Synthesis of Metalloporphyrins and Metallochlorins for Immobilization on Electrode Surfaces

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Dedicated to Professor Burchard Franck on the occasion of his 75th birthday

Keywords: Porphyrinoids / Pyrroles / Phosphonic acid / Immobilization / Biomimetic systems

New metalloporphyrinoid complexes functionalized with two pyrrole groups and bearing two phosphonate residues have been synthesized starting from readily accessible deuterioporphyrin derivatives. The functional pyrrole groups allow the formation of metalloporphyrinoid films on electrodes by oxidative electropolymerization. On the other hand, the phosphonate functionalities could be used to immobilize the metalloporphyrinoids on polycrystalline titanium dioxide electrodes. Electrodes modified by immobilization of the metalloporphyrinoid complexes have been shown to be useful for electrocatalysis and as electrochemical sensors.

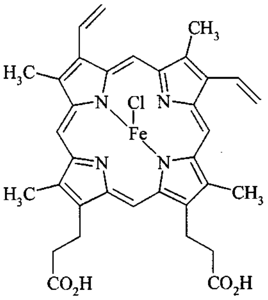
Introduction

Porphyrins, hydroporphyrins, and corrins are biologically important cofactors, the functions of which are based on the complexation of the inner cores with different metal ions such as iron, cobalt, and nickel.[1] Iron-containing hemes, including the red blood pigment heme **1**, play an important biological role in oxygen transport, redox reactions, and various oxygen-transfer reactions.[2]

Corrinoid cobalt complexes based on the vitamin B_{12} structure **3** are involved in several unique rearrangement processes.[3] Factor F430 (**2**) with its central nickel ion, acts as a key cofactor for coenzyme M reductase of primitive methanogenic bacteria in the formation of methane from 2-(methylthio)ethanesulfonate.[4]

With a view to mimicking the biological activity[5] of such coenzymes, the development of electrodes modified by polymer films containing metalloporphyrinoids has become an attractive area of research in electrocatalysis.[6] Among the various electropolymerization processes, an interesting method is the anodic oxidation of pyrrole-substituted metalloporphyrins.[6a,7]

Another immobilization procedure is based on the direct covalent linkage of appropriately functionalized metalloporphyrinoids to electrode surfaces.[8]



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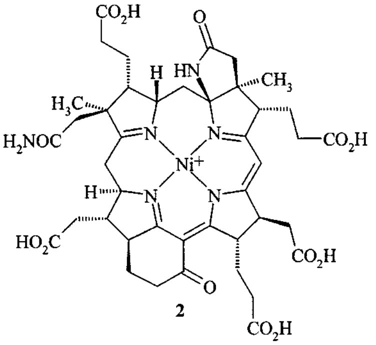

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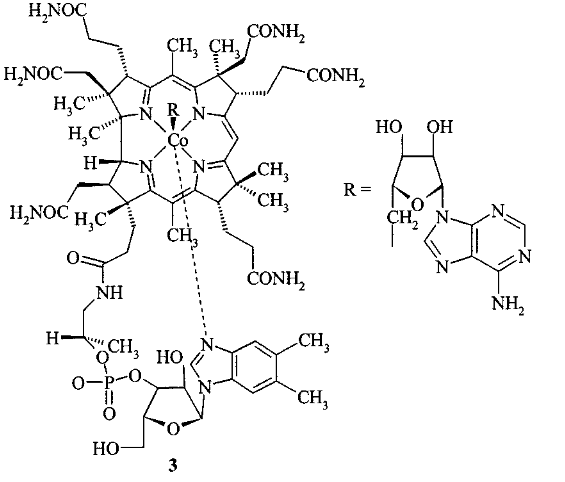

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We describe herein the synthesis of some porphyrin and chlorin (dihydroporphyrin) metal complexes that are suited for immobilization on electrode surfaces. The common starting material for the preparation of the various metalloporphyrinoids has been deuterioporphyrin dimethyl ester, a direct transformation product of the red blood pigment heme. The ready accessibility of heme from slaughterhouse wastes and its efficient transformation into deuterioporphyrin dimethyl ester[9] makes the synthetic routes leading to the various immobilizable metalloporphyrin derivatives attractive with regard to technical applications.

Results and Discussion

Porphyrin **4a**, derived from deuterioporphyrin dimethyl ester by reduction with $LiAlH_4$,[10] was our starting point

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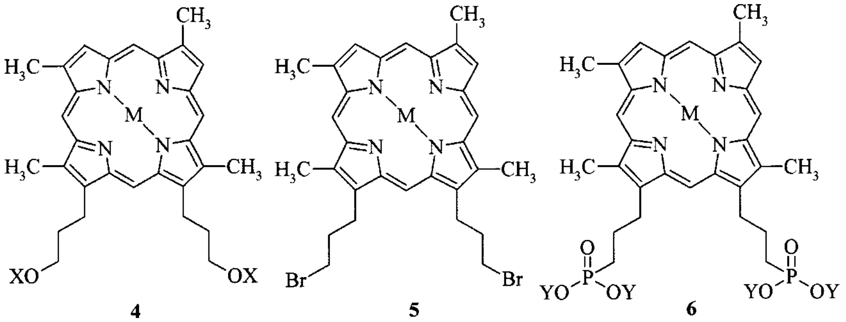


