High π-Facial Selectivity Through Chelation of Magnesium Ions in the DMD Epoxidation of α,β-Unsaturated Imides with Chiral Pyrrolidinone Auxiliaries

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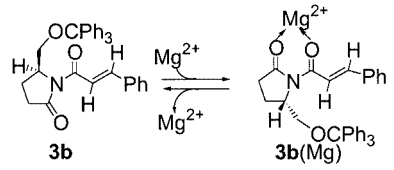
High diastereoselectivity, but of the opposite sense, is observed in the epoxidation (DMD or *m*CPBA) of α,β-unsaturated imides equipped with pyrrolidinone-type chiral auxiliaries that bear either a hydroxymethyl or trityloxymethyl side chain. This unprecedented reversed π-facial differentiation is promoted by chelation of a magnesium ion, which results in conformational control over the essential steric interactions.

Introduction

Optically active epoxides are key building blocks in organic synthesis,[1] and are usually prepared through the oxidation of the corresponding olefins.[2] Stereoselectivity is achieved through substrate manipulation,[2a] or the use of chiral oxidants,[2b] in which steric,[2a] electronic,[2b−2d] stereoelectronic,[2e−2f] and conformational[3] effects play a decisive role. An alternative approach utilizes chiral auxiliaries to effect the π-facial selectivity in the oxygen-transfer process. A recent application of this methodology is the highly diastereoselective epoxidation of enecarbamates[4] that are equipped with oxazolidinone-type chiral auxiliaries. Through the synergistic interplay of conformational and steric effects, the attack by DMD and *m*CPBA may be directed at will to the desired π face of the substrate. In the present study, we show that metal chelation of the chiral auxiliary and olefinic functionality can result in effective diastereoselective epoxidation.

Such advantageous metal chelation has been reported in the asymmetric conjugate addition[5a] and Diels−Alder reaction[5b] of the triphenylmethyl ether **3b** derived from the chiral pyrrolidinone imide **3a**. With $Mg(ClO_4)_2$ as the chelating agent, it was shown through NMR spectroscopy studies[5c] that the preferred **3b**(Mg) conformer results from coordination of a magnesium ion to the two carbonyl functionalities (Scheme 1).

For the best conjugation of the C=C and the C=O groups, the s-*cis* conformation is favored over the *s*-*trans* form by ca. 5 kcal/mol as a result of steric interactions between the olefinic methylene unit and the lactam carbonyl group.[5c,5d] Inspection of molecular models discloses that



3b **3b**(Mg)

Scheme 1. Chelation of a magnesium ion to the imide **3b**

one π face is severely obstructed by the trityloxymethyl substituent and, consequently, the reagent attacks from the other face. So far, this concept of diastereoselective control has not been employed in epoxidations; thus, we became interested in applying it to the oxidation of the chiral pyrrolidinone imides **3**. Indeed, we demonstrate herein that metal chelation is a productive method to induce stereoselective oxygen transfer in the epoxidation of the olefinic substrates **3** with *m*CPBA and DMD.

Results and Discussion

To study this stereochemical concept in the epoxidations mediated by *m*-chloroperbenzoic acid (*m*CPBA) and dimethyldioxirane (DMD), the imides **3a**−**c** were prepared from the commercially available (*S*)-5-hydroxymethyl-2-pyrrolidinone (Scheme 2). Protection of the hydroxy group as its silyl ether **1**, followed by acylation[6] and subsequent deprotection (TBAF, THF), provided the imide **3a** in an overall yield of 91%. The cinnamoyl and crotonoyl derivatives of Koga's chiral auxiliaries **3b** and **3c** were synthesized as reported.[7]

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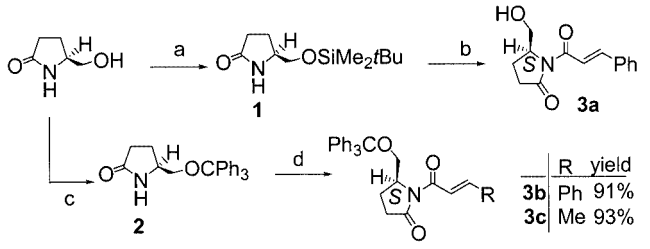


Scheme 2. Preparation of the imides **3a**−**c.** a. tBuMe$_2$SiCl, imidazole, DMAP, 97%; b. i. nBuLi, THF, (*E*)-PhCHCHCOCl, −78 °C; ii. TBAF, THF, 94%; c. Ph_3CCl, Et_3N, DMAP, CH_2Cl_2, 73%; d. i. nBuLi, THF, −78 °C. ii. (*E*)-PhCH=CHCOCl or (*E*)-CH_3CH=CHCOCl

The results of the epoxidations are summarized in Table 1. With *m*CPBA (1.5 equiv.), the epoxidation was conducted at 20 °C for 8 h, and the corresponding isomeric epoxides **4** were obtained in good diastereoselectivities (Entries 1 and 2). The low yield of epoxide in Entry 2 is due presumably to hydrolysis of the trityl functionality in ether **3b** on account of the acidic conditions experienced during the epoxidation with *m*CPBA.

