# Self-assembly of Molecular Devices Containing a Ferrocene, a Porphyrin and a Quinone in a Triple Macrocyclic Architecture

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Porphyrinogen self-assembly is compatible with a structurally diverse set of *meta*-linked dialdehyde building blocks, providing rapid access under gentle conditions to porphyrins bearing redox-active units positioned in a 3-dimensional architecture.

Self-assembly, the spontaneous formation of higher-ordered molecular architectures, is a hallmark of biological systems. In several classic biological examples, self-assembly minimizes information through the use of modular subunits, enables control of assembly and disassembly through multiple bonds of low energy, exploits error-checking *via* reversible interactions, and achieves a level of architectural control and efficiency without parallel in chemical synthesis.[1] Self-assembly is attractive from a synthetic chemistry standpoint, letting nature do by itself what has traditionally been achieved synthetically in step-by-step operations.[1,2]

We have employed the self-assembly of a porphyrinogen as the first step in a two-step biomimetic synthesis of *meso*-porphyrins.[1,3] The self-assembly of the porphyrinogen involves formation of 8 C–C bonds among 4 aldehyde and 4 pyrrole molecules. The porphyrinogen is converted to the porphyrin upon addition of an oxidant. This two-step one-flask process is performed at room temperature and is compatible with a broad selection of aldehyde precursors.[4]

We have investigated the condensation of covalently linked dialdehydes *via* this synthetic route, yielding the corresponding strapped porphyrins (Fig. 1). The first syntheses of