4 **5** **6**

4	M	X
a	2H	H
b	Ni	H
c	Ni	Ts
d	Zn	H

5	M
a	2H
b	Ni
c	Co
d	FeCl

6	M	Y
a	Ni	TMS
b	Ni	H
c	Co	TMS
d	Co	H
e	FeCl	TMS
f	FeCl	H

$$\mathbf{4a} \xrightarrow{a} \mathbf{4b} \xrightarrow{b} \mathbf{4c} \xrightarrow{c} \mathbf{5b} \xrightarrow{d} \mathbf{6a} \xrightarrow{e} \mathbf{6b}$$

$$\begin{tikzcd}
 & & \mathbf{5c} \arrow[r, "d"] & \mathbf{6c} \arrow[r, "e"] & \mathbf{6d} \\
\mathbf{4a} \arrow[r, "f"] & \mathbf{4d} \arrow[r, "g"] & \mathbf{5a} \arrow[u, "h"] \arrow[d, "i"] & & \\
 & & \mathbf{5d} \arrow[r, "d"] & \mathbf{6e} \arrow[r, "e"] & \mathbf{6f}
\end{tikzcd}$$

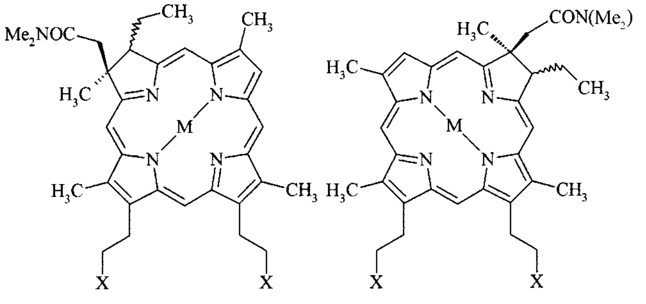
Scheme 1. (a) Ni(acac)$_2$, THF, reflux, 85%; (b) CH_2Cl_2, NEt_3, TsCl, 0 °C, 91%; (c) acetone, KBr, 18-crown-6, 78%; (d) $P(OSiMe_3)_3$, reflux; (e) $MeOH/H_2O$, 67−77% (from **5b−d**); (f) Zn(acac)$_2$, THF, reflux, 66%; (g) (1) CH_2Cl_2, CBr_4, PPh_3, 0 °C, 77%, (2) CH_2Cl_2, 5 N HCl, 76%; (h) Co(acac)$_2$, THF, reflux, 90%; (i) $FeCl_3$, NaOAc, HOAc, reflux, 88%

for the preparation of a series of metalloporphyrins bearing phosphonate groups suitable for immobilization.

In view of the known high stability and diamagnetic properties of nickel porphyrins, the reaction sequence leading to the phosphonate-functionalized porphyrins was first investigated for the nickel porphyrin **6b** (Scheme 1). Complexation of metal-free porphyrin **4a** with nickel(II) (→ **4b**), followed by tosylation of the alcohol functions (→ **4c**) and nucleophilic displacement of the tosyl groups, yielded nickel porphyrin dibromide **5b**. Nucleophilic substitution of the bromide substituents in **5b** with tris(trimethylsilyl) phosphite[11] gave the nickel porphyrin phosphonate ester **6a**, treatment of which with methanol/water[12] furnished the free acid **6b**. Attempted direct nucleophilic displacement of the tosyl groups in **4c** failed, hence the dibromides had to be prepared as intermediates.

For the preparation of the cobalt and iron porphyrin phosphonates, the aforementioned synthetic sequence was slightly modified. The metal-free porphyrin dibromide **5a** was directly prepared from the zinc porphyrin bis(alcohol) **4d** according to the method of Appel.[13] Insertion of cobalt or iron into **5a** yielded porphyrins **5c** and **5d**, respectively.[9a] The preparative sequences were then completed by introduction of the phosphonate functions to give the metalloporphyrins **6d** and **6f**.

The chlorin phosphonates *rac*-**7e**, **8e** were prepared starting from the known chlorins *rac*-**7a**, **8a**. The chlorins *rac*-**7a**, **8a** (Scheme 2), which were also prepared from deuterioporphyrin dimethyl ester according to a route developed in our laboratory,[9b,9c,14] should allow access to electrodes coated with films having a chiral porphyrinoid environment due the chiral centers present in the chlorins.



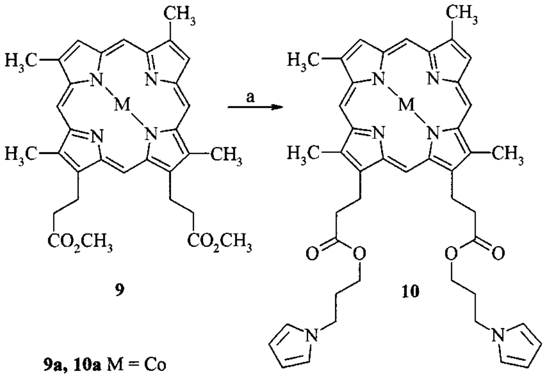
rac-**7** *rac*-**8**

	X	M	
a	CO_2CH_3	2H	a
b	CO_2CH_3	Ni	b
c	CH_2OH	Ni	c
d	CH_2Br	Ni	d
e	CH_2-P(O)(OEt)$_2$	Ni	

