Oxidation of hydroquinones with *meso*-hexakispentafluorophenyl [26]hexaphyrin(1.1.1.1.1.1)

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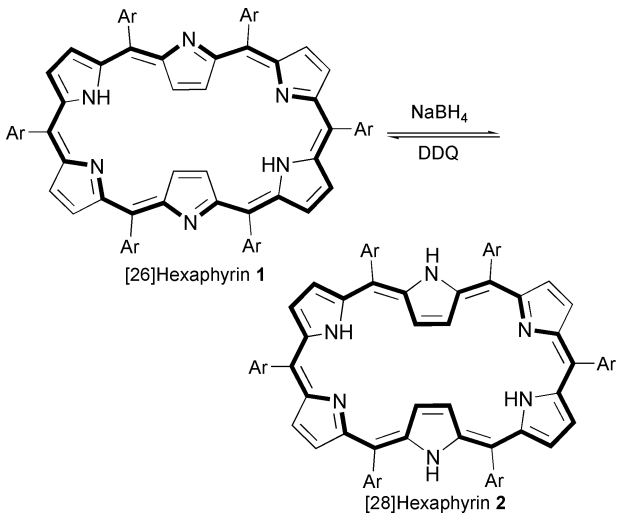
Treatment of various hydroquinones and catechols with *meso*-pentafluorophenyl [26]hexaphyrin(1.1.1.1.1.1) provided the corresponding quinones quantitatively.

Expanded porphyrins that are porphyrin analogues with more than five pyrrolic subunits have attracted much attention because of their unique properties, such as their interesting structural features and unique metal-coordination capability.[1] In addition, expanded porphyrins often exhibit stable multi-redox states, while porphyrins seldom show such behaviour. For instance, *meso*-pentafluorophenyl hexaphyrin(1.1.1.1.1.1) consists of two compounds **1** and **2**, which have different oxidation states with 26π and 28π conjugation respectively, and they are easily interconvertible upon reduction with $NaBH_4$ and oxidation with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) (Scheme 1).[2]

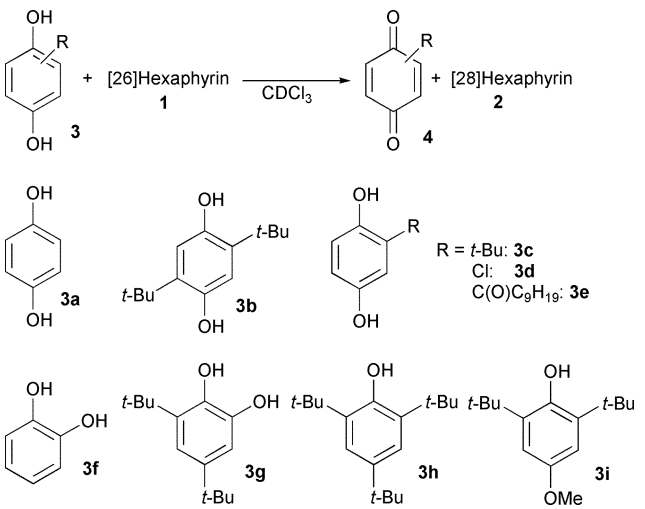


Scheme 1 Interconversion of [26]hexaphyrin and [28]hexaphyrin.

This multi-redox phenomenon reminds us of transition metal ions, because multi-valency plays an essential role in a number of metal-mediated oxidation processes. It then occurred to us that expanded porphyrins can oxidize organic compounds such as alcohols in a similar manner to a number of transition metal ions, and hopefully may act as an organocatalyst for oxidation reactions. Currently, organocatalysts for carbon–carbon bond forming processes have been a hot topic in organic synthesis in view of sustainable processes and high enantiomeric induction, but oxidation-organocatalysts based on their multi-redox behaviour remain mainly unexplored.[3] Here we wish to report a hexaphyrin-mediated oxidation of hydroquinones, catechols, and pinacols. Although metal–porphyrin complexes often serve as the catalyst for various types of oxidation reactions both in natural and artificial systems,[4] this is the first example of non-metalated porphyrinoid-mediated oxidation of organic molecules.

