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Hydrolytic Kinetic Resolution of Epoxides Catalyzed by Chromium(III)-*endo*,*endo*-2,5-diaminonorbornane-salen [Cr(III)-DIANANE-salen] Complexes. Improved Activity, Low Catalyst Loading

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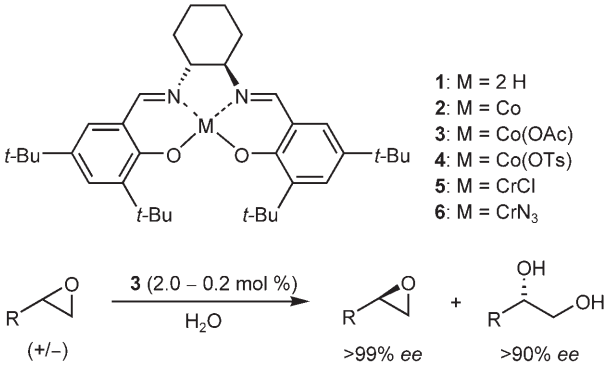
Abstract: The hydrolytic kinetic resolution (HKR) of terminal epoxides, using chiral chromium(III)-salen catalysts based on DIANANE (*endo,endo*-2,5-diaminonorbornane), was studied. A broad substrate scope was found for the chromium(III)-DIANANE catalysts, and very low loadings (down to 0.05 mol%) were needed to achieve high enantiomeric purities of both the remaining epoxides and the product diols (up to >99% *ee*). Besides monosubstituted epoxides, 2-methyl-2-*n*-pentyloxirane, which is an example for 2,2-disubstituted epoxides, could be ring-opened in an asymmetric fashion with water in the presence of an electronically tuned chromium(III)-DIANANE complex.

Keywords: asymmetric catalysis; chromium; DIANANE-salen; epoxide opening; hydrolytic kinetic resolution

Introduction

Epoxides play an important role in organic synthesis because they can be converted to a variety of highly valuable products, usually in one further step.[1] The asymmetric ring-opening (ARO) of epoxides with heteroatom nucleophiles[2] and radicals[3] is well documented. Very recently, a number of catalytic systems for the ARO of *meso*-epoxides has been developed.[4] Highly efficient methods were contributed by Jacobsen et al., using Cr(III)- and Co(III)-salen complexes based on *trans*-1,2-diaminocyclohexane. The latter catalysts show very high selectivities, broad substrate scope, they are readily available and air-stable.[4a,b,n] A particularly successful variant of the ARO is the kinetic resolution of racemic epoxides using half an equivalent of the nucleophile.[5] In 1997, the non-enzymatic hydrolytic kinetic resolution (HKR) of monosubstituted racemic epoxides was discovered by Jacobsen et al. (Scheme 1).[6] A very broad substrate spectrum, and high selectivities are the typical features of the HKR of epoxides, effected by low amounts (0.2–2.0 mol%) of Co(III)-salen acetate complexes such as **3** (Scheme 1). This method is particularly well suited for the generation of enantiomerically pure aliphatic terminal epoxides. Currently, no general method exists for the synthesis of terminal epoxides (in comparable enantiopurity) by asymmetric epoxidation of the corresponding olefins.[6b,7]



Scheme 1. Hydrolytic kinetic resolution (HKR) of epoxides according to Jacobsen et al.

While the HKR of monosubstituted epoxides is catalyzed by the Co(III) complexes **3** and **4** with broad substrate scope, the HKR of 2,2- and 2,3-disubstituted epoxides is not efficiently effected by **3** or **4**, which are easily prepared by oxidation of the Co(II) complex **2** in the presence of 2.00 equivs. of acetic acid or *p*-toluenesulfonic acid, respectively. Co(III) com-

plexes of this type are more or less inactive in the HKR of disubstituted epoxides. However, the kinetic resolution of 2,2-disubstituted epoxides could be achieved using Cr(III) complex **6** as catalyst, and $TMSN_3$ as reagent.[8] Recently, the kinetic resolution of 2,3-disubstituted and 2,2,3-trisubstituted epoxides catalyzed by **5**, and using arylamines as nucleophiles, was reported. The selectivity factors were in the range $S = 10–21$.[9] Epoxide hydrolase (EH)-catalyzed HKR reactions of disubsituted epoxides have also been reported. The main problems encountered in the enzyme-catalyzed HKR of epoxides are the limited substrate scope and varying selectivities with regard to the remaining starting material and the product.[10] We recently reported the enantioselective synthesis of a new type of salen ligand **7**, based on the DIANANE (*endo,endo*-2,5-diaminonorbornane) backbone (Figure 1).[11a] This new salen ligand **7** furnished a wider

