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Oligocyclization of 2-(hydroxymethyl)pyrroles with electron-withdrawing groups at β-positions: formation and structural elucidation of porphyrinogens and hexaphyrinogens †

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Acid-catalyzed oligomerization of 2-(hydroxymethyl)pyrroles bearing C_6F_5, 2,6-$Cl_2C_6H_3$, CF_3 and CO_2Et groups at β-positions was examined. The reaction of ethyl pyrrole-3-carboxylates gave a mixture of oligomers and type I isomers of porphyrinogens and hexaphyrinogens were isolated when the other β-substituents were sufficiently bulky, for example, mesityl, 2,6-$Cl_2C_6H_3$ and C_6F_5 groups. On the other hand, the pyrroles having other electron-withdrawing groups afforded porphyrinogens as the only isolable products.

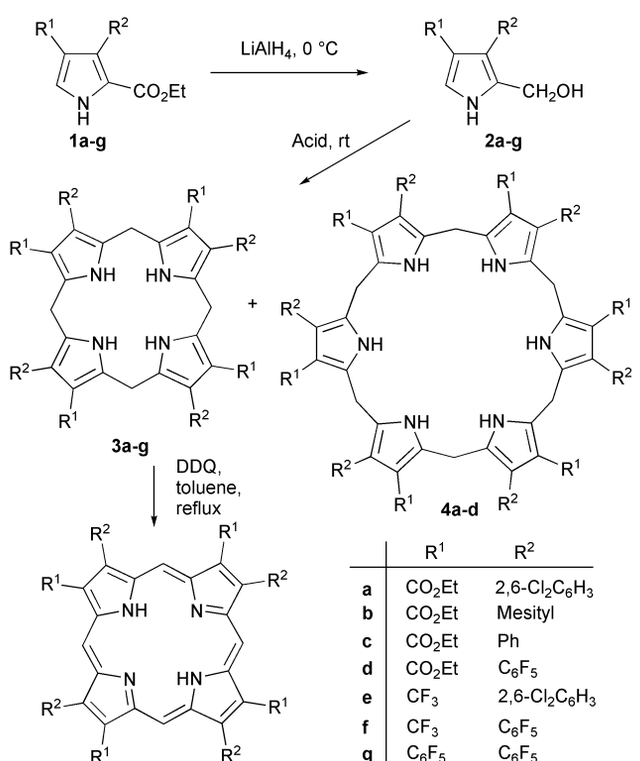
Introduction

The preparation of porphyrins has attracted much attention from an increasing number of scientists from many fields due not only to their important biological roles but also because of their applications as highly functional materials. For the latter purpose, many excellent and reliable methods represented by Lindsey, MacDonald, and [3 + 1] porphyrin syntheses have been developed.[1,2] Above all, the Lindsey and related methods, based on the cyclotetramerization of pyrroles with aldehydes or the condensation of dipyrromethanes with aldehydes are the best in terms of the versatility, efficiency and applicability of preparations of a wide variety of *meso*-substituted porphyrins.[1] In the Lindsey procedure, however, only pyrroles with the same β-substituents can be employed as the pyrrolic unit, as otherwise there is a great intrinsic problem with mixtures of peripheral substitution-type isomers being formed. Moreover, scrambling of the pyrrole units became a major problem in porphyrinogen formation when different dipyrromethanes were condensed.[3] In order to prepare isomerically pure porphyrins with a variety of substituents at the β-positions, methods involving the tetrameric condensation of α-hydroxymethyl- or α-aminomethyl-substituted pyrroles and the dimeric condensation of dipyrromethanes under mild conditions were developed.[4] Even in this case, the success of the synthesis depended on the nature of the pyrrolic β-substituents: electron-withdrawing groups tended to suppress pyrrole migration, while electron-donating groups promoted the migration yielding mixtures.[5] We found that a combination of bulky and electron-withdrawing substituents at the β-pyrrolic position is successful in suppressing the problematic pyrrole migration in the acid-catalyzed cyclo-oligomerization of α-hydroxymethylpyrrole derivatives[6] and we succeeded in the first isolation of isomerically pure *meso*-unsubstituted porphyrinogens and hexaphyrinogens.[7] In this paper, we discuss the detailed study of the cyclo-oligomerization reaction as well as the structural elucidation of the porphyrinogens, hexaphyrinogens, and porphyrins with electron-withdrawing groups.

Results and discussion

Oligocyclization of 2-hydroxymethylpyrroles

Acid-catalyzed oligomerization of ethyl 2-(hydroxymethyl)-3-(2,6-dichlorophenyl)pyrrole-4-carboxylate (**2a**, 0.04 M), which was obtained by regioselective reduction of the corresponding pyrrole-2,4-dicarboxylate **1a**,[8] was carried out by treatment with *p*-toluenesulfonic acid (pTSA) in chloroform for 12 h to give a rather intractable mixture. GPC analysis of this mixture revealed the existence of two major components, which were proven to be porphyrinogen (26%) and hexaphyrinogen (2%) by column chromatographic isolation (Scheme 1). Isolation of



Scheme 1 Oligocyclization of 2-hydroxymethylpyrroles with electron-withdrawing groups at the β-positions.

† Electronic Supporting Information Available: Ortep drawings of **3d**·2EtOH, **3d**·2DMF, **3e**, **3e**·2H_2O, **3g**·2(i-PrOH), **3g**·2DMF·2$CHCl_3$, **4a**·4$CHCl_3$, **4a**·4PhCl, **5a**·2PhCl, **5d**, **5d**·½PhCl, and **5e**; packing diagrams of **5d** and **5d**·½PhCl; and their X-ray analyses data in CIF format. See http://www.rsc.org/suppdata/ob/b3/b307132d/

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Table 1 Cyclo-oligomerization of pyrrole-2-carboxylates **1** *via* 2-(hydroxymethyl)pyrroles **2**

Entry	1,2	Solvent (conc./M)	Acid (equiv.)	Yield (%) 3 (5)[a]	Yield (%) 4
1	**a**	$CHCl_3$ (0.04)	pTSA (0.5)	26	2
2	**a**	$C_2H_4Cl_2$ (0.04)	pTSA (0.5)	64	6
3	**a**	$C_2H_4Cl_2$ (0.04)	pTSA (1.0)	63	6
4	**a**	$C_2H_4Cl_2$ (0.02)	pTSA (1.0)	57	5
5	**a**	$C_2H_4Cl_2$ (0.02)	$Sc(OTf)_3$ (1.0)	22	—
6	**a**	$C_2H_4Cl_2$ (0.04)	K-10 (1.0[b])	8	3
7	**a**	$C_2H_4Cl_2$ (0.04)	TFA (1.0)	47	13
8	**a**	$C_2H_4Cl_2$ (0.04)	$BF_3{\cdot}OEt_2$ (1.0)	40	10
9	**b**	$C_2H_4Cl_2$ (0.04)	pTSA (1.0)	(8)	22
10	**b**	$C_2H_4Cl_2$ (0.04)	$BF_3{\cdot}OEt_2$ (1.0)	(3)[c]	20
11	**c**	$C_2H_4Cl_2$ (0.04)	pTSA (1.0)	(20)[c,d]	—
12	**c**	$C_2H_4Cl_2$ (0.04)	K-10 (1.0[b])	(5)[c,e]	—
13	**d**	$C_2H_4Cl_2$ (0.04)	pTSA (1.0)	19	6
14	**e**	$C_2H_4Cl_2$ (0.04)	pTSA (1.0)	17[c]	—
15	**f**	$C_2H_4Cl_2$ (0.04)	pTSA (1.0)	12	—
16	**g**	$C_2H_4Cl_2$ (0.04)	pTSA (1.0)	12	—

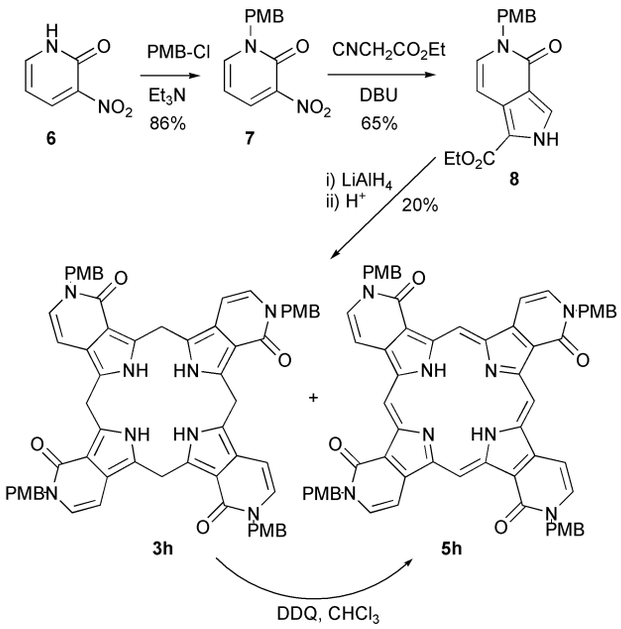
[a] Yields of **5** are given in the parentheses. [b] g mmol^{-1}. [c] Oxidation with *p*-chloranil or DDQ was carried out at room temperature after termination of the oligomerization with Et_3N. [d] An isomeric mixture (3 : trace : 2 : 1) was obtained. [e] Only the type I isomer was obtained.

other components was not successful due to their instability, although cyclic pentamer, heptamer, or higher oligomers were formed, as diagnosed from the GPC chromatogram and MALDI-TOF mass spectroscopy. In order to increase the amounts of these products, the reaction conditions were tested and the results are summarized in Table 1.

