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Auxiliary controlled singlet-oxygen ene reactions of cyclohexenes

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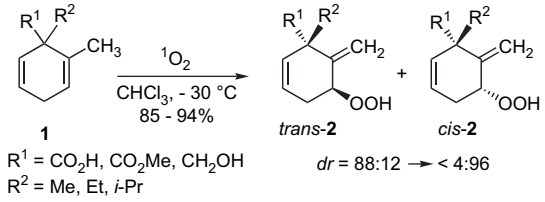
Abstract—The photooxygenation of homochiral cyclohexene ketals, which are easily available from 2-cyclohexenone and L-tartrates, affords hydroperoxides and after reduction the corresponding allylic alcohols in good yields and high regioselectivities. This can be rationalized by electronic repulsions in a perepoxide intermediate and provides evidence for unfavorable 1,3 diaxial interactions with a dioxolane oxygen atom. Only low stereoselectivities were observed, due to the flexibility of the cyclohexene ring. However, the diastereomers could be separated and after cleavage of the auxiliary, 4-hydroxy-2-cyclohexen-1-one was isolated in enantiomerically pure form, which can serve as a building block for natural product synthesis.

1. Introduction

Singlet oxygen ($^1O_2$), which can be conveniently generated by the sensitized photoreaction of molecular oxygen with visible light (photooxygenation), has become an important reagent for the synthesis of oxyfunctionalized products from simple precursors.[1] Especially the ene reaction of $^1O_2$ with alkenes provides a powerful route to allylic hydroperoxides and after reduction to allylic alcohols. The regioselectivity of this transformation was studied in detail during the last years[2] and more recently, the selectivities were improved by reactions in zeolites or polymeric containers.[3] Singlet-oxygen ene reactions with high diastereoselectivities are based on the pioneering work of Adam.[4] More recently, auxiliary controlled[5] and even organocatalytic[6] enantioselective photooxygenations were realized. Finally, singlet oxygen was applied for reversible light- and air-driven lithography.[7]

Although the singlet-oxygen ene reaction of five- and seven-membered cycloalkenes proceeds with high regioselectivity, the photooxygenation of cyclohexenes affords hydroperoxides with only moderate yield and selectivities.[2,8] During our work on synthetic applications of singlet oxygen,[9] we found excellent regio- and high diastereoselectivities in the photooxygenation of cyclohexadienes **1** to afford hydroperoxides **2** (Scheme 1).



Scheme 1. Photooxygenations of the cyclohexadienes **1**.

Furthermore, the reactions are strongly controlled by steric and polar factors and especially carboxylic acids and esters provide high selectivities. This prompted us to investigate chiral auxiliaries with such functional groups in photooxygenations. Commercially available tartaric acid and esters seemed to be the ideal candidates, since they are often used in asymmetric synthesis.[10] Herein we report our results on the singlet-oxygen ene reaction of homochiral cyclohexene ketals, in view of regio- and stereoselectivities as well as synthetic applications.

2. Results and discussion

Homochiral ketals can be conveniently prepared by the reaction of a ketone with a chiral diol by azeotropic removal of water.[10a,11] However, the ketalization of cyclic enones with simple diols might proceed under migration of the double bond, due to the acidic conditions.[12] Indeed, the reaction of 2-cyclohexenone (**3**) with commercially available tartrates **4a–c** or glycol (**4d**) and catalytic amounts of *p*-toluenesulfonic acid (PTS) afforded mixtures of 2-cyclohexene ketals **5a–d** and the rearranged 3-cyclohexene ketals **6a–d** in moderate yields (Scheme 2). Unfortunately, the regioisomers **5** and **6** could not be separated by column

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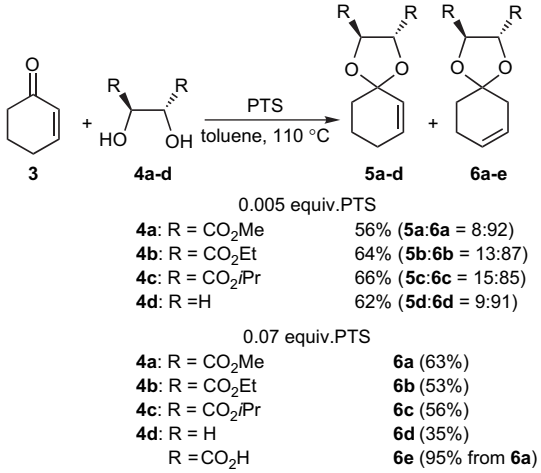
chromatography. Therefore, we developed a new procedure for the selective synthesis of the rearranged products by simply increasing the amount of *p*-toluenesulfonic acid (PTS). Under such conditions, the desired 3-cyclohexene ketals **6a–c** were isolated in moderate yields in analytically pure form (Scheme 2). Thus, this one-pot procedure is superior to the literature-known process by a two-step elimination.[13]



Scheme 2. Synthesis of the cyclohexene acetals **6**.

On the other hand, the 2-cyclohexene ketal **5a**, where the double bond is closer to the stereogenic centers, was selectively obtained by a multi-step procedure.[14] To investigate the influence of polar groups, the free dicarboxylic acid **6e** was synthesized by saponification of the methylester **6a** in 95% yield (Scheme 2).

For the ene reactions, singlet oxygen ($^1O_2$) was conveniently generated at −30 °C from molecular oxygen by irradiation with a sodium lamp in the presence of catalytic amounts of tetraphenylporphin (TPP) as sensitizer (photooxygenations). To establish the influence of the ketal auxiliaries, 2-cyclohexenone (**3**) was employed as substrate for the first photooxygenations. However, even after prolonged irradiation for several days no conversion could be achieved, which can be rationalized by the electron poor double bond. Another explanation for the failure of the singlet-oxygen ene reaction might be the unfavorable conformation of 2-cyclohexenone (**3**). To distinguish between these two effects, the reaction of 2-cyclohexene ketal **5a** was examined next. Furthermore, this substrate should provide higher stereoselectivities than the regioisomer **6a**, since the double bond is located closer to the stereogenic centers. Unfortunately, again no conversion was achieved, which speaks for a preferred conformation of the 2-cyclohexene ketal **5a** with pseudo-equatorial allylic hydrogen atoms, which cannot undergo an ene reaction (Fig. 1).

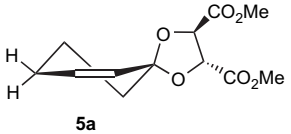


Figure 1. Preferred conformation of the 2-cyclohexene acetal **5a**.