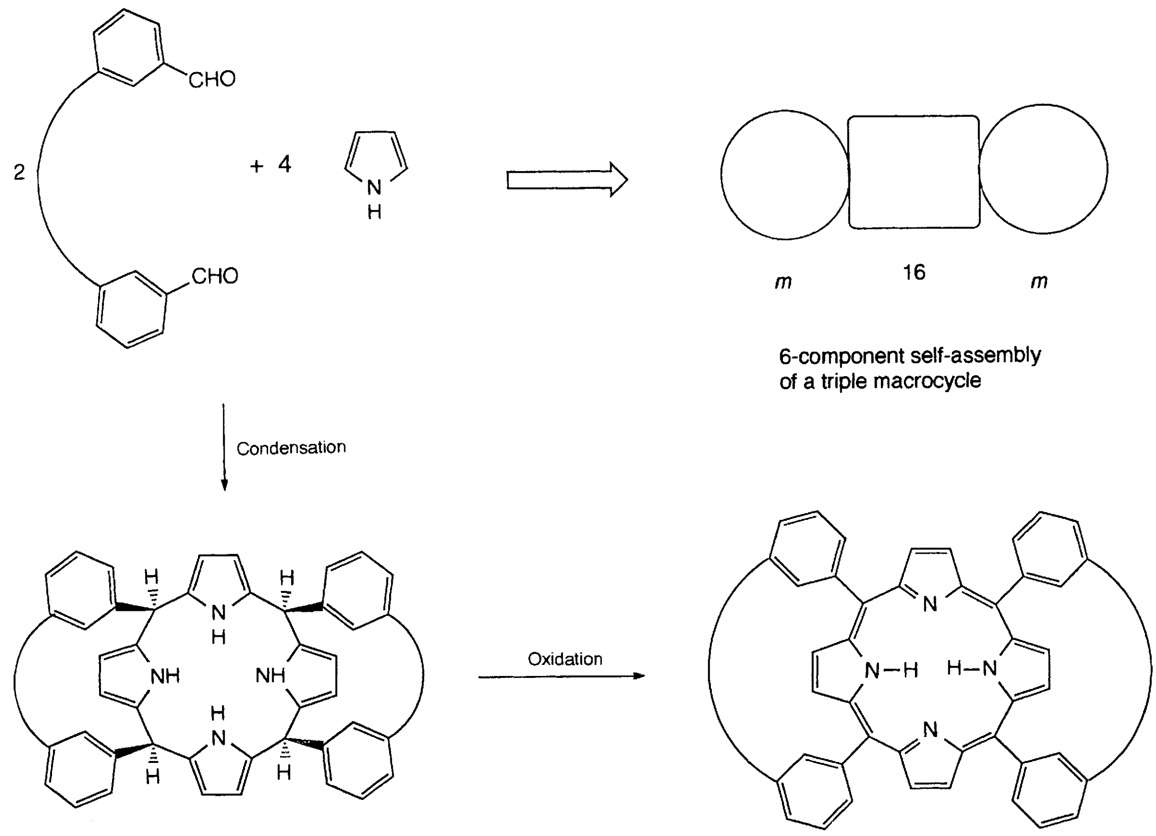


**Fig. 1** Condensation of a dialdehyde with pyrrole affords the bis(strapped) porphyrin (shown as *meta*-strapped). Only one possible stereoisomer of the porphyrinogen is indicated. The term *m* indicates the number of atoms in the outer macrocycles.

strapped porphyrins, pioneered by the research groups of Staab,[5] Momenteau[6] and Walker,[7] condensed *ortho*-alkoxy-linked benzaldehydes with pyrrole *via* the Adler reaction. However, alkylation of the *ortho*-hydroxy groups of a pre-formed porphyrin with bifunctional alkylating agents has proved far more popular for model systems applications.[8] Our goals in these studies are twofold. First, we seek to understand the effects of strap structural features in the self-assembly process leading to the porphyrins, and secondly, we want to lay the foundation for converting prefunctionalized dialdehyde building blocks into strapped porphyrins for model systems applications. In a striking display of this synthetic strategy, Bonar-Law and Sanders reported the one-flask conversion of a bis(steroidal) *meta*-substituted dialdehyde to the *trans*-strapped porphyrin model system in 7% yield.[9] We now report the reactions of 14 *ortho-*, *meta-*, or *para*-substituted dialdehydes bearing straps of different lengths, orientations and rigidities.[10]

The effects of position of substitution and strap length were examined by reaction of a series of alkoxy-dialdehydes (Table 1). The porphyrin yields steadily increased with increasing strap length at the *ortho* position, from 12 ($n = 5$) to 33% ($n = 10$). In each case the yield of *trans*-strapped porphyrin was $\leq$ 1%. In contrast, the *m*-alkoxy-strapped porphyrins were formed in yields of approximately 5% for all chain lengths, and no *trans*-strapped porphyrins were observed. The *p*-alkoxy-strapped porphyrin ($n = 12$) was not obtained upon condensation of the corresponding dialdehyde. In comparison, *o*- and *m*-anisaldehyde gave yields of 20 and 38%, respectively. Higher yields were obtained only with the longer ($n = 8$, 10) *o*-alkoxy straps, which indicates that these straps enhance the self-assembly process relative to their unstrapped counterparts.

The rigid bis(phenol) dialdehyde gave the *meta*-strapped porphyrin **9** in 25% yield (Fig. 2). This strapped porphyrin has 24 atoms in the outer macrocycles ($m = 24$). In contrast, the *m*-alkoxy-strapped porphyrin **8**, which is of similar size ($m = 23$) but contains a flexible strap, was formed in only 5% yield. Thus, the rigid bis(phenol) strap results in a fivefold yield enhancement. An illustration of the deleterious effects of strap rigidity is provided by the xylene linker, which gave porphyrin **10** ($m = 19$) in less than 1% yield, compared with the 5% yield of the flexibly-strapped porphyrin **6** ($m = 19$).

*Ortho*-strapped porphyrins exist as atropisomers which can be easily separated *via* chromatography.[6,7] However, in no instance have we observed *meta*-strapped atropisomers chromatographically. Some of the *meta*-strapped porphyrins showed NMR splitting patterns of the β-pyrrole protons characteristic of strapped porphyrin atropisomers. A variable temperature $^1$H NMR study of porphyrin **7** showed coalescence of the splitting patterns commensurate with an energy activation of 70 kJ mol$^{-1}$ for atropisomer interconversion. Similar energies of activation have been reported for rotation of the phenyl rings in tetraphenylporphyrins.[11]

The concentration dependence of the reaction was characterized in the synthesis of the bis(phenol) strapped porphyrin **9**. The highest yield was obtained at $10^{-2}$ [CHO] and $10^{-2}$ mol dm$^{-3}$ [pyrrole], and the yield declined approximately threefold both at $10^{-1}$ and at $10^{-3}$ mol dm$^{-3}$.

