **Diastereomer A:** $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 21.63 (CH_2), 22.76 (CH_2), 27.54 (CH_3), 28.94 (CH_2), 33.48 (CH_2), 37.07 (CH_2), 43.84 (CH_2), 50.65 (C), 52.27 (CH_3), 81.49 (C), 105.40 (C), 124.38 (CH), 126.76 (CH), 128.23 (CH), 147.21 (C), 178.34 (C) ppm. **Diastereomer D:** $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 23.45 (CH_3), 23.60 (CH_2), 24.85 (CH_2), 26.48 (CH_2), 36.00 (CH_2), 37.74 (CH_2), 43.63 (CH_2), 50.37 (C), 51.75 (CH_3), 80.29 (C), 102.95 (C), 124.11 (CH), 127.66 (CH), 128.45 (CH), 145.06 (C), 174.80 (C) ppm. **Diastereomers B and C:** M.p. 124−129 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.22−1.37 (m, 2 H), 1.38 (s, 3 H, CH_3, isomer B), 1.39−1.51 (m, 2 H), 1.53−1.63 (m, 3 H), 1.57 (s, 3 H, CH_3, isomer C), 1.67−1.75 (m, 4 H), 1.77−1.82 (m, 5 H), 1.95−2.08 (m, 3 H), 2.12−2.22 (m, 2 H), 2.27 (d, *J* = 14.3 Hz, 1 H, CH_2, isomer C), 2.33−2.39 (m, 1 H), 2.69 (d, *J* = 14.4 Hz, 1 H, CH_2, isomer C), 2.83 (br. s, 1 H, CH_3, OH, isomer B), 2.83 (br. s, 3 H, CH_3, isomer B), 3.03 (s, 3

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H, CH_3, isomer C), 3.35 (s, 1 H, OH, isomer C), 7.20−7.26 (m, 2 H, CH), 7.33−7.37 (m, 6 H, CH), 7.46−7.44 (m, 2 H, CH) ppm. IR (ATR): $\tilde{\nu}$ = 3464 (br. m), 3329 (br. m), 2924 (m), 1696 (s), 1441 (m), 1336 (m), 1215 (m) cm^{-1}. MS (FAB, glycerol): *m*/*z* (%) = 321 (45) [MH^+], 303 (32) [$MH^+ - H_2O$], 271 (8), [$MH^+ - H_2O - O_2$], 243 (18), 287 (70), 243 (18), 209 (100), 177 (52), 105 (24). $C_{18}H_{24}O_5$ (320.38): calcd. C 67.48, H 7.55; found C 67.28, H 7.55. **Diastereomer B:** $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 22.31 (CH_2), 22.51 (CH_2), 30.05 (CH_2), 30.31 (CH_3), 32.11 (CH_2), 38.12 (CH_2), 45.12 (CH_2), 49.27 (C), 51.20 (CH_3), 81.84 (C), 107.04 (C), 124.69 (CH), 126.53 (CH), 127.90 (CH), 143.88 (C), 178.12 (C) ppm. **Diastereomer C:** $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 23.29 (CH_2), 24.87 (CH_2), 26.02 (CH_2), 30.97 (CH_3), 35.26 (CH_2), 37.91 (CH_2), 42.43 (CH_2), 49.36 (C), 50.80 (CH_3), 81.54 (C), 102.50 (C), 125.60 (CH), 126.64 (CH), 127.79 (CH), 142.53 (C), 172.80 (C) ppm. The data of **2c** were in accordance with the literature.[1b]