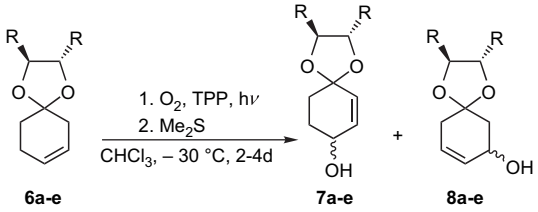
This result is in accordance with our previous studies on the photooxygenation of cyclohexadienes,[9] which don't react at the bisallylic position (Scheme 1) and points out the importance of pseudo-axial oriented hydrogen atoms in singlet-oxygen ene reactions.

Therefore, the photooxygenations were carried out with the 3-cyclohexene ketals **6a–e**. Indeed, the reactions proceeded smoothly with tetraphenylporphin (TPP) as sensitizer at −30 °C (Table 1). Complete conversion was achieved after 2–4 d and the labile hydroperoxides were directly reduced by dimethylsulfide. To determine the product ratios, ^1H NMR spectra (500 MHz) were directly recorded on the crude reaction mixtures after evaporation of the solvents. Finally, the corresponding allylic alcohols **7** and **8** were isolated in good overall yields by column chromatography (Table 1).

The first photooxygenations were conducted with ketals **6a–c**, derived from chiral tartrates **4a–c** (Table 1, entries 1–3). Interestingly, a high degree of regioselectivity from 81:19 to 89:11 was observed for all substrates. Thus, the allylic alcohols **7a–c** were isolated as main products in good yields. This result is in contrast to the singlet-oxygen ene reaction of substituted cyclohexenes, which afford hydroperoxides with only moderate yield and selectivities.[2,8] To exclude an influence of the stereogenic centers of the chiral auxiliaries, the achiral ketal **6d** was photooxygenated next (entry 4). Indeed, the same degree of regioselectivity was observed, which can only be rationalized by repulsive interactions of the attacking $^1O_2$ with the dioxolane ring. Four different allylic hydrogen atoms are available for the ene reaction and thus four perepoxide intermediates **9** can be discussed (Fig. 2).

The importance of pseudo-axial oriented hydrogen atoms in the singlet-oxygen ene reaction was already pointed out in

Table 1. Photooxygenations of the 3-cyclohexene ketals **6**



Entry	Ketal	R	**7**:**8**[a]	dr **7**[a]	dr **8**[a]	Yield (%)[b]
1	**6a**	CO_2Me	82:18	57:43	62:38	75
2	**6b**	CO_2Et	81:19	53:47	55:45	75
3	**6c**	CO_2i-Pr	89:11	54:46	n.d.	73
4	**6d**	H	87:13	—	—	77
5	**6e**	CO_2H	n.d.	n.d.	n.d.	<10[c]
6	**6e**	CO_2H[d]	>95:5	52:48	n.d.	[e]
7	**6e**	CO_2^-[f]	>95:5	56:44	n.d.	[e]

[a] Ratios determined (dr=diastereomeric ratio) by ^1H NMR analysis of the crude product (500 MHz).
[b] Yield of isolated allylic alcohols. Main isomers were separated by column chromatography in analytically pure form.
[c] Low yield is due to cleavage of the ketal under the acidic conditions.
[d] Addition of tetra-*n*-butylammonium hydroxide as base.
[e] Products **7e** were not isolated but are identical to saponified **7a**.
[f] Deprotonation with 4 equiv of $NaOCD_3$, reaction in CD_3OD with rose bengal as sensitizer.

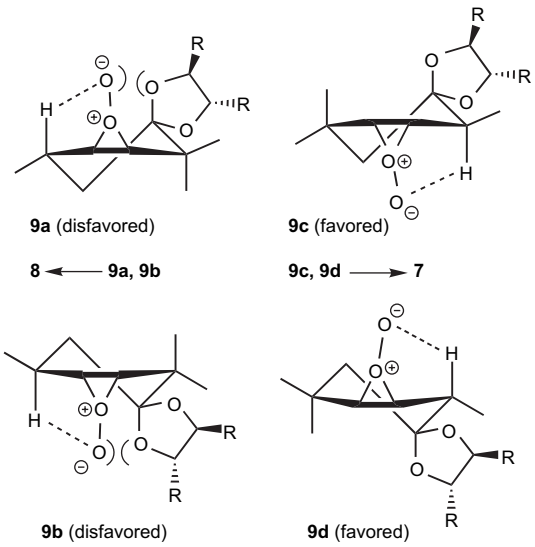


Figure 2. Four possible perepoxide intermediates **9**.

Figure 1. If the remote allylic position reacts (Fig. 2, perepoxides **9a** and **9b**), an unfavorable 1,3 diaxial interaction between the negatively charged perepoxide and one dioxolane oxygen atom results, irrespective of the attack of $^1O_2$ from the top or bottom of the double bond. Both intermediates afford the regioisomers **8**, which are therefore formed only as side products. On the other hand, if the allylic position adjacent to the ketal reacts (Fig. 2, perepoxides **9c** and **9d**), no unfavorable 1,3 diaxial interactions are operative and the regioisomers **7** are obtained as the main products.

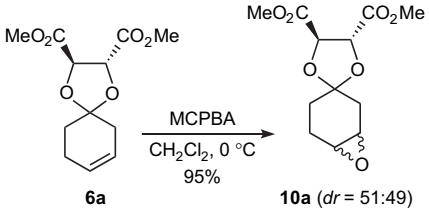
This result is in accordance with the large group effect,[2] and very recently steric interactions between $^1O_2$ and a pseudo-axial methyl group were discussed during the photooxygenation of cyclogeranyl derivatives.[15] However, the herein investigated ketal auxiliaries increase the unfavorable 1,3 diaxial interactions by severe electronic repulsions between the perepoxide and one dioxolane oxygen atom and thus control the regioselectivity of the singlet-oxygen ene reaction.

Besides the high regioselectivities, only low stereoselectivities were observed for the chiral esters **6a–c** (Table 1, entries 1–3). The diastereomeric ratios could be determined from the crude products by ^1H NMR spectroscopy (500 MHz) and all isomers showed distinctive chemical shifts. Furthermore, a separation and complete characterization of the main products was possible by column chromatography. Thus, the major diastereomers of the allylic alcohols **7** always have the *S* configuration at the newly formed stereogenic center, which was established by cleavage of the chiral auxiliary (see below). However, because of the low selectivities, an explanation and discussion for the formation of these isomers in excess is not possible.

To increase the stereoselectivities, the free dicarboxylic acid **6e** was photooxygenated next, since strong directing effects of such functional groups were found in the singlet-oxygen ene reaction in our previous studies.[9] However, the acidic reaction conditions led to the cleavage of the chiral auxiliary (Table 1, entry 5). To overcome this problem, bases were added to the reaction mixture. Indeed, an increase in the regioselectivity resulted due to the stronger 1,3 diaxial polar repulsions, but no influence on the diastereoselectivity was observed (entries 6 and 7).