Scheme 2. (a) Ni(acac)$_2$, THF, reflux; (b) $LiBH_4$, THF, reflux; (c) CH_2Cl_2, NBu_4Br, NEt_3, Tf_2O, 78%; (d) $P(OEt)_3$, reflux, 21%

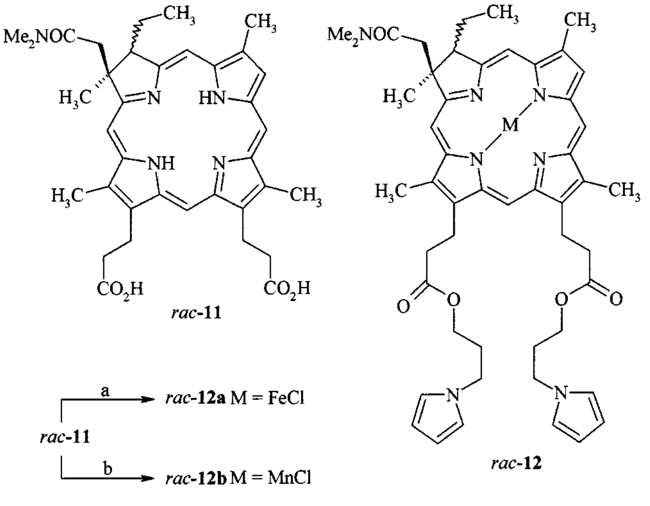
Complexation of the metal-free chlorins by nickel(II) followed by selective reduction of the ester carbonyl groups in *rac*-**7b**, **8b** yielded the nickel chlorin bis(alcohol)s *rac*-**7c**, **8c**. After direct transformation of the alcohols into the bromides *rac*-**7d**, **8d**, the nickel chlorin phosphonates *rac*-**7e**, **8e** were generated by treatment with triethyl phosphite.

Various metalloporphyrin derivatives **10a** with two pyrrole functions attached to carboxylic acid side chains on deuterioporphyrin can be directly obtained from the corresponding metal complexes of deuterioporphyrin dimethyl ester.[9a] Thus, the ester functions of **9a** were hydrolyzed, activated with *n*-propylphosphonic anhydride,[15] and treated with 3-(1-pyrrolyl)propan-1-ol[16] to give the desired electropolymerizable porphyrinoid metal complex **10a** (Scheme 3). This synthesis represents a very facile route for the preparation of immobilizable porphyrinoid metal complexes due to the availability of the porphyrin macrocycle and the simplicity of the transformation sequence. We have already demonstrated the utility of the concept by preparing iron-, manganese-, nickel-, and copper-containing systems.[7i,17] This series has now been supplemented by the preparation of the hitherto missing cobalt deuterioporphyrin derivative **10a**.



Scheme 3. (a) (1) 5 N $KOH_{aq.}$/THF, (2) THF, NEt_3, *n*-propylphosphonic anhydride, 3-(1-pyrrolyl)propan-1-ol, 55%

Iron and manganese chlorins *rac*-**12a** and *rac*-**12b** (Scheme 4), bearing electropolymerizable pyrrole groups, were prepared from the known chlorin dicarboxylic acid *rac*-**11**.[18] The central metal ions were first inserted[19] into the chlorin macrocycle, the carboxylic acid functions were activated with *n*-propylphosphonic anhydride,[15] and finally the activated esters were treated with 3-(1-pyrrolyl)propan-1-ol as described above.[16]



Scheme 4. (a) (1) $CHCl_3$, MeOH, $FeCl_2$, 2,6-lutidine, 60 °C, (2) THF, NEt_3, *n*-propylphosphonic anhydride, 3-(1-pyrrolyl)propan-1-ol, 94%; (b) (1) $CHCl_3$, MeOH, $MnCl_2$, 2,6-lutidine, 60 °C, (2) THF, NEt_3, *n*-propylphosphonic anhydride, 3-(1-pyrrolyl)propan-1-ol, 66%

As demonstrated in recent studies, *two* pyrrole functions, as in **10a**, *rac*-**12a**, and *rac*-**12b**, are of crucial importance for an effective immobilization of porphyrinoid metallomacrocycles on electrode surfaces by electropolymerization.[7i,17]

Conclusion

In this contribution, we have demonstrated that various metalloporphyrins and metallochlorins bearing pyrrole groups and phosphonate functionalities suitable for immobilization are easily accessible from deuterioporphyrin, a degradation product of the red blood pigment heme. Preliminary studies[7i,17] have shown that the prepared metallomacrocycles can indeed be immobilized on electrode surfaces. The cobalt porphyrin phosphonate **6d** could be immobilized on polycrystalline titanium dioxide. The electrode thus obtained showed sensor activity towards organohalogen compounds, based on interactions of the highly nucleophilic Co^I species generated upon electroreduction of Co^{II} in the porphyrin macrocycle.[20]

For an effective immobilization of the porphyrinoids bearing pyrrole groups, the presence of two electropolymerizable pyrrole rings at the macrocycle is essential. The modified electrodes are useful as sensors and for electrocatalysis. For instance, electrodes modified by the electropolymerization of manganese deuterioporphyrin dipyrrole ester show catalytic activity in oxygen transfer from electrochemically generated manganese(V) oxo species to alkenes. Electrodes modified with films incorporating the corresponding iron porphyrins have been investigated as sensors for cyanide detection.[17a]