6-Hydroxy-6-methyl-9-phenyl-2,7,8-trioxaspiro[4.5]decan-1-one (5g): According to the General Procedure, **1d** (197 mg, 1.54 mmol), $CeCl_3 \cdot 7H_2O$ (30 mg, 0.081 mmol) and **4a** (342 mg, 3.28 mmol) in *i*PrOH (0.5 mL) were converted. Chromatography (SiO_2, PE:EA, 2:1) gave two fractions. The first fraction contained diastereomer A of **5g** (130 mg, 0.492 mmol, 32 %) and ketone **6g** (30 mg, 0.12 mmol, 8 %). The second fraction contained diastereomer B of **5g** (129 mg, 0.488 mmol, 32 %) and alcohol **2d** (39 mg, 0.27 mmol, 18 %). By repeated chromatography (SiO_2, PE:EA, 2:1) diastereoisomer A (R_f = 0.25) and B (R_f = 0.13) could be separated completely. **Diastereomer A of 5g (*cis*):** M.p. 145 °C. ^1H NMR (500 MHz, $CDCl_3$): δ = 1.90 (s, 3 H), 1.90 (dd, *J* = 14.1, *J* = 2.6 Hz, 1 H), 2.21 (ddd, *J* = 13.0, *J* = 9.7, *J* = 9.7 Hz, 1 H), 2.79 (dd, *J* = 14.1, *J* = 12.2 Hz, 1 H), 2.98 (s, 1 H), 3.15 (ddd, *J* = 13.0, *J* = 7.5, *J* = 2.5 Hz, 1 H), 4.34−4.38 (m, 1 H), 4.43−4.48 (m, 1 H), 5.12 (dd, *J* = 12.3, *J* = 2.6 Hz, 1 H), 7.34−7.41 (m, 5 H) ppm. $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$): δ = 22.56 (CH_3), 31.34 (CH_2), 39.67 (CH_2), 49.52 (C), 67.40 (CH_2), 80.21 (CH), 102.21 (C), 127.30 (CH), 128.79 (CH), 129.30 (CH), 135.92 (C), 177.46 (C) ppm. MS (FAB): *m*/*z* (%) = 265 (6) [MH^+], 246 (70) [$M^+ - H_2O$], 231 (100), 189 (12), 133 (33), 109 (30), 99 (17), 75 (76). $C_{14}H_{16}O_5$ (264.27): calcd. C 63.63, H 6.10; found C 63.68, H 6.19. **Diastereomer B of 5g (*trans*):** ^1H NMR (500 MHz, $CDCl_3$): δ = 1.49 (s, 3 H), 2.12 (ddd, *J* = 14.1, *J* = 8.0, *J* = 5.7 Hz, 1 H), 2.15 (dd, *J* = 14.4, *J* = 2.2 Hz, 1 H), 2.40 (dd, *J* = 14.0, *J* = 11.8 Hz, 1 H), 2.73 (ddd, *J* = 8.7, *J* = 7.7, *J* = 14.0 Hz, 1 H), 3.49 (s, 1 H), 4.25−4.39 (m, 2 H), 5.80 (dd, *J* = 11.7, *J* = 2.3 Hz, 1 H), 7.32−7.39 (m, 5 H) ppm. $^{13}C\{^1H\}$ NMR ($CDCl_3$, 125 MHz): δ = 21.26 (CH_3), 33.13 (CH_2), 35.53 (CH_2), 47.11 (C), 64.85 (CH_2), 78.51 (CH), 99.68 (C), 127.12 (CH), 128.75 (CH), 129.15 (CH), 136.75 (C), 176.72 (C=O) ppm. **Ketone 6g:** ^1H NMR (500 MHz, $CDCl_3$): δ = 2.15 (t, *J* = 13.2 Hz, 1 H), 2.29 (s, 3 H), 3.12 (ddd, *J* = 13.1, *J* = 5.7, *J* = 3.2 Hz, 1 H), 3.59 (d, *J* = 18.6 Hz, 1 H), 4.00 (d, *J* = 18.5 Hz, 1 H), 4.42−4.52 (m, 2 H), 7.48−7.52 (m, 2 H), 7.61−7.64 (m, 1 H), 7.96−7.98 (m, 2 H) ppm. $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$): δ = 25.70 (CH_3), 31.34 (CH_2), 44.20 (CH_2), 58.32 (C), 67.14 (CH_2), 128.16 (CH), 128.90 (CH), 134.10 (CH), 135.62 (C), 175.18 (C=O), 196.09 (C=O), 201.00 (C=O) ppm. MS (CI): *m*/*z* (%) = 247 (52) [MH^+], 229 (67), 205 (30), 185 (100), 169 (1), 127 (11), 105 (41), 97 (5), 51 (5). The data of **2d** were in accordance with the literature.[1b]