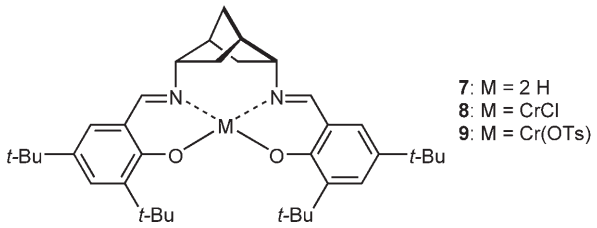


Figure 1. DIANANE-salen **7** and Cr(III) complexes **8** and **9**.

substrate scope and higher enantioselectivities than Jacobsen's salen ligand **1** in the asymmetric Nozaki–Hiyama–Kishi (NHK) reaction.[11b] Salen ligands based on DIANANE have a larger N,N-distance compared to those based on *trans*-1,2-diaminocyclohexane.[11a] Expecting that the Cr(III) complexes **8** and **9** of the salen ligand **7** will be more electrophilic than the ones derived from Jacobsen's salen ligand, we employed the Cr(III) chelates **8** and **9** as Lewis acid catalysts for the HKR reaction of epoxides (Figure 1). Herein, we report the initial results of our study.

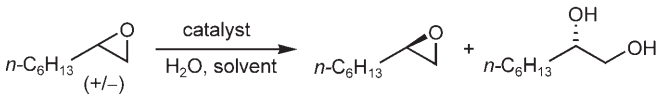
Results and Discussion

The salen ligand **7** was prepared according to our previous publication.[11a] The chromium insertion into **7** was achieved by reaction with $CrCl_2$ in THF under argon. Two equivalents of triethylamine had to be added to drive the Cr(II) complex formation to completion. Subsequent air oxidation to the Cr(III) complex, followed by work-up with aqueous NH_4Cl and NaCl (see Experimental Section) completed the preparation of **8**. In this way, the Cr(III) complex **8** was obtained in 93% yield. The Cr(III) complex **9** was prepared by treating **8** with AgOTs in acetonitrile (73%).

In order to compare the Cr(III) catalysts **8**, **9**, and **5** with regard to activity and selectivity, the HKR of racemic 1-octene oxide (*rac*-**10a**) was performed (Table 1). In the presence of 1 mol% of Cr(III) complex **8** and 0.55 equivs. of water (Table 1, entry 1), this substrate was fully resolved after 14 h at room temperature, giving enantiopure epoxide **10a** (>99% *ee*) in 49% yield and practically enantiopure diol **11a** (>99% *ee*). Changing the chloride counterion of the catalyst **8** to tosylate (**9**) furnished higher reactivity (entry 2). The HKR of *rac*-**10a** was complete within 6 h.[6c,12] For comparison, we have also used the Cr(III) complex **5** for the same reaction under identical conditions (Table 1, entries 1 and 3). Although some ring opening of racemic 1-octene oxide (*rac*-**10a**) with water occurred in the presence of the Cr(III) complex **5**, the HKR of *rac*-**10a** did not reach completion after 14 h at room temperature, nor upon extending the reaction time to 32 h (60% of remaining **10a**, 65% *ee*). This comparison supports the idea that Cr(III) complexes of the DIANANE-based ligand **7** appear to be more Lewis acidic than the corresponding Cr(III) complexes based on the salen ligand **1**.