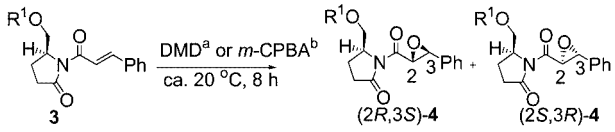
It is mechanistically significant to note the reversed sense in the π-facial selectivity between the imides **3a** and **3b**; that is, for **3a**, which features a free hydroxy group, the major epoxide is the diastereoisomer (2*R*,3*S*)-**4a**, but for the triphenylmethyl ether derivative **3b** it is (2*S*,3*R*)-**4b**. As expected, the *m*CPBA epoxidation of the triphenylmethyl ethers derived from cinnamoyl **3b** (Entry 2) and crotonyl **3c** (data not shown) gave the same (2*S*,3*R*)-configured epoxides **4b** and **4c** with similar *dr* values.

The DMD epoxidation of the imides (*S*)-**3** furnished the same epoxides **4** in high yields (Entries 3 and 4). The high conversions are impressive because electron-poor olefins usually exhibit rather low reactivity toward electrophilic oxidants.[8] In contrast to the results obtained when using *m*CPBA (Entries 1 and 2), the π-facial selectivity for the DMD epoxidations (Entries 3 and 4) is significantly lower; in fact, for the hydroxy imide **3a**, the oxygen transfer takes place unselectively. Nevertheless, with the triphenylmethyl derivatives **3b** and **3c**, the same major diastereoisomers, namely the (2*S*,3*R*)-epoxides **4b** and **4c**, were produced in the epoxidations with both *m*CPBA (Entry 2) and DMD (Entry 4). The higher *dr* values for *m*CPBA versus DMD may be reconciled in terms of hydrogen bonding between the carbonyl group of the imide and the proton of the peracid.[5]

Chelation effects[9] were assessed by the addition of magnesium perchlorate during the DMD oxidation of the triphenylmethyl ether imide **3b** (Entries 5−9). Maximum diastereoselectivity (Entry 7) was obtained when 0.5 equiv. of magnesium perchlorate was employed. Larger amounts of magnesium perchlorate (Entries 8 and 9) did not improve the *dr* values; instead, at high salt loading the yield of the epoxide **4b** was substantially lowered. We attempted aqueous workup, but, unfortunately, the epoxides are too labile and deteriorated on workup, especially when purification was attempted by chromatography on silica gel. Several other purification methods were also tested, e.g., Al_2O_3 chromatography and HPLC, but the epoxides were too sensitive to survive.

We note that the major epoxide diastereoisomer again is the (2*S*,3*R*)-configured one (Entries 5−9), the same one that formed in the absence of the chelating agent $Mg(ClO_4)_2$ (Entry 4). The fact that only 0.5 equiv. of $Mg(ClO_4)_2$ is necessary for optimal diastereoselectivity sug-

Table 1. Data for the products of the diastereoselective epoxidation of α,β-unsaturated imides **3**



Entry	Substrate	R^1	Oxidant	Additive (equiv.)	Conversion (%)[c]	m.b.(%)[c][d]	Yield (%)[c][e]	*dr*[c]	Config.[f]
1	**3a**	H	*m*CPBA	−	91	86	86 (78)	13:87	(2*R*,3*S*)
2	**3b**	Ph_3C	*m*CPBA	−	23	89	52 (12)[g]	84:16	(2*S*,3*R*)
3	**3a**	H	DMD	−	95	95	95 (90)	48:52	(2*R*,3*S*)
4	**3b**	Ph_3C	DMD	−	96	95	95 (91)	73:27	(2*S*,3*R*)
5	**3b**	Ph_3C	DMD	$Mg(ClO_4)_2$ (0.1)	95	96	96 (91)	72:28	(2*S*,3*R*)
6	**3b**	Ph_3C	DMD	$Mg(ClO_4)_2$ (0.3)	95	92	92 (87)	87:13	(2*S*,3*R*)
7	**3b**	Ph_3C	DMD	$Mg(ClO_4)_2$ (0.5)	95	90	89 (85)	91:09	(2*S*,3*R*)
8	**3b**	Ph_3C	DMD	$Mg(ClO_4)_2$ (1.0)	92	85	84 (77)	90:10	(2*S*,3*R*)
9	**3b**	Ph_3C	DMD	$Mg(ClO_4)_2$ (3.0)	83	80	76 (63)	91:09	(2*S*,3*R*)
10	**3a**	H	DMD	$Mg(ClO_4)_2$ (0.5)	85	69	63 (54)	14:86	(2*R*,3*S*)