Use of pTSA (0.5–1.0 equiv.) as the acid catalyst, dichloroethane as the solvent and a concentration of **2** of 0.02–0.04 mmol cm^{-3} gave the best results (entries 2–4). All hexaphyrinogens obtained were very stable toward oxidation even on treatment with DDQ at room temperature, while only porphyrinogens derived from pyrroles bearing a bulky electron-deficient aromatic group, such as 2,6-dichlorophenyl and pentafluorophenyl, were stable and these could be isolated by chromatography (entries 1–8 and 13–16). Porphyrinogens with phenyl and mesityl groups were readily oxidized to the corresponding porphyrins **5b** and **5c** even during the workup manipulation, and mixtures of porphyrinogens and porphyrins were obtained. Therefore, the reaction mixtures were treated with *p*-chloranil at room temperature before chromatographic isolation (entries 10–12). When the acid was changed from pTSA to acidic clay (K-10)[4c] in the reaction of **2c**, only the type I isomer of porphyrin **5c** was obtained, although the yield was poor (entry 12).

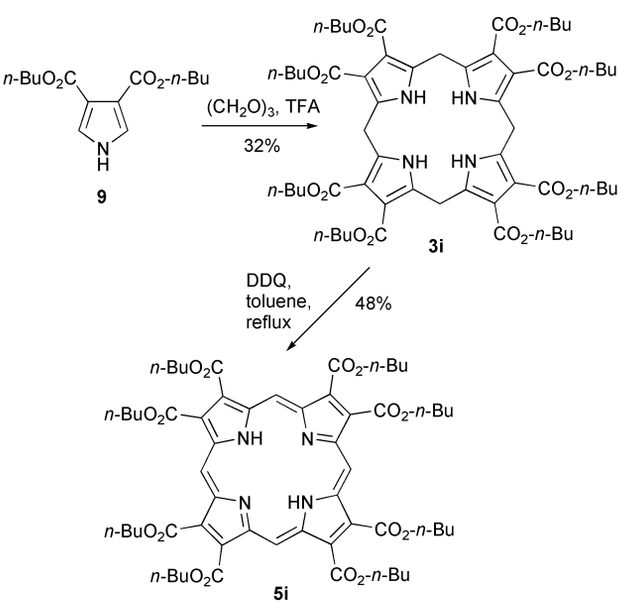
Two distinctive features emerged from Table 1. First, the hexaphyrinogens were only isolated in the reactions of pyrroles which had ester and bulky electron-withdrawing aromatic groups at the β-positions. Secondly, the readily formed porphyrin **5c** was a mixture of peripheral-substituted type isomers, whereas the other porphyrinogens listed in Table 1 were isomerically pure. These facts suggest that the bulkiness of the aromatic substituents does not only suppress the pyrrole isomerization process[9] but also favours the structure of the key intermediates in hexaphyrinogen formation in the cyclo-oligomerization. The hexaphyrinogens showed a quite interesting hexagonal columnar structure (discussed later), and would be a new type of host molecules[10] if the bulkiness of the aromatic rings was reduced. We carried out the cyclo-oligomerization of the following compounds.

Pyridone-fused pyrrole **8**[11] was synthesized from 3-nitro-2-pyridone *via* *p*-methoxybenzyl-protection (PMB) followed by the Barton–Zard reaction with ethyl isocyanoacetate, and was subject to the cyclo-oligomerization reaction. None of the corresponding hexaphyrinogens was formed even in the reaction mixture, and porphyrinogen **3h** contaminated with a small amount of porphyrin **5h** was isolated in 20% yield (Scheme 2). This mixture was oxidized by DDQ to give porphyrin **5h** with poor solubility in common solvents.



Scheme 2 Cyclo-oligomerization of pyridone-fused pyrrole.

Pyrrole-3,4-dicarboxylates **9** were prepared according to the method reported by van Leusen.[12] Cyclo-oligomerization of **9** with formaldehyde equivalents such as trioxane was performed under several conditions similar to those listed in Table 1. However, no reaction was observed under any of the reaction conditions. Finally, we treated **9** with trioxane in TFA as the solvent at room temperature overnight, and porphyrinogen **3i** was obtained in 32% yield (Scheme 3). In this case, formation of the hexaphyrinogen could not be detected by the MALDI-TOF analysis of the reaction mixture. The porphyrinogen **3i** was oxidized with DDQ in refluxing toluene to give the corresponding porphyrin octaester in 48% yield.



Scheme 3 Cyclo-oligomerization of dibutyl pyrrole-3,4-dicarboxylate.

X-Ray analysis of porphyrinogens

We attempted to prepare crystals for X-ray analysis by slow evaporation of alcoholic (MeOH, EtOH, and i-PrOH) or

Table 2 Crystallographic data for porphyrinogens[a]

Compound	**3a**·2(i-PrOH)[b]	**3d**·2EtOH	**3d**·2DMF	**3e**	**3e**·2H_2O	**3g**·2(i-PrOH)	**3g**·2DMF·$CHCl_3$
Formula	$C_{62}H_{60}Cl_8N_4O_{10}$	$C_{60}H_{44}F_{20}N_4O_{10}$	$C_{62}H_{46}F_{20}N_6O_{10}$	$C_{48}H_{24}Cl_8F_{12}N_4$	$C_{48}H_{28}Cl_8F_{12}N_4O_2$	$C_{74}H_{28}F_{40}N_4O_2$	$C_{75}H_{27}Cl_3F_{40}N_6O_2$
FW	1304.8	1361.0	1415.1	1168.4	1204.4	1765.0	1910.38
Temp./°C	rt	−150	rt	rt	rt	−100	rt
System	Triclinic	Triclinic	Triclinic	Tetragonal	Tetragonal	Monoclinic	Monoclinic
Space group	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$	$I4_1/a$	$I4_1/a$	$P2_1/n$	$P2_1/n$
a/Å	12.571(6)	8.728(1)	9.599(1)	15.963(1)	13.102(2)	18.886(2)	15.679(3)
b/Å	14.418(7)	11.841(1)	11.653(2)	15.963(1)	13.102(2)	18.183(2)	10.995(3)
c/Å	9.414(4)	14.930(2)	15.605(2)	20.165(2)	27.375(3)	9.886(2)	23.426(2)
α/°	100.63(4)	71.632 (9)	110.08(1)	90	90	90	90
β/°	95.88(4)	80.69(1)	95.75(1)	90	90	90.428(3)	100.469(3)
γ/°	112.38(4)	81.70(1)	106.70(1)	90	90	90	90
V/Å^3	1522(2)	1437.9(3)	1531.5(4)	5138.3(6)	4699(1)	3394.8(8)	3971(2)
Z	1	1	1	4	4	2	2
μ/cm^{-1}	3.89	1.49	1.44	5.20	5.74	1.81	3.62
$2\theta_{max}$/°	123.2	55.0	55.0	55.0	55.0	50.7	55.0
Unique refln.	4728	6023	7046	3165	2697	6072	9129
No. obs.[c]	3168[d]	4923	3256	1394	1507	3725	4033
R_{int}	0.024	0.021	0.039	0.026	0.022	0.060	0.054
No. var.	387	448	467	203	224	570	609
R_1[e]	0.053[d]	0.055	0.061	0.069	0.052	0.069	0.077
R[f]	0.053[d]	0.066	0.106	0.123	0.081	0.091	0.151
wR[g]	0.069[d]	0.126	0.159	0.202	0.117	0.142	0.202
GOF	1.980	1.403	1.104	1.647	1.16	1.209	1.32

[a] Unless otherwise noted, Mo-Kα was employed. [b] Cu-Kα was used. [c] $I > 2\sigma(I)$. [d] $I > 3\sigma(I)$. [e] $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$ for $I > 2\sigma(I)$ data. [f] $R = \Sigma(F_o^2 - F_c^2)/\Sigma F_o^2$ for all data. [g] $wR = \{\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[w(F_o^2)^2]\}^{1/2}$ for all data.

chloroform solutions containing a small amount of DMF. In some cases, suitable crystals for X-ray analysis were obtained and the crystallographic data for successfully solved structures of porphyrinogens are listed in Table 2.