6-Hydroxy-6,9-dimethyl-9-phenyl-2,7,8-trioxaspiro[4.5]decan-1-one (5h): According to the General Procedure, **1d** (202 mg, 1.58 mmol), $CeCl_3 \cdot 7H_2O$ (30 mg, 0.081 mmol), and **4b** (379 mg, 3.21 mmol) in *i*PrOH (0.5 mL) were converted. Chromatography (SiO_2, PE:EA, 5:1) gave two fractions. The first fraction contained diastereoisomer A and B of **5h** in a ratio 7:1 (R_f = 0.22−0.40, 260 mg, 0.934 mmol, 59 %) as a colorless solid. The second fraction contained diastereoisomer C of **5h** (R_f = 0.15, 63 mg, 0.23 mmol, 14%) as a colorless solid. **Diastereomers A and B:** M.p. 140 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 1.33 (s, 3 H, CH_3, isomer B), 1.46 (s, 3 H, CH_3, isomer A), 1.47 (s, 3 H, CH_3, isomer B), 1.54 (ddd, *J* = 9.8, *J* = 9.9, *J* = 13.6 Hz, 1 H, CH_2, isomer A), 1.67−1.75 (m, 2 H, CH_2, isomer B), 1.81 (s, 3 H, CH_3, isomer A), 2.10−2.16 (m, 1 H, CH_2, isomer A), 2.25 (d, *J* = 14.2 Hz, 1 H, C*H*H, isomer B), 2.39 (d, *J* = 14.3 Hz, 1 H, C*H*H, isomer A), 2.73 (d, *J* = 14.3 Hz, 1 H, CH*H*, isomer A), 2.83 (d, *J* = 14.2 Hz, 1 H, CH*H*, isomer B), 3.62 (s, 1 H, OH, isomer A), 3.99−4.07 (m, 2 H, CH_2), 4.12−4.22 (m, 2 H, CH_2), 4.39 (s, 1 H, OH, isomer B), 7.23−7.30 (m, 2 H, CH), 7.33−7.40 (m, 4 H, CH), 7.45−7.50 (m, 4 H, CH) ppm. IR (ATR): $\tilde{\nu}$ = 3400 (br. s), 1756 (m), 1735 (s), 1447 (m), 1381 (s), 1224 (s), 1194 (m), 1179 (m), 1029 (s) cm^{-1}. MS (FAB, glycerol): *m*/*z* (%) = 279 (50) [MH^+], 261 (30) [$MH^+ - H_2O$], 245 (100), 243 (71) [$MH^+ - 2\ H_2O$], 227 (16), 183 (18), 154 (26), 123 (26), 99 (33). $C_{15}H_{18}O_5$ (278.30): calcd. C 64.74, H 6.52; found C 64.35, H 6.49. **Diastereomer A:** $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 22.31 (CH_3), 29.91 (CH_3), 31.30 (CH_2), 42.70 (CH_2), 48.81 (C), 67.82 (CH_2), 81.61 (C), 101.87 (C), 125.18 (CH), 126.96 (CH), 128.20 (CH), 143.37 (C), 178.19 (C) ppm. **Diastereomer B:** $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 21.62 (CH_3), 30.43 (CH_3), 31.49 (CH_2), 38.91 (CH_2), 47.14 (C), 66.12 (CH_2), 80.86 (C), 99.14 (C), 125.34 (CH), 127.10 (CH), 128.32 (CH), 142.94 (C), 177.99 (C) ppm. **Diastereomer C:** ^1H NMR (500 MHz, $CDCl_3$): δ = 1.57 (br. s, 6 H, CH_3), 2.13 (br. s, 1 H, CH_2), 2.27 (ddd, *J* = 9.3, *J* = 9.3, *J* = 12.9 Hz, 1 H, CH_2), 2.74−2.79 (m, 1 H, CH_2), 3.05 (s, 1 H, OH), 3.15 (ddd, *J* = 2.3, *J* = 6.7, *J* = 12.9 Hz, 1 H, CH_2), 4.33 (dt, *J* = 2.3, *J* = 8.7 Hz, 1 H, CH_2), 4.38−4.43 (m, 1 H, CH_2), 7.26−7.30 (m, 1 H, CH), 7.34−7.39 (m, 4 H, CH) ppm. $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 21.44 (CH_3), 22.67 (CH_3), 33.90 (CH_2), 40.96 (CH_2), 47.48 (C), 67.28 (CH_2), 79.56 (C), 99.39 (C), 124.34 (CH), 128.39 (CH), 128.54 (CH), 143.68 (CH), 177.14 (CH) ppm.