[a] In acetone. [b] In dichloromethane. [c] Determined by ^{1}H NMR spectroscopic analysis directly on the crude reaction mixture, using dimethyl isophthalate as an internal standard; error ± 5% of the stated value. [d] m.b. = material balance. The material balance represents the sum of isolated products and recovered starting material. [e] Yield is based on 100% conversion; in parenthesis is given the yield of isolated epoxide. [f] Configuration of major product. [g] The low yield of epoxide is presumably due to hydrolysis of the trityl ether on account of the acidic conditions experienced during the oxidation with *m*CPBA.

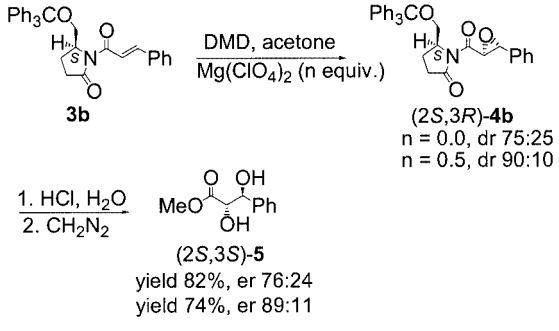
gests that the stoichiometry of chelation is two molecules of the imide **3b** substrate per $Mg(ClO_4)_2$ chelating agent.[5]

The epoxidation of the *tert*-butyldimethylsilyl (TBDMS)-protected ether was also examined in the presence of the Mg^{2+} salt. We observed a similar trend, but the trityloxymethyl ether is more effective in controlling the diastereoselectivity. For this reason, all subsequent epoxidations were conducted using only the trityl ether **3b**.

Tomioka[5c] reported a detailed study, by means of theoretical work and NMR spectroscopy, on the preferred conformation of imide **3** upon metal ion chelation. ^{1}H NMR spectra disclosed that under such conditions the olefinic methine proton H5′ is shifted to low field in the presence of magnesium perchlorate; thus, an NOE effect operates between protons H2 and H5′. This observation was explained in terms of a shielding effect by the trityloxymethyl group, which becomes positioned favorably for such interactions upon the chelation of the magnesium ion between the two carbonyl functionalities.

In a manner similar to that observed for substrate **3b**, we found that the diastereoselectivity is significantly increased in the DMD oxidation of imides **3a** and **3c** when 0.5 equiv. of magnesium perchlorate were added. Thus, the diastereoselectivity increased from 48:52 to 14:86 for epoxide **4a** (Entries 3 and 10) and from 73:27 to 85:15 for epoxide **4c** (data not shown).

The assignment of the epoxide configuration is exemplified for (2*S*,3*R*)-**4b**, based on the chemical correlation outlined in Scheme 3. For this purpose, the epoxide **4b** was treated with aqueous hydrochloric acid, followed by diazomethane, to give the diol **5**. In the absence of magnesium perchlorate, the diastereoisomeric ratio (*dr*) of **4b** was 75:25, as determined by ^{1}H NMR spectroscopy, which is the same as the enantiomeric ratio (*er*, 76:24) of the diol **5**, as determined by optical rotation. Analogously, in the presence of 0.5 equiv. of magnesium perchlorate, the enantiomeric ratio of diol ester **5** (89:11) is in accordance with the diastereoisomeric ratio of epoxide **4b** (90:10), within experimental error.



Scheme 3. Transformation of the epoxide **4b** to the diol **5**

The absolute configuration of the diol **5** was assigned to be (2*S*,3*S*) by comparison of the sign of rotation with an authentic sample of optically pure diol **5**, which was prepared as reported.[11] Since the acid-catalyzed ring opening of the epoxide **4b** takes place with inversion at the C3 position,[12] its configuration must be (3*R*) to comply with the observed (3*S*) assignment in the diol **5**. Consequently, the configuration of the C2 position in the epoxide **4b** must be (2*S*), that is, the same as in the diol **5**, since this stereogenic center is not involved in the process of ring-opening of the epoxide. Thus, by means of this chemical correlation, we assign the absolute (2*S*,3*R*) configuration to epoxide **4b** and infer that the remaining epoxides **4** have the same structure.

Additionally, the (2*S*,3*R*)-**4b** configuration was confirmed by 2D-NOESY analysis (Figure 1).