CCDC reference numbers 213884–213889. †

3a·2(i-PrOH)[7]. The porphyrinogen **3a** occupies one of the special positions (−1) and has a *1,2-alternate* structure which is constructed by hydrogen bonds between the *i*-PrOH oxygen and two adjacent pyrrolic NH atoms [NH ··· O, 2.950(4) and 3.022(3) Å]. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 43.5(1)° and 58.8(1)°.

3d·2EtOH. The porphyrinogen **3d** occupies one of the special positions (−1) and has a *1,2-alternate* structure which is constructed by hydrogen bonds between the EtOH oxygen and two adjacent pyrrolic NH atoms [NH ··· O, 2.842(1) and 3.022(2) Å]. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 59.98(6)° and 60.46(6)°.

3d·2DMF. The porphyrinogen **3d** occupies one of the special positions (−1) and has a *1,2-alternate* structure which is constructed by hydrogen bonds between the DMF oxygen and two adjacent pyrrolic NH atoms [NH ··· O, 2.802(3) and 2.917(3) Å]. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 42.05(11)° and 66.01(11)°.

3e and 3e·2H_2O. Two types of crystals were obtained by slow evaporation of the solvent from a solution of **3e** in i-PrOH. Elemental analysis showed that one molecule of water existed in the crystals. First, a block crystal, which easily formed large crystals, was subject to the X-ray analysis, and the crystal was revealed to consist of only **3e**. The porphyrinogen **3e** in this crystal occupies one of the special positions (−4) and has a *1,3-alternate* structure. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 71.2(1)°. X-Ray analysis of an octahedral crystal shows that this crystal of **3e** contains two molecules of water. The porphyrinogen **3e** in this crystal occupies one of the special positions (−4) and adopts a *1,3-alternate* structure. The oxygen atoms of the water molecules sit on the special axis with (2.) symmetry which goes through the center of **3e**. Hydrogen bonds are observed between the water oxygen and two facing pyrrolic NH atoms [NH ··· O, 3.002(3) Å]. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 56.0(1)°.

3g·2(i-PrOH). The porphyrinogen **3g** occupies one of the special positions (−1) and has a *1,2-alternate* structure which is constructed by hydrogen bonds between the i-PrOH oxygen and two adjacent pyrrolic NH atoms [NH ··· O, 2.964(3) and 2.944(3) Å]. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 45.1(1)° and 54.5(1)°.

3g·2DMF·2$CHCl_3$. The porphyrinogen **3g** occupies one of the special positions (−1) and has a *1,2-alternate* structure which is constructed by hydrogen bonds between the DMF oxygen and two adjacent pyrrolic NH atoms [NH ··· O, 2.819(4) and 2.843(3) Å]. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 42.2(1)° and 47.6(1)°.

Radial views from the centre of the porphyrinogen are shown in Fig. 1. In the 1,2-alternate structures (**3a**, **3d**, and **3g**), the angles between the pyrrole rings and the mean plane of the *meso*-carbons are from 42.2(1)° to 60.46(6)°. The difference between the angles in **3d**·2EtOH is very small compared to the others, which may be attributed to the steric effects of the included solvent molecules: ethanol is smaller than i-PrOH and DMF. The crystal structures of the *meso*-octasubstituted porphyrinogens, namely calix[4]pyrroles,[13] have been extensively studied in order to prove their interesting anion-binding ability[14] and ability to π-donate to metal cations.[15] In calix[4]pyrroles, 1,2-alternate and 1,3-alternate structures have often been observed, while the cone structures have only been reported when the calix[4]pyrroles were co-crystallized with halide anions such as fluoride.[16] In our case too, no cone structure was observed. The tendency to adopt the 1,2-alternate or 1,3-alternate structure remains unclear, and it is probably affected by even a small change in the steric and electronic properties of the substituents on the porphyrinogens and included solvents.[16] It is worthy to note that the cell volume of **3e** is larger than that of **3e**·2H_2O. According to PLATON calculations,[17] there are eight solvent accessible areas (53 Å^3 each) centered at specific positions (−1) in the unit cell of **3e**. Although the voids are large enough for water molecules, water

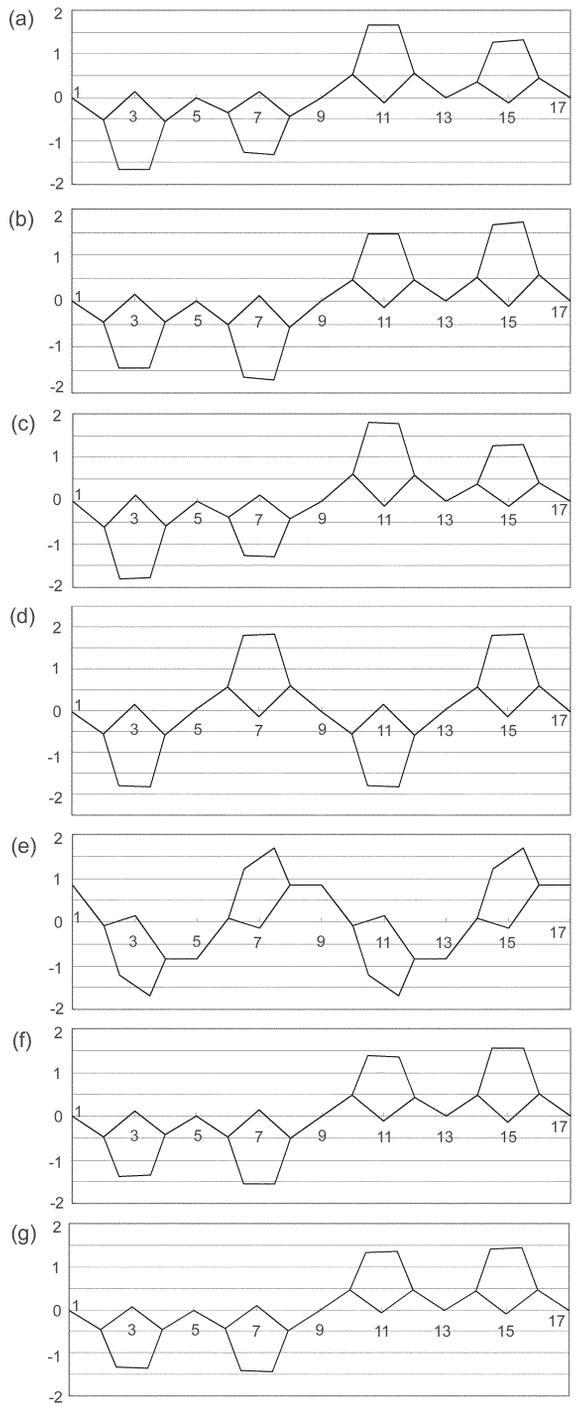


Fig. 1 Radial views from the centre of the porphyrinogen. The distances (Å) are calculated from the mean plane of the *meso* carbons. Atoms labelled as 1 and 17 are the same *meso* carbon. (a) **3a**·2(i-PrOH). (b) **3d**·2EtOH. (c) **3d**·2DMF. (d) **3e**. (e) **3e**·2H_2O. (f) **3g**·2(i-PrOH). (g) **3g**·2DMF·2$CHCl_3$.

may not be incorporated into this crystal because the voids are surrounded by highly hydrophobic groups such as dichlorophenyl or trifluoromethyl groups. The dihedral angles between the pyrrole planes and a plane made by the methylene carbon and its adjacent pyrrolic α-carbons are similar and the values are 54.0(1)° and 53.1(1)°. Therefore, the methylene protons are nearly eclipsed with respect to the pyrrole planes and the porphyrinogen in this structure forms an almost complete saddle conformation (Fig. 1d). On the other hand, the angles are 47.53(9)° and 64.40(9)° in the crystal of **3e**·2H_2O and the porphyrinogen in this structure exists as a distorted saddle conformation (Fig. 1e).

X-Ray analysis of hexaphyrinogens

Crystallographic data for successfully solved structures of hexaphyrinogens **4** are listed in Table 3.

CCDC reference numbers 213890–213892. †

4a·4$CHCl_3$. The hexaphyrinogen **4a** occupies one of the special positions (−1) and has a *1,3,5-alternate* structure which is constructed by intermolecular hydrogen bonds between the pyrrolic NH and the ester oxygen on the adjacent pyrrole ring [NH ··· O, 2.894(5), 2.906(5), and 2.978(5) Å]. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 85.9(2)°, 87.2(2)°, and 88.4(2)°. Thus, the hexaphyrinogen **4a** in this crystal forms a hexagonal tubular structure. Chloroform molecules occupy side areas between the tubular hexaphyrinogen molecules with a disordered structure.