Obviously, the homochiral cyclohexene ketals **6** are too flexible (compare different structures in Fig. 2) to prefer one conformation and induce a high stereoselectivity. Furthermore, the chiral auxiliary is too far away from the newly formed stereogenic center and thus, only a 1,6 induction results. This is in accordance with a somewhat higher stereoselectivity for the minor regioisomer **8a** (Table 1, entry 1), which is formed by a 1,5 induction. The best substrates for a stereoselective photooxygenation would be the 2-cyclohexene ketals **5**, since the double bond is located closer to the chiral auxiliaries. Indeed, alkene **5a** exhibits a higher stereoselectivity in cyclopropanations than the corresponding isomer **6a**.[13,14] Unfortunately, the 2-cyclohexene ketal **5a** does not undergo a singlet-oxygen ene reaction, due to the pseudo-equatorial allylic hydrogen atoms (Fig. 1).

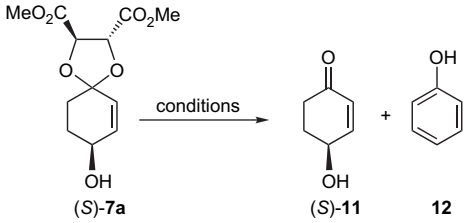
To compare steric and polar interactions in the oxidation of 3-cyclohexene ketal **6a**, we became interested in the epoxidation with *m*-chloroperbenzoic acid (MCPBA). The reaction proceeded smoothly at 0 °C and the epoxides **10a** were isolated in high yield (Scheme 3). However, both diastereomers were obtained in a ratio of almost 1:1. Thus, the photooxygenation of ketal **6a** proceeds with a higher selectivity, although MCPBA is sterically more demanding than singlet oxygen. This interesting result is a further proof of the importance of polar interactions in the perepoxide intermediates **9**, leading to stereoselectivities of up to 57:43 for a 1,6 induction.



Scheme 3. Epoxidation of the 3-cyclohexene acetal **6a**.

From the synthetic point of view, it was important that the major allylic alcohols **7** could be conveniently separated by column chromatography and were isolated in diastereomerically and analytically pure form. The absolute configuration of the newly formed stereogenic center could not be established by the coupling constants or NOE effects. Therefore, we examined the cleavage of the chiral auxiliary from the ketal **7a** (Table 2), to afford 4-hydroxy-2-cyclohexen-1-one (**11**), which is literature-known.[16] However, the lability of the desired product under the acidic reaction conditions was problematic. Thus, cleavage with diluted hydrochloric acid led to the elimination of water and formation of phenol (**12**) as the main product (entry 1). After optimization of the reaction conditions, the best results were obtained with buffered clay, which afforded 4-(*S*)-hydroxy-2-cyclohexen-1-one (**11**) in high yield (Table 2, entry 3). The *S* configuration was unequivocally determined by comparison of the optical rotations and thus the major diastereomers **7** have the same absolute configuration. Finally, from 2-cyclohexenone, the

Table 2. Cleavage of the chiral auxiliary from ketal *S*-**7a**



Entry	Conditions	Conv. (%)	**11** (%)	**12** (%)
1	MeOH, dil HCl	>98	32	64
2	Montmorillonite	>98	70	18
3	Montmorillonite, NaOAc	76	74 (97)[a]	—

[a] Yield based on reisolated starting material.

auxiliary controlled singlet-oxygen ene reaction offers an easy access to the enantiomerically pure ketone **11**, which can serve as a precursor for natural product synthesis.[16]

3. Conclusions

Homochiral cyclohexene ketals were conveniently synthesized from 2-cyclohexenone and L-tartrates. Under the acidic reaction conditions an isomerization of the double bond was observed, which afforded 3-cyclohexene ketals regioselectively. The singlet-oxygen ene reactions proceeded smoothly at −30 °C and the corresponding allylic alcohols were isolated in good yields after reduction. All reactions exhibited a high degree of regioselectivity, which can be rationalized by electronic repulsions in a perepoxide intermediate and gives evidence for unfavorable 1,3 dipolar interactions with a dioxolane oxygen atom. On the other hand, the photooxygenations proceeded with low stereoselectivities, due to the flexibility of the cyclohexene ring. However, compared with the epoxidation of the homochiral cyclohexene ketals, the singlet-oxygen ene reaction provided higher stereoselectivities by a 1,6 induction. The isomeric allylic alcohols could be separated by column chromatography and the major diastereomers were isolated in analytically pure form. Finally, the *S* configuration of the newly formed stereogenic center was unequivocally established by cleavage of the chiral auxiliary with clay in high yield. In summary, starting from 2-cyclohexenone, the auxiliary controlled singlet-oxygen ene reaction offers an easy access to an enantiomerically pure hydroxycyclohexenone, which can serve as a precursor for natural product synthesis.

4. Experimental

4.1. General

Commercially available compounds were used without further purification; solvents were dried according to standard procedures. Flash chromatography was performed using Merck Kieselgel 60 silica. TLC analysis was carried out on Alugram silica gel 60 F_{254} plates (Macherey-Nagel). Molybdatophosphate was used as developing reagent. NMR spectra were measured on a Bruker AC 300 (300 MHz) and AC 500 (500 MHz) spectrometers using deuterochloroform ($CDCl_3$), deuterodimethylsulfoxide (DMSO-d_6) or deuteromethanol (CD_3OD) as internal standard. IR spectra were recorded on a Perkin–Elmer 1600 FT-IR and optical rotations on a JASCO P-1020 polarimeter. Elemental analyses were performed on a Vario El 3 instrument (Elementar).

4.2. General procedure for the ketalizations

A solution of 2-cyclohexenone (**3**) (4 g, 42 mmol), the diol (42 mmol), and *p*-toluenesulfonic acid (0.5 g, 2.9 mmol, 0.07 equiv) in dry toluene (200 mL) was refluxed by using a Dean–Stark trap for 8 h. After cooling the reaction mixture was washed with a saturated aqueous solution of $NaHCO_3$ (100 mL) followed by washing with water (100 mL). After drying ($MgSO_4$) the solvent was evaporated and the crude product was purified by flash chromatography.

4.2.1. Dimethyl 1,4-dioxa-spiro[4,5]dec-7-ene-2(*R*),3(*R*)-dicarboxylate (6a). The ketalization was carried out as described above using dimethyl L-tartrate (**4a**) (7.4 g, 42 mmol) to afford after chromatography (hexane/ethyl acetate=3:1, R_f=0.43) a colorless oil (6.65 g, 63%).

