Biomimetic iron porphyrin-catalysed oxidation of cyclopenta[*a*]phenanthrenones

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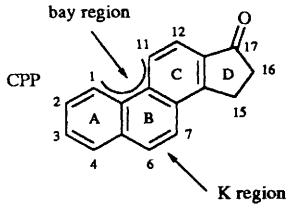
Peracid oxidation of two cyclopenta[*a*]phenanthrenones occurs at the chemically active K-region to yield the *cis*-6,7-epoxides. Biomimetic oxidation of these compounds as substrates in an iron porphyrin–iodosylbenzene system produces similarly high yields of these oxidation products. The steric hindrance around the periphery of the porphyrin has been increased to the extent that access of the K-region to the active iron centre is impossible. However, these steric constraints do not encourage stereoselective substrate oxidation at the more accessible terminal rings, the site of attack with the natural enzymatic system. Methoxy substitution around the porphyrin periphery produces a highly effective catalyst for these substrates. Cyclohexene oxidation is not so encouraged, suggesting a 'pocket' attractive to the cyclopenta[*a*]phenanthrenones.

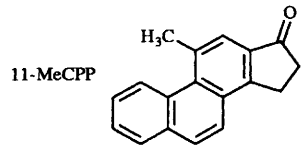
Iron porphyrin complexes have been used extensively as biomimetic catalysts for the oxidation of aliphatic and olefinic hydrocarbons.[1] In striking contrast, very few oxidations of polycyclic hydrocarbons (PAH) have been reported,[2] despite the importance of these compounds in biological systems.[3] Most P-450 model compounds have exhibited low reactivity towards aromatic nuclei.[4] The first efficient biomimetic oxidation of PAH utilised a bifacially hindered iron tetraphenylporphyrin/*m*-chloroperoxybenzoic acid homogeneous mixture[5] to yield mainly quinones from pyrene, benzo[*a*]pyrene and benz[*a*]anthracene. Some success has been achieved with other systems, for example, cobalt tetraphenylporphyrin has been activated with dioxygen to oxidise 1-naphthol to 1,4 naphthoquinone at room temperature.[6] This system also produces carboxylic acids from aromatic aldehydes without oxidation of the aryl ring.[7] A manganese porphyrin has been similarly used to oxidise anthracene to the diketone.[8]

Other important biological materials, such as steroids, have suffered from a similar lack of attention. Sterically hindered (tetramesityl) ruthenium porphyrin and atmospheric oxygen have been used to epoxidise olefinic cholest-5-ene.[9] Also of interest is that Fe(TPP)Cl† and PhIO have activated aflatoxin B_1 to a plasmid mutagen.[10] Cyclopenta[*a*]phenanthrenones present interesting substrates for biomimetic oxidations due to their relationship to both PAH and steroids. 15,16-Dihydrocyclopenta[*a*]phenanthren-17-one (CPP) **I** exhibits no carcinogenicity in mouse skin painting tests,[11] but the addition of an 11-methyl (11-MeCPP) **II** group leads to a potency similar to that of benzo[*a*]pyrene.[12]

A considerable amount of work has been carried out on these compounds[13] revealing that biological attack occurs predominantly on the A-ring to yield, amongst other compounds, the



