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Macroporous chiral ruthenium porphyrin polymers: a new solid-phase material used as a device for catalytic asymmetric carbene transfer

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Abstract—A chiral ruthenium porphyrin complex, functionalized with four vinyl groups, has been polymerized with styrene, divinylbenzene (or ethylene glycol dimethacrylate) to obtain supported ruthenium complexes. The asymmetric addition of ethyl diazoacetate (or diazoacetonitrile) to styrene derivatives was carried out by using these polymers as catalysts. The reaction proceeded under mild conditions and gave *trans*-cyclopropanes with good enantiomeric excess (up to 90%).

1. Introduction

The design of new heterogeneous catalysts to induce enantiocontrol in carbene transfer reactions is presently under extensive investigation due to the inherent advantages of heterogeneous catalysis in the industrial preparation of fine chemicals.[1–3] In an ideal case, the supported catalysts can be recovered from reaction mixtures by simple filtration, can be recycled and can help selectivity. Chiral porphyrins are well-known ligands with numerous variations of substituents and their ruthenium complexes have been used in a large number of homogeneous asymmetric reactions, in particular cyclopropanations.[4,5] Thus, the development of efficient methods to immobilize chiral metalloporphyrins will open a general way to the preparation of heterogeneous catalysts for enantioselective reactions. However, there are few strategies available to obtain chiral heterogeneous metalloporphyrin catalysts.[6–8] We have previously reported the use of optically active electropolymers bearing chiral metallospirobifluorenylporphyrins for asymmetric heterogeneous catalysis.[8] Herein, we report the preparation of macroporous optically active polymers bearing chiral metalloporphyrins and asymmetric heterogeneous carbene transfer reactions catalyzed by these polymers. It is expected that these polymers containing large pores are well suited for use in asymmetric reactions catalyzed by rigid and large chiral metalloporphyrin species. As an application, an asymmetric cyanocarbene transfer to alkenes using diazoacetonitrile as a reactive reagent is also described.

2. Results

2.1. Porphyrin and metalloporphyrin syntheses

The starting point of the work described herein was the introduction of a vinyl group onto an optically active ruthenium porphyrin with the aim of preparing polymers using the chiral metalloporphyrin as a co-monomer. We choose a *C*2-symmetric group, which contains two norbornane groups fused to the central benzene ring, previously reported by Halterman and Jan.[9] It was therefore necessary to first prepare the chiral *p*-bromoaldehyde **2**[10] and then introduce the vinyl group using the Stille coupling reaction. Thus, addition of tributylvinyltin in toluene solution to the optically active aldehyde in the presence of $Pd(Ph_3P)_2Cl_2$[11,12] gave the expected chiral vinylaldehyde **3** in 90% yield. The desired chiral metalloporphyrins were obtained using the Lindsey procedure under mild conditions[13] and then metal insertion. The ruthenium complexes were