In recent years, a series of *meso*-aryl expanded porphyrins have been synthesized in moderate yields under the modified Rothemund–Lindsey conditions.[5a] We have also achieved an improved synthesis of *meso*-aryl expanded porphyrins from dipyrromethanes or tripyrromethanes as starting substrates.[5b] Although a number of expanded porphyrins exhibit multi-redox behaviour, we picked up hexaphyrin because of its availability, and tested its ability for the oxidation of organic molecules.

We had noticed that the reduction of [26]hexaphyrin to [28]hexaphyrin with a brilliant colour change from red–purple to blue occurs in the presence of acids and alcohols. Thus, [26]hexaphyrin **1** was treated with benzyl alcohol in the presence of a trace of trifluoroacetic acid to provide **2** quantitatively, but benzaldehyde could not be detected by the ^1H NMR analysis. After several experiments, we found that an addition of 1.0 equiv. of 1,4-hydroquinone (**3a**) to a solution of [26]hexaphyrin **1** in $CDCl_3$ provided 1,4-benzoquinone (**4a**) instantly and quantitatively at room temperature (Scheme 2). ^1H NMR analysis of the resulting solution revealed the quantitative formation of [28]hexaphyrin



Scheme 2 Oxidation of hydroquinones and catechols with [26]hexaphyrin.

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2. An equimolar amount of **4a** and **2** were detected, and this indicates that [26]hexaphyrin acts as a two-electron oxidant for hydroquinones. Treatment of **3b**, **3c** and **3d** with **1** also afforded the corresponding quinones **4b**, **4c** and **4d** in more than 90% yields in 10 min. However, oxidation of electron-deficient hydroquinone **3e** with an electron-withdrawing acyl group proceeded very slowly.[6] Furthermore, oxidation of catechols **3f** and **3g** to *o*-benzoquinones was also effected with [26]hexaphyrin efficiently.

Oxidation of phenols with [26]hexaphyrin **1** turned out to be inefficient. Thus, the reaction of 2,4,6-tri-*tert*-butylphenol (**3h**) with [26]hexaphyrin **1** afforded a small amount of [28]hexaphyrin in less than 5% yield, which was detected by the TLC and ^{1}H NMR analysis of the reaction mixture, but none of oxidized product was observed. Oxidation of electron-rich phenol, 2,6-di-*tert*-butyl-4-methoxyphenol (**3i**), was still sluggish to afford 2,6-di-*tert*-butyl-1,4-benzoquinone (**4i**) in 25% yield in 10 days *via* the cleavage of the ether linkage. The ESR spectrum of the reaction mixture of 2,4,6-tri-*tert*-butylphenol (**3h**) and [26]hexaphyrin in benzene at room temperature confirmed the formation of a radical species, which we tentatively assigned as the corresponding 2,4,6-tri-*tert*-butylphenoxyl radical, although the signal was weak probably due to inefficient formation of the radical (Fig. 1).[7] In contrast, both [26]hexaphyrin and **3h** were silent for the ESR analysis before mixing. On the basis of these observations, we assume that this oxidation reaction would proceed through two sequential one-electron transfer steps from **1** to hydroquinone involving a semiquinone radical intermediate.[8]

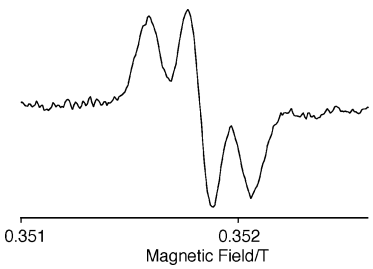
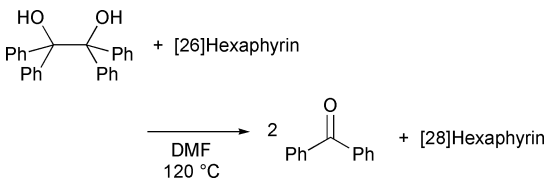


Fig. 1 ESR spectrum of a mixture of 2,4,6-tri-*tert*-butylphenol (**3h**) and [26]hexaphyrin **1** in benzene at room temperature.