I



II

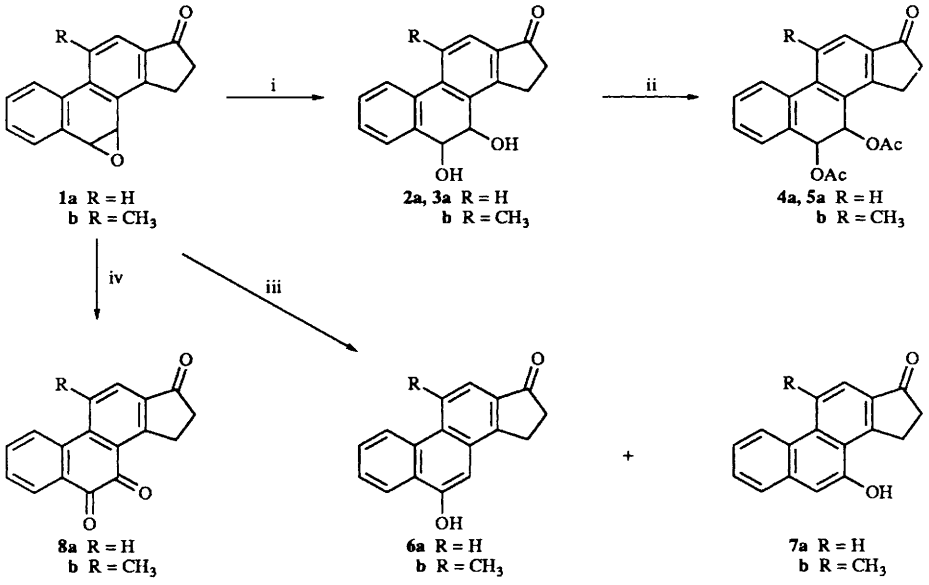
trans-3,4-dihydrodiol identified as the proximate carcinogen from **II**. Classical chemical reaction sites are conversely centred around the dipole at C-17 and the most electron-rich 6,7-double bond. The site of attack from the iron porphyrin biomimetic oxidation system is therefore of interest.

The potential of the metalloporphyrin system to provide stereoselective control over aliphatic and alicylic substrate oxidation has been explored, mainly utilising manganese porphyrins. With increasingly sterically hindered manganese porphyrins a series of alkanes could be stereoselectively hydroxylated.[14] Extremely bulky porphyrin substituents were subsequently seen to produce limonene oxidation at the external double bond as opposed to the previously exclusive ring-only oxidation.[15] With an iron porphyrin–iodosylbenzene system, a preference for substrate alkanes of increasing chain length was observed with Fe(TMP)Cl over Fe(TPP)Cl.[16] The more stable manganese porphyrin system subsequently produced changes in oxidation stereochemistry with modification of the axial ligand on the metal centre.[17] An initial theoretical treatise explored the approach of an olefinic substrate to the active metalloporphyrin.[18] The first step in epoxidation involves the coordination of the olefin to the iron atom, explaining the preference for *cis*-olefins. The proposal[19] was then of a transition state involving the iron porphyrin, oxygen and substrate, with the porphyrin periphery controlling the alkene oxidation stereospecificity. In this paper we present the results of the oxidation of **I** and **II** with a previously explored efficient homogeneous catalyst system[20] and a series of hindered iron porphyrins.

Results and discussion

The direct peracid oxidation of CPP and 11-MeCPP produces the K-region epoxides **1a,b** in quantitative yield. The resulting epoxides are subsequently converted into a range of compounds (Scheme 1).

† Abbreviations: Fe(TPP)Cl, 5,10,15,20-tetraphenylporphyrinatoiron(III) chloride; Fe(TPFPP)Cl, 5,10,15,20-tetrakis(pentafluorophenyl)-porphyrinatoiron(III) chloride; Fe($T_{4\text{-MeO}}$PP)Cl, 5,10,15,20-tetrakis(4′-methoxyphenyl)porphyrinatoiron(III) chloride; Fe($T_{3,4,5\text{-MeO}}$PP)Cl, 5,10,15,20-tetrakis(3′,4′,5′-trimethoxyphenyl)porphyrinatoiron(III) chloride; Fe(TMP)Cl, 5,10,15,20-tetrakis(2′,4′,6′-trimethylphenyl)-porphyrinatoiron(III) chloride; Fe($T_{2,4,6\text{-MeO}}$PP)Cl, 5,10,15,20-tetrakis (2′,4′,6′-trimethoxyphenyl)porphyrinatoiron(III) chloride; Fe(T_{PIV}PP)-Br, bromo-*meso*-tetrakis(α^4-2′-pivalamidophenyl)porphyrinatoiron-(III); Fe(TAP)Cl, 5,10,15,20-tetrakis(9-anthryl)porphyrinatoiron(III) chloride; Fe(TTPPP)I, 5,10,15,20-tetrakis(2′,4′,6′-triphenylphenyl)-porphyrinatoiron(III) iodide; PhIO, iodosylbenzene; PFIB, pentafluoro-iodosylbenzene; MCPBA, *m*-chloroperbenzoic acid.