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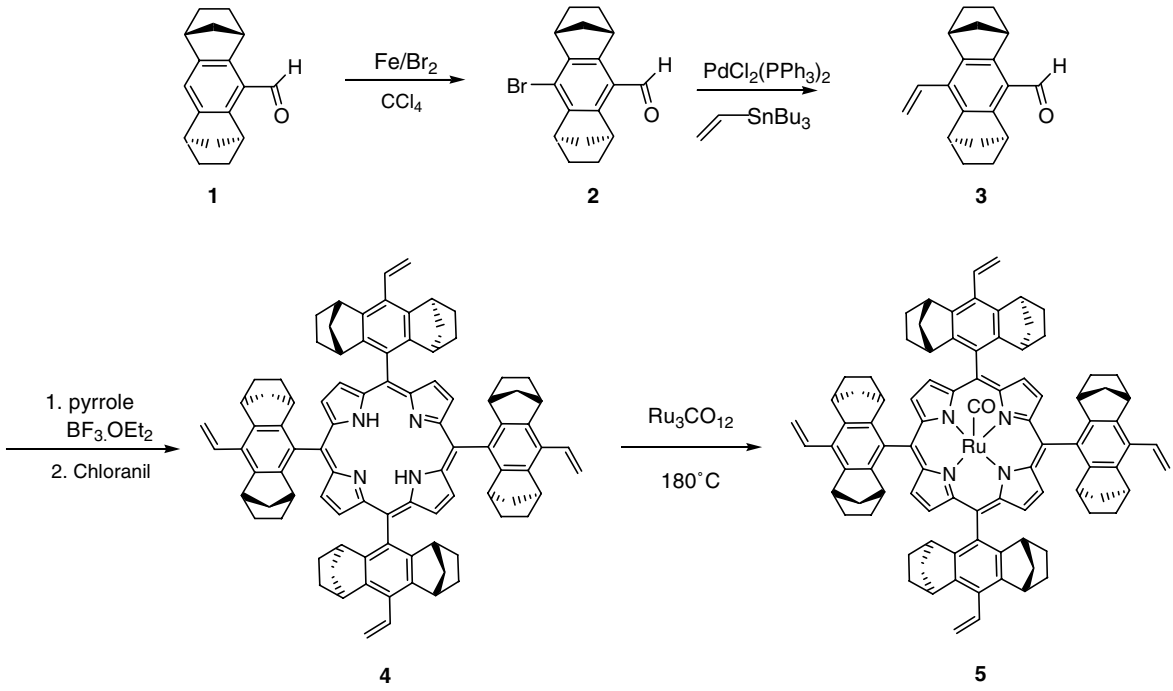
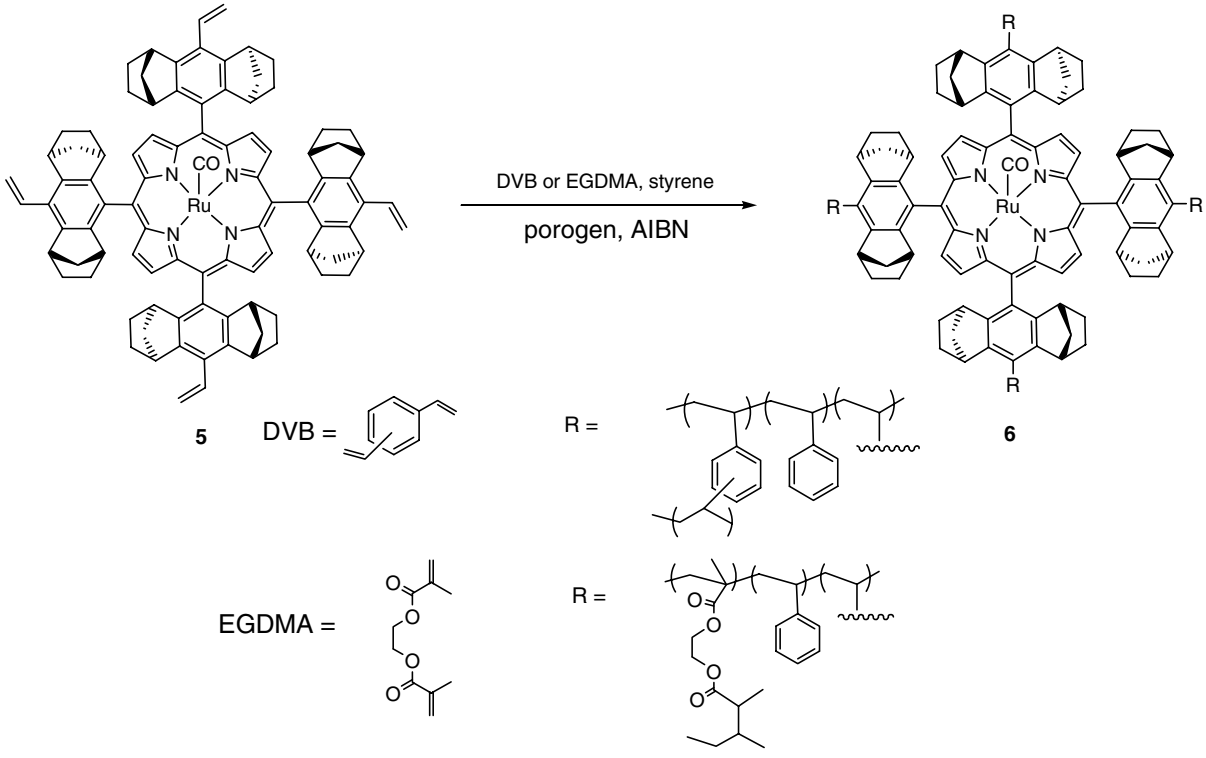


Scheme 1.

prepared by treatment of the porphyrins with Ru_3CO_{12} in degassed *o*-dichlorobenzene at 180 °C for 2 h to give the expected complex **5**. The synthetic pathway is represented in Scheme 1. This route is particularly interesting because it can open many different possibilities to obtain various optically active polymers bearing chiral metalloporphyrins.

2.2. Polymerization

First, the chiral ruthenium vinylporphyrin **5** was used in different block copolymerizations with divinyl benzene (DVB) using a protocol previously described for the preparation of monolithic resins (Scheme 2).[14–16] Three different chiral ruthenium polymers **P1-(RuCO)**,



Scheme 2.

P2-(RuCO) and **P3-(RuCO)** were prepared from **5** by changing the degree of cross-linking and the porogen (toluene or chloroform/dodecan), using AIBN as a radical initiator. The different ratios are summarized in Table 1. The orange-red polymers were ground and the near quantitative incorporation of the ruthenium porphyrin in the polymer was evidenced by the fact that the chloroform washing solutions were colourless. These polymers were characterized by IR spectroscopy (Fig. 1) and scanning electron microscopy (Fig. 2). All the ruthenium polymers showed the FT-IR band in KBr corresponding to the CO ligand at 1945 cm^{-1}, which is similar to the value observed for the monomer **5**. The ruthenium contents were determined by electronic microanalysis. The more polar monomer ethyleneglycol dimethacrylate (EGDMA) was also chosen because it forms highly cross-linked polymers, which can be used as supports for metal catalysts.[17] It must be emphasized that such a system, supporting non-chiral ruthenium porphyrins, has been recently reported by Nestler and Severin for the epoxidation of olefins.[18] Thus copolymerization of the ruthenium monomer **5** with ethylene glycol dimethacrylate in the presence of toluene as the porogen, which is necessary for creating the pore structure, resulted in the orange, insoluble polymer **P4-(RuCO)**.