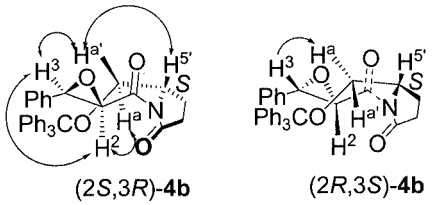
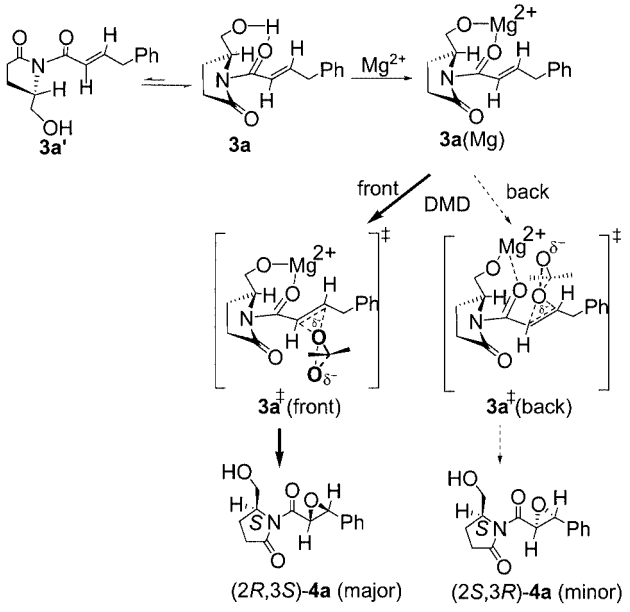


Figure 1. 2D-NOE effects observed for the diastereoisomeric epoxides (2*S*,3*R*)-**4b** and (2*R*,3*S*)-**4b**

Strong NOE effects were found between the protons H3 with H^{a}′ (one of the methylene protons of the trityloxymethyl group) and with H2 for the (2*S*,3*R*)-**4b** diastereoisomer (left side), while for the isomer (2*R*,3*S*)-**4b** (right side), a strong effect was observed between the protons H3 and H^{a} (the other methylene proton), which concords with the configurational assignment from the chemical correlation (Scheme 3). Moreover, the NOE effects between the proton H2 with the protons H^{a} and H3, as well as between the protons H^{a}′ and H3 and the methine proton H5′, corroborate the proposed structure of (2*S*,3*R*)-**4b**.

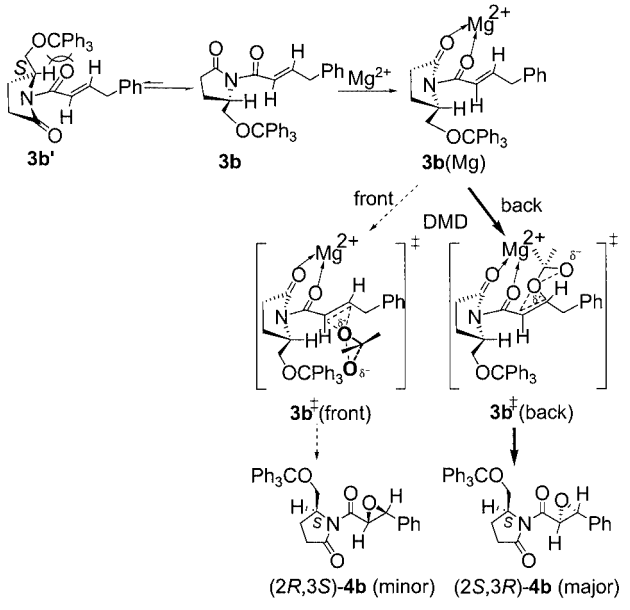
To rationalize the opposite sense in the π-facial selectivity observed for the epoxidation of the imide **3a** versus its ether derivative **3b**, and the substantially higher diastereoselectivity in the presence of magnesium perchlorate, we believe that conformational control of steric effects seems to be at play (Scheme 4). In the imide **3a**, the conformational equilibrium between **3a** and **3a**′ should lie to the side of **3a** because of the intramolecular hydrogen bonding that exists between the hydroxy group and the carbonyl functionality of the cinnamoyl imide (in Scheme 4, the five-membered ring of the pyrrolidinone is perpendicular, whereas the carbon−carbon double bond is parallel, to the plane of the page). For the epoxidation of substrate **3a** by DMD (the spiro transition structure is assumed to apply[13]) in acetone solution in the absence of Mg^{2+} ions, the intermolecular hydrogen bonding with acetone overrides any intramolecular interaction. Accordingly, no π-facial selectivity through conformational control is observed (see Entry 3); in the presence of magnesium ions, however, chelation between the hydroxy and carbonyl functionalities should afford the conformationally fixed chelate **3a**(Mg). Since the back side of the double bond is sterically obstructed towards DMD attack, the major epoxide diastereoisomer (2*R*,3*S*)-**4a** is formed by way of the favored transition structure **3a**‡(front), in which the DMD attack occurs from the front side, i.e., above the plane of the page. Back-side attack



Scheme 4. Proposed mechanism for the diastereoselective DMD epoxidation of imide **3a** through chelation of a magnesium ion with the hydroxy/carbonyl functionalities

through transition structure **3a**‡(back) would afford the minor (2*S*,3*R*)-**4a** epoxide, but is disfavored in view of steric impediments.