4a·4PhCl. The hexaphyrinogen **4a** occupies one of the special positions (−1) and has a *1,3,5-alternate* structure which is constructed by intermolecular hydrogen bonds between the pyrrolic NH and the ester oxygen on the adjacent pyrrole ring [NH ··· O, 2.891(5), 2.891(5), and 2.913(5) Å]. The angles between the pyrrole rings and the mean plane of the *meso*-carbons are 87.0(1)°, 87.3(1)°, and 90.0(1)°. The structure of the hexaphyrinogen **4a** in this crystal is almost the same as that of **4a**·4$CHCl_3$.

4b·$CHCl_3$[7]**.** Crystallographically, two independent hexagonal tube molecules of **4b** exist in the unit cell, occupy special positions with −3 and −1 symmetries, and adopt an almost complete *1,3,5-alternate* conformation. The solvent chloroform molecules also occupy other −3 and −1 symmetric positions with disordered structures. The pyrrole rings of **4b** are almost perpendicular to the mean plane of the six *meso*-methylenes [88.8(1)° for the −3 structure; 82.8(2)°, 88.2(2)°, and 89.1(2)° for the −1 structure]. The intramolecular hydrogen bond [NH ··· O, 2.842(5) Å for the −3 structure; 2.772(5), 2.894(5), and 2.822(5) Å for the −1 structure] keeps this conformation tight.

Radial views from the centre of the hexaphyrinogen are shown in Fig. 2. In all 1,3,5-alternate structures, the angles between the pyrrole rings and the mean plane of the *meso*-

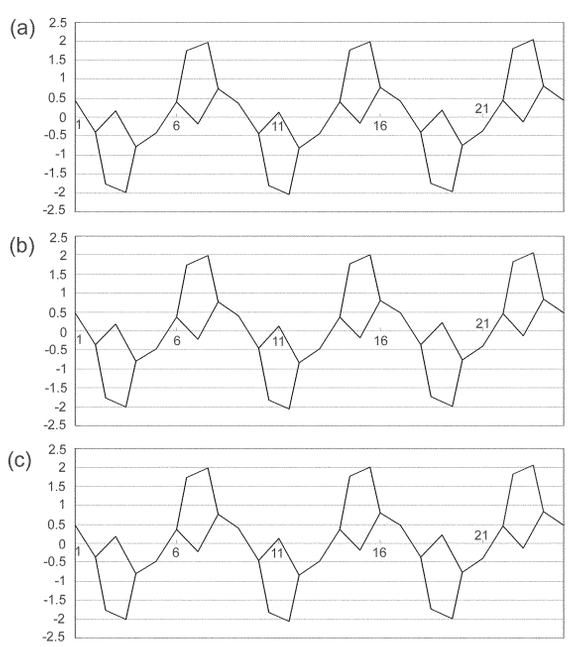


Fig. 2 Radial views from the centre of the porphyrinogen. The distances (Å) are calculated from the mean plane of the *meso*-carbons. Atoms labelled as 1 and 25 are the same *meso*-carbon. (a) **4a**·4$CHCl_3$. (b) **4a**·4PhCl. (c) **4b**·$CHCl_3$.

Table 3 Crystallographic data for hexaphyrinogens[a]

Compound	**4a**·4$CHCl_3$[b]	**4a**·4ClPh[b]	**4b**·$CHCl_3$
Formula	$C_{88}H_{70}Cl_{24}N_6O_{12}$	$C_{108}H_{86}Cl_{16}N_6O_{12}$	$C_{103}H_{115}Cl_3N_6O_{12}$
FW	2254.4	2227.2	1735.4
Temp./°C	−100	rt	−130
System	Orthorombic	Monoclinic	Trigonal
Space group	*Pbca*	$P2_1/n$	$R\bar{3}$
a/Å	25.555(9)	18.487(2)	43.981(2)
b/Å	15.884(9)	15.093(2)	43.981(1)
c/Å	25.659(8)	19.312(1)	17.017(1)
α/°	90	90	90
β/°	90	94.823(7)	90
γ/°	90	90	120
V/Å^3	10415(5)	5369.2(8)	28507(2)
Z	4	2	12
μ/cm^{-1}	6.84	4.71	1.60
$2\theta_{max}$/°	51.4	55.0	55.0
Unique refln.	6475	12641	14402
No. obs.[c]	6472 [3785]	4422 [4324]	6480[d]
R_{int}	0.015	0.027	0.074
No. var.	610 [518]	562 [514]	765
R_1[e]	0.073 [0.087]	0.088 [0.062]	0.076[d]
R[f]	0.134 [0.093]	0.171 [0.148]	0.076[d]
wR[g]	0.176 [0.248]	0.247 [0.201]	0.094[d]
GOF	1.976 [1.136]	1.668 [0.820]	1.739

[a] Mo-Kα was employed. [b] Values in brackets were obtained when the hexaphyrinogen molecule in the absence of solvent was refined by several cycles of the SHELXL and PLATON-SQUEEZE programs. For detailed information, see the supporting information.† [c] $I > 2\sigma(I)$. [d] $I > 3\sigma(I)$. [e] $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$ for $I > 2\sigma(I)$ data. [f] $R = \Sigma(F_o^2 - F_c^2)/\Sigma F$ for all data. [g] $wR = \{\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[w(F_o^2)^2]\}^{1/2}$ for all data.

carbons are almost perpendicular and within a range from 82.8(2)° to 90.0(1)°, even though the space groups of the crystals are different. The pyrrole β carbons bearing the ester group are closer to the mean planes than the other β carbons due to the hydrogen bonding with the adjacent pyrrolic protons. The tight intramolecular hydrogen bonding is probably the main reason for the structural differences between this and calix[6]pyrrole,[10e] three *1,3,5-alternate* pyrroles of which point towards the center of the cavity. These hexaphyrinogen structures are also refined in the absence of solvent molecules by several cycles of the SHELXL refinement and the SQUEEZE program of PLATON,[17] and the results are also listed in Table 3. According to the PLATON calculation,[17] there is a void (59–66 Å^3) in the center of the hexaphyrinogens. Although the voids are large enough for small molecules such as water, no molecule could be found by the differential Fourier map.

NMR analysis of oligophyrinogens

In the proton NMR spectra of porphyrinogen **3a** in $CDCl_3$, very broad signals due to *meso*-methylene protons were observed at δ 3.1–4.9 at room temperature and became a sharp AB-quartet at low temperatures. The coalescence temperatures and approximate $\Delta E^{\ddagger}$ values for the conformational change were *ca*. 35 °C and 58 kJ mol^{-1} for **3a**. For the other porphyrinogens, **3d**, **3e**, **3f** and **3g**, the *meso*-methylene proton signals appeared as slightly broad singlets and showed almost no change in the temperature range measured (−50 to 50 °C). On the other hand, *meso*-methylene protons of hexaphyrinogens **4a**, **4b** and **4d** in $CDCl_3$ appeared as AB-quartets. Pyrrolic protons appeared in rather lower fields compared to the parent pyrroles and the stretching of NH and C=O in the IR spectra supported the presence of intramolecular hydrogen bonding in solution. The non-equivalence of the *meso*-protons in **4a** and **4b** persisted in toluene-d_8 solution even at 100 °C. On the other hand, the *meso*-protons of **4d** appeared as two broad singlet signals at 50 °C in $CDCl_3$, although the coalescence temperature could not be measured due to poor solubility in toluene-d_8. These facts suggested that the hexagonal columnar structure of the hexaphyrinogens was stabilized both by the intramolecular hydrogen bonding and by the steric effect of the aromatic substituents.

Table 4 Oxidation of Porphyrinogens

Porphyrinogen	Porphyrin	Yield (%)
3a	**5a**	66
3d	**5d**	38
3e	**5e**	50
3f	**5f**	38
3g	**5g**	Trace
3i	**5i**	48

Oxidation of porphyrinogens

The porphyrinogens **3** with electron-withdrawing groups were oxidized by refluxing with DDQ in toluene or chloroform to give isomerically pure porphyrins in good yields except for **3g** and the results are summarized in Table 4. In the case of **3g**, severe oxidation conditions caused the decomposition of the starting material and/or product. Only trace amounts of the porphyrin could be obtained in spite of all of our efforts. In contrast to the porphyrinogens, the isolated hexaphyrinogens **4** were inert to oxidation. The isolated hexaphyrinogen **4a** could not be oxidized with DDQ either under reflux in toluene or in the presence of an acid such as pTSA and BF_3·OEt_2.[18] Some good porphyrin crystals were obtained for X-ray analysis by slow evaporation of the saturated solution of the porphyrins in chlorobenzene or chloroform. Crystallographic data for successfully solved structures of porphyrins **5** are listed in Table 5.