Experimental Section

General Remarks: Starting materials were either prepared according to literature procedures or were purchased from Fluka, Merck, or Aldrich and used without further purification. All solvents were purified and dried by standard methods. All reactions were carried out under argon. – ^1H NMR spectra: Bruker DPX-200 Avance spectrometer; chemical shifts are referenced to TMS ($\delta = 0.00$). – MS: Finnigan MAT 8200 spectrometer [EI (70 eV) and DCI (NH_3, 8 mA/s)], Bruker Daltonik Biflex III (MALDI-TOF). – IR: Perkin–Elmer Paragon 500 FT-IR spectrometer. – UV/Vis: Varian Cary 50 spectrophotometer, ε [L $M^{-1}cm^{-1}$]. – Elemental analysis: Microanalytical Laboratory Beller, Göttingen, Germany. – Column chromatographic separations were performed on silica gel (32–63 µm, 60 Å, ICN) or aluminium oxide (activity grade II–III, neutral, ICN).

[13,17-Bis(3-hydroxypropyl)-2,7,12,18-tetramethylporphyrinato]nickel(II) (4b): A mixture of 13,17-bis(3-hydroxypropyl)-2,7,12,18-

tetramethylporphyrin (**4a**) (5.0 g, 10.4 mmol) and nickel(II) acetylacetonate (12.9 g, 50 mmol) in THF (200 mL) was refluxed under argon for 48 h. After removal of 100−150 mL of the THF, the concentrated reaction mixture was extracted with chloroform and the organic phase was washed with brine. Filtration through aluminium oxide and evaporation of the solvents from the filtrate yielded 4.7 g (8.8 mmol, 85%) of nickel(II) deuterioporphyrin bis(alcohol) **4b**. − ^{1}H NMR (CDCl$_3$): δ = 2.51 (m, 4 H), 3.47, 3.52, 3.62, 3.62 (4 s, 12 H), 3.75 (m, 4 H), 4.00 (m, 4 H), 9.56, 9.58 (2 s, 2 H), 10.02, 10.04, 10.06, 10.08 (4 s, 4 H). − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 391 (5.24), 514 (3.92), 549 nm (4.24). − MS (DCI): *m/z* (%) = 539 [M$^-$] (100). − HRMS ($C_{30}H_{32}N_4{}^{58}NiO_2$): calcd. 538.1879; found 538.1870.

[13,17-Bis{3-[(4-methylphenyl)sulfonyloxy]propyl}-2,7,12,18-tetramethylporphyrinato]nickel(II) (4c): A mixture of nickel(II) deuterioporphyrin bis(alcohol) **4b** (2.0 g, 3.7 mmol) and triethylamine (16.2 mL, 111.3 mmol) was stirred at room temperature for 10 min. After cooling to 0 °C, *p*-toluenesulfonyl chloride (10.6 g, 55.7 mmol) was added and the resulting mixture was stirred for 3 h at the same temperature. The flask was then sealed and stored in a refrigerator overnight. The mixture was subsequently washed twice with saturated sodium hydrogen carbonate solution and once with water. The organic phase was filtered through hot cotton wool and the filtrate was concentrated. Flash chromatography [silica gel, dichloromethane] of the residue and subsequent crystallization from dichloromethane/diethyl ether gave a slurry, which was treated with further diethyl ether and subjected to ultrasound. After filtration through a frit, the collected solid was washed several times with diethyl ether. Drying under high vacuum gave 2.86 g (3.38 mmol, 91%) of **4c** as a red powder. − ^{1}H NMR (CDCl$_3$): δ = 2.14, 2.18 (2 s, 6 H), 2.50, 2.61 (2 m, 4 H), 3.36, 3.40, 3.43, 3.46 (4 s, 12 H), 3.75, 3.92 (2 m, 4 H), 4.03, 4.23 (2 m, 4 H), 7.05, 7.65 (2 m, 8 H), 8.88, 8.90 (2 s, 2 H), 9.66, 9.68, 9.73, 9.78 (4 s, 4 H). − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 391 (5.30), 514 (4.13), 549 nm (4.51). − MS (DCI): *m/z* (%) = 846 [M$^-$] (100), 674 (87), 172 (22), 127 (26). − $C_{44}H_{44}N_4NiO_6S_2$ (847.68): calcd. C 62.34, H 5.23, N 6.61, S 7.56; found C 62.37, H 5.18, N 6.76, S 7.40.

[13,17-Bis(3-hydroxypropyl)-2,7,12,18-tetramethylporphyrinato]zinc(II) (4d): A mixture of deuterioporphyrin bis(alcohol) **4a** (1.6 g, 3.3 mmol) and zinc(II) acetylacetonate (5.0 g, 19.1 mmol) in THF (150 mL) was refluxed under argon for 17 h. After removal of about 100 mL of the THF, the concentrated reaction mixture was extracted with chloroform and the organic phase was washed with brine. Filtration through aluminium oxide and subsequent chromatography [silica gel, dichloromethane/THF (3:2)] yielded 1.2 g (2.2 mmol, 66%) of zinc(II) deuterioporphyrin bis(alcohol) (**4d**) as a red solid. − ^{1}H NMR ([D$_6$]DMSO): δ = 2.40 (m, 4 H), 3.58, 3.62, 3.70, 3.74 (4 s, 12 H), 3.80 (m, 4 H), 4.10 (m, 4 H), 4.79 (m, 2 H), 9.19, 9.21 (2 s, 2 H), 10.06, 10.11, 10.14, 10.16 (4 s, 4 H). − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 323 (4.45), 401 (5.35), 532 (4.27) 567 nm (4.27). − MS (DCI): *m/z* (%) = 545 [M + H$^+$] (100). − HRMS ($C_{30}H_{32}N_4O_2{}^{64}Zn$): calcd. 544.1817; found 544.1817.