2-Benzyl-6-hydroxy-6-methyl-9-phenyl-7,8-dioxa-2-azaspiro[4.5]-decan-1-one (5i): According to the General Procedure, **1e** (332 mg, 1.53 mmol), $CeCl_3 \cdot 7H_2O$ (30 mg, 0.081 mmol), and **4a** (337 mg, 3.24 mmol) in *i*PrOH (0.5 mL) were converted. Chromatography (SiO_2, PE:EA, 5:1) gave two fractions. The first fraction contained ketone **6i** [R_f (PE:EA, 2:1) = 0.17, 229 mg, 0.683 mmol, 45%] as a yellow oil. In the second fraction, **5i** was obtained [R_f (PE:EA, 2:1) = 0.14, 28 mg, 0.079 mmol, 5 %] as a colorless solid, m.p. 171 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 1.30 (s, 3 H, CH_3), 1.63 (dd, *J* = 2.1, *J* = 13.5 Hz, 1 H, CH_2), 2.15 (ddd, *J* = 8.5, *J* = 5.8, *J* = 14.0 Hz, 1 H, C*H*H), 2.42 (ddd, *J* = 8.3, *J* = 5.7, *J* = 13.9 Hz, 1 H, CH*H*), 2.80−2.88 (m, 1 H, CH_2), 3.21−3.35 (m, 2 H, CH_2), 4.42 (d, *J* = 14.4 Hz, 1 H, C*H*H), 4.59 (d, *J* = 14.4 Hz, 1 H, CH*H*), 5.15 (dd, *J* = 2.0, *J* = 12.0 Hz, 1 H, CH), 5.85 (s, 1 H, OH), 7.22−7.25 (m, 2 H, CH), 7.30−7.42 (m, 8 H, CH) ppm. $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ = 22.31 (CH_3), 27.37 (CH_2), 35.77 (CH_2), 43.89 (CH_2), 47.21 (CH_2), 48.71 (C), 78.71 (CH), 100.25 (C), 127.44 (CH), 128.10 (CH), 128.28 (CH), 128.62 (CH), 128.95 (CH), 129.07 (CH), 135.48 (C), 136.95 (C), 175.64 (C) ppm. IR (ATR): $\tilde{\nu}$ = 3227 (br. s), 2951 (m), 1651 (s), 1494 (m), 1451 (m), 1290 (m), 1244 (m), 1124 (m), 1097 (s) cm^{-1}. MS (FAB): *m*/*z* (%) = 354 (32) [MH^+], 336 (61) [$MH^+ - H_2O$], 320 (24), 296 (11), 275 (15), 245 (12), 215 (16), 188 (26), 183 (32), 91 (100). HRMS calcd. for $C_{21}H_{23}NO_4$: 354.1705 [MH^+]; found 354.1724. $C_{21}H_{23}NO_4$ (353.16): calcd. C 71.37, H 6.56, N 3.96; found C 71.19, H 6.54, N 3.19. **Ketone 6i:** ^1H NMR (300 MHz, $CDCl_3$): δ = 1.84 (ddd, *J* = 7.8, *J* = 9.6, *J* = 13.4 Hz, 1 H, CH_2), 2.25 (s, 3 H, CH_3), 2.92 (ddd, *J* = 2.7, *J* = 8.2, *J* = 13.4 Hz, 1 H, CH_2), 3.25 (ddd, *J* = 9.6, *J* =