CCDC reference numbers 213893–213897. †

5a·2PhCl. The porphyrin **5a** occupies one of the special positions (−1) and the porphyrin ring is slightly distorted. The porphyrin molecules do not stack due to the steric hindrance of the dichlorophenyl groups which are nearly perpendicular to the porphyrin ring [83.0(2)° and 83.5(1)°].

5d. The space group is *C*2/*c*. Two porphyrin molecules stack to form a dimeric structure and the porphyrin ring is distorted in a cone structure due to the steric repulsion of peripheral substituents in the dimeric form. The angles between the porphyrin mean plane and the pentafluorophenyl group are 54.31(6)°, 59.47(6)°, 62.94(6)°, and 67.53(7)°.

Table 5 Crystallographic data for porphyrins[a]

Compound	**5a**·2PhCl	**5d**	**5d**·½PhCl	**5e**
FW	1403.7	1262.81	1319.1	1162.3
Temp./°C	rt	−100	−150	−100
System	Monoclinic	Monoclinic	Monoclinic	Monoclinic
Space group	$P2_1/a$	$C2/c$	$C2/c$	$P2_1/a$
a/Å	14.020(3)	21.856(3)	21.093(3)	14.995(3)
b/Å	18.711(3)	25.827(3)	25.700(3)	12.084(2)
c/Å	14.289(3)	19.842(3)	19.961(2)	15.045(3)
α/°	90	90	90	90
β/°	117.76(1)	115.244(3)	107.100(3)	116.762(4)
γ/°	90	90	90	90
V/Å^3	3317(1)	10130(2)	10342(2)	2434.1(9)
Z	2	8	8	2
μ/cm^{-1}	4.77	1.60	1.86	5.48
$2\theta_{max}$/°	55.0	55.0	55.0	55.0
Unique refln.	7608	11439	11738	5777
No. obs.[b]	3122	8310	8228	3298
R_{int}	0.054	0.042	0.045	0.038
No. var.	439	793	829	337
R_1[c]	0.070	0.051	0.047	0.074
R[d]	0.145	0.073	0.086	0.115
wR[e]	0.179	0.127	0.108	0.178
GOF	1.104	1.239	0.990	1.665

[a] Mo-Kα was employed. [b] $I > 2\sigma(I)$. [c] $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$ for $I > 2\sigma(I)$ data. [d] $R = \Sigma(F_o^2 - F_c^2)/\Sigma F$ for all data. [e] $wR = \{\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[w(F_o^2)^2]\}^{1/2}$ for all data.

5d·½PhCl. Two porphyrin molecules stack to form a dimeric structure and the porphyrin ring is distorted to form a dome structure.[19] The chlorobenzene molecule also occupies a special position (−1) with a disordered structure on the concave face of the porphyrin. The angles between the porphyrin mean plane and the pentafluorophenyl group are 52.30(8)°, 56.30(7)°, 68.83(8)°, and 71.97(7)°.

5e. The porphyrin **5e** occupies one of the special positions (−1) and the porphyrin ring is slightly distorted. The porphyrin molecules do not stack due to the steric hindrance of the dichlorophenyl groups which are nearly perpendicular to the porphyrin ring [84.4(1)° and 85.3(1)°].

Porphyrins with bulky 2,6-dichlorophenyl groups **5a** and **5e** were almost flat but slightly undulated to adopt a wave conformation (Fig. 3).[19] On the other hand, porphyrins with pentafluorophenyl groups formed π-stacking dimers facing the convex faces of the dome structure due to the repulsive interactions between the peripheral substituents. One disordered chlorobenzene molecule was caught between the concave faces of the dimers in the crystal of **5d**·½PhCl.

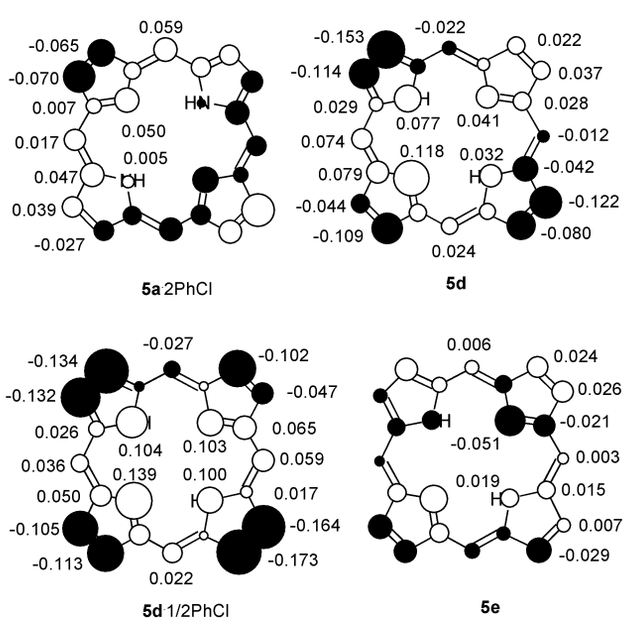


Fig. 3 Distortion of porphyrins. The numerals represent the distances (Å) from the mean porphyrin plane.

In conclusion, we have explored the acid oligomerization of α-pyrrolylmethyl alcohols which gives porphyrinogens and hexaphyrinogens. Substituents at the pyrrole β-positions played an important role in product selectivity. Hexaphyrinogens were successfully isolated only when both ester groups and bulky aromatic groups, such as pentafluorophenyl, 2,6-dichlorophenyl, and mesityl, existed on the pyrrole. In these cases, the formation of positional isomers was not observed for either oligomer. When the substituents were bulky aromatic and trifluoromethyl groups, porphyrinogens were formed as the only isolable product. X-Ray and NMR structural analyses revealed that the structures of the *meso*-unsubstituted porphyrinogens were very flexible and showed various types of conformations even in the solid state, while the structures of the hexaphyrinogens adopted a rigid hexagonal columnar conformation constructed by intramolecular hydrogen bonds. The porphyrinogens obtained could be converted to the corresponding isomerically pure porphyrins.

Experimental

Melting points are uncorrected. Unless otherwise specified, NMR spectra were obtained with a JEOL GSX-270 or EX-400 spectrometer at ambient temperature by using $CDCl_3$ as solvent and tetramethylsilane as the internal standard for ^1H and ^{13}C NMR. Mass spectra were measured with a Hitachi M80B [EI (electron impact, 20 eV) and CI (chemical ionization, 70 eV, isobutane as CI gas)], JEOL MStation [EI (electron impact, 20 eV), CI (chemical ionization, 70 eV, isobutane as CI gas), and FAB (nitrobenzyl alcohol as the matrix)], or Voyager-DE Pro (MALDI-TOF, sinapinic acid as the calibration matrix) spectrometer. THF was distilled from sodium benzophenone ketyl and dichloromethane was distilled from CaH_2 prior to use. DMF was distilled under reduced pressure and then stored over MS 4A. Pyridine was distilled from CaH_2 and stored over MS 4A. Deuterated solvents were used without further purification. DBU, chlorobenzene and hexane were distilled prior to use. Chloroform was successively treated with sulfuric acid, water, saturated sodium hydrogencarbonate, and calcium chloride, passed through an alumina column, and distilled. In

the nomenclature of **4**, we encountered difficulty about the choice of the oxidation state for the so-called hexaphyrin which had two oxidation states. Therefore, we have called the cyclic hexa(pyrrolylmethyl) compounds hexaphyrinogen, the numbering of which is similar to that of porphyrin. Similarly, the cyclic tetra(pyrrolylmethyl) compound was named as porphyrinogen, although it is 5,10,15,20,22,23-hexahydro-21*H*,23*H*-porphine in IUPAC nomenclature. The melting point is not indicated when the melting point of a compound exceeded the upper limit of the apparatus (250 °C). Ethyl pyrrole-2-carboxylates **1b**,[6b] **1c**,[8] **1e**,[8] **1f**[8] and **1g**[20] were prepared according to the literature procedures.