^{1}H NMR (300 MHz, $CDCl_3$) δ 1.84 (t, J=6.3 Hz, 1H, 10-H), 2.26–2.50 (m, 4H, 6-H, 9-H), 3.82 (s, 6H, Me), 4.84 (d, J=5.0 Hz, 1H, 2-H), 4.88 (d, J=5.0 Hz, 1H, 3-H), 5.58–5.62, 5.69–5.74 (2dm, J=10 Hz, 2H, 7-H, 8-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 24.4 (t, C-10), 31.6 (t, C-6), 36.2 (t, C-9), 52.8, 52.8 (2q, Me), 76.9, 77.1 (2d, C-2, C-3), 113.6 (s, C-5), 123.6 (d, C-7), 126.4 (d, C-8), 170.1, 170.4 (2s, COOMe); IR (film) 3034, 2976, 2945, 1765, 1478, 1372, 1237, 1047, 857, 759, 662 cm^{-1}; $[\alpha]_D^{20}$ −43.2 (*c* 1.02, $CHCl_3$). Anal. Calcd for $C_{12}H_{16}O_6$: C, 56.25; H, 6.29. Found: C, 56.58; H, 6.61.

4.2.2. Diethyl 1,4-dioxa-spiro[4,5]dec-7-ene-2(*R*),3(*R*)-dicarboxylate (6b). The ketalization was carried out as described above using diethyl L-tartrate (**4b**) (8.6 g, 42 mmol) to afford after chromatography (hexane/ethyl acetate=3:1, R_f=0.51) a colorless oil (6.2 g, 53%).

^{1}H NMR (300 MHz, $CDCl_3$) δ 1.33 (t, J=7.1 Hz, 6H, CH_3), 1.86 (t, J=6.2 Hz, 1H, 10-H), 2.26–2.48 (m, 4H, 6-H, 9-H), 4.28 (q, J=7.1 Hz, 4H, CH_2CH$_3$), 4.80 (d, J=5.0 Hz, 1H, 2-H), 4.85 (d, J=5.0 Hz, 1H, 3-H), 5.61, 5.72 (2dm, J=10 Hz, 2H, 7-H, 8-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.1, 14.1 (2q, CH_3), 24.4 (t, C-10), 31.6 (t, C-6), 36.3 (t, C-9), 61.8, 61.9 (2t, CH_2CH_3), 77.0, 77.2 (2d, C-2, C-3), 113.4 (s, C-5), 123.6 (d, C-7), 126.4 (d, C-8), 169.7, 169.9 (2s, COOEt); IR (film) 3030, 2981, 2934, 1759, 1448, 1371, 1218, 1137, 1047, 943, 857, 753, 662 cm^{-1}; $[\alpha]_D^{20}$ −44.9 (*c* 1.07, $CHCl_3$). Anal. Calcd for $C_{14}H_{20}O_6$: C, 59.14; H, 7.09. Found: C, 59.33; H, 7.27.

4.2.3. Diisopropyl 1,4-dioxa-spiro[4,5]dec-7-ene-2(*R*),3(*R*)-dicarboxylate (6c). The ketalization was carried out as described above using diisopropyl L-tartrate (**4c**) (9.8 g, 42 mmol) to afford after chromatography (hexane/ethyl acetate=3:1, R_f=0.67) a colorless oil (7.3 g, 56%).

^{1}H NMR (300 MHz, $CDCl_3$) δ 1.29 (d, J=6.2 Hz, 12H, CH_3), 1.83 (m, 1H, 10-H), 2.24–2.53 (m, 4H, 6-H, 9-H), 4.71 (d, J=5.2 Hz, 1H, 2-H), 4.78 (d, J=5.2 Hz, 1H, 3-H), 5.12 (sept, J=6.2 Hz, 2H, CH(CH$_3$)$_2$), 5.56, 5.64

(2dm, J=9.9 Hz, 2H, 7-H, 8-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.6, 21.6, 21.7, 21.7 (4q, CH_3), 24.5 (t, C-10), 31.7 (t, C-6), 36.4 (t, C-9), 69.6, 69.7 (2d, $CH(CH_3)_2$), 77.2, 78.0 (2d, C-2, C-3), 113.4 (s, C-5), 123.7 (d, C-7), 126.4 (d, C-8), 169.3, 169.5 (2s, COO*i*-Pr); IR (film) 3030, 2981, 2935, 1753, 1467, 1376, 1220, 1107, 751, 657 cm^{-1}; $[\alpha]_D^{20}$ −38.0 (c 0.98, $CHCl_3$). Anal. Calcd for $C_{16}H_{24}O_6$: C, 61.52; H, 7.74. Found: C, 61.77; H, 7.68.

4.2.4. 1,4-Dioxa-spiro[4,5]dec-7-ene (6d). The ketalization was carried out as described above using ethylene glycol (**4d**) (2.6 g, 42 mmol) to afford after chromatography (hexane/ethyl acetate=3:1, R_f=0.60) a colorless oil (2.1 g, 35%).

^{1}H NMR (300 MHz, $CDCl_3$) δ 1.51 (t, J=6.4 Hz, 2H, 10-H), 1.98–2.06 (m, 4H, 6-H, 9-H), 3.72–3.75 (m, 4H, 2-H, 3-H), 5.36, 5.47 (2dm, J=9.7 Hz, 2H, 7-H, 8-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 24.7 (t, C-10), 31.2 (t, C-6), 35.9 (t, C-9), 64.4 (2t, C-2, C-3), 107.8 (s, C-5), 124.4 (d, C-7), 126.4 (d, C-8). IR (KBr) 3026, 2925, 1653, 1476, 1432, 1388, 1361, 1335, 1262, 1221, 1172, 1114, 1058, 1027, 948, 850 cm^{-1}. Anal. Calcd for $C_8H_{12}O_2$: C, 68.55; H, 8.63. Found: C, 68.03; H, 9.16.

4.2.5. 1,4-Dioxa-spiro[4,5]dec-7-ene-2(*R*),3(*R*)-dicarboxylic acid (6e). To a solution of the methylester **6a** (300 mg, 1.1 mmol) in methanol (10 mL) was added NaOH (360 mg, 9 mmol) dissolved in water (2 mL). After refluxing for 6 h the solvent was evaporated and water (20 mL) and diethyl ether (20 mL) were added. After separation the aqueous phase was acidified with 1 M aqueous HCl and extracted three times with diethyl ether. The combined ether extracts were washed with water, dried ($MgSO_4$), and the solvent was removed to afford the carboxylic acid **6e** as a yellow solid (240 mg, 95%); mp 114 °C.

^{1}H NMR (500 MHz, DMSO-d_6) δ 1.79–1.88 (m, 2H, 10-H), 2.16–2.51 (m, 4H, 6-H, 9-H), 4.81, 4.82 (2d, J=9.2 Hz, 2H, 2-H, 3-H), 5.45–5.50 (m, J=11.6 Hz, 1H, 8-H), 5.65–5.7 (m, J=11.6 Hz, 1H, 7-H); ^{13}C NMR (125 MHz, DMSO-d_6) δ 25.1 (t, C-9), 32.3 (t, C-10), 37.1 (t, C-6), 77.4, 77.6 (2d, C-2, C-3), 112.8 (s, C-5), 124.4 (d, C-7), 127.1 (d, C-8), 172.0, 172.4 (2s, COOH); IR (film) 3038, 2934, 1737, 1425, 1361, 1271, 1142, 1042, 944 cm^{-1}; $[\alpha]_D^{20}$ −2.6 (c 1.0, MeOH). Anal. Calcd for $C_{10}H_{12}O_6$: C, 52.63; H, 5.26. Found: C, 52.54; H, 4.97.