In the case of the triphenylmethyl ether derivative **3b**, the greater steric hindrance between the trityloxymethyl group and the carbonyl group of the cinnamoyl moiety in the **3b**′ versus **3b** conformers should favor the latter. The **3b** conformer is predestined for coordination of a magnesium ion with the two carbonyl functionalities, to afford preferentially the **3b**(Mg) chelate (Scheme 5). The front-side attack of DMD is then sterically obstructed by the large trityloxy-



Scheme 5. Proposed mechanism for the diastereoselective DMD epoxidation of imide **3b** through chelation of a magnesium ion to the carbonyl/carbonyl functionalities

methyl group; therefore, the (2*S*,3*R*)-**4b** diastereoisomer is the major epoxide product, formed by way of the **3b**‡(back) transition structure, in which the DMD attack occurs from the back side, i.e., below the plane of the page. Oxygen atom transfer from the front side through the transition structure **3b**‡(front) would afford the minor epoxide diastereoisomer (2*R*,3*S*)-**4b**, but again this pathway is sterically obstructed.

Conclusion

In summary, we have shown that either one of the two diastereoisomeric epoxides may be obtained diastereoselectively by using 5-hydroxymethyl-2-pyrrolidinone or its triphenylmethyl ether derivative as a chiral auxiliary. Chelation of a magnesium ion between the chiral auxiliary and the imide functionality provides the necessary conformational control to induce steric obstruction towards the attacking oxidant. Since the acid-catalyzed deprotection of the chiral auxiliary in the resulting epoxy imides affords the respective diols **5** in high enantiomeric ratio, our present results may have preparative applications in oxidation chemistry, in that useful methodologies may be developed for the syntheses of valuable building blocks bearing oxygen functionalities.

Experimental Section

General Remarks: ^{1}H and ^{13}C NMR spectra were recorded with a Bruker AC 200 (^{1}H: 200 MHz, ^{13}C: 50 MHz) or with a Bruker Avance 400 (^{1}H: 400 MHz, ^{13}C: 101 MHz) spectrometer. IR spectra were measured with a Perkin−Elmer 1600 FT-IR spectrophotometer. Silica gel (20−63 mm, Woelm) was used for flash chromatography. TLC analysis was conducted on precoated silica gel foils 60 F_{254} (20 × 20 cm) obtained from Merck, Darmstadt, Germany. The spots were visualized either by UV (254 nm) irradiation or by staining with a 5% solution of polymolybdic acid in ethanol. Silica gel (32−62 mm) from Woelm, Erlangen, Germany was used for column chromatography. The solvents were dried by standard methods and purified by distillation before use. Melting points (uncorrected) were determined on a Buchi B-545. Elemental analyses were carried out by the Microanalytical Division of the Institute of Inorganic Chemistry, University of Würzburg. All commercial reagents were used without further purification.

(5*S*)-5-(*tert*-Butyldimethylsiloxymethyl)-2-pyrrolidinone (1):[6b] Imidazole (2.35 g, 39.0 mmol), *tert*-butyldimethylsilyl chloride (3.00 g, 20.0 mmol), and DMAP (200 mg, 1.78 mmol) was added to a solution of (*S*)-5-hydroxymethyl-2-pyrrolidinone (1.50 g, 13.0 mmol) in dry THF (60 mL). The reaction mixture was stirred magnetically at room temperature (ca. 20 °C) for 24 h and then the solvent was evaporated (40 °C, 20 Torr). The resultant oil was taken up in ethyl acetate (200 mL) and washed with water (3 × 30 mL) and brine (3 × 30 mL), and then dried with Na_2SO_4. Evaporation of the solvent (40 °C, 20 Torr) afforded pyrrodinone **1** (2.90 g, 97%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.05 (s, 6 H), 0.85 (s, 9 H), 1.7 (m, 1 H), 2.15 (m, 1 H), 2.3 (m, 2 H), 3.42 (dd, *J* = 10.1, 6.9 Hz, 1 H), 3.6 (dd, *J* = 10.1, 4.1 Hz, 1 H), 3.74 (m, 1 H), 6.59 (br. s, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = −5.0, −4.8, −3.2, 18.5, 23.2, 25.8, 26.1, 30.0, 56.2, 66.4, 178.8 (s, C=O) ppm.