Table 1. Polymerization conditions used for preparation of Ru catalysts

Polymer	Monomer (w/w)	DVB/ styrene	Porogen	AIBN (%)
P1-(RuCO)	**5** (10%)	1.2	Toluene	3
P2-(RuCO)	**5** (10%)	5.0	Toluene	3
P3-(RuCO)	**5** (10%)	1.2	$CHCl_3$/dodecane	3
P4-(RuCO)	**5** (10%)	1.2[a]	Toluene	3

In an oven dried thermolysis tube, metalloporphyrin **5** was dissolved in the porogen (toluene 1.5 mmol). Then, styrene and divinylbenzene were added to the solution. The polymerization reaction was initiated by AIBN (60 μmol). The mixture was heated at 65 °C for 16 h without stirring.

[a] EGDMA/styrene.

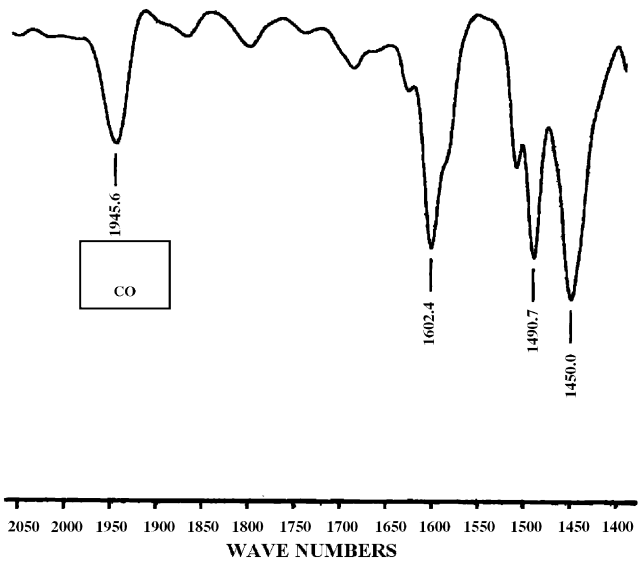


Figure 1. IR spectrum of the chiral ruthenium polymer **P1-(RuCO)** in KBr.

2.3. Catalytic cyclopropanation reactions

The bench-mark reaction between styrene and ethyl diazoacetate to give cyclopropane esters was first tested (Table 2). In all cases, the polymer catalyst was filtered off and an additional quantity of substrates was added to the solution to confirm the heterogeneous character of the catalyst. We chose these two reagents, extensively used both in homogeneous and heterogeneous processes, as suitable substrates to show differences in terms of enantioselectivity, diastereoselectivity and reactivity.[1] Using **P1-(RuCO)** as the heterogeneous catalyst, the cyclopropane was formed with good yield (77%), high diastereoselectivity (*trans*/*cis*: 92/8) and good enantioselectivity for the *trans*-isomer (82%) (Table 2, entry 1). We also investigated the cyclopropanation of *para*-substituted styrenes. As shown in Table 2, *para*-substitution (*p*-Y-styrene, Y = MeO and Br) has a weak effect upon the enantioselectivity of styrene cyclopropanation, the best ee (90%) being obtained with the bromo derivative. A similar effect was noted in the asymmetric cyclopropanation with ethyl diazoacetate using a different chiral ruthenium catalyst.[19]

It can also be seen from Table 2 that the use of $CHCl_3$/dodecane as a porogenic mixture: **P3-(RuCO)** seems to be detrimental to the enantiomeric excess, the diastereoselectivity and the yield (entry 3). This may be due to the reduced accessibility of the sites, as also evidenced by the results obtained with **P2-(RuCO)**, a polymer prepared with a high DVD/styrene ratio (entry 2). To shed some light on this area, we also carried out a comparative study with a different polymer **P4-(RuCO)**, using a different cross-linker, ethylene glycol dimethacrylate.