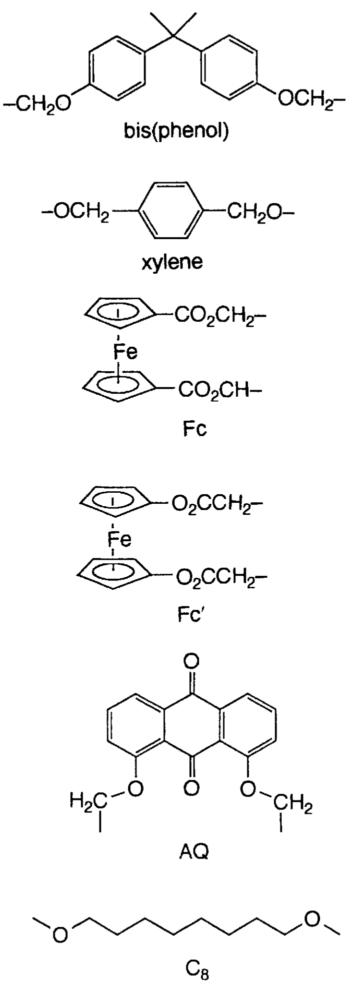
The *o*-alkoxy-strapped porphyrins ($n = 5$ or 6) exhibit typical porphyrin absorption spectra.[7] However, straps of the same lengths at the *meta* sites yield a red-shift of the Soret band (430 for $n = 5$; 428 nm for $n = 6$), compared with 418 nm for *meso*-tetrakis(3-methoxyphenyl)porphyrin. These spectral distortions are attributed to strain in the porphyrin ring induced by the short strap.[12] No spectral distortions were observed in porphyrins with longer straps such as **8** and **9**.

The *meta*-positions have trajectories directed away from the porphyrin, enabling groups spanning adjacent *meso*-phenyl groups to be held close to the porphyrin but not projecting

**Table 1** Synthesis of strapped porphyrins[a]

| Strapped porphyrin | Strap | Ring size ($m$) | Isolated yield (%) |
|---|---|---|---|
| | $-O(CH_2)_nO-$, $n$ | | |
| *Ortho*-alkoxy straps[b] | | | |
| **1** | 5 | 16 | 12 |
| **2** | 6 | 17 | 15 |
| **3** | 8 | 19 | 23 |
| **4** | 10 | 21 | 33 |
| *Meta*-alkoxy straps[c] | | | |
| **5** | 5 | 18 | 5.4 |
| **6** | 6 | 19 | 5.2 |
| **7** | 8 | 21 | 5.9 |
| **8** | 10 | 23 | 5.0 |
| *Para*-alkoxy straps[d] | | | |
| | 12 | 27 | 0 |
| Rigid *meta*-linked straps[e] | | | |
| **9** | Bis(phenol) | 24 | 25 |
| **10** | Xylene | 19 | <1 |
| **11** | Fc | 20 | 21 |
| **12** | Fc′ | 20 | 10 |
| **13** | Fc, $C_8$ | 20, 21 | 7.2 |
| **14** | AQ, $C_8$ | 20, 21 | 4.4 |
| **15** | Fc, AQ | 20, 20 | 4.2 |

[a] All reactions were performed at room temperature, with $10^{-2}$ pyrrole and $10^{-2}$ mol dm$^{-3}$ [CHO], and *p*-chloranil for oxidation. [b] $BF_3 \cdot OEt_2$, 3.3 mmol dm$^{-3}$ in $CHCl_3$. [c] $BF_3 \cdot OEt_2$, $10^{-3}$ mol dm$^{-3}$ in $CH_2Cl_2$. [d] Both trifluoroacetic acid (TFA) and $BF_3 \cdot OEt_2$ were examined. [e] TFA, $2 \times 10^{-2}$ mol dm$^{-3}$ in $CH_2Cl_2$.