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Table 2. X-ray crystallographic data for **5g** and **5h**

	cis-**5g**	*trans*-**5g**	*cis*-**5h**	*trans*-**5h**
Empirical formula	$C_{14}H_{16}O_5$	$C_{14}H_{16}O_5$	$C_{15}H_{18}O_5$	$C_{15}H_{18}O_5$
Formula mass [g mol^{-1}]	264.27	264.27	278.28	278.28
Crystal system	monoclinic	monoclinic	monoclinic	monoclinic
Space group	$P2_1/c$	$P2_1/c$	$P2_1/c$	$P2_1/c$
a (Å)	10.9452(6)	6.5947(2)	8.1593(9)	8.3476(12)
b (Å)	11.6229(8)	15.5436(6)	10.7326(8)	16.156(3)
c (Å)	10.3322(9)	12.8034(9)	15.6899(11)	10.6008(13)
β [°]	102.948(6)	102.690(5)	92.689(7)	103.217(10)
Z	4	4	4	4
V (Å^3)	1280.99(16)	1280.36(11)	1372.5(2)	1391.8(3)
$\delta_{calcd.}$ [g cm^{-3}]	1.370	1.371	1.347	1.328
R_w (F^2)	0.1703	0.1573	0.1567	0.0991
$R(F)$ [$I > 2\sigma(I)$]	0.0639	0.0560	0.0513	0.0582

2.7, J = 9.7 Hz, 1 H, CH_2), 3.43 (ddd, J = 8.0, J = 8.1, J = 12.6 Hz, 1 H, CH_2), 3.46 (d, J = 18.8 Hz, 1 H, CH_2), 4.12 (d, J = 18.7 Hz, 1 H, CH_2), 4.44−4.54 (m, 2 H, CH_2), 7.20−7.24 (m, 2 H, CH), 7.27−7.39 (m, 3 H, CH), 7.46−7.51 (m, 2 H, CH), 7.57−7.63 (m, 1 H, CH), 7.97−7.98 (m, 1 H, CH), 7.99−8.01 (m, 1 H, CH) ppm. $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 26.11 (CH_3), 27.78 (CH_2), 44.60 (CH_2), 44.71 (CH_2), 47.31 (CH_2), 60.21 (C), 127.77 (CH), 128.06 (CH), 128.13 (CH), 128.76 (CH), 128.81 (CH), 133.70 (CH), 135.87 (C), 136.18 (C), 171.56 (C), 197.20 (C), 203.95 (C) ppm. IR (ATR): $\tilde{\nu}$ = 1712 (m), 1679 (s), 1449 (m), 1430 (m), 1260 (m), 1215 (m) cm^{-1}. MS (EI, 70 eV): *m*/*z* (%) = 335 (45) [M^+], 292 (20) [M^+ − COMe], 215 (43) [M^+ − COMe − Ph], 188 (99), 105 (34), 91 (100). HRMS calcd. for $C_{21}H_{21}NO_3$: 335.1521 [M^+]; found 335.1521.