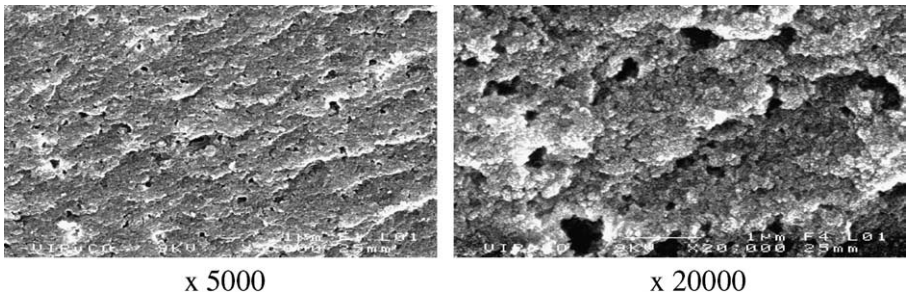
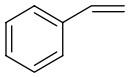
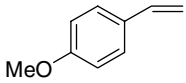
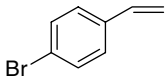


Figure 2. Scanning electron microscopy of **P1-(RuCO)**.

Table 2. Asymmetric cyclopropanation of styrene by ethyl diazoacetate catalyzed by Ru polymers[a]

	Substrates	Catalysts	Yield[b] (%)	*trans*/*cis* (%)	ee_{trans}[c] (1*S*,2*S*)	ee_{cis}[c] (1*R*,2*S*)	Turnover
1		**P1-(RuCO)**	77	92/8	82	8	1075
2		**P2-(RuCO)**	66	85/15	76	8	905
3		**P3-(RuCO)**	60	82/18	71	11	820
4		**P4-(RuCO)**	62	89/11	77	8	850
5		**P1-(RuCO)**	88	92/8	80	14	1205
6	MeO	**P4-(RuCO)**	81	91/9	79	16	1110
7		**P1-(RuCO)**	75	93/7	90	10	1030
8	Br	**P4-(RuCO)**	74	93/7	83	17	1010

[a] Reactions were performed in CH_2Cl_2 at room temperature for 24 h with a catalyst/diazo/substrate molar ratio of 0.5/600/500.
[b] Isolated yields based on substrates.
[c] Determined by chiral GC (see Section 5).

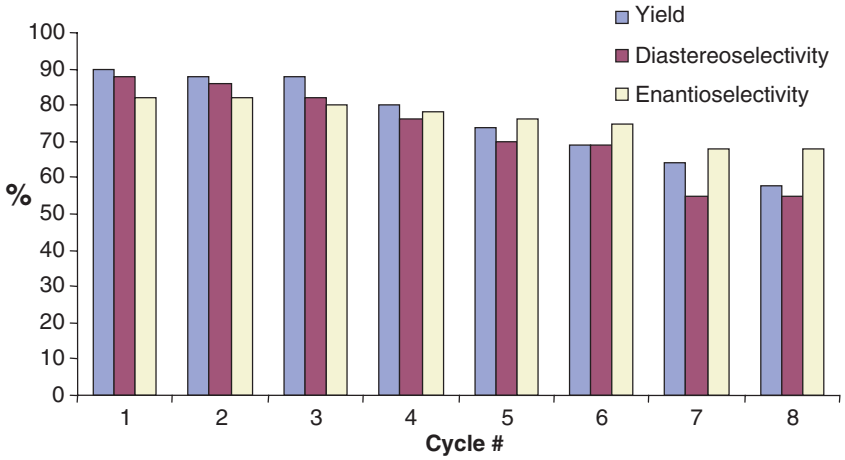


Figure 3. Recovery–reuse outcome from the cyclopropanation of styrene with ethyl diazoacetate using **P1-(RuCO)** as catalyst.

As can be seen in Table 2 (entries 4, 6 and 8), the results are only slightly lower than those obtained with **P1-(RuCO)**.

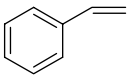
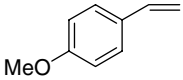
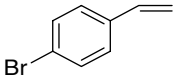
The recovery and recyclability of **P1-(RuCO)** polymer have been also examined. The polymer was tested for enantioselectivity and reactivity in the cyclopropanation of styrene with ethyl diazoacetate leading three recycling steps with a weak progressive decrease of enantioselectivity (from 82% to 78%) and a decrease of yield (from 90% to 71%) (Fig. 3). However, the yield markedly decreased to 53% after the eighth run whereas the enantioselectivity was maintained at ~68%.

To evaluate the reactivity of the diazoacetonitrile, its ruthenium-catalyzed decomposition was first examined in the presence of styrene in dichloromethane at room temperature under homogeneous conditions (Table 3). We used **7**[20] (Scheme 3), a chiral ruthenium catalyst, whose structure is directly related to that found in the polymers. This ruthenium porphyrin catalyst is particularly interesting since the enantiomeric excesses are quite high (90%) when the catalytic reactions are undertaken under homogeneous conditions with ethyl diazoacetate[20] and diisopropyl diazomethylphosphonate[21] as reagents. The cyclopropane was formed with 63% yield, 67/33 *trans*/*cis* ratio and 66% enantioselectivity for the *trans*-isomer (entry 1). We also investigated the cyclopropanation of *para*-substituted styrenes (Table 3). As shown in Table 3, *para*-substitution (*p*-Y-styrene, Y = MeO, Br and H) does not have a significant effect upon the enantioselectivity of styrene cyclopropanation and the best ee (72%) for the *trans*-isomer was obtained with the *para*-Br derivative. The different chiral ruthenium polymers were also used with diazoacetonitrile and the representative results are summarized in Table 3. With the inserted ruthenium porphyrins, porous solids exhibited moderate activity and correct enantioselectivity in heterogeneous cyclopropanation of styrene with diazoacetonitrile. The best ee (71%, entry 9) was obtained with **P1-(RuCO)** and is similar to those obtained with the homogeneous chiral ruthenium porphyrins (Table 3, entry 8).