(5*S*)-1-Cinnamoyl-5-(hydroxymethyl)-2-pyrrolidinone (3a): A solution of *n*BuLi (5.7 mL, 1.6 M in THF, 9.1 mmol) was added dropwise over a period of 3 min to a magnetically well-stirred solution of pyrrolidinone **1** (1.40 g, 6.10 mmol) in THF (50 mL) at −78 °C (dry ice/acetone). After magnetic stirring for 30 min at this temperature, *trans*-cinnamoyl chloride (1.53 g, 9.1 mmol) in THF (10 mL) was administered over a period of 5 min. The resulting mixture was stirred magnetically at −78 °C for 2 h and warmed to room temperature (ca. 20 °C). A saturated, aqueous solution of NH_4Cl (50 mL) was added and the organic layer was extracted with ethyl acetate (3 × 50 mL). The combined organic layers were dried (Na_2SO_4) and evaporated (40 °C, 20 Torr) and then the residue was purified by chromatography on silica gel (petroleum ether/ethyl acetate, 5:1), to provide (5*S*)-5-(*tert*-butyldimethylsiloxymethyl)-1-cinnamoyl-2-pyrrolidinone (2.10 g, 96%) as a colorless oil.[7] ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.03 (s, 6 H), 0.88 (s, 9 H), 2.1−2.9 (m, 4 H), 3.72 (dd, *J* = 6.0, 2.1 Hz, 1 H), 4.0 (dd, *J* = 10.5, 3.5 Hz, 1 H), 4.55 (m, 1 H, H5′), 7.35−7.6 (m, 5 H, aryl H), 7.8 (d, *J* = 15.6 Hz, 1 H, H3), 8.0 (d, *J* = 15.6 Hz, 1 H, H2) ppm. The residue (670 mg, 1.87 mmol) was dissolved in THF (10 mL) and then TBAF (2 mL, 1 M in THF) was added. The resulting mixture was stirred magnetically at room temperature (ca. 20 °C) for 4 h. Saturated, aqueous sodium hydrogen carbonate (20 mL) was added and the mixture was extracted with ethyl acetate (3 × 50 mL). The combined organic layers were dried (Na_2SO_4) and evaporated (40 °C, 20 Torr) and then the residue was purified by chromatography on silica gel (CH_2Cl_2/CH_3OH, 10:1) to provide the imide **3a** (430 mg, 94%) as colorless needles, m.p. 123−125 °C. ^{1}H NMR (200 MHz, $CDCl_3$): δ = 1.9−2.7 (m, 4 H), 4.05 (m, 2 H), 4.32 (m, 1 H), 6.43 (d, *J* = 16 Hz, 1 H), 6.59 (br. s, 1 H, OH), 7.26−7.55 (m, 5 H, aryl H), 7.73 (d, *J* = 16.0 Hz, 1 H, H3) ppm. IR (KBr): $\tilde{\nu}$ = 3350, 2966, 1760, 1670 cm^{-1}. HRMS (EI): *m*/*z* calcd for $C_{14}H_{15}N_2O_3$ $[M + NH_4]^+$ 263.1396; found 263.1402.

(5*S*)-5-(Trityloxymethyl)-2-pyrrolidinone (2):[6b] Triphenylmethyl chloride (8.40 g, 30.0 mmol) was added over 5 min at room temperature (ca. 20 °C) to a mixture of *S*-5-hydroxymethyl-2-pyrrolidinone (2.30 g, 20.0 mmol), triethylamine (4.2 mL, 30.0 mmol), and DMAP (300 mg, 2.67 mmol) in dry CH_2Cl_2 (200 mL). The reaction mixture was stirred magnetically overnight and then washed with water (3 × 30 mL) and brine (3 × 30 mL); the combined extracts were dried (Na_2SO_4) and the solvent was evaporated (40 °C, 20 Torr). The crude product was purified by chromatography on silica gel (dichloromethane/methanol, 5:1) to afford the ether **2** (5.21 g, 73%). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.65 (m, 1 H), 2.15 (m, 1 H), 2.31 (m, 2 H), 3.0 (t, *J* = 8.1 Hz, 1 H), 3.2 (dd, *J* = 9.3, 3.8 Hz, 1 H), 3.88 (m, 1 H), 5.98 (br., 1 H), 7.26−7.43 (m, 15 H) ppm.