Encouraged by these results in the HKR of 1-octene oxide, we applied the catalyst **9** to other monosubstituted epoxides (Table 2). First, the HKR

Table 1. The HKR of racemic 1-octene oxide (*rac*-**10a**), catalyzed by the Cr(III) complexes **5**, **8**, and **9**.[a]

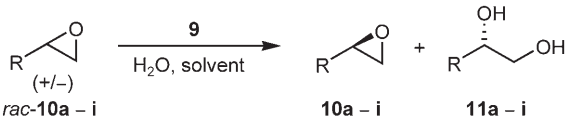


Entry	Catalyst [1 mol%]	Time [h]	Epoxide (**10a**)		Diol (**11a**)
			ee [%][b]	Yield [%][c]	*ee* [%][b]
1	**8**	14	>99	49	>99
2	**9**	6	>99	48	>99
3	**5**	14	36	73	>99

[a] The reactions were run at room temperature, using 1.00 equiv. of *rac*-**10a** and 0.55 equivs. of water in *rac*-1,2-hexanediol as solvent, approx. 0.40 equivs. of epoxide volume (see also ref.[6a]).
[b] Determined by chiral GC analysis.
[c] Yield based on *rac*-**10a** was determined by chiral GC analysis using bromobenzene as internal standard.

method was optimized separately for each epoxide with regard to catalyst loading, conversion, and selectivity by means of GC, using an internal standard. The optimized conditions were then applied in preparative scale experiments as summarized in Table 2. As shown in Table 2, the HKR of 1-octene oxide (*rac*-**10a**) proceeded well using THF as the solvent, giving the epoxide **10a** (>99% *ee*, 46% yield) and the diol **11a** (>95% *ee*, 50% yield), when 0.5 mol% of the catalyst **9** were used (entry 1). Under solvent-free conditions, as little as 0.05 mol% of the complex **9** effected the HKR of propylene oxide (*rac*-**10b**), providing propylene oxide (**10b**, 45% yield) and 1,2-propanediol (**11b**, 48% yield) in enantiopure form, demonstrating the high activity of the Cr(III) complex **9** (entry 2). The HKR of epichlorohydrin (*rac*-**10c**) was also accomplished using 0.05 mol% of the catalyst **9**, affording **10c** in 46% yield (>99% *ee*), and **11c** in 49% yield (95% *ee*, entry 3). 1-Hexene oxide (*rac*-**10d**) could be reacted with 0.55 equivs. of water in the presence of 0.20 mol% of **9** to give **10d** (>99% *ee*, 46% yield) and **11d** (>95% *ee*, 51% yield) under solvent-free conditions (entry 4). The HKR of vinylcyclohexane oxide (*rac*-**10e**) took place affording the resolved products **10e** (>99% *ee*, 43% yield) and **11e** (96% *ee*, 50% yield) in 54 h in the presence of 0.20 mol% of the catalyst **9** (entry 5). The HKR of sterically hindered *tert*-butyloxirane (*rac*-**10f**) required a higher catalyst loading (2.50 mol%), THF and *rac*-1,2-hexanediol as solvents, and yielded 46% of **10f** (>95% *ee*) and **11f** (90% *ee*) (entry 6). The HKR of *rac*-styrene oxide (*rac*-**10g**) was effected using 2.50 mol% **9** and 0.70 equivs. of H_2O (entry 7). Styrene oxide (**10g**) was obtained in enantiomerically highly enriched form (97% *ee*, 20% yield). The corresponding diol **11g** was obtained in 53% yield and 88% *ee*. The HKR of racemic methyl glycidate (*rac*-**10h**), an epoxide bearing an ester functionality, was effected using 2.50 mol% of the catalyst **9**. The enantiopure epoxide **10h** and the corresponding diol (88% *ee*) were isolated in 37% and 48% yield, respectively (entry 8). In the HKR of racemic epibromohydrin (*rac*-**10i**), racemization was observed, as reported earlier by Jacobsen et al.[6b] The hydrolytic *dynamic* kinetic resolution (HDKR) of this substrate could be effected using only 1.00 mol% of the catalyst **9**. After 22 h at room temperature, the diol **11i** was obtained in 90% yield and 94% *ee* (entry 9). The comparison of Table 2 with literature data reveals that the performance of the Cr(III)-DIANANE-salen catalyst **9** even exceeds that of the Co(III)-salen **3** in some cases.[6b] Significantly lower loadings of the Cr(III)-DIANANE catalyst **9** could be applied in the HKR of racemic propylene oxide (*rac*-**10b**; Table 2, entry 2)[13], epichlorohydrin (*rac*-**10c**; Table 2, entry 3)[13], 1-hexene oxide (*rac*-**10d**; Table 2,