4.2.6. Dimethyl 1,4-dioxa-spiro[4,5]dec-6-ene-2(*R*),3(*R*)-dicarboxylate (5a). The ene ketal was prepared via transketalization of 1,1-dimethoxy-2-cyclohexene.[14]

^{1}H NMR (300 MHz, $CDCl_3$) δ 1.75–1.84 (m, 2H, 9-H), 1.87–1.97 (m, 2H, 10-H), 1.98–2.07 (m, 2H, 8-H), 3.80 (s, 6H, CH_3), 4.83 (s, 2H, 2-H, 3-H), 5.65 (d, J=10.0 Hz, 1H, 6-H), 6.02 (dt, J=3.5, 10.0 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 20.7 (t, C-9), 24.9 (t, C-10), 34.4 (t, C-8), 53.2, 53.1 (2s, Me), 77.4, 77.2 (2d, C-2, C-3), 111.4 (s, C-5), 127.1 (d, C-6), 134.8 (d, C-7), 170.4, 170.5 (2s, COOMe); IR (film) 3033, 2978, 2945, 1764, 1478, 1371, 1237, 1045, 857, 759, 662 cm^{-1}; $[\alpha]_D^{20}$ −7.3 (c 1.0, $CHCl_3$), lit.:[14] $[\alpha]_D^{24}$ −8.5 (c 3.5, $CHCl_3$).

4.3. General procedures for the photooxygenations

4.3.1. Procedure A. The ketals **6a–d** (2 mmol) and tetraphenylporphin (1 mg) were dissolved in $CHCl_3$ (4 mL) and CCl_4 (12 mL) in a glass tube. The tube was irradiated at −30 °C with two sodium lamps (250 W) for 2–4 d. During the irradiation a slow stream of oxygen was bubbled through the solution and additional portions of the sensitizer were added, when the color of the solution faded. After completion, dimethylsulfide (1 mL) was added and the reaction solution was kept for 24 h. The solvent was evaporated and the ratio of the isomers was determined from the NMR spectra (500 MHz).

4.3.2. Procedure B. The ketal **6e** (100 mg, 0.4 mmol) was dissolved in 2 mL CD_3OD in a glass tube. After addition of rose bengal (1 mg) and sodium (40 mg, 1.7 mmol) the tube was irradiated under the same conditions as described for the general procedure for a period of 7 d. After completion, dimethylsulfide (1 mL) was added and the reaction solution was kept for 24 h. The solvent was evaporated and the ratio of the isomers was determined from the NMR spectra (500 MHz) in CD_3OD.

4.3.3. Photooxygenation of ketal 6a. Following procedure A, compound **6a** was irradiated for 4 d and the allylic alcohols were isolated as colorless oils. The ratio **7a/8a** (82:18) and the diastereomeric ratios for **7a** (57:43) and **8a** (62:38) were determined from the crude spectra by NMR spectroscopy (500 MHz). Chromatography (hexane/ethyl acetate=1:2, R_f=0.42–0.50) afforded first the major diastereomer of **8a**, followed by the minor diastereomer of **8a**, the minor diastereomer of isomer **7a**, and finally, the major diastereomer of **7a** (overall yield: 410 mg, 75%).

4.3.3.1. Dimethyl 8(*S*)-hydroxy-1,4-dioxa-spiro[4,5]-dec-6-ene-2(*R*),3(*R*)-dicarboxylate (*S*-7a) (main product). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.72–1.92 (m, 2H, 9-H), 2.08–2.2 (m, 2H, 10-H), 3.82, 3.83 (2s, 6H, CH_3), 4.21 (m, 1H, 4-H), 4.81, 4.83 (2d, J=4.5 Hz, 2H, 2-H, 3-H), 5.69 (d, J=10.5 Hz, 1H, 6-H), 5.97–6.04 (dm, J=10.5 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 30.6 (t, C-9), 32.0 (t, C-10), 53.2, 53.3 (2q, Me), 66.4 (d, C-8), 77.8, 77.9 (2d, C-2, C-3), 111.0 (s, C-5), 129.0 (d, C-6), 137.5 (d, C-7), 170.8 (2s, CO_2Me); IR (KBr) 3425, 2975, 2920, 1738, 1402, 1234, 1156, 1042, 931, 745 cm^{-1}; $[\alpha]_D^{25}$ −54.9 (c 0.25, $CHCl_3$). Anal. Calcd for $C_{12}H_{16}O_7$: C, 52.94; H, 5.88. Found: C, 52.66; H, 5.88.

4.3.3.2. Dimethyl 8(*R*)-hydroxy-1,4-dioxa-spiro[4,5]-dec-6-ene-2(*R*),3(*R*)-dicarboxylate (*R*-7a) (minor diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.75–1.89 (m, 2H, 9-H), 2.09–2.19 (m, 2H, 10-H), 3.83, 3.84 (2s, 6H, CH_3), 4.27 (m, 1H, 8-H), 4.85, 4.87 (2d, J=4.5 Hz, 2H, 2-H, 3-H), 5.73 (d, J=10.4 Hz, 1H, 6-H), 5.99–6.03 (dm, J=10.4 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 30.6 (t, C-9), 31.8 (t, C-10), 55.2, 55.3 (2q, Me), 66.0 (d, C-8), 77.2, 77.3 (2d, C-2, C-3), 110.8 (s, C-5), 128.8 (d, C-6), 136.8 (d, C-7), 170.3 (2s, CO_2Me); IR (KBr) 3425, 2975, 2920, 1738, 1402, 1234, 1156, 1042, 931, 745 cm^{-1}; $[\alpha]_D^{20}$ +2.3 (c 1.0, $CHCl_3$).

4.3.3.3. Dimethyl 7-hydroxy-1,4-dioxa-spiro[4,5]dec-8-ene-2(*R*),3(*R*)-dicarboxylate (8a) (major diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.95–2.14 (m, 2H, 10-H), 2.25–2.46 (m, 2H, 6-H), 3.76, 3.77 (2s, 6H, CH_3), 4.29 (m, 1H, 7-H), 4.79, 4.84 (2d, J=4.7 Hz, 2H, 2-H, 3-H), 5.64–5.71 (dm, J=9.7 Hz, 1H, 9-H), 5.8–5.87 (dm, J=9.7 Hz, 1H, 8-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 36.8 (t, C-10), 40.1 (t, C-6), 53.3, 53.4 (2q, Me), 66.4 (d, C-7), 77.0, 77.1 (2d, C-2, C-3), 113.7 (s, C-5), 125.5 (d, C-9), 129.9 (d, C-8), 170.0, 170.5 (2s, CO_2Me); $[\alpha]_D^{20}$ +14.8 (*c* 0.96, $CHCl_3$).