13,17-Bis(3-bromopropyl)-2,7,12,18-tetramethylporphyrin (5a): A mixture of **4d** (50 mg, 90 μmol) and carbon tetrabromide (83.6 mg, 0.25 mmol) in dry dichloromethane (20 mL) was stirred for 10 min at room temperature. After cooling to 0 °C, triphenylphosphane (132.2 mg, 0.50 mmol) was added and the resulting mixture was stirred for 12 h at room temperature. The organic phase was subsequently washed with water, 1 N aq. HCl, and saturated sodium hydrogen carbonate solution. After filtration through cotton wool, the filtrate was concentrated. The crude product was taken up in dichloromethane (20 mL) and stirred with 5 N aq. HCl (20 mL) for 1.5 h at room temperature. The aqueous phase was discarded and the organic phase was washed twice with saturated sodium hydrogen carbonate solution. Filtration through cotton wool, evaporation of the solvent, and chromatography (silica gel, dichloromethane) of the residue yielded 41.8 mg (69 μmol, 77%) of **5a** as a purple solid. − ^{1}H NMR ([D$_6$]DMSO): δ = −4.00 (s, 2 H), 2.79 (m, 4 H), 3.69, 3.73, 3.77, 3.90 (4 s, 12 H), 3.91, 3.93 (2 t, 4 H), 4.27 (m, 4 H), 9.34, 9.36 (2 s, 2 H), 10.27, 10.33, 10.33, 10.35 (4 s, 4 H). − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 398 (5.25), 495 (4.21), 528 (3.92), 564 (3.89), 617 nm (3.66). − MS (DCI): *m/z* (%) = 606 [M$^-$] (55), 527 (41), 448 (8). − HRMS ($C_{30}H_{32}N_4{}^{79}Br_2$): calcd. 606.0994; found 606.0988.

[13,17-Bis(3-bromopropyl)-2,7,12,18-tetramethylporphyrinato]nickel(II) (5b): A mixture of **4c** (848 mg, 1.0 mmol), potassium bromide (6.0 g, 50 mmol), and 18-crown-6 (6.0 g, 22.7 mmol) in dry acetone (150 mL) was subjected to ultrasound for 30 min and then vigorously stirred for 24 h at room temperature. After evaporation of about 2/3 of the solvent, the concentrated mixture was taken up in dichloromethane. This solution was washed twice with water and filtered through cotton wool. The solvent was evaporated in vacuo and the red residue was purified by flash chromatography (silica gel, dichloromethane). Crystallization from dichloromethane/petroleum ether yielded 519 mg (0.78 mmol, 78%) of **5b** as red crystals. − ^{1}H NMR (CDCl$_3$): δ = 2.71 (m, 4 H), 3.45, 3.60, 3.58, 3.59 (4 s, 12 H), 3.68 (m, 4 H), 4.08 (m, 4 H), 8.91, 8.93 (2 s, 2 H), 9.70, 9.74, 9.79, 9.80 (4 s, 4 H). − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 391 (5.32), 514 (4.17), 549 nm (4.53). − MS (DCI): *m/z* (%) = 664 [M$^-$, ^{58}Ni^{79}Br^{81}Br] (100), 584 (63). − HRMS ($C_{30}H_{30}N_4{}^{58}Ni^{79}Br^{81}Br$): calcd. 664.0170; found 664.0106.

[13,17-Bis(3-bromopropyl)-2,7,12,18-tetramethylporphyrinato]cobalt(II) (5c): A mixture of porphyrin **5a** (50 mg, 82 μmol) and cobalt(II) acetylacetonate (63 mg, 0.25 mmol) in THF (30 mL) was refluxed under argon for 19 h. The red solution was then transferred to a separatory funnel with dichloromethane and washed five times with brine. After filtration through aluminium oxide, the filtrate was concentrated. Chromatography (silica gel, dichloromethane) of the residue yielded 49 mg (74 μmol, 90%) of **5c** as a red-brown solid. − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 323 (4.41), 391 (5.21), 531 (4.18, sh), 549 (4.26), 617 nm (3.85). − MS (DCI): *m/z* (%) = 665 [M$^-$, ^{79}Br^{81}Br] (100), 585 (24). − HRMS ($C_{30}H_{30}{}^{79}Br_2{}^{59}CoN_4$): calcd: 663.0169; found 663.0161.