Table 2. The hydrolytic kinetic resolution (HKR) of epoxides catalyzed by the Cr(III)-complex **9**.



rac-**10a – i** **10a – i** **11a – i**

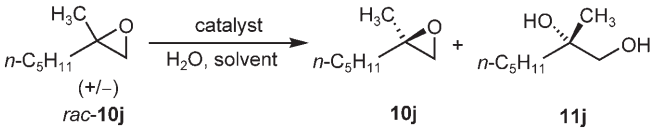
a: R = *n*-C_6H_{13}; **b:** R = CH_3; **c:** R = $ClCH_2$; **d:** R = *n*-C_4H_9;
e: R = *c*-C_6H_{11}; **f:** R = *t*-C_4H_9; **g:** R = Ph; **h:** R = CH_3O_2C; **i:** R = $BrCH_2$

Entry	Epoxide	**9** [mol%]	Water [equivs.]	Solvent	*T* [°C]	Time [h]	Epoxide (**10a–i**) *ee*[a] [%]	Epoxide (**10a–i**) Yield[b] (C)[c] [%]	Diol (**11a–i**) *ee*[a] [%]	Diol (**11a–i**) Yield[b] [%]
1	*rac*-**10a**	0.50	0.55	THF	r.t.	24	>99	46 (51)	>95	50
2	*rac*-**10b**	0.05	0.55	—	1	34	>99	45 (n.d.)	>99	48
3	*rac*-**10c**	0.05	0.55	THF	r.t.	42	>99	46 (51)	>95	49
4	*rac*-**10d**	0.20	0.55	—	r.t.	26	>99	46 (52)	>95	51
5	*rac*-**10e**	0.20	0.55	THF	r.t.	54	>99	43 (n.d.)	96	50
6	*rac*-**10f**	2.50	0.60	THF, 1,2-hexanediol	r.t.	42	>95	46 (53)	90	n.d.
7	*rac*-**10g**	2.50	0.70	THF	r.t.	34	97	20[d] (80)	88	53[d]
8	*rac*-**10h**	2.50	0.60	THF	r.t.	48	>99	37 (52)	88	48
9	*rac*-**10i**[e]	1.00	1.50	THF	r.t.	22	–	- (quant.)	94	90

[a] Determined by chiral GC analysis (see Supporting Information).
[b] Isolated yield.
[c] C: Conversion determined by GC analysis using bromobenzene as internal standard.
[d] GC yield determined by using bromobenzene as internal standard.
[e] Hydrolytic dynamic kinetic resolution (HDKR).

entry 4)[13], and in the HDKR of epibromohydrin (*rac*-**10i**; Table 2, entry 9).[14]

Since the Cr(III) complex **9** showed very high catalytic activities and selectivities in the HKR of monosubstituted teminal epoxides, we reasoned that it might as well be suitable for the HKR of 2,2-disubstituted epoxides. We chose racemic 2-methyl-2-*n*-pentyloxirane (*rac*-**10j**) as the test substrate (Scheme 2).



Scheme 2. The HKR of racemic 2-methyl-2-*n*-pentyloxirane (*rac*-**10j**).

First, the Cr(III) complex **9** was employed as catalyst for this reaction. In the presence of 2.00 mol% of **9**, 0.55 equivs. of water and THF as solvent at room temperature, no conversion of epoxide was detected after two days at room temperature. After one week, 13% *ee* for **10j** and 55% *ee* for **11j** were detected. This result points to a relatively high stability of the Cr(III) complex **9** under the reaction conditions, in the presence of water, for long periods of time. In spite of all attempts to enhance the catalytic activity of catalyst **9** by varying the solvent (e.g., 2-propanol and *rac*-1,2-hexanediol), by adding an excess of water (up to 2.0 equivs.), and by increasing the temperature (40 °C), the initial result could not be improved.