Diethyl 3-(2,6-dichlorophenyl)pyrrole-2,4-dicarboxylate (1a)

A solution of 2,6-dichlorobenzaldehyde (43.75 g, 250 mmol), ethyl tosylacetate (48.40 g, 200 mmol), piperidine (1.0 mL), and acetic acid (3.0 mL) in toluene (150 mL) was refluxed with a Dean–Stark apparatus, and water was removed. When the distillate did not separate, piperidine (1.0 mL) and acetic acid (3.0 mL) were added, and the reflux was continued. After 3 days, the reaction was quenched by the addition of water. The organic layer was separated and the aqueous layer was extracted with toluene. The combined organic layer was washed successively with diluted HCl (1.0 M), water, sat. $NaHCO_3$, and brine, dried over Na_2SO_4, and concentrated. The residue was chromatographed on silica gel (15% EtOAc–hexane) to give a white solid. Recrystallization from CH_2Cl_2–hexane gave 27.86 g (32%) of ethyl (*Z*)-3-(2,6-dichlorophenyl)-2-tosyl-2-propenoate as white crystals, mp 89 °C; δ_H ($CDCl_3$) 8.27 (1H, s), 7.91 (2H, m), 7.32 (4H, m), 7.27 (1H, m), 4.00 (2H, q, J = 7.3 Hz), 2.46 (3H, s) and 0.91 (3H, J = 7.3 Hz); δ_C ($CDCl_3$) 160.3, 144.7, 143.4, 139.5, 136.4, 133.2, 131.4, 130.4, 129.5, 128.6, 127.8, 61.8, 21.6 and 13.2; ν_{max} (KBr)/cm^{-1} 1722, 1323, 1151 and 781; MS (DI-EI) *m*/*z* 399 (M^+, 88), 353 (100) and 243 (13) (Found: C, 54.12; H, 4.02. $C_{18}H_{16}Cl_2O_4S$ requires C, 54.14; H, 4.04%). To a stirred solution of the tosylpropenoate (1.99 g, 5.0 mmol) and ethyl isocyanoacetate (0.75 mL, 7.5 mmol) in dry THF (20 mL) was slowly added freshly distilled DBU (1.0 mL, 10 mmol) at 0 °C under argon. The mixture was allowed to warm to room temperature and stirred for 12 h. Dilute HCl (1.0 M) was added and the mixture was extracted with EtOAc. The organic extract was washed with water and brine, dried over Na_2SO_4, and concentrated. The residue was chromatographed on silica gel ($CHCl_3$) to give 1.21 g (68%) of the title compound as colorless crystals, mp 164–166 °C; δ_H ($CDCl_3$) 10.32 (1H, br s), 7.67 (1H, d, J = 3.4 Hz), 7.36–7.20 (3H, m), 4.17–4.08 (4H, m), 1.08 (3H, t, J = 7.0 Hz) and 1.01 (3H, t, J = 7.0 Hz); δ_C ($CDCl_3$) 163.4, 160.7, 135.2, 133.7, 128.6, 127.4, 127.0, 125.9, 121.3, 116.9, 60.7, 59.8, 13.8 and 13.6; ν_{max} (KBr)/cm^{-1} 3296, 1716, 1684, 1282, 1190 and 1036; MS (EI) 355 (M^+, 14), 320 (100), 274 (64) and 246 (45) (Found: C, 53.89; H, 4.24; N, 3.99. $C_{16}H_{15}Cl_2NO_4$ requires C, 53.95; H, 4.24; N, 3.93%).

Diethyl 3-(pentafluorophenyl)pyrrole-2,4-dicarboxylate (1d)

Pentafluorobenzaldehyde (45.10 g, 230 mmol) and ethyl tosylacetate (48.40 g, 200 mmol) were reacted according to the procedure described above to give 68.90 g (82%) of ethyl (*Z*)-3-pentafluorophenyl-2-tosyl-2-propenoate as yellow crystals, mp 87 °C; δ_H ($CDCl_3$) 7.99 (1H, s), 7.85 (2H, m), 7.37 (2H, m), 4.17 (2H, q, J = 7.3 Hz), 2.47 (3H, s) and 1.15 (3H, t, J = 7.3 Hz); δ_C ($CDCl_3$) 160.8, 145.4, 144.4 (dm, J = 253 Hz), 142.4 (dm, J = 259 Hz), 141.8, 137.8 (dm, J = 255.1 Hz), 135.7, 129.9, 129.7, 128.9, 108.9 (td, J = 17 and 4 Hz), 62.5, 21.6 and 13.4; δ_F ($CDCl_3$) −136.5 (2F, m), −149.6 (1F, m) and −161.3 (2F, m); ν_{max} (KBr)/cm^{-1} 1734, 1523, 1500, 1329, 1155 and 982; MS (CI) *m*/*z* 421 (M^+ + 1, 95), 375 (100), 356 (28) and 327 (4) (Found: C, 51.68; H, 3.33. $C_{18}H_{13}F_5O_4S$ requires C, 51.43; H, 3.12%). The reaction of tosylpropenoate (2.102 g, 5.0 mmol) and ethyl isocyanoacetate (0.75 mL, 7.5 mmol) was carried out according to the procedure described above to give 1.240 g (66%) of the title pyrrole as colorless crystals, mp 116–117 °C; δ_H ($CDCl_3$) 10.50 (1H, br s), 7.69 (1H, d, J = 3.4 Hz), 4.22 (4H, m), 1.22 (3H, t, J = 6.8 Hz) and 1.17 (3H, t, J = 6.8 Hz); δ_C ($CDCl_3$) 163.0, 160.1, 144.6 (dm, J = 243 Hz), 140.7 (dm, J = 253 Hz), 137.2 (dm, J = 251 Hz), 127.6, 122.6, 117.7, 114.1, 109.4 (td, J = 4 and 18 Hz), 61.2, 60.3, 13.9 and 13.7; δ_F ($CDCl_3$) −139.4 (2F, m), −156.4 (1F, m) and −164.8 (2F, m); ν_{max} (KBr)/cm^{-1} 3271, 1724, 1697, 1506, 1281 and 1196; MS (EI) *m*/*z* 377 (M^+, 81), 332 (58) and 286 (100) (Found: C, 50.88; H, 3.28; N, 3.76. $C_{16}H_{12}F_5NO_4$ requires C, 50.94; H, 3.21; N, 3.71%).

General procedure for acid-catalyzed cyclo-oligomerization (Table 1)

Ethyl pyrrole-2-carboxylate (**1**; 2.0 mmol) was treated with $LiAlH_4$ (2.0 mmol) in THF (10 mL) at 0 °C for 1 h. The reaction was quenched by addition of aq. NaOH. The supernatant solution was concentrated to give the corresponding 2-hydroxymethylpyrrole **2**, which was used without purification. The crude 2-hydroxymethylpyrrole **2** was treated with an acid in a dry solvent (50 mL) at room temperature under the conditions listed in Table 1. After the disappearance of **2**, as determined by TLC, the reaction was quenched by neutralization with Et_3N. The mixture was washed with saturated $NaHCO_3$ and brine, dried over $MgSO_4$, and concentrated *in vacuo* to give a syrupy solid, which was chromatographed on silica gel. In some cases, oxidation was carried before the chromatography as follows. The residue was dissolved in dichloromethane (50 mL), chloranil or DDQ (4 mmol) was added and the mixture was stirred for 12 h. After removal of the solvent, the residue was chromatographed on silica gel.

Tetraethyl 3,8,13,18-tetrakis(2,6-dichlorophenyl)porphyrinogen-2,7,12,17-tetracarboxylate (3a). White powder; δ_H ($CDCl_3$) 8.35 (4H, br s), 7.39–7.20 (12H, m), 4.9–3.1 (8H, br s), 4.06 (8H, q, J = 7.3 Hz) and 0.98 (12H, t, J = 7.3 Hz); δ_C ($CDCl_3$) 164.5, 136.5, 135.9, 133.9, 129.0, 127.7, 127.2, 117.4, 110.9, 59.4, 22.6 and 13.8; ν_{max} (KBr)/cm^{-1} 3265, 1705, 1674, 1541, 1429, 1186, 1088 and 781; MS (FAB$^+$) *m*/*z* 1185 (M^+ + 1) (Found: C, 56.66; H, 3.67; N, 4.67. Anal. $C_{56}H_{44}Cl_8N_4O_8$ requires C, 56.78; H, 3.74; N, 4.73%).

Hexaethyl 3,8,13,18,23,28-hexakis(2,6-dichlorophenyl)-hexaphyrinogen-2,7,12,17,22,27-hexacarboxylate (4a). White powder; δ_H (DMSO-d_6) 10.6 (6H, br s), 7.31–7.18 (18H, m), 4.10–3.76 (24H, m) and 0.83 (18H, m); δ_C (DMSO-d_6) 166.9, 135.8, 135.0, 128.3, 127.2, 126.9, 116.1, 109.9, 98.9, 59.3, 24.0 and 13.5; ν_{max} (KBr)/cm^{-1} 3330, 2978, 1707, 1674, 1429, 1304, 1190, 1097 and 783; MS (FAB$^+$) *m*/*z* 1777 (M^+ + 1) (Found: C, 56.71; H, 3.60; N, 4.72. $C_{84}H_{66}Cl_{12}N_6O_{12}$ requires C, 56.78; H, 3.74; N, 4.73%).