2-Benzyl-6-hydroxy-6,9-dimethyl-9-phenyl-7,8-dioxa-2-azaspiro-[4.5]decan-1-one (5j): According to the General Procedure, **1e** (126 mg, 0.580 mmol), $CeCl_3{\cdot}7H_2O$ (10 mg, 0.027 mmol), and **4b** (126 mg, 1.06 mmol) in *i*PrOH (0.2 mL) were converted. Chromatography (SiO_2, PE:EA, 2:1) gave a fraction containing diastereomers A and B of **5j** in a ratio 60:40 (R_f = 0.19, 110 mg, 0.299 mmol, 52 %) as a colorless solid, m.p. 144 °C. ^1H NMR (500 MHz, $CDCl_3$): δ = 1.15 (s, 3 H, CH_3, isomer B), 1.24−1.29 (m, 1 H, CH_2, isomer A), 1.40−1.46 (m, 1 H, CH_2, isomer B), 1.48 (s, 3 H, CH_3, isomer A), 1.49 (s, 3 H, CH_3, isomer A), 1.76−1.77 (m, 1 H, CH_2, isomer A), 1.88 (s, 3 H, CH_3, isomer A), 2.19 (d, J = 14.0 Hz, 1 H, C*H*H, isomer B), 2.35 (d, J = 14.6 Hz, 1 H, C*H*H, isomer A), 2.81−2.87 (m, 2 H, CH_2), 2.85 (d, J = 14.0 Hz, 1 H, CH*H*), 2.93−2.98 (m, 1 H, CH_2, isomer B), 3.00−3.05 (m, 1 H, CH_2, isomer B), 3.17−3.22 (m, 1 H, CH_2, isomer A), 3.32−3.37 (m, 1 H, CH_2, isomer A), 4.38 (d, J = 14.0 Hz, 1 H, C*H*H, isomer B), 4.42 (d, J = 14.6 Hz, 1 H, C*H*H, isomer A), 4.54 (d, J = 14.6 Hz, 1 H, CH*H*, isomer A), 4.59 (d, J = 14.0 Hz, 1 H, CH*H*, isomer B), 5.54 (s, 1 H, OH, isomer B), 7.22−7.23 (m, 2 H, CH), 7.25−7.30 (m, 5 H, CH, OH), 7.30−7.34 (m, 2 H, CH), 7.34−7.39 (m, 8 H, CH), 7.50−7.53 (m, 4 H, CH) ppm. IR (ATR): $\tilde{\nu}$ = 3317 (br. s), 1670 (s), 1495 (m), 1453 (m), 1444 (m), 1212 (m), 1178 (m), 1126 (m), 1067 (m) cm^{-1}. $C_{22}H_{25}NO_4$ (367.43): calcd. C 71.91, H 6.86, N 3.81; found C 72.18, H 6.69, N 3.73. **Diastereomer A:** $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 22.65 (CH_3), 28.37 (CH_2), 30.23 (CH_3), 42.78 (CH_2), 45.43 (CH_2), 46.85 (CH_2), 50.62 (C), 81.68 (C), 103.00 (C), 125.28 (CH), 126.58 (CH), 127.36 (CH), 127.83 (CH), 127.98 (CH), 128.54 (CH), 136.36 (C), 144.89 (C), 174.13 (C) ppm. **Diastereomer B:** $^{13}C\{^1H\}$ NMR (63 MHz, $CDCl_3$): δ = 21.72 (CH_3), 27.87 (CH_2), 30.75 (CH_3), 38.84 (CH_2), 44.41 (CH_2), 47.26 (CH_2), 50.35 (C), 80.50 (C), 99.81 (C), 125.46 (CH), 126.72 (CH), 128.02 (CH), 128.09 (CH), 128.37 (CH), 128.86 (CH), 135.52 (C), 143.89 (C), 175.56 (C) ppm.

Transformation of Hydroperoxide 5a into Dioxo Ester 6a: AcCl (100 mg, 1.3 mmol) was added at 0 °C to a solution of **5a** (165 mg, 0.56 mmol) and pyridine (112 mg, 1.4 mmol) in CH_2Cl_2 (0.5 mL), and the reaction mixture was stirred at room temp. for 20 h. After removal of all volatile materials under vacuum, the residue was purified by chromatography on SiO_2 with PE/EA, 5:1 (R_f = 0.22) to give **6a** as a colorless oil (121 mg, 0.44 mmol, 78 %). ^1H NMR (300 MHz, $CDCl_3$): δ = 1.24 (t, J = 7.1 Hz, 3 H), 2.03−2.17 (m, 3 H), 2.53−2.69 (m, 3 H), 3.48 (d, J = 18.6 Hz, 1 H), 3.86 (d, J = 18.6 Hz, 1 H), 4.17 (q, J = 7.1 Hz, 2 H), 7.43−7.49 (m, 2 H), 7.55−7.60 (m, 1 H), 7.93−7.97 (m, 2 H) ppm. $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$): δ = 14.00 (CH_3), 19.86 (CH_2), 33.40 (CH_2), 37.76 (CH_2), 43.48 (CH_2), 57.47 (C), 61.66 (CH_2), 128.11 (CH), 128.65 (CH), 133.47 (CH), 136.31 (C), 170.71 (C), 196.74 (C), 215.11 (C) ppm. IR (film): $\tilde{\nu}$ = 1755 (s), 1721 (s), 1684 (s), 1451 (m), 1401 (m), 1359 (m), 1285 (m), 1224 (s), 1186 (m), 1153 (m), 1105 (m), 1039 (m), 1001 (m) cm^{-1}. HRMS for $C_{16}H_{18}O_4$ (70 eV, EI): calcd. 274.1205, found 274.1205. $C_{16}H_{18}O_4$ (274.32): calcd. C 70.06, H 6.61; found C 69.57, H 6.62.

Acknowledgments

The authors acknowledge support by the Deutsche Forschungsgemeinschaft and the Fonds der Chemischen Industrie.

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Received July 15, 2003

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