Therefore, we synthesized the sterically and electronically tuned Cr(III) complexes **13**, **14**, **16** and **17** from the salen ligands **12** and **15**[15], respectively (Figure 2). The Cr(III) complexes **13**, **14** (and also the complexes **3**, **4**, and **5**) showed initially no catalytic activity in the test reaction (almost no conversion after one week at room temperature). However, the complexes **16** and **17** were more active. Again, the Cr(III)-salen complex with a tosylate anion (**17**) proved superior to the one bearing a chloride anion (**16**). The results obtained in the HKR of *rac*-**10j** catalyzed by **17** are summarized in Table 3. Enantioselective opening of *rac*-**10j** was achieved using 2.00 mol%, of the catalyst **17**. By using 2.00 equivs. of water (rel. to *rac*-**10j**) and a 1:1 mixture of THF/*rac*-1,2-hexanediol as solvent, 50% conversion and 28% *ee* for *rac*-**10j** were detected after 46 h at room temperature (Table 3, entry 1). The enantiomeric excess of the diol product **11j** was 33% at this point of the reaction. Prolonged reaction times resulted in higher conversion, and higher *ee* of the remaining epoxide **10j** (Table 3, entries 2 and 3). However, the catalyst selectivity in this transformation ($S=2.38$) is still rather low and requires further improvement.

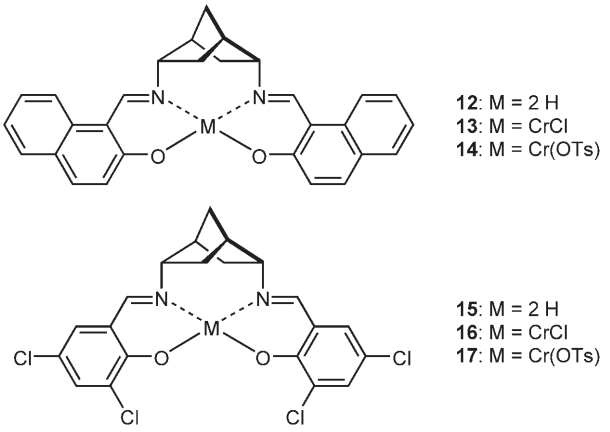


Figure 2. Sterically and electronically tuned chromium(III) complexes based on DIANANE.

Table 3. The HKR of racemic 2-methyl-2-*n*-pentyloxirane (*rac*-**10j**), catalyzed by the Cr(III)-complex **17**.[a]

Entry	Time [h]	**10j**		**11j**	
		ee [%][b]	Conversion[%][c]	*ee* [%][b]	S[d]
1	46	28	50	33	2.3
2	96	33	56	33	2.3
3	144	51	72	26	2.3

[a] The reaction was conducted using 1.00 equiv. of *rac*-**10j**, 2.00 equivs. of water, and 2 mol% of the catalyst **17** in a 1:1 mixture of THF/*rac*-1,2-hexanediol at room temperature (see Supporting Information).
[b] Determined by chiral GC.
[c] Determined by GC analysis using 1,3-dibromobenzene as internal standard.
[d] Selectivity, calculated using the equation $S=k_{rel}=\ln[(1-C)(1-ee)]/\ln[(1-C)(1+ee)]$, where *ee* and C are the enantiomeric excess and the conversion of epoxide **10j** in the reaction mixture, respectively.[16]

Conclusions

We have shown that the readily available chiral Cr(III)-DIANANE-salen complexes perform excellently in the HKR of monosubstituted epoxides, giving high yields and >99% *ee* for the remaining epoxides, and up to >99% *ee* for the product diols. Furthermore, the enantioselective opening of racemic 2-methyl-2-*n*-pentyloxirane (*rac*-**10j**), an example for 2,2-disubstituted epoxides, could also be performed with water in a non-enzymatic manner for the first time. For the latter purpose, the electronically tuned Cr(III)-salen complex **17** proved best. We expect that both the catalyst activity and selectivity can be enhanced further by careful electronic and structural tuning. Work in this direction is underway in our laboratory.