4.3.3.4. Dimethyl 7-hydroxy-1,4-dioxa-spiro[4,5]dec-8-ene-2(*R*),3(*R*)-dicarboxylate (8a) (minor diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.05–2.22 (m, 2H, 10-H), 2.32–2.52 (m, 2H, 6-H), 3.84, 3.85 (2s, 6H, CH_3), 4.37 (m, 1H, 8-H), 4.86, 4.92 (2d, J=4.7 Hz, 2H, 2-H, 3-H), 5.72–5.8 (dm, J=9.7 Hz, 1H, 9-H), 5.89–5.97 (dm, J=9.7 Hz, 1H, 8-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 36.8 (t, C-10), 39.9 (t, C-6), 53.3, 53.4 (2q, Me), 66.4 (d, C-7), 77.1, 77.6 (2d, C-2, C-3), 113.2 (s, C-5), 125.8 (d, C-9), 129.6 (d, C-8), 170.2, 170.5 (2s, CO_2Me).

4.3.4. Photooxygenation of ketal 6b. Following procedure A, compound **6b** was irradiated for 4 d and the allylic alcohols were isolated as colorless oils. The ratio **7b/8b** (81:19) and the diastereomeric ratios for **7b** (53:47) and **8b** (55:45) were determined from the crude spectra by NMR spectroscopy (500 MHz). Chromatography (hexane/ethyl acetate=1:2, R_f=0.50–0.58) afforded first the major diastereomer of **8b**, followed by the minor diastereomer of **8b**, the minor diastereomer of isomer **7b**, and finally, the major diastereomer of **7b** (overall yield: 450 mg, 75%).

4.3.4.1. Diethyl 8(*S*)-hydroxy-1,4-dioxa-spiro[4,5]dec-6-ene-2(*R*),3(*R*)-dicarboxylate (*S*-7b) (major diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.33 (t, J=6.6 Hz, 6H, CH_3), 1.73–1.92 (m, 2H, 9-H), 2.0–2.17 (m, 2H, 10-H), 4.21 (m, 1H, 8-H), 4.25 (t, J=6.6 Hz, 4H, CH_2), 4.76 (m, 2H, 2-H, 3-H), 5.69 (d, J=10.1 Hz, 1H, 6-H), 5.94 (dm, J=10.1 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.6 (q, CH_3), 29.3 (t, C-9), 30.7 (t, C-10), 61.1 (2t, OCH_2), 64.6 (d, C-8), 76.1 (d, C-2, C-3), 109.1 (s, C-5), 127.4 (d, C-6), 135.3 (d, C-7), 168.6 (2s, CO_2Et); IR (KBr) 3420, 2982, 2940, 1740, 1445, 1395, 1221, 1127, 1022, 939 cm^{-1}. Anal. Calcd for $C_{14}H_{20}O_7$: C, 55.99; H, 6.71. Found: C, 55.85; H, 6.72.

4.3.4.2. Diethyl 8(*R*)-hydroxy-1,4-dioxa-spiro[4,5]dec-6-ene-2(*R*),3(*R*)-dicarboxylate (*R*-7b) (minor diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.33 (t, J=6.6 Hz, 6H, CH_3), 1.73–1.92 (m, 2H, 9-H), 2.0–2.17 (m, 2H, 10-H), 4.21 (m, 1H, 8-H), 4.25 (t, J=6.6 Hz, 4H, CH_2), 4.78, 4.82 (2d, J=4.7 Hz, 2H, 2-H, 3-H), 5.66 (d, J=10.1 Hz, 1H, 6-H), 5.94 (dm, J=10.1 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.6 (q, CH_3), 29.2 (t, C-9), 30.5 (t, C-10), 61.0 (2t, OCH_2), 64.6 (d, C-8), 76.2 (d, C-2, C-3), 109.3 (s, C-5), 127.5 (d, C-6), 135.4 (d, C-7), 168.4 (2s, CO_2Et).

4.3.4.3. Diethyl 7-hydroxy-1,4-dioxa-spiro[4,5]dec-8-ene-2(*R*),3(*R*)-dicarboxylate (8b) (major diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.33 (t, J=7.1 Hz, 6H, CH_3), 2.05–2.22 (m, 2H, 10-H), 2.32–2.56 (m, 2H, 6-H), 4.30 (q, J=7.1 Hz, 4H, OCH_2), 4.35 (m, 1H, 7-H), 4.8–4.91 (m, 2H, 2-H, 3-H), 5.76–5.80 (dm, J=9.89 Hz, 2H, 9-H), 5.89–5.97 (dm, J=9.89 Hz, 1H, 8-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.6 (2q, CH_3), 35.5 (t, C-10), 39.7 (t, C-6), 62.2, 62.3 (2t, OCH_2), 70.1 (d, C-7), 75.9, 76.1 (2d, C-2, C-3), 112.2 (s, C-1), 124.5 (d, C-9), 128.3 (C-8), 168.6, 168.7 (CO_2Et).

4.3.4.4. Diethyl 7-hydroxy-1,4-dioxa-spiro[4,5]dec-8-ene-2(*R*),3(*R*)-dicarboxylate (8b) (minor diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.33 (t, J=7.1 Hz, 6H, CH_3), 2.05–2.22 (m, 2H, 10-H), 2.32–2.56 (m, 2H, 6-H), 4.30 (q, J=7.1 Hz, 4H, OCH_2), 4.29 (m, 1H, 7-H), 4.83–4.96 (m, 2H, 2-H, 3-H), 5.76–5.80 (dm, J=9.9 Hz, 2H, 9-H), 5.82–5.91 (dm, J=9.9 Hz, 1H, 8-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.6 (2q, CH_3), 35.7 (t, C-10), 39.3 (t, C-6), 65.1, 65.2 (2t, OCH_2), 70.9 (d, C-7), 75.9, 76.1 (2d, C-2, C-3), 112.3 (s, C-1), 124.2 (d, C-9), 128.5 (C-8), 168.6, 168.7 (CO_2Et).

4.3.5. Photooxygenation of ketal 6c. Following procedure A, compound **6c** was irradiated for 4 d and the allylic alcohols were isolated as colorless oils. The ratio **7c/8c** (89:11) and the diastereomeric ratio for **7c** (54:46) were determined from the crude spectra by NMR spectroscopy (500 MHz). Chromatography (hexane/ethyl acetate=1:2, R_f=0.65–0.72) afforded first the major diastereomer of **8c**, followed by the minor diastereomer of isomer **7c**, and finally, the major diastereomer of **7c**. The minor diastereomer of **8c** could not be isolated (overall yield: 480 mg, 73%).