Oxidative cleavage of 1,2-diols with some oxidants such as lead tetraacetate is known to proceed in a radical mechanism involving an alkoxyl radical.[9] We then examined the reaction of benzopinacol with **1** (Scheme 3). To our delight, treatment of benzopinacol with [26]hexaphyrin in *N*,*N*-dimethylformamide provided benzophenone quantitatively in 30 min at 120 °C.



Scheme 3 Oxidative C–C bond cleavage of benzopinacol.

We also attempted re-oxidation of [28]hexaphyrin to [26]hexaphyrin with molecular oxygen as an oxidant. This would enable a hexaphyrin-catalyzed oxidation reaction of organic molecules with dioxygen as the terminal oxidant. We found that **2** was oxidized to **1** quantitatively in 3 days with air at room temperature in basic aqueous isopropyl alcohol (Scheme 4).

In summary, we have found that treatment of hydroquinones and catechols with [26]hexaphyrin provided *p*- and *o*-quinones, most likely through a radical mechanism. [26]Hexaphyrin also mediates oxidative C–C bond cleavage of benzopinacol to benzophenone. We also found an aerobic oxidation of [28]hexaphyrin to [26]hexaphyrin. These results demonstrate that multi-redox behaviour of expanded porphyrins can be utilized for oxidation of organic compounds. Further effort on the use of hexaphyrin as an oxidation catalyst is currently under way in our laboratory.

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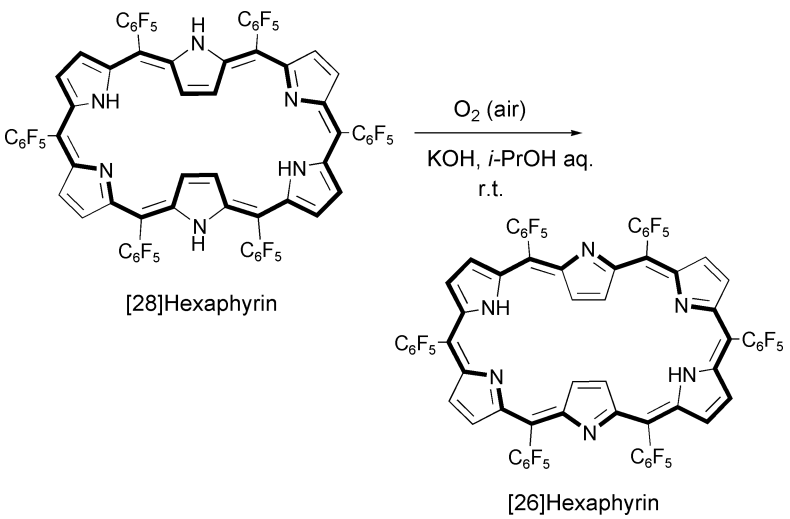

Scheme 4 Oxidation of [28]hexaphyrin to [26]hexaphyrin.

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6 An addition of trifluoroacetic acid to the reaction mixture did not improve the yield of the product **4e**.

7 Resolution of this spectrum was not sufficient as to analyze hyperfine constants, but the splitting may be assigned for the coupling between the phenoxyl radical and protons at the 3-, and 5-positions.

8 Cyclic voltammetry of **1** in CH_2Cl_2 containing tetrabutylammonium tetrafluoroborate as an electrolyte showed two electrochemical waves at -0.52 and -0.85 V (*vs* ferrocene/ferrocenium ion). See S. Mori and A. Osuka, *J. Am. Chem. Soc.*, 2005, **127**, 8030.

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