bis(phenol)

xylene

Fc

Fc′

AQ

$C_8$

**Fig. 2** Strap units for *meta*-strapped tetraarylporphyrins

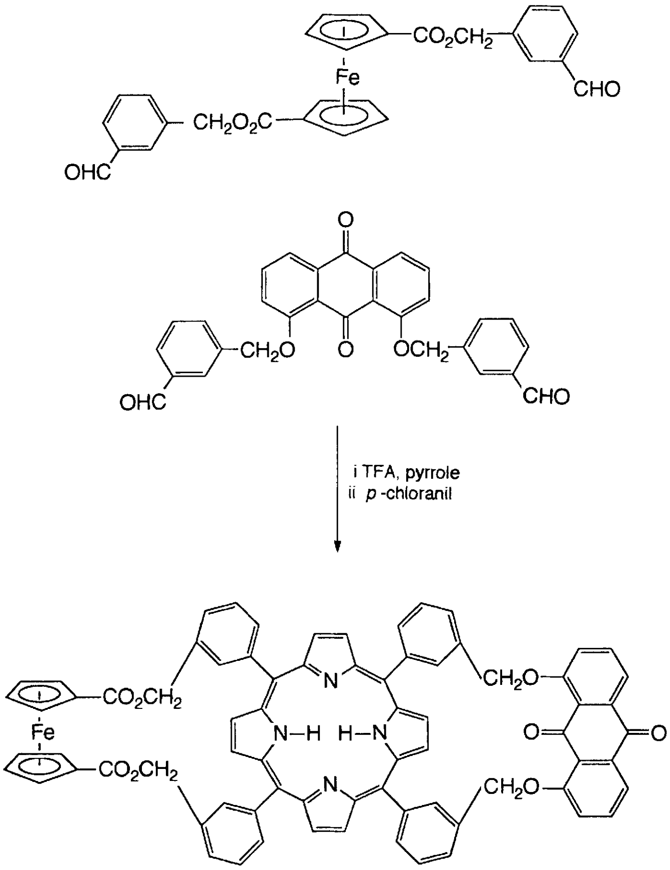


**Fig. 3** Synthesis of ferrocene–porphyrin–quinone **15**. The bis(ferrocene)–porphyrin and bis(anthraquinone)–porphyrin, which also are formed in the reaction are not shown.

over the macrocycle. This architecture appeared attractive for positioning redox-active moieties around the periphery of the porphyrin. Indeed, the ferrocene dialdehydes, Fc and Fc′, each reacted smoothly, giving the corresponding bis(ferrocene)porphyrins **11** and **12** in yields of 21 and 10%, respectively (Fig. 2). These bis(ferrocenyl)porphyrins illustrate the capacity of the oxidation potential of the ferrocenes to be 'tuned' by substitution while maintaining the same number of atoms in the straps.

Condensation of the Fc dialdehyde and the $C_8$ dialdehyde with pyrrole yielded the bis(Fc)porphyrin **11** (4.6%), the bis($C_8$)porphyrin **7** (2.1%) and the Fc-$C_8$-porphyrin **13** (7.2%) upon chromatographic separation (Table 1). The similar condensation of the Fc dialdehyde and an anthraquinone (AQ) dialdehyde afforded the bis(Fc)porphyrin **11** (9.7%), the Fc-AQ-porphyrin **15** (4.2%), but the bis(AQ)porphyrin could not be isolated (Fig. 3). Although the yields are low relative to traditional organic synthetic procedures, multigram quantities of the dialdehydes and 20–100 mg quantities of porphyrins are easily obtained. The low yields are mitigated by such rapid access to architecturally complex molecules. Indeed, though innumerable porphyrin model systems have been prepared for studies of electron transfer, only a handful comprise both an electron donor and an electron acceptor. Substantial quenching of the porphyrin fluorescence occurs in the ferrocene–porphyrin–quinones, and we are currently examining the photochemical features of this family of ferrocene–porphyrin–quinones.

In summary, *ortho*- and *meta*-linked dialdehyde building blocks readily yield the corresponding strapped porphyrins. The crucial step in this transformation is the self-assembly of the porphyrinogen, involving the condensation of 6 components, the formation of 8 C–C bonds, and the concomitant construction of three macrocycles. Our results illustrate how porphyrinogen self-assembly, a robust biomimetic process, can be melded with a modular building block approach to gain rapid access to model systems featuring a porphyrin, an electron donor and an electron acceptor held in a controlled 3-dimensional architecture.

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