Chloro[13,17-bis(3-bromopropyl)-2,7,12,18-tetramethylporphyrinato]iron(III) (5d): Anhydrous iron(III) chloride (50 mg, 0.31 mmol) and sodium acetate (25 mg, 0.3 mmol) were dissolved in glacial acetic acid (20 mL). An extraction thimble was then loaded with porphyrin **5a** (50 mg, 82 μmol) and refluxed for 18 h in a Soxhlet apparatus. The resulting brown solution was transferred to a separatory funnel with dichloromethane and was washed twice with water and once with saturated sodium hydrogen carbonate solution. The organic phase was dried by filtration through cotton wool, concentrated, and the residue was chromatographed on silica gel eluting with dichloromethane/methanol (4:1). Crystallization from dichloromethane/*n*-pentane yielded 50.4 mg (72 μmol, 87%) of the iron porphyrin **5d** as a brown solid. − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 381 (4.80), 483 (4.00), 528 (3.99), 572 (3.81), 628 nm (3.76). − MS (DCI): *m/z* (%) = 697 [M$^-$, ^{56}Fe^{35}Cl^{79}Br^{81}Br] (2), 662 (6). − HRMS ($C_{30}H_{30}{}^{79}Br_2{}^{56}FeN_4$): calcd: 660.0187; found 660.0190.

General Procedure for the Preparation of the Porphyrin Phosphonates 6b, 6d, and 6f

[13,17-Bis(3-phosphonopropyl)-2,7,12,18-tetramethylporphyrinato]nickel(II) (6b): A mixture of **5b** (20 mg, 30 μmol) and tris(trimethylsilyl) phosphite (5 mL, 15 mmol) was refluxed at 150 °C for 4 h. Excess tris(trimethylsilyl) phosphite was then removed by high vacuum distillation at 90 °C in a kugelrohr apparatus. The resulting intermediate **6a** was analysed. − MS (DCI): *m*/*z* (%) = 954 (91), 883 (42), 789 (32), 764 (85). − After the addition of methanol (8 mL) and water (2 mL), the intermediate was hydrolysed by stirring for 48 h at room temperature. Removal of the solvents under high vacuum and crystallization of the residue from methanol/chloroform gave 15.4 mg (23 μmol, 77%) of **6b**. − ^{1}H NMR (CDCl$_3$): δ = 1.97 (m, 4 H), 2.29 (m, 4 H), 3.30, 3.37, 3.45, 3.48 (4 s, 12 H), 3.92 (m, 4 H), 7.95 (s, 4 H), 8.93, 8.98 (2 s, 2 H), 9.72, 9.73, 9.78, 9.80 (4 s, 4 H). − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 390 (5.22), 513 (4.03), 548 nm (4.41). − MS (FAB neg., NBA): *m*/*z* (%) = 665 [M$^-$] (30), 459 (22). − HRMS ($C_{30}H_{34}N_4{}^{58}NiO_6P_2$): calcd. 665.1229; found 665.1127.

[13,17-Bis(3-phosphonopropyl)-2,7,12,18-tetramethylporphyrinato]cobalt(II) (6d): The cobalt derivative was prepared according to the general procedure described for **6b**. **6d** (71%) was obtained as a black solid. − IR (KBr): ṽ = 2940, 2905, 2867, 1592, 1455, 1150, 1118, 980, 934, 848, 759, 668 cm^{-1}. − UV/Vis (MeOH): λ_{max} (log ε) = 408 (4.67), 495 (3.87), 524 (3.92), 556 (3.91), 614 nm (3.69). − MS (MALDI-TOF, sinapinic acid): *m*/*z* = 666.17, 633.24, 611.25.

Chloro[13,17-bis(3-phosphonopropyl)-2,7,12,18-tetramethylporphyrinato]iron(III) (6f): The iron derivative was prepared according to the general procedure described for **6b**. **6f** (67%) was obtained as a black solid. − IR (KBr): ṽ = 2926, 2905, 1664, 1540, 1457, 1129, 1060, 936, 526 cm^{-1}. − UV/Vis (MeOH): λ_{max} (log ε) = 344 (4.23), 392 (4.49), 468 (3.70), 568 nm (3.52). − MS (MALDI-TOF, sinapinic acid): *m*/*z* = 664.14.