Tertaethyl 3,8,13,18-tetrakis(2,6-dichlorophenyl)-21*H*,23*H*-porphine-2,7,12,17-tetracarboxylate (5a). Purple crystals; δ_H ($CDCl_3$) 10.84 (4H, s), 7.80–7.62 (12H, m), 4.52 (8H, q, J = 7.0 Hz), 1.23 (12H, t, J = 7.0 Hz) and −2.48 (2H, s); δ_C ($CDCl_3$) 164.0, 146.5, 144.5, 143.5, 136.4, 134.3, 130.9, 130.5, 128.1, 105.5, 61.2 and 13.9; ν_{max} (KBr)/cm^{-1} 2981, 1716, 1558, 1429, 1184, 1084 and 783; MS (FAB$^+$) *m*/*z* 1179 (M^+ + 1); λ_{max} ($CHCl_3$)/nm ($\log_{10}$ ε/L mol^{-1} cm^{-1}) 660 (4.08), 606 (4.26), 563 (4.23), 528 (4.55) and 437 (5.58) (Found: C, 56.99; H, 3.36; N, 4.76. $C_{56}H_{38}Cl_8N_4O_8$ requires C, 57.07; H, 3.25; N, 4.75%).

Hexaethyl 3,8,13,18,23,28-hexakis(2,4,6-trimethylphenyl)-hexaphyrinogen-2,7,12,17,22,27-hexacarboxylate (4b). White crystals; δ_H ($CDCl_3$) 9.81 (6H, br s), 6.85 (6H, s), 6.71 (6H, s), 4.06 (6H, d, J = 15.0 Hz), 4.04 (12H, m), 3.18 (6H, d, J = 15.0 Hz), 2.27 (18H, s), 1.88 (18H, s), 1.72 (18H, br s) and 0.89 (18H, t, J = 7.2 Hz); δ_C ($CDCl_3$) 167.6, 138.7, 136.3, 135.6, 132.4,

127.2, 127.0, 126.3, 119.6, 110.1, 59.3, 23.8, 22.0, 20.8, 20.5, 13.5 and one sp^2 carbon was not found; MS (FAB$^+$) m/z = 1615 (M^+ + 1) (Found: C, 75.44; H, 7.11; N, 5.11. $C_{102}H_{114}N_6O_{12}$ requires C, 75.81; H, 7.11; N, 5.20%).

Tetraethyl 3,8,13,18-tetrakis(2,4,6-trimethylphenyl)-21*H*,23*H*-porphine-2,7,12,17-tetracarboxylate (5b). Purple crystals; δ_H ($CDCl_3$) 10.69 (4H, s), 7.26 (8H, s), 4.50 (8H, q, J = 7.3 Hz), 2,55 (12H, s), 2.11 (24H, s), 1.22 (12H, t, J = 7.3 Hz) and −2.74 (2H, br s); δ_C ($CDCl_3$) 164.6, 139.6, 137.9, 137.3, 137.5, 137.3, 132.7, 128.2, 104.5, 61.3, 21.4, 21.3, 13.6 and one sp^2 carbon was not found; ν_{max} (KBr)/cm^{-1} 3444, 3307, 2977, 1718, 1226 and 1184; MS (FAB$^+$) m/z 1071 (M^+ + 1); λ_{max} (CH_2Cl_2)/nm ($\log_{10}$ ε//L mol^{-1} cm^{-1}) 652 (3.49), 596 (3.85), 559 (3.80), 523 (4.32) and 432 (5.48) (Found: C, 75.06; H, 6.65; N, 5.23. $C_{68}H_{70}N_4O_8$ + H_2O requires C, 74.98; H, 6.66; N, 5.14%).

Tetraethyl 3,8,13,18-tetraphenyl-21*H*,23*H*-porphine-2,7,12,-17-tetracarboxylate (5c). Purple powder; isomeric mixture (3 : trace : 2 : 1); type I isomer: δ_H ($CDCl_3$) 10.89 (4H, s), 8.10–8.14 (8H, m), 7.72–7.85 (12H, m), 4.55 (8H, q, J = 7.3 Hz), 1.26 (12H, t, J = 7.3 Hz) and −2.92 (2H, s); type II isomer: δ_H (typical signals) 11.79 (2H, s) and 9.89 (2H, s); type III isomer: δ_H (typical signals) 10.82 (1H, s), 10.86 (2H, m) and 9.89 (1H, s); type IV isomer: δ_H (typical signals) 10.82 (2H, s) and 10.86 (2H, s); MS (FAB$^+$) m/z = 903 (M^+ + 1) (Found: C, 65.39; H, 4.81; N, 4.87. $C_{56}H_{46}N_4O_8$ + $2CH_2Cl_2$ requires C, 64.93; H, 4.70; N, 5.22%).

Tetraethyl 3,8,13,18-tetrakis(pentafluorophenyl)porphyrinongen-2,7,12,17-tetracarboxylate (3d). Light brown crystals; δ_H ($CDCl_3$) 8.40 (4H, br s), 4.16 (8H, q, J = 6.8 Hz), 4.03 (8H, br s) and 1.04 (12H, t, J = 6.8 Hz); δ_C ($CDCl_3$) 164.7, 144.9 (dm, J = 243 Hz), 140.6 (dm, J = 253 Hz), 137.5 (dm, J = 249 Hz), 136.1, 128.8, 111.9, 109.8 (td, J = 18 and 4 Hz), 105.3, 60.1, 23.4 and 13.7; δ_F ($CDCl_3$) −140.6 (8F, m), −155.5 (4F, m) and −163.3 (8F, m); ν_{max} (KBr)/cm^{-1} 3440, 1720, 1088 and 991 cm^{-1}; MS (MALDI-TOF) m/z 1268 (M^+) (Found: C, 52.84; H, 2.71; N, 4.44. $C_{56}H_{32}F_{20}N_4O_8$ requires C, 53.01; H, 2.54; N, 4.42%).

Hexaethyl 3,8,13,18,23,28-hexakis(pentafluorophenyl)hexaphyrinogen-2,7,12,17,23,28-hexacarboxylate (4d). Light brown crystals; δ_H ($CDCl_3$) 10.57 (6H, br s), 4.20 (6H, br d, J = 14.9 Hz), 3.99 (12H, q, J = 7.3 Hz), 3.34 (6H, br d, J = 14.9 Hz) and 1.11 (18H, t, J = 6.8 Hz); δ_F ($CDCl_3$) −138.1 (6F, br s), −139.0 (6F, m), −157.4 (6F, m), −163.8 (6F, m) and −164.9 (6F, br s); ν_{max} (KBr)/cm^{-1} 3225, 1678, 1492 and 987; MS (ESI-TOF) m/z 1903 (M^+) [HRMS (FAB$^+$) Found: 1903.2941. $C_{84}H_{48}F_{30}N_6O_{12}$ + H^+ requires 1903.2930].

Tetraethyl 3,8,13,18-tetrakis(pentafluorophenyl)-21*H*,23*H*-porphine-2,7,12,17-tetracarboxylate (5d). Purple crystals; δ_H ($CDCl_3$) 11.03 (4H, s), 4.68 (8H, q, J = 6.8 Hz), 1.45 (12H, t, J = 6.8 Hz) and −2.51(2H, br s); δ_C ($CDCl_3$) 163.5, 145.2 (dm, J = 248 Hz), 142.2 (dm, J = 257 Hz), 138.0 (dm, J = 254 Hz), 109.8 (td, J = 18 and 4 Hz) 106.1, 61.9, 13.9 and pyrrolic carbons could not be found; δ_F ($CDCl_3$) −137.1 (8F, m), −151.9 (4F, m) and −161.8 (8F, m); ν_{max} (KBr)/cm^{-1} 3440, 1720, 1088 and 991; MS (MALDI-TOF) m/z 1263 (M^+); λ_{max} ($CHCl_3$)/nm ($\log_{10}$ ε/L mol^{-1} cm^{-1}) 663 (3.94), 612 (4.06), 564 (4.01), 529 (4.28) and 439 (5.22) (Found: C, 53.13; H, 2.20; N, 4.51. $C_{90}H_{28}F_{20}N_4O_8$ requires C, 53.26; H, 2.08; N, 4.44%).

2,7,12,17-Tetrakis(2,6-dichlorophenyl)-3,8,13,18-tetrakis(trifluoromethyl)porphyrinogen (3e). White crystals, mp 133–135 °C; δ_H ($CDCl_3$) 8.27 (4H, br s), 7.49–7.21 (12H, m) and 4.01–3.35 (8H, br s); δ_C (DMSO-d_6) 136.1, 131.2, 129.8, 128.3 (q, J = 4.0 Hz), 127.3, 124.5, 123.9 (q, J = 268 Hz), 114.5 (q, J = 2 Hz), 107.6 (q, J = 33 Hz), 22.0; δ_F ($CDCl_3$) −55.1 (s); ν_{max} (KBr)/cm^{-1} 3302, 1158, 1431, 1394, 1358, 1157, 1142, 1051, 987 and 793; MS (FAB$^+$) m/z 1168 (M^+) (Found: C, 48.60; H, 2.24; N, 4.75. $C_{48}H_{24}Cl_8F_{12}N_4$ + H_2O requires C, 48.60; H, 2.21; N, 4.72%).