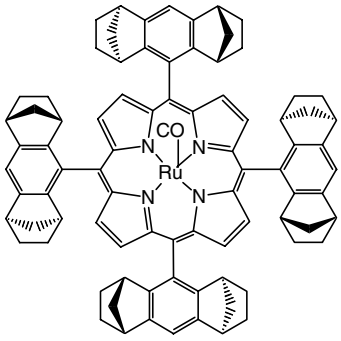
3. Discussion

Optically active cyclopropane-containing compounds are of great interest, particularly to synthetic organic chemists and to bioorganic chemists.[22] Thus optically active ruthenium porphyrin complexes have been the

Table 3. Asymmetric cyclopropanation of styrene by diazonitrile catalyzed by Ru polymers[a]

	Substrates	Catalysts	Yield[b] (%)	*trans*/*cis* (%)	ee_{trans}[c] (1*S*,2*S*)	ee_{cis}[c] (1*R*,2*S*)
1		**7**[d]	63	67/33	66	27
2		**P1-(RuCO)**	53	76/24	70	20
3		**P2-(RuCO)**	46	64/36	52	20
4		**P3-(RuCO)**	35	62/38	41	12
5		**P4-(RuCO)**	61	76/24	69	23
6		**7**	44	68/32	69	7
7		**P1-(RuCO)**	55	70/30	68	16
8		**7**	47	70/30	72	29
9		**P1-(RuCO)**	40	75/25	71	29

[a] Reactions were performed in CH_2Cl_2 at room temperature for 24 h with a catalyst/diazo/substrate molar ratio of 0.5/100/500.
[b] Isolated yields based on diazoacetonitrile.
[c] Determined by chiral GC (see Section 5).
[d] **7**: chiral ruthenium porphyrin prepared following Ref. 21 (Scheme 3).



7

Scheme 3.

focus of intense studies by us[4,21,23] and others[5,24–26] as catalysts for asymmetric cyclopropanation. In contrast, immobilizing chiral metalloporphyrins as insoluble materials is still rare.[6–8] We previously reported the use of optically active electropolymers bearing chiral metallospirobifluorenylporphyrins for asymmetric heterogeneous catalysis.[8] However, despite their good stability and recyclability, these polymeric catalysts suffer from the drawback of moderate enantioselectivity compared to the homogeneous counterpart. We describe herein the development of novel chiral ruthenium porphyrin polymers for asymmetric heterogeneous carbene transfer to olefins showing much higher enantioselectivity in the cyclopropanation reaction. The best ee was obtained with the less cross-linked polymer and it should emphasized that the results obtained with this polymer **P1-(RuCO)** are similar to those obtained with the homogeneous chiral ruthenium porphyrins.[20] However, with all series, the rigidity of the chiral macrocycle seems to be maintained. Thus, the polymer morphology, which is controlled by the degree of cross-linking, the nature of the porogen and the cross-linker determines the performance of the polymer catalyst. This situation was previously observed with the immobilization of pyridine-bis(oxazoline) chiral ligand[2] and bis(oxazoline)-copper[27] complexes but much larger influence of the polymeric matrix on the stereochemical course of the reaction was observed, due to a weak rigidity of the catalytic sites, grafted on the support.

The recovery and recyclability of the polymers were examined. Although, no leaching of the metalloporphyrins was observed, a significant decrease of reactivity is noted whereas the enantioselectivity is maintained. It is difficult to suggest an explanation at this stage but it should be noted that the CO ligand is replaced by the carbene ligand in the first catalytic cycle. The IR spectrum shows the disappearance of the vibration corresponding to the CO ligand at 1945 cm^{-1}. The coordination of by-products may be responsible of the deactivation and, if the situation is reversible, recovery of theses polymers under CO atmosphere may improve the catalytic recyclability.

The different chiral ruthenium polymers were also used for the asymmetric cyclopropanation with diazoacetonitrile. Diazoacetonitrile can be a potent explosive[28] and does not appear to have many applications in the field of organic synthesis[29–31] and, as far we are aware, only a single example of enantioselective intermolecular cyclopropanation is known.[32] This situation may be due to the small size of the cyano substituent, which disfavours high diastereoselectivity for the *trans*-isomer. A few publications also exist on the racemic synthesis of cyanocyclopropane by means of reaction of diazoacetonitrile with alkenes[29–31] or cyanoalkenes with tosylhydrazones.[33] Thus it was quite exciting to explore the catalytic properties of these polymers towards diazoacetonitrile addition to olefinic bonds. The results reported herein demonstrate that the asymmetric cyclopropanation using diazoacetonitrile catalyzed by chiral metalloporphyrins, both under homogeneous and heterogeneous conditions, occurs in a good stereoselective manner, offering for the first time, a general access to optically active *trans*-cyanocyclopropanes, with possible biological applications after subsequent reduction with $LiAlH_4$.[34] Furthermore, the crude material can be readily enriched by recrystallization in a mixture of dichloromethane/pentane to give *trans*-cyanocyclopropanes in 50% isolated yield and 99% ee.