4.3.5.1. Diisopropyl 8(*S*)-hydroxy-1,4-dioxa-spiro[4,5]-dec-6-ene-2(*R*),3(*R*)-dicarboxylate (*S*-7c) (major diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.23 (d, J=6.1 Hz, 12H, CH_3), 1.50–2.14 (m, 4H, 10-H, 12-H), 4.14 (m, 1H, 8-H), 4.59 (m, 2H, 2-H, 3-H), 5.06 (sept, J=6.1 Hz, 2H, CH), 5.62–5.72 (d, J=10.0 Hz, 1H, 6-H), 5.89–5.96 (d, J=10.0 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.8 (q, CH_3), 30.3 (t, C-9), 32.0 (t, C-10), 65.7 (d, C-8), 70.1 (2d, $CHMe_2$), 77.7, 78.1 (2d, C-2, C-3), 110.6 (s, C-5), 128.5 (d, C-6), 137.0 (d, C-7), 169.4, 169.5 (2s, COO*i*-Pr). Anal. Calcd for $C_{16}H_{24}O_7$: C, 58.53; H, 7.37. Found: C, 58.26; H, 7.29.

4.3.5.2. Diisopropyl 8(*R*)-hydroxy-1,4-dioxa-spiro-[4,5]dec-6-ene-2(*R*),3(*R*)-dicarboxylate (*R*-7c) (minor diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.21 (d, J=6.1 Hz, 12H, CH_3), 1.62–2.19 (m, 4H, 10-H, 12-H), 4.11 (m, 1H, 8-H), 4.61–5.13 (m, 2H, 2-H, 3-H), 5.06 (sept, J=6.1 Hz, 2H, CH), 5.62–5.72 (d, J=10.0 Hz, 1H, 6-H), 5.89–5.96 (d, J=10.0 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.9 (q, CH_3), 30.3 (t, C-9), 31.9 (t, C-10), 65.6 (d, C-8), 70.0 (2d, $CHMe_2$), 77.2, 77.6 (2d, C-2, C-3), 110.4 (s, C-5), 128.3 (d, C-6), 136.9 (d, C-7), 169.3, 169.4 (2s, COO*i*-Pr).

4.3.5.3. Diisopropyl 7-hydroxy-1,4-dioxa-spiro[4,5]-dec-8-ene-2(*R*),3(*R*)-dicarboxylate (8c) (major diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.29, 1.31 (2d, J=6.1 Hz, 12-H, CH_3), 2.05–2.25 (m, 2H, 10-H), 2.25–2.61 (m, 2H, 6-H), 4.41 (m, 1H, 7-H), 4.71, 4.80 (2d, J=5.2 Hz, 2H, 2-H, 3-H), 5.12 (sept, J=6.2 Hz, 2H, OCH), 5.70–5.79 (m, 1H, 9-H), 5.85–5.92 (m, 1H, 8-H);

^{13}C NMR (75 MHz, $CDCl_3$) δ 22.0 (q, CH_3), 36.6 (t, C-10), 40.1 (t, C-6), 66.3 (d, C-7), 70.3, 70.7 (2d, $CHMe_2$), 77.7 (2d, C-2, C-3), 113.4 (s, C-5), 125.5 (d, C-9), 129.9 (d, C-8), 169.6, 169.1 (2s, COO*i*-Pr); IR (KBr) 3415, 2980, 2957, 1738, 1365, 1245, 1098, 1024, 754 cm^{-1}; $[\alpha]_D^{20}$ −4.8 (*c* 1.02, $CHCl_3$). Anal. Calcd for $C_{16}H_{24}O_7$: C, 58.53; H, 7.37. Found: C, 58.96; H, 6.89.

4.3.6. Photooxygenation of ketal 6d. Following procedure A, compound **6d** (200 mg, 1.4 mmol) was irradiated for 2 d and the allylic alcohols were isolated as colorless oils. The ratio **7d/8d** (87:13) was determined from the crude spectra by NMR spectroscopy (500 MHz). Chromatography (hexane/ethyl acetate=1:2, R_f=0.35) afforded **8d** in the first fractions, followed by **7d** (overall yield: 170 mg, 77%).

4.3.6.1. 8-Hydroxy-1,4-dioxa-spiro[4,5]dec-6-ene (7d). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.69–1.80 (m, 2H, 10-H), 1.91–2.18 (m, 2H, 9-H), 3.89–4.04 (m, 4H, 2-H, 3-H), 4.22 (br, 1H, 8-H), 5.63 (dt, *J*=1.4, 10.0 Hz, 1H, 6-H), 5.95 (dd, *J*=1.1, 10.0 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 31.0 (t, C-10), 31.3 (t, C-9), 64.9, 65.0 (2d, C-2, C-3), 66.3 (d, C-8), 105.4 (s, C-1), 129.5 (d, C-6), 135.3 (d, C-7). IR (KBr) 3032, 2948, 2883, 1675, 1396, 1346, 1272, 1066, 1012, 939, 863 cm^{-1}.

4.3.6.2. 7-Hydroxy-1,4-dioxa-spiro[4,5]dec-8-ene (8d). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.96 (d, *J*=4.4 Hz, 2H, 10-H), 2.23 (br, 2H, 6-H), 2.71 (d, *J*=10.3 Hz, 1H, OH), 3.85–3.98 (m, 4H, 2-H, 3-H), 4.24 (m, 1H, 7-H), 5.69 (dt, *J*=3.6, 9.8 Hz, 1H, 8-H), 5.79–5.89 (m, 1H, 9-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 36.1 (t, C-10), 39.4 (t, C-6), 64.7 (t, C-2, C-3), 66.7 (d, C-7), 108.4 (s, C-1), 126.5 (d, C-8), 127.7 (d, C-9).

4.3.7. Photooxygenation of ketal 6e. Following procedure B, compound **6e** was irradiated for 7 d. The NMR spectrum (500 MHz) of the crude product showed exclusively regioisomer **7e** in a diastereomeric ratio of 56:44. The configuration of the main diastereomer was established by saponification of the corresponding methylester **8a** (MeOH/H_2O, catalytic amount of NaOH) and comparison of their NMR spectra.

4.3.7.1. 8(*S*)-Hydroxy-1,4-dioxa-spiro[4,5]dec-6-ene-2(*R*),3(*R*)-dicarboxylic acid (7e) (major diastereomer). ^{1}H NMR (300 MHz, CD_3OD) δ 1.69–2.0 (m, 2H, 10-H), 2.02–2.30 (m, 2H, 9-H), 4.15 (m, 1H, 8-H), 4.54, 4.56 (2d, *J*=6.6 Hz, 2H, 2-H, 3-H), 5.77 (d, *J*=10 Hz, 1H, 6-H), 5.87 (d, *J*=10 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 30.3 (t, C-9), 32.0 (t, C-10), 65.7 (d, C-8), 80.4, 80.7 (2d, C-2, C-3), 107.4 (s, C-5), 129.9 (d, C-6), 135.1 (d, C-7), 176.7, 176.8 (2s, COOH).