2,7,12,17-Tetrakis(2,6-dichlorophenyl)-3,8,13,18-tetrakis(trifluoromethyl)-21*H*,23*H*-porphine (5e). Purple crystals; δ_H ($CDCl_3$) 9.98 (4H, s), 7.81–7.68 (12H, m) and −2.79 (2H, br s); ν_{max} (KBr)/cm^{-1} 1520, 1496, 1329, 1128 and 989 cm^{-1}; MS (FAB$^+$) m/z 1163 (M^+); λ_{max} ($CHCl_3$)/nm ($\log_{10}$ ε/L mol^{-1} cm^{-1}) 640 (4.07), 585 (4.22), 540 (4.19), 508 (4.48) and 414 (5.53) (Found: C, 49.21; H, 1.68; N, 4.70. $C_{48}H_{18}Cl_8F_{12}N_4$ requires C, 49.60; H, 1.56; N, 4.82%).

2,7,12,17-Tetrakis(pentafluorophenyl)-3,8,13,18-tetrakis(trifluoromethyl)porphyrinogen (3f). White crystals, mp 129–131 °C; δ_H ($CDCl_3$) 9.54 (4H, br s) and 3.87 (8H, br s); δ_C ($CDCl_3$) 144.9 (dm, J = 245 Hz), 141.3 (dm, J = 257 Hz), 137.7 (dm, J = 255 Hz), 130.8 (q, J = 2 Hz), 125.6, 123.6 (q, J = 268 Hz), 110.4 (q, J = 35.0 Hz), 107.5 (td, J = 19 and 4 Hz), 105.7 and 23.0; δ_F ($CDCl_3$) −55.8 (12F, s), −139.7 (8F, m), −153.5 (4F, m) and −161.9 (8F, m); ν_{max} (KBr)/cm^{-1} 3288, 1519, 1496, 1155, 1128, 1109 and 987; MS (FAB$^+$) m/z 1252 (M^+) (Found: C, 45.95; H, 1.15; N, 4.42. $C_{48}H_{18}Cl_8F_{12}N_4$ requires C, 46.03; H, 0.97; N, 4.47%).

2,7,12,17-Tetrakis(pentafluorophenyl)-3,8,13,18-tetrakis(trifluoromethyl)-21*H*,23*H*-porphine (5f). Purple crystals; δ_H ($CDCl_3$) 10.18 (4H, s) and −2.87 (2H, br s); δ_F ($CDCl_3$) −136.9 (12F, s), −148.8 (8F, m), −152.7 (4F, m) and −160.1 (8F, m); ν_{max} (KBr)/cm^{-1} 3444, 1519, 1496, 1086, 993 and 941; MS (MALDI-TOF) m/z 1247 (M^+ + 1); λ_{max} ($CHCl_3$)/nm ($\log_{10}$ ε/L mol^{-1} cm^{-1}) 643, 589, 541, 509 and 416 [HRMS (FAB$^+$) Found: 1247.0164. $C_{48}H_6F_{32}N_4$ + H^+ requires 1247.0160].

2,3,7,8,12,13,17,18-Octakis(pentafluorophenyl)porphyrinogen (3g). White crystals, mp 150–152 °C; δ_H ($CDCl_3$) 9.45 (4H, br s) and 3.71 (8H, s); δ_C ($CDCl_3$) 144.4 (dm, J = 242 Hz), 140.7 (dm, J = 252 Hz), 137.8 (dm, J = 252 Hz), 128.8, 108.2 (td, J = 19 and 4 Hz), 106.9 and 23.6; δ_F ($CDCl_3$) −141.7 (16F, m), −153.7 (8F, m), and −160.9 (16F, m); ν_{max} (KBr)/cm^{-1} 3454, 1519, 1491, 1061, 991 and 839; MS (MALDI-TOF) m/z 1645 (M^+ + 1) (Found: C, 49.65; H, 1.50; N, 3.26. $C_{68}H_{12}F_{40}N_4$ + 2EtOH requires C, 49.79; H, 1.39; N, 3.23%).

2,3,7,8,12,13,17,18-Octakis(pentafluorophenyl)-21*H*,23*H*-porphine (5g). MS (FAB$^+$) m/z 1639 (M^+ + 1); λ_{max} ($CHCl_3$)/nm 644, 591, 548, 515 and 426 [HRMS (FAB$^+$) Found: 1639.0045. $C_{68}H_6F_{40}N_4$ + H^+ requires 1639.0032].

Porphyrinogen bearing 2-pyridone (3h). Black solid; δ_H ($CDCl_3$) 11.85 (4H, br s), 7.09 (8H, m), 6.85 (8H, m), 6.28 (4H, d, J = 7.3 Hz), 6.23 (4H, d, J = 7.3 Hz), 5.35 (4H, d, J = 14.9 Hz), 4.64 (4H, d, J = 15.1 Hz), 4.49 (4H, d, J = 14.9 Hz), 3.90 (4H, d, J = 14.9 Hz) and 3.81 (12H, s); δ_C ($CDCl_3$) 162.8, 158.9, 130.0, 129.0, 128.7, 126.1, 120.2, 119.8, 114.3, 110.4, 101.0, 55.3, 48.9 and 23.5; ν_{max} (KBr)/cm^{-1} 2929, 1643, 1599, 1512, 1248 and 727; MS (MALDI-TOF) m/z 1065 (M^+ + 1) [HRMS (FAB$^+$) Found: 1064.4213. $C_{64}H_{58}N_8O_8$ requires 1064.4221].

Di-*n*-butyl pyrrole-3,4-dicarboxylate (9). White crystal, mp 102–103 °C; δ_H ($CDCl_3$) 10.61 (1H, br s), 7.42 (2H, s), 4.23 (4H, q, J = 6.8 Hz), 1.69 (4H, m), 1.42 (4H, m), and 0.95 (6H, t, J = 7.3 Hz); δ_C ($CDCl_3$) 164.3, 126.7, 115.2, 64.0, 30.7, 19.2 and 13.7; ν_{max} (KBr)/cm^{-1} 3265, 1716, 1286, 1053 and 796; MS (EI) m/z 267 (M^+, 7), 212 (10), 194 (24), 138 (100) (Found: C, 62.81; H, 7.77; N, 5.20. $C_{14}H_{21}NO_4$ requires C, 62.90; H, 7.92; N, 5.24%).

Octabutyl porphyrinogen-2,3,7,8,12,13,17,18-octacarboxylate (3i). Di-*n*-butyl pyrrole-3,4-dicarboxylate (0.535 g, 2.0 mmol) and trioxane (0.072 g, 2.0 mmol) were dissolved in TFA (12 mL) at room temperature and the mixture was refluxed for 2 days. The reaction was quenched by aq. $NaHCO_3$ and the mixture was extracted with chloroform. The organic extract was washed with brine, dried over Na_2SO_4, and concentrated. The residue was chromatographed on silica gel (EtOAc–hexane) to give 0.180 g (32%) of the title compound as a pale brown solid; δ_H ($CDCl_3$) 9.89 (4H, br s), 4.20 (24H, m), 2.35 (16H, br s), 1.66 (16H, m), 1.37 (16H, m) and 0.94 (24H, t, J = 7.3 Hz); δ_C ($CDCl_3$) 165.5, 133.7, 112.1, 64.6, 30.6, 23.2, 19.2 and 13.7; ν_{max} (KBr)/cm^{-1} 2929 and 1643; MS (FAB^+) m/z 1117 (M^+ + 1) [HRMS (FAB^+) Found: 1117.5945. $C_{60}H_{84}N_4O_{16}$ + H^+ requires 1117.5961].

Octabutyl 21*H*,23*H*-porphin-2,3,7,8,12,13,17,18-octacarboxylate (5i). Black solid; δ_H ($CDCl_3$) 11.22 (4H, s), 4.86 (16H, t, J = 7.8 Hz), 2.09 (16H, m), 1.71 (16H, m), 1.13 (24H, t, J = 7.3 Hz) and −2.94 (2H, br s); δ_C ($CDCl_3$) 164.8, 130.9, 128.8, 106.5, 66.5, 30.9, 19.4 and 13.9; ν_{max} (KBr)/cm^{-1} 3313 and 1728; MS (FAB^+) 1111 (M^+ + 1); λ_{max} ($CHCl_3$)/nm 663, 607, 560, 527 and 434 [HRMS (FAB^+) Found: 1111.5500. $C_{60}H_{78}N_4O_{16}$ + H^+ requires 1111.5491].

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