Experimental Section

General Remarks

The epoxides *rac*-**10h**[17] and *rac*-**10j**[18] were prepared according to literature methods. All other epoxides were purchased from Fluka or Aldrich and distilled prior to use. Solvents were purified using standard techniques. The salen ligands **7**,[11] **12**,[15] and **15**[13] were synthesized according to our published procedures.[15] The Co(II)-salen complex **2** and the Cr(III)-salen complex **5** were purchased from Aldrich. Co(III)-salen acetate[6a] (**3**) and Co(III)-salen *p*-toluenesulfonate[4a] (**4**) were prepared by oxidation of Co(II)-salen (**2**) according to the literature. $CrCl_2$ (99.99%) was purchased from Aldrich. NMR spectra were recorded on a Bruker AC 300 instrument. The IR measurements were performed on a Perkin–Elmer Paragon 1000 spectrometer. UV-Vis spectra were recorded on a Beckman Coulter DU 800 spectrometer. ESI mass spectra were recorded on a Finnigan MAT 900. The optical rotations of the epoxides **10a–h** and of the 1,2-diols **11a–i** were measured on a Perkin–Elmer polarimeter 343 plus. The absolute configurations of the products **10a–h** and **11a–i** were determined by comparison of their optical rotations with literature data. Capillary GC data were obtained using a Hewlett–Packard HP 6890 GC system using chiral columns (see Supporting Information).

(1*S*,2*S*,4*S*,5*S*)-*N*,*N*′-Bis-(3,5-di-*tert*-butylsalicylidene)-2,5-diaminobicyclo[2.2.1]heptanechromium(III) Chloride [8]

The salen ligand **7** (838 mg, 1.50 mmol) and $CrCl_2$ (203 mg, 1.65 mmol) were dissolved in 40 mL of absolute THF under argon. To the resulting yellow solution was added triethylamine (304 mg, 3.00 mmol), and the solution turned deep brown instantaneously. The mixture was strirred overnight at room temperature under argon. The mixture was then stirred open to air for an additional 6 h. The mixture was then diluted with 200 mL of diethyl ether, and successively washed with aqueous NH_4Cl (3×100 mL) and aqueous saturated NaCl (4×100 mL).The organic phase was dried over Na_2SO_4, and the solvent was evaporated under reduced pressure. After drying under vacuum overnight, the chromium complex **8** was obtained as a deep-brown solid; yield: 904 mg (1.40 mmol, 93%); mp >250 °C; FT-IR (film): $\tilde{\nu}$= 2949, 1607, 1414, 1359, 1310, 1255, 1200, 1186, 1171, 1029, 831, 782 cm^{-1}; UV-Vis (CH_2Cl_2): λ_{max} (abs.)=250 (0.91), 407 nm (0.16); HR-EI-MS (70 eV): *m/z*=643.313, calcd. for $C_{37}H_{52}Cl^{52}CrN_2O_2$: 643.312; ESI-MS ($CH_2Cl_2$/MeOH): *m/z* (%)=642.4 (13, $[M(^{54}Cr)-Cl+MeOH]^+$), 641 (43, $[M(^{53}Cr)-Cl+MeOH]^+$), 640.4 (82, $[M(^{52}Cr)-Cl+MeOH]^+$), 609.4 (56, $[M(^{53}Cr)-Cl]^+$), 608.4 (100, $[M(^{52}Cr)-Cl]^+$).

(1*S*,2*S*,4*S*,5*S*)-*N*,*N*′-Bis-(3,5-di-*tert*-butylsalicylidene)-2,5-diaminobicyclo[2.2.1]heptanechromium(III) *p*-Toluenesulfonate [9]