(5*S*)-1-Cinnamoyl-5-(trityloxymethyl)-2-pyrrolidinone (3b):[7] A solution of *n*BuLi (5.3 mL, 1.6 M in THF, 8.5 mmol) was added dropwise over a period of 3 min to a magnetically well-stirred solution of pyrrolidinone **2** (2.00 g, 5.60 mmol) in THF (50 mL) at −78 °C (dry ice/acetone). After magnetic stirring for 30 min at this temperature (ca. 20 °C), *trans*-cinnamoyl chloride (1.40 g, 8.40 mmol) in THF (10 mL) was administered over a period of 5 min. The resulting mixture was stirred at −78 °C for 2 h and then warmed to room temperature. Saturated aqueous NH_4Cl (50 mL) was added and the organic layer was extracted with ethyl acetate (3 × 50 mL). The combined organic layers were dried (Na_2SO_4) and evaporated (40 °C, 20 Torr) and then the residue was purified by chromatography on silica gel (petroleum ether/ethyl acetate, 5:1), to provide the imide **3b** (2.48 g, 91%). ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.1 (m, 1 H), 2.52 (ddd, *J* = 10.7, 8.5, 2.1 Hz, 1 H), 2.94−3.23 (m, 2 H), 3.65 (dd, *J* = 9.8, 3.7 Hz, 1 H), 4.61 (m, 1 H, H5′), 7.2−7.7 (m, 20 H, aryl H), 7.8 (d, *J* = 15.6 Hz, 1 H, H3), 8.05 (d, *J* = 15.6 Hz, 1 H, H2) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 14.6, 21.4, 33.9, 57.3, 60.8, 64.5, 87.5, 119.9, 127.5, 128.1, 128.2, 128.4, 128.9, 129, 129.3, 130, 130.7, 135.4, 144, 145.9, 166 (s, C=O), 176 (s, C=O) ppm.

(5*S*)-1-Crotonoyl-5-(trityloxymethyl)-2-pyrrolidinone (3c):[7] A solution of *n*BuLi (5.3 mL, 1.6 M in THF, 8.5 mmol) was added dropwise over a period of 3 min to a magnetically well-stirred solution of pyrrolidinone **2** (2.00 g, 5.60 mmol) in THF (50 mL) at −78 °C (dry ice/acetone). After magnetic stirring for 30 min at this temperature, *trans*-crotonoyl chloride (0.9 mL, 8.4 mmol) in THF (10 mL) was administered over a period of 5 min. The resulting mixture was stirred at −78 °C for 2 h and then warmed to room temperature (ca. 20 °C). Saturated aqueous NH_4Cl (50 mL) was added and then the organic layer was extracted with ethyl acetate (3 × 50 mL). The combined organic layers were dried (Na_2SO_4) and evaporated (40 °C, 20 Torr) and then the residue was purified by chromatography on silica gel (petroleum ether/ethyl acetate, 5:1) to provide the imide **3c** (2.21 g, 93%). ^{1}H NMR (200 MHz, $CDCl_3$): δ = 1.9−2.15 (m, 5 H), 2.52 (ddd, *J* = 17.8, 9.3, 2.4 Hz, 1 H), 3.0 (m, 1 H), 3.15 (dd, *J* = 9.6, 2.6 Hz, 1 H), 5.57 (dd, *J* = 9.6, 3.8 Hz, 1 H), 4.52 (m, 1 H), 7.0−7.2 (m, 15 H, aryl H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 18.8, 21.5, 3.8, 57.2, 64.5, 87.4, 124.4, 127.6, 128.3, 129, 144, 146, 166 (s, C=O), 176.9 (s, C=O) ppm.

General Procedure for the Epoxidation by *meta*-Chloroperbenzoic Acid (*m*CPBA): A sample of the olefin (100 mg, 0.24 mmol) was dissolved in dichloromethene (20 mL) and then *m*CPBA (1.5 equiv.) was added. After magnetic stirring at 20 °C for 8 h, the solid material was removed by filtration, potassium carbonate (ca. 200 mg) was added, and the mixture was stirred magnetically at 20 °C for 30 min. Again the solid materials were removed by filtration and the product distribution was determined quantitatively by ^{1}H NMR spectroscopy, using dimethyl isophthalate as the internal standard.

General Procedure for the Epoxidation by Dimethyldioxirane (DMD) in the Absence and Presence of Magnesium Perchlorate: A sample of the olefin (100 mg, 0.24 mmol), and, when necessary, magnesium perchlorate (0.1−3 equiv.), was dissolved in acetone (15 mL) and then a solution of DMD (0.05 ≈ 0.08 M, 2 equiv.) in acetone was added. After magnetic stirring at 20 °C for 8 h, the solvent was evaporated (20 °C, 20 Torr) and the product distribution was determined quantitatively by ^{1}H NMR spectroscopy using dimethyl isophthalate as the internal standard.

Epoxide 4a: A colorless, viscous oil was isolated (95% yield) as a mixture of the (2*R*,3*S*) (main) and (2*S*,3*R*) (minor) diastereoisomers, which were too labile to be purified by chromatography. ^{1}H NMR (200 MHz, $CDCl_3$): δ = 1.8−2.7 (m, 4 H), 3.55 (d, *J* = 1.7 Hz, 1 H, H3), 4.0−4.4 (m, 4 H), 7.27−7.37 (m, 5 H, aryl H) ppm.