These cyclopropanes can be used as direct precursors of several melatonin agonists.[35]

4. Conclusion

In summary, the heterogeneous asymmetric cyclopropanation of styrene catalyzed by new chiral ruthenium porphyrin polymers occurs in a highly stereoselective manner. Additionally, application to the synthesis of cyanocyclopropane unknown in optically active form was successful. Investigation of the catalytic properties of these chiral ruthenium polymers for the epoxidation of olefins is currently underway in our laboratory and will be reported in due course.

5. Experimental

5.1. General experiments

All reactions were performed under argon and were magnetically stirred. Solvents were distilled from appropriate drying agent prior to use: Et_2O and THF from sodium and benzophenone, toluene from sodium, CH_2Cl_2 from CaH_2, $CHCl_3$ from P_2O_5 and all other solvents were HPLC grade. Commercially available reagents were used without further purification unless otherwise stated. All reactions were monitored by TLC with Merck precoated aluminium foil sheets (Silica gel 60 with fluorescent indicator UV_{254}). Compounds were visualized with UV light at 254 and 365 nm. Column chromatographies were carried out using silica gel from Merck (0.063–0.200 mm). ^1H NMR and ^{13}C NMR in $CDCl_3$ were recorded using Bruker (Advance 500dpx and 300dpx spectrometers) at 500 and 75 MHz, respectively. High-resolution mass spectra were recorded on a ZabSpec TOF Micromass spectrometer in ESI positif mode at the CRMPO. Liquid UV–visible spectra were recorded on a UVIKON XL from Biotech. All catalytic reactions were controlled on a Varian CP-3380 Gas Chromatograph equipped with a CP-Chirasil-Dex Column.

5.2. Preparation of ruthenium porphyrin monomer

5.2.1. (+)-10-Bromo-1,2,3,4,5,6,7,8-octahydro-1,4:5,8-dimethanoanthracene-9-carboxaldehyde (+)-2.[10] To iron powder (4.2 mmol) was added Br_2 (12.6 mmol) to form the corresponding Lewis acid, after 30 min, pure aldehyde (+)**1** (4.2 mmol) in CCl_4 (20 mL) was added. After 24 h at room temperature, the mixture was extracted with 10% aqueous NaOH and water. Then, the combined aqueous portions were extracted with CH_2Cl_2 three times. The combined organic portions were dried and evaporated to give a brown solid. The crude product was purified by column chromatography (pentane/CH_2Cl_2 9/1) to give the pure bromoaldehyde (+)-**2** (80%). $[\alpha]_D^{20} = +44$ (*c* 0.48, CH_2Cl_2). ^1H NMR δ 10.44 (s, 1H); 4.26 (m, 2H); 3.61 (m, 2H); 2.06–1.89 (m, 4H); 1.80 (m, 2H); 1.57 (m, 2H); 1.25–1.10 (m, 4H). ^{13}C NMR δ 190.6, 149.0, 146.2, 128.6, 126.8, 48.5, 43.6, 42.3, 26.3, 25.7. Mass EI (*m*/*z*): calculated for $C_{17}H_{17}OBr$ ($M^{+\cdot}$): 316.0462, found: 316.0460.

5.2.2. (−)-10-Vinyl-1,2,3,4,5,6,7,8-octahydro-1,4:5,8-dimethanoanthracene-9-carboxaldehyde (−)-3. To solution of pure bromoaldehyde (+)-**2** (1.58 mmol) in dry toluene (15 mL) was added a solution of tributylvinyltin (2 mmol) followed by $Pd(Ph_3P)_2Cl_2$ (0.079 mmol) at room temperature. The resulting mixture was heated at 60 °C for 12 h. The reaction was monitored by TLC and when the starting material had completely reacted, the mixture was allowed to cool to room temperature. The solvent was removed and the crude product was purified by column chromatography (pentane/CH_2Cl_2 9/1). A white waxy solid was thus obtained in 90% yield. $[\alpha]_D^{20} = -44$ (*c* 0.50, CH_2Cl_2). ^1H NMR δ 10.46 (s, 1H); 6.92 (dd, 1H); 5.64 (m, 2H); 4.20 (m, 2H); 3.65 (m, 2H); 2.00 (m, 4H); 1.75 (m, 2H); 1.57 (m, 2H); 1.20 (m, 4H). ^{13}C NMR δ 192.2, 148.4, 144.5, 133.7, 130.4, 122.1, 120.4, 49.3, 41.7, 41.5, 26.9, 26.6. Mass EI (*m*/*z*): calculated for $C_{19}H_{20}O$ ($M^{+\cdot}$): 264.1514, found: 264.1507.