To a solution of silver *p*-toluenesulfonate (389 mg, 1.40 mmol) in acetonitrile (20 mL) under argon was slowly added a solution of the chromium(III) complex **8** (840 mg, 1.30 mmol) in acetonitrile (200 mL) at room temperature. The reaction mixture was stirred overnight. The reaction mixture was then filtered over celite, washed with acetonitrile (2×50 mL), and the solvent was removed by rotary evaporation. The residue was dissolved in *tert*-butyl methyl ether (TBME, 250 mL) and quickly extracted two times with water (2×50 mL). After drying of the organic phase over Na_2SO_4, evaporation of the solvent under reduced pressure, and drying of the solid under vacuum (2×10^{-2} mbar) overnight, the chromium(III) complex **9** was obtained as a black-green powder; yield: 745 mg (0.96 mmol, 73%); FT-IR (film): $\tilde{\nu}$=2950, 1593, 1531, 1475, 1413, 1385, 1359, 1307, 1254, 1200, 1185, 1171, 1118, 1058, 1033, 837, 782, 732, 693 cm^{-1}; UV-Vis (CH_2Cl_2): λ_{max} (abs.)=250 (1.00), 407 nm (0.241); EI-MS (70 eV): *m/z* (%)=611 (8), 610 (62, $[M(^{54}Cr)-OTs]^+$) 608 (100, $[M(^{52}Cr)-OTs]^+$), 521 (4), 297 (18), 290 (28), 289 (82).

(1*S*,2*S*,4*S*,5*S*)-*N*,*N*′-Bis-(2-hydroxy-1-naphthylmethylene)-2,5-diaminobicyclo[2.2.1]heptanechromium(III) Chloride [13]

The chromium(III) complex **13** was prepared by chromium insertion into the salen ligand **12** under conditions analogous to those for the synthesis of the chromium complex **8** (see above). Employing the ligand **12** (130 mg, 0.30 mmol), $CrCl_2$ (41 mg, 0.33 mmol), and triethylamine (74 mg, 0.60 mmol) in 30 mL of absolute THF, the complex **13** was obtained as a brown solid; yield: 153 mg (0.29 mmol, 97%); FT-IR (film): $\tilde{\nu}$=2954, 1766, 1715, 1614, 1597, 1538, 1506, 1456, 1422, 1361, 1341, 1252, 1191, 1031, 824, 743, 649 cm^{-1}; UV-Vis (CH_2Cl_2): λ_{max} (abs.)=250 (0.78), 309 (0.30), 403 nm (0.15); HR-ESI-MS (CH_2Cl_2/MeOH): *m/z*=516.150, calcd. for $C_{29}H_{24}{}^{52}CrN_2O_2$ ($[M(MeOH)-Cl]^+$): 516.151; ESI-MS (CH_2Cl_2/MeOH): *m/z* (%)=518.2 (16, $[M(^{54}Cr)-Cl+MeOH]^+$), 517.2 (43, $[M(^{53}Cr)-Cl+MeOH]^+$), 516.2 (100, $[M(^{52}Cr)-Cl+MeOH]^+$), 486.2 (4.5, $[M(^{54}Cr)-Cl]^+$), 485 (21, $[M(^{53}Cr)-Cl]^+$), 484.2 (41, $[M(^{52}Cr)-Cl]^+$), 482.2 (22).

(1*S*,2*S*,4*S*,5*S*)-*N*,*N*′-Bis-(2-hydroxy-1-naphthylmethylene)-2,5-diaminobicyclo[2.2.1]heptanechromium(III) *p*-Toluenesulfonate [14]

The anion exchange was conducted under conditions analogous to those for the synthesis of the chromium complex **9** (see above). Employing the chromium(III) complex **13** (96 mg, 0.19 mmol) and AgOTs (57 mg, 0.20 mmol) in a mixture of 25 mL absolute THF and 75 mL acetonitrile gave the complex **14** as a brown solid; yield: 100 mg (0.15 mmol, 83%); FT-IR (film): $\tilde{\nu}$=2951, 1716, 1715, 1614, 1598, 1538, 1361, 1341, 1257, 1164, 1031, 827, 749 cm^{-1}; UV-Vis (CH_2Cl_2): λ_{max} (abs.)=250 (2.17), 308 (0.80), 405 nm (0.39); ESI-MS (CH_2Cl_2/MeOH): *m/z* (%)=518.2 (12, $[M(^{54}Cr)-OTs+MeOH]^+$), 517.1 (50, $[M(^{53}Cr)-OTs+MeOH]^+$), 516.1 (100, $[M(^{52}Cr)-OTs+MeOH]^+$), 486.1 (8, $[M(^{54}Cr)-OTs]^+$), 485.1 (24, $[M(^{53}Cr)-OTs]^+$), 484.1 (56, $[M(^{52}Cr)-OTs]^+$).