4.3.7.2. 7(*R*)-Hydroxy-1,4-dioxa-spiro[4,5]dec-8-ene-2(*R*),3(*R*)-dicarboxylic acid (7e) (minor diastereomer). ^{1}H NMR (300 MHz, CD_3OD) δ 1.69–2.0 (m, 2H, 10-H), 2.02–2.30 (m, 2H, 9-H), 4.15 (m, 1H, 8-H), 4.48, 4.50 (2d, *J*=6.2 Hz, 2H, 2-H, 3-H), 5.77 (d, *J*=10 Hz, 1H, 6-H), 5.87 (d, *J*=10 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 30.2 (t, C-9), 31.7 (t, C-10), 65.7 (d, C-8), 80.4, 80.7 (2d, C-2, C-3), 107.6 (s, C-5), 130.0 (d, C-6), 134.7 (d, C-7), 177.0, 177.1 (2s, COOH).

4.4. Epoxidation of the ketal 6a

The cyclohexene ketal **6a** (420 mg, 1.6 mmol) was dissolved in dichloromethane (30 mL) and *m*-chloroperbenzoic acid (440 mg, 1.9 mmol) was added at 0 °C in several portions. The course of the reaction was followed by TLC (hexane/ethyl acetate=3:1). After completion (4 h) a saturated solution of $NaHCO_3$ (100 mL) was added. After separation, the aqueous phase was washed with diethyl ether (100 mL), and the combined organic extracts were washed with water, dried ($NaSO_4$), and the solvent was evaporated. The diastereomeric ratio (51:49) was determined from the crude spectra by NMR spectroscopy (500 MHz). The product was purified by column chromatography (hexane/ethyl acetate=1:1, R_f=0.19) to afford the epoxides **10** as white solids (415 mg, 95%).

4.4.1. Dimethyl 7,8-epoxy-1,4-dioxa-spiro[4,5]decane-2(*R*),3(*R*)-dicarboxylate (10) (major diastereomer). Mp 56.5 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.47–1.56, 1.65–1.77 (2m, 2H, 10-H), 2.10–2.32 (m, 4H, 6-H, 9-H), 3.12–3.20 (m, 2H, 7-H, 8-H), 3.80, 3.81 (2s, 6H, Me), 4.75, 4.79 (2d, *J*=5.1 Hz, 2H, 2-H, 3-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 22.8 (t, C-10), 28.1 (t, C-9), 35.8 (t, C-6), 51.1 (d, C-8), 52.1 (d, C-7), 53.1, 53.2 (2s, Me), 77.1, 77.2 (2d, C-2, C-3), 112.5 (s, C-1), 170.1, 170.3 (2s, COOMe); $[\alpha]_D^{20}$ −29.3 (*c* 0.98, $CHCl_3$); IR (KBr) 3015, 2959, 1761, 1436, 1373, 1344, 1254, 1217, 1164, 1125, 1086, 992, 933 cm^{-1}. Anal. Calcd for $C_{12}H_{16}O_7$: C, 52.94; H, 5.88. Found: C, 52.85; H, 6.24.

4.4.2. Dimethyl 7,8-epoxy-1,4-dioxa-spiro[4,5]decane-2(*R*),3(*R*)-dicarboxylate (10) (minor diastereomer). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.44–1.56, 1.63–1.78 (2m, 2H, 10-H), 2.0–2.30 (m, 4H, 7-H, 8-H), 3.41 (br, 2H, 7-H, 8-H), 3.77, 3.78 (2s, 6H, Me), 4.74 (m, 2H, 2-H, 3-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 23.5 (t, C-10), 29.2 (t, C-9), 36.3 (t, C-6), 52.0 (d, C-8), 52.8 (d, C-7), 53.1, 53.2 (s, Me), 78.0, 78.1 (2d, C-2, C-3), 113.5 (s, C-1), 171.2, 171.3 (2s, COOMe).

4.5. Cleavage of the chiral auxiliary from ketal 7a

4.5.1. Cleavage with HCl. The ketal (*S*)-**7a** (100 mg, 0.36 mmol) was dissolved in methanol (10 mL). Hydrochloric acid (1 N, 0.5 mL) was added dropwise at 0 °C. After 12 h diethyl ether (20 mL) and water (10 mL) were added, the organic phase was separated, dried ($MgSO_4$), and the solvent was evaporated. NMR analysis of the residue resulted in a 1:2 mixture of the ketone **11** and phenol (**12**).

4.5.2. Cleavage with montmorillonite K-10. The ketal (*S*)-**7a** (100 mg, 0.36 mmol) was dissolved in dichloromethane (10 mL). Montmorillonite K-10 (800 mg) was added at 0 °C and the mixture was stirred at room temperature for 24 h. After filtration and evaporation of the solvent NMR analysis of the residue resulted in a 4:1 mixture of the ketone **11** and phenol (**12**).

4.5.3. Cleavage with buffered montmorillonite K-10. The ketal (*S*)-**7a** (100 mg, 0.36 mmol) was dissolved in dichloromethane (10 mL). Sodium acetate (45 mg, 0.4 mmol) and montmorillonite K-10 (800 mg) were added at 0 °C and

the mixture was stirred at room temperature for 24 h. The conversion was followed by TLC but was not complete even after longer reaction times. However, no phenol could be detected. After filtration and evaporation of the solvent, flash chromatography (hexane/ethyl acetate=1:2, R_f=0.3) afforded the ketone **11** as a colorless oil (30 mg, 74%, 97% based on the conversion). In addition, unreacted ketal (*S*)-**7a** was recovered (24 mg, 24%).

4.5.3.1. 4(*S*)-Hydroxy-2-cyclohexen-1-one (11). ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.85–2.09 (m, 1H, 5-H), 2.22–2.45 (m, 2H, 6-H), 2.55–2.68 (m, 1H, 5-H), 4.60 (br, 1H, 4-H), 5.99 (d, J=10.2 Hz, 1H, 2-H), 6.95 (dt, J=2.0, 10.2 Hz, 1H, H-3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 32.8 (t, C-5), 35.7 (t, C-6), 66.7 (d, C-4), 129.6 (d, C-2), 153.0 (d, C-3), 199.1 (s, CO); $[\alpha]_D^{25}$ −85.3 (*c* 0.16, $CHCl_3$), lit.:[16] $[\alpha]_D^{20}$ −90.0 (*c* 0.2, $CHCl_3$).

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