5.2.3. 5,10,15,20-Tetrakis-[(1*S*,4*R*,5*R*,8*S*)-10-vinyl-1,2,3,4,5,6,7,8-octahydro-1,4:5,8-dimethanoanthracene-9-yl]-porphyrin 4. In a round bottom flask, a solution of (−)-**3** (0.75 mmol) in $CHCl_3$ (60 mL) was mixed with freshly distilled pyrrole (0.75 mmol). Argon was bubbled through the solution for 5 min and $BF_3{\cdot}Et_2O$ (0.22 mmol) was then added. The reaction mixture, protected from light, was stirred for 16 h at room temperature, then *p*-chloranil (0.56 mmol) was added. The solution was heated under reflux for 1 h and then allowed to cool to room temperature. The solution was concentrated and purified by column chromatography (pentane/CH_2Cl_2 8/2) to give porphyrin **4** (26%). ^1H NMR δ 8.80 (s, 8H); 7.26 (dd, 4H); 5.77 (m, 8H); 3.94 (m, 8H); 2.83 (m, 8H); 2.10–1.85 (m, 16H); 1.55–1.20 (m, 32H). UV–vis (CH_2Cl_2): $\lambda_{max/nm}$ ($\log\varepsilon$): 425 (5.75); 517 (4.41); 554 (4.22); 592 (4.14); 649 (4.19). Mass (ESI, CH_2Cl_2/MeOH 9/1) (*m*/*z*): calculated for $C_{92}H_{87}N_4[M+H]^+$: 1247.6930, found:1247.6921.

5.2.4. Carbonyl[5,10,15,20-tetrakis-[(1*S*,4*R*,5*R*,8*S*)-10-vinyl-1,2,3,4,5,6,7,8-octahydro-1,4:5,8-dimethanoanthracene-9-yl]-porphyrinato] ruthenium (II) 5. A mixture of the free base porphyrin **4** (48 μmol) and Ru_3CO_{12} (144 μmol) in refluxing *o*-dichlorobenzene was let to react for 2 h. The solvent was removed under high vacuum, and the crude product was purified by column chromatography (pentane/CH_2Cl_2 8/2) to obtain the pure metalloporphyrin **5** (43 μmol 90%). ^1H NMR δ 8.62 (AB system (5 Hz), 8H); 7.26 (dd, 4H); 5.73 (m, 8H); 3.91 (m, 8H); 2.95 (m, 4H); 2.64 (m, 4H); 2.15–1.90 (m, 16H); 1.55–1.20 (m, 32H); UV–vis (CH_2Cl_2): $\lambda_{max/nm}$ ($\log\varepsilon$): 416 (5.45), 531 (4.47). Mass (ESI, CH_2Cl_2/MeOH 9/1) (*m*/*z*): calculated for $C_{93}H_{84}ON_4Ru$ $[M+H]^+$: 1397.5586, found: 1397.5663; IR (KBr): $\nu_{CO} = 1943.9\ cm^{-1}$.

5.3. Preparation of polymers

In an oven dried hemolysis tube, metalloporphyrin **5** (7.2 μmol) was dissolved in the porogen (toluene 1.5 mmol). Then, styrene (277 μmol) and divinylbenzene (or EGDMA) (340 μmol) were added to the solution.

The polymerization reaction was initiated by AIBN (60 μmol). The mixture was heated at 65 °C for 16 h without stirring. The resulting polymer was extracted from the polymerization tube, crushed in a mortar, washed with dichloromethane and filtered on Büchner funnel (85 mg).

5.4. General procedure for cyclopropanation reactions with ruthenium porphyrin complexes

For homogeneous reactions, the catalyst (0.2%, w/w) was placed in an oven-dried thermolysis tube. This tube was evacuated, and backfilled with argon. CH_2Cl_2 (1 mL) was added via syringe, followed by alkene (1 mmol). Then, diazoacetonitrile (0.2 mmol) was added slowly to the mixture over a period of 3 h. After 24 h, the enantiomeric excess was measured by GC and the resulting mixture was evaporated and purified by flash silica gel chromatography to give pure *cis*- and *trans*-diastereoisomers. *trans*-Cyanocyclopropanes (ee > 70%) can be recrystallized in pentane/CH_2Cl_2 to give enantiomerically pure compounds. For cyclopropanation reactions with ruthenium polymers, the same procedure was used. Then, the filtered polymer was washed several times by acetone and dichloromethane. The polymer was dried under vacuum and used for another run with the same experimental conditions.