Epoxide 4b: A colorless, viscous oil was isolated (89% yield) as a mixture of (2*S*,3*R*) (main) and (2*R*,3*S*) (minor) diastereoisomers after purification by chromatography on silica gel (petroleum ether/ethyl acetate, 5:1). ^{1}H NMR (200 MHz, $CDCl_3$): δ = 1.9−2.24 (m, 2 H), 2.5 (m, 1 H), 2.96 (m, 1 H), 3.22 (dd, *J* = 9.8, 2.7 Hz, 1 H), 3.62 (dd, *J* = 9.8, 3.8 Hz, 1 H), 3.99 (d, *J* = 1.5 Hz, 1 H, H2), 4.50 (m, 1 H, H5′), 4.76 (d, *J* = 1.7 Hz, 1 H, H3), 7.26−7.37 (m, 20 H, aryl H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 22.3, 32.8, 57.1, 57.8, 59.6, 61.2, 87.5, 126.7, 126.7, 127.7, 128.3, 128.3, 128.4, 128.9, 129, 129, 129.3, 135.6, 143.9, 168.6 (s, C=O), 177.2 (s, C=O) ppm.

IR (KBr): $\tilde{\nu}$ = 2966, 1757, 1670 cm^{-1}. HRMS (EI): *m*/*z* calcd for $C_{33}H_{29}NO_4$ [M^+] 504.2175; found 504.2170.

Epoxide 4c: A colorless, viscous oil was isolated (75% yield) as a mixture of (2*S*,3*R*) (main) and (2*R*,3*S*) (minor) diastereoisomers, after purification by chromatography on silica gel (petroleum ether/ethyl acetate, 5:1). ^1H NMR (200 MHz, $CDCl_3$): δ = 1.5 (d, *J* = 8.0 Hz, 3 H, CH_3), 1.9−2.23 (m, 2 H), 2.54 (m, 1 H), 2.91−3.2 (m, 3 H), 3.58 (dd, *J* = 9.8, 4.0 Hz, 1 H), 4.3 (d, *J* = 1.7 Hz, 1 H, H3), 4.43 (m, 1 H, H5′), 7.26−7.37 (m, 15 H, aryl H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 17.9, 22.4, 32.9, 56.2, 56.7, 57.1, 64.2, 87.5, 127.6, 127.6, 128.3, 128.4, 128.9, 143.9, 147.3, 169.5 (s, C=O), 177.3 (s, C=O) ppm. IR (KBr): $\tilde{\nu}$ = 2966, 1750, 1670 cm^{-1}. $C_{28}H_{27}NO_4$ (441.5): calcd. C 76.17, H 6.16, N 3.17; found C 76.54, H 6.07, N 2.67.

Methyl (2*S*,3*S*)-2,3-Dihydroxy-3-phenylpropanoate (5):[11] DMD (7.5 mL, 0.08 M in acetone, 0.60 mmol) was added to a mixture of imide **3b** (100.0 mg, 0.21 mmol) and magnesium perchlorate (23.0 mg, 0.10 mmol) in acetone (15 mL) and then the resulting mixture was stirred magnetically for 8 h at room temperature (ca. 20 °C). The solvent was evaporated (40 °C, 20 Torr), the residue was dissolved in water (20 mL), and then 37% aqueous hydrochloric acid (1 mL) was added. The reaction mixture was stirred magnetically overnight and then the solvent was evaporated (40 °C, 20 Torr). The resultant acid was treated at room temperature with an ethereal solution of diazomethane (20 mL). After evaporation of the solvent (40 °C, 20 Torr), the residue was purified by chromatography on silica gel (petroleum ether/ethyl acetate, 2:1) to provide the diol **5** (30.0 mg, 75%) as a colorless oil. $[\alpha]_D^{20}$ = 32.3 (*c* = 0.65, $CHCl_3$), {ref.[12] for (2*R*,3*R*)-**5**, $[\alpha]_D^{20}$ = −41.3 (*c* = 0.48, $CHCl_3$)}. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.68 (br., 1 H, OH), 3.61 (s, 3 H, CH_3), 4.42 (d, *J* = 4.2 Hz, 1 H, H2), 4.93 (d, *J* = 4.2 Hz, 1 H, H3), 5.22 (br., 1 H, OH), 7.26−7.29 (m, 5 H, aryl H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 52.8(q, CH_3), 75.2 (d, C-2), 75.4 (d, C-3), 126.7 (d), 128.6 (d), 128.7 (d, 139.0 (s9, 172.8 (s, C=O) ppm.

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