(2*RS*,3*RS*)- and (2*RS*,3*SR*)-[13,17-Bis(3-bromopropyl)-2-(*N*,*N*-dimethylcarbamoylmethyl)-3-ethyl-2,7,12,18-tetramethyl-2,3-dihydroporphyrinato]nickel(II) (*rac*-7d) and (7*RS*,8*RS*)- and (7*RS*,8*SR*)-[13,17-Bis(3-bromopropyl)-7-(*N*,*N*-dimethylcarbamoylmethyl)-8-ethyl-2,7,12,18-tetramethyl-7,8-dihydroporphyrinato]nickel(II) (*rac*-8d). − 1. Complexation: A mixture of (2*RS*,3*RS*)- and (2*RS*,3*SR*)-dimethyl 2-(*N*,*N*-dimethylcarbamoylmethyl)-3-ethyl-2,7,12,18-tetramethyl-2,3-dihydro-22*H*,24*H*-porphyrin-13,17-dipropionate (*rac*-**7a**) and (7*RS*,8*RS*)- and (7*RS*,8*SR*)-dimethyl 7-(*N*,*N*-dimethylcarbamoylmethyl)-8-ethyl-2,7,12,18-tetramethyl-7,8-dihydro-21*H*,23*H*-porphyrin-13,17-dipropionate (*rac*-**8a**) (30 mg, 46 μmol) and nickel(II) acetylacetonate (118 mg, 0.46 mmol) were dissolved in dry THF (20 mL) and the resulting solution was heated under reflux for 18 h. It was then filtered through aluminium oxide with THF; the crude products *rac*-**7b** and *rac*-**8b** were used without further purification. − **2. Reduction:** The nickel chlorins *rac*-**7b** and *rac*-**8b** (39.8 mg, 56 μmol) and LiBH$_4$ (6.1 mg, 0.3 mmol) were dissolved in dry THF (20 mL) under argon. The resulting solution was refluxed for 24 h. After the addition of acetic acid (1 mL), the solvent was evaporated and the residue was chromatographed on silica gel eluting with dichloromethane/methanol (15:1) to give the chlorin alcohols *rac*-**7c** and *rac*-**8c** as a green solid. − **3. Substitution:** The chlorin alcohols *rac*-**7c** and *rac*-**8c** (13 mg, 20 μmol) and tetrabutylammonium bromide (430 mg, 0.19 mmol) were dissolved in dry CH$_2$Cl$_2$ (2 mL) under argon. The resulting solution was cooled to 0 °C. After the addition of triethylamine (0.5 mL), trifluoromethanesulfonic anhydride (36 μL, 0.23 mmol) was added and the resulting mixture was stirred for 12 h at room temperature. After washing with water, 0.1 N aq. HCl, and saturated sodium hydrogen carbonate solution, the solvent was evaporated. The residue was chromatographed on silica gel eluting with dichloromethane/methanol (15:1) to give the chlorin bromides (*rac*-**7d**) and (*rac*-**8d**) as a green solid. Yield: 12 mg (15 μmol, 78%). − IR (KBr): ṽ = 2924, 2855, 1643, 1609, 1452, 1399, 1206, 1132, 1077, 951, 892 cm^{-1}. − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 400 (5.10), 490 (3.82), 573 (4.11, sh), 619 nm (4.74). − MS (DCI): *m*/*z* (%) = 653 [M$^+$] (27), 580 (27), 566 (11).

(2*RS*,3*RS*)- and (2*RS*,3*SR*)-[13,17-Bis{3-(diethoxyphosphoryl)propyl}-2-(*N*,*N*-dimethylcarbamoylmethyl)-3-ethyl-2,7,12,18-tetramethyl-2,3-dihydroporphyrinato]nickel(II) (*rac*-7e) and (7*RS*,8*RS*)- and (7*RS*,8*SR*)-[13,17-Bis{3-(diethoxyphosphoryl)propyl}-7-(*N*,*N*-dimethylcarbamoylmethyl)-8-ethyl-2,7,12,18-tetramethyl-7,8-dihydroporphyrinato]nickel(II) (*rac*-8e): The chlorin bromides *rac*-**7d** and *rac*-**8d** (4 mg, 5.4 μmol) were dissolved in triethyl phosphite (5 mL, 29 mmol) under argon and the solution was heated for 4 h at 150 °C. The solvent was then removed by high vacuum distillation at 60 °C in a kugelrohr apparatus. The residue was chromatographed on silica gel eluting with dichloromethane/methanol (15:1) to give the chlorin phosphonates *rac*-**7e** and *rac*-**8e** as a green solid. Yield: 1 mg (1.1 μmol, 21%). − IR (KBr): ṽ = 2928, 2857, 1716, 1650, 1555, 1540, 1502, 1450, 1393, 1265, 1232, 1165, 1027, 961, 819 cm^{-1}. − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 400 (4.99), 493 (3.72), 579 (4.14, sh), 619 nm (4.61). − MS (DCI): *m*/*z* (%) = 892 [M$^-$ − H] (27), 288 (100).

[13,17-Bis{2-[3-(1-pyrrolyl)propyloxycarbonyl]ethyl}-2,7,12,18-tetramethylporphyrinato]cobalt(II) (10a): Cobalt(II) deuterioporphyrin dimethyl ester (**9a**) (200 mg, 0.34 mmol) was dissolved in THF (20 mL). After the addition of 5 N aq. KOH (20 mL), the reaction mixture was vigorously stirred under argon at 70 °C for 18 h. The colourless THF phase was discarded and 5 N aq. HCl (25 mL) and *tert*-butyl methyl ether (20 mL) were carefully added to the aqueous phase, which led to the separation of a precipitate at the phase boundary. The suspension was filtered through a Buchner funnel. Drying of the collected solid under high vacuum yielded the black cobalt(II) deuterioporphyrin, which was used in the next step without further purification. Cobalt(II) deuterioporphyrin (21 mg, 38 μmol), 3-(1-pyrrolyl)propan-1-ol (63 mg, 0.50 mmol), and DMAP (13 mg, 0.1 mmol) were dissolved in dry THF (10 mL) and the resulting mixture was stirred under argon at room temperature. After the addition of triethylamine (3 mL), the mixture was cooled to 0 °C, whereupon a 50% solution of *n*-propylphosphonic anhydride in ethyl acetate (0.4 mL) was slowly added. The resulting mixture was stirred for 30 min at 0 °C and then for 12 h at room temperature. It was subsequently taken up in dichloromethane (50 mL), and washed four times with 1 N aq. HCl and once with saturated sodium hydrogen carbonate solution. The organic phase was concentrated and the residue was chromatographed on aluminium oxide eluting with dichloromethane/methanol (15:1). Crystallization from chloroform/diethyl ether gave **10a** as a red-brown solid. Yield: 16.2 mg (21 μmol, 55%). − UV/Vis (CHCl$_3$): λ_{max} (log ε) = 376 (4.84), 400 (4.77, sh), 488 (4.33), 528 (4.31), 616 nm (4.18). − MS (EI): *m*/*z* (%) = 781 [M$^+$] (85). − HRMS ($C_{44}H_{46}{}^{59}CoN_6O_4$): calcd. 781.2913; found 781.2918.