(1*S*,2*S*,4*S*,5*S*)-*N*,*N*′-Bis-(3,5-dichlorosalicylidene)-2,5-diaminobicyclo[2.2.1]heptanechromium(III) Chloride [16]

The chromium(III) complex **16** was prepared by chromium insertion into the salen ligand **15** under conditions analogous

to those for the synthesis of the chromium complex **8** (see above). Employing the ligand **15** (236 mg, 0.50 mmol), $CrCl_2$ (68 mg, 0.55 mmol), and triethylamine (101 mg, 1.00 mmol) in 40 mL of absolute THF, the chromium(III) complex **16** was obtained as a brown solid; yield: 243 mg (0.44 mmol, 87%); FT-IR (film): $\tilde{\nu}$ = 2959, 1717, 1606, 1444, 1308, 1259, 1175, 1027, 866, 799, 766 cm^{-1}; UV-Vis (CH_2Cl_2): λ_{max} (abs.) = 250 (0.88), 402 nm (0.20); HR-ESI-MS (CH_2Cl_2/MeOH): m/z = 551.964, calcd. for $C_{22}H_{20}Cl_4{}^{52}CrN_2O_3$ ([M-(MeOH)−Cl]$^+$): 551.963; ESI-MS (CH_2Cl_2-MeOH): *m/z* (%) = 559 (2), 558 (11), 557 (21), 556 (57), 554 (100, [M-(^{54}Cr)−Cl+MeOH]$^+$), 553 (31, [M(^{53}Cr)−Cl+MeOH]$^+$), 552 (74, [M(^{52}Cr)−Cl+MeOH]$^+$), 524 (7), 522 (16, [M-(^{54}Cr)−Cl]$^+$), 520 (11, [M(^{52}Cr)−Cl]$^+$).

(1*S*,2*S*,4*S*,5*S*)-*N*,*N*′-Bis-(3,5-dichlorosalicylidene)-2,5-diaminobicyclo[2.2.1]heptanechromium(III) *p*-Toluenesulfonate [17]

The anion exchange was conducted under conditions analogous to those for the synthesis of the chromium complex **9** (see above). Employing the chromium(III) complex **16** (115 mg, 0.20 mmol) and AgOTs (62 mg, 0.22 mmol) in a mixture of 15 mL absolute THF and 50 mL acetonitrile gave the complex **17** as a brown solid; yield: 115 mg (0.17 mmol, 83%); FT-IR (film): $\tilde{\nu}$ = 2958, 1719, 1605, 1443, 1308, 1259, 1173, 1025, 865, 798, 766, 732; UV-Vis (CH_2Cl_2): λ_{max} (abs.) = 250 (1.86), 398 nm (0.37); ESI-MS (CH_2Cl_2/MeOH): *m/z* (%) = 559 (6), 558 (14), 557 (11), 556 (46), 554 (100, [M-(^{54}Cr)−OTs+MeOH]$^+$), 553 (23, [M(^{53}Cr)−OTs+MeOH]$^+$), 552 (81, [M(^{52}Cr)−OTs+MeOH]$^+$), 522 (6, [M-(^{54}Cr)−OTs]$^+$), 520 (3, [M(^{52}Cr)−OTs]$^+$).

Representative Procedure for the HKR of Terminal Epoxides (Table 2)

To the mixture of the racemic epoxide (1.00 eq) and the catalyst **9** (0.05–2.50 mol%) (in a solvent, if necessary) was added water (0.55 equivs.). Approx. 50 μL samples were taken periodically, diluted with 200 μL of ethyl acetate, and filtered through a plug of neutral alumina. The latter was flushed with ethyl acetate or diethyl ether. The enantiomeric excesses of the starting epoxide and the product diol were followed by means of chiral GC. Upon detection of >99% *ee* for the epoxide, the reaction was stopped. The epoxide (**10a–h**) and the diol (**11a–i**) were isolated by fractionating (vacuum) distillation (see Supporting Information).

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