5.4.1. 2-Phenylcyclopropanecarbonitrile: *trans*-isomer. ^{1}H NMR ($CDCl_3$, 500 MHz): δ (ppm) 7.34 (m, 2H); 7.18 (m, 1H); 7.13 (m, 2H); 2.66 (m, 1H); 1.65 (m, 1H); 1.58 (m, 1H); 1.48 (m, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ (ppm) 137.6; 128.8; 127.5; 126.3; 121.6; 24.9; 15.3; 6.7. Optical rotation: $[\alpha]_D^{20} = +240$ (*c* 0.88, CH_2Cl_2). *cis*-Isomer ^{1}H NMR ($CDCl_3$, 500 MHz): δ (ppm) 7.39 (m, 2H); 7.31 (m, 3H); 2.57 (m, 1H); 1.87 (m, 1H); 1.58 (m, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ (ppm) 135.2; 128.6; 128.0; 127.7; 119.5; 23.2; 12.9; 6.4. Mass (EI): (*m*/*z*): calculated for $C_{10}H_9N$ [$M^{+\cdot}$]: 143.0735, found: 143.0747.

5.4.2. 2-(4-Methoxyphenyl)cyclopropanecarbonitrile: *trans*-isomer. ^{1}H NMR ($CDCl_3$, 500 MHz): δ (ppm) 7.06 (m, 2H); 6.86 (m, 2H); 3.82 (s, 3H); 2.62 (m, 1H); 1.60 (m, 1H); 1.48 (m, 1H); 1.42 (m, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ (ppm) 158.9; 129.5; 127.7; 121.3; 114.2; 55.4; 24.4; 15.0; 6.3. Optical rotation: $[\alpha]_D^{20} = +201$ (*c* 0.50, CH_2Cl_2). *cis*-Isomer ^{1}H NMR ($CDCl_3$, 500 MHz): δ (ppm) 7.23 (m, 2H); 6.91 (m, 2H); 3.82 (s, 3H); 2.53 (m, 1H); 1.81 (m, 1H); 1.52 (m, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ (ppm) 159.1; 129.3; 127.2; 119.7; 114,1; 55.3; 22.6; 12.9; 6.2. Mass (EI): (*m*/*z*): calculated for $C_{11}H_{11}NO$ [$M^{+\cdot}$]: 173.0840, found: 173.0857.

5.4.3. 2-(4-Bromophenyl)cyclopropanecarbonitrile: *trans*-isomer. ^{1}H NMR ($CDCl_3$, 500 MHz): δ (ppm) 7.46 (m, 2H); 7.01 (m, 2H); 2.61 (m, 1H); 1.66 (m, 1H); 1.55 (m, 1H); 1.45 (m, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ (ppm) 137.0; 132.3; 128.5; 121.7; 121.1; 24.8; 15.6; 7.1. Optical rotation: $[\alpha]_D^{20} = +237$ (*c* 1.20, CH_2Cl_2). *cis*-Isomer ^{1}H NMR ($CDCl_3$, 500 MHz): δ (ppm) 7.52 (m, 1H); 7.18 (m, 1H); 2.52 (m, 1H); 1.89 (m, 1H); 1.56 (m, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ (ppm) 134.3; 131.8; 129.8; 121.7; 22.7; 13.0; 6.5. Mass (EI): (*m*/*z*): calculated for $C_{10}H_8N\ ^{79}Br$ [$M^{+\cdot}$]: 220.9840, found: 220.9839.

Absolute configurations were determined from the specific rotations by comparison with previously reported cyanocyclopropanes.[36,37]

5.5. Gas chromatography conditions

Cyclopropanation of styrene with diazoacetonitrile: GC CP-Chirasil-Dex column, injector 200 °C (pulsed split mode), detector (FID 220 °C, oven: 120 °C; 2.5 °C min^{-1}), pressure = 15 psi. *cis*-(1*R*,2*S*) $\tau_r = 14.56$ min and *cis*-(1*S*,2*R*) $\tau_r = 14.80$ min; *trans*-(1*R*,2*R*) $\tau_r = 13.76$ and *trans*-(1*S*,2*S*) $\tau_r = 14.21$ min.

Cyclopropanation of 4-OMe styrene with diazoacetonitrile: GC CP-Chirasil-Dex column, injector 200 °C (pulsed split mode), detector (FID 220 °C, oven: 120 °C; 2.5 °C min^{-1}), pressure = 15 psi. *cis*-(1*R*,2*S*) $\tau_r = 23.49$ min and *cis*-(1*S*,2*R*) $\tau_r = 23.82$ min; *trans*-(*R*,*R*) $\tau_r = 22.94$ and *trans*-(*S*,*S*) $\tau_r = 23.10$ min.

Cyclopropanation of 4-Br styrene with diazoacetonitrile: GC CP-Chirasil-Dex column, injector 200 °C (pulsed split mode), detector (FID 220 °C, oven: 120 °C; 2.5 °C min^{-1}), pression = 15 psi. *cis*-(1*R*,2*S*) $\tau_r = 27.40$ min and *cis*-(1*S*,2*R*) $\tau_r = 27.96$ min; *trans*-(*R*,*R*) $\tau_r = 26.50$ and *trans*-(*S*,*S*) $\tau_r = 26.66$ min.

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