(2*RS*,3*RS*)- and (2*RS*,3*SR*)-Chloro[13,17-bis{2-[3-(1-pyrrolyl)propyloxycarbonyl]ethyl}-3-(*N*,*N*-dimethylcarbamoylmethyl)-3-ethyl-2,7,12,18-tetramethyl-2,3-dihydroporphyrinato]iron(III) (*rac*-12a): At room temperature, (2*RS*,3*RS*)- and (2*RS*,3*SR*)-2-(*N*,*N*-dimethylcarbamoylmethyl)-3-ethyl-2,7,12,18-tetramethyl-2,3-dihydro-22*H*,24*H*-porphyrin-13,17-dipropionic acid (*rac*-**11**) (24 mg) was dissolved in CHCl$_3$ (15 mL) and methanol (15 mL). After the addition of iron(II) chloride tetrahydrate (151 mg, 0.76 mmol) and 2,6-lutidine (1 mL), the green solution was stirred for 16 h at 60 °C. The solvent was subsequently evaporated and the residue was dried under high vacuum. The iron chlorin was then dissolved in dry THF (20 mL) along with 3-(1-pyrrolyl)propan-1-ol (190 mg, 1.52 mmol) and DMAP (14 mg, 0.1 mmol) and the resulting mixture was stirred under argon at room temperature. After the addition of triethylamine (3 mL), the mixture was cooled to 0 °C, whereupon a 50% solution of *n*-propylphosphonic anhydride in ethyl acetate (0.45 mL) was slowly added. The resulting mixture was stirred for 30 min at 0 °C and then for 18 h at room temperature. It was subsequently taken up in dichloromethane (50 mL), and washed with 0.5 N aq. HCl and saturated sodium hydrogen carbonate solution. The organic phase was concentrated and the residue was chromatographed on silica gel eluting with dichloromethane/methanol (8:1) to give *rac*-**12a** as a green solid. Yield: 33 mg (36 μmol, 94%). − UV/Vis ($CHCl_3$): λ_{max} (log ε) = 384 (4.78), 464 (4.11, sh), 559 (3.90), 606 (3.98), 664 nm (3.89). − MS (DCI): *m*/*z* (%) = 927 [M^- − H, ^{56}Fe], 893 (29), 840 (3), 805 (23).

(2*RS*,3*RS*)- and (2*RS*,3*SR*)-Chloro[13,17-bis{2-[3-(1-pyrrolyl)propyloxycarbonyl]ethyl}-3-(*N*,*N*-dimethylcarbamoylmethyl)-3-ethyl-2,7,12,18-tetramethyl-2,3-dihydroporphyrinato]manganese(III) (*rac*-12b): At room temperature, (2*RS*,3*RS*)- and (2*RS*,3*SR*)-2-(*N*,*N*-dimethylcarbamoylmethyl)-3-ethyl-2,7,12,18-tetramethyl-2,3-dihydro-22*H*,24*H*-porphyrin-13,17-dipropionic acid (*rac*-**11**) was dissolved in $CHCl_3$ (15 mL) and methanol (15 mL). After the addition of manganese(II) chloride (73 mg, 0.6 mmol) and 2,6-lutidine (1 mL), the green solution was stirred for 16 h at 60 °C. The solvent was then evaporated and the residue was dried under high vacuum. The manganese chlorin was then dissolved in dry THF (20 mL) together with 3-(1-pyrrolyl)propan-1-ol (143 mg, 1.14 mmol) and DMAP (11 mg, 86 μmol) and the resulting mixture was stirred under argon at room temperature. After the addition of triethylamine (3 mL), the mixture was cooled to 0 °C, whereupon a 50% solution of *n*-propylphosphonic anhydride in ethyl acetate (0.3 mL) was slowly added. The resulting mixture was stirred for 30 min at 0 °C and then for 18 h at room temperature. It was subsequently taken up in dichloromethane (50 mL), and washed four times with 0.5 N aq. HCl and once with saturated sodium hydrogen carbonate solution. The organic phase was concentrated and the residue was chromatographed on silica gel eluting with dichloromethane/methanol (8:1 → 4:1) to give *rac*-**12b** as a dark-green solid. Yield: 17.6 mg (19 μmol, 66%). − UV/Vis ($CHCl_3$): λ_{max} (log ε) = 365 (4.92), 438 (4.56), 485 (4.34), 527 (3.96), 611 (3.96, sh), 654 nm (4.50). − MS (DCI): *m*/*z* (%) = 891 [M^- − HCl] (15), 839 (5), 805 (31). − HRMS ($C_{50}H_{58}{}^{55}MnN_7O_5$): calcd. 891.3880; found 891.3880 ± 5 ppm.

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