Scheme 1 *Reagents and conditions:* i, MeOH, dil H^+, room temp.; ii, pyridine, Ac_2O, 12 h, room temp.; iii, H_2SO_4 2.5 mol dm^{-3}, under N_2, 5–20 h, 100 °C; iv, H_2SO_4 2.5 mol dm^{-3}, 5 h, 100 °C

Mild acid hydrolysis yields two *trans*-6,7-diols (pseudo-diaxial **2a**,**b**), (pseudo-diequatorial **3a**,**b**) from each *cis*-epoxide in the ratio 0.6 : 1 (by HPLC separation); in each case the second (pseudo-diequatorial) diol to elute is present as the major component. Acetylation of the diols produces the corresponding 6,7-diacetates (pseudo-diaxial **4a**,**b**), (pseudo-diequatorial **5a**,**b**) with retention of configuration evidenced by four different extended HPLC retention times. Vigorous hydrolysis of **1a** gives both 6- and 7-phenols **6a**,**7a** in equal amounts, almost quantitatively, after 5 h. Hydrolysis of **1b** gives incomplete conversion into the 6-phenol **6b** after some 20 h, with the 7-phenol **7b** produced in trace amounts. Vigorous hydrolysis of **1a**,**b**, but in the presence of air, produces the 6,7,17-triones **8a**,**b** as the major products. The difference in the ease of hydrolysis and the nature of the phenolic products has also been noted for the hydrolysis of the CPP and 11-MeCPP-*cis*-6,7-diols.[21] Attempts to hydrolyse **1a** or **1b** under basic conditions only produced eventual destruction of the D-ring, no K-region diols being formed.

The chemically reactive K-region was also the target for the oxidation of **I** and **II** with PFIB catalysed by Fe(TPFPP)Cl, cleanly producing the pair of 6,7-diols and the 6,7-epoxide. No rearrangement of the epoxide occurred with time, a process that might have explained the unexpected dibenzoxepine found among the urinary metabolites of **II**.[22] No other products resulting from the oxidation of the terminal A- and D-rings of either CPP or 11-MeCPP were seen, the unhindered biomimetic system performing in a classical chemical fashion. The results obtained from the oxidation of CPP and 11-MeCPP with the hindered iron porphyrins are displayed in Tables 1 and 2, presenting some notable differences in catalytic activity.

Very similar results were obtained with PhIO substituted for PFIB, suggesting no notable kinetic effects upon diol/epoxide formation and a similar mechanistic pathway. The iron porphyrins Fe($T_{4\text{-MeO}}$PP)Cl, Fe(T_{PIV}PP)Cl and Fe(TTPPP)I exhibited no ability to catalyse the oxidation of the cyclopenta[*a*]phenanthrenones. Rapid bleaching, hence inactivation, of the former two unhindered catalysts occurred. Instantaneous bleaching of Fe(TPP)Cl occurred, throughout this study, demonstrating a requirement for at least partial bulk around the porphyrin periphery to prevent μ-oxo dimer formation.[23] Such porphyrin self-oxidation exists as the main non-catalytic pathway when considering the effective oxidation of the desired substrate.[24] Totally restricted access of the Fe(TTPPP)Cl active iron centre to the cyclopenta[*a*]phenanthrenones is evidenced by comparisons with a smaller substrate, cyclohexene (Table 3). Hexane marked the access limit for the similar Mn(TTPPP)OAc.[25]

The reduced catalytic activity of Fe(TMP)Cl over Fe(TPFPP)Cl for cyclohexene oxidation is not in agreement with steric considerations of the greater reluctance of the former to form a μ-oxo dimer. These considerations are outweighed by the electronegative substituents stabilising the ferryl intermediate, as seen in kinetic investigations.[26] However, both the methoxy-substituted porphyrins Fe($T_{2,4,6\text{-MeO}}$PP)Cl and Fe($T_{3,4,5\text{-MeO}}$PP)Cl produce higher yields of the K-region epoxides from the cyclopenta[*a*]phenanthrenones than from Fe(TPFPP)Cl catalysis. Implications are that, steric and porphyrin-iron interaction considerations apart, an attractive catalytic site is presented to the cyclopenta[*a*]phenanthrenones. Both Fe($T_{2,4,6\text{-MeO}}$PP)Cl and Fe($T_{3,4,5\text{-MeO}}$PP)Cl are also seen

Table 1 Yields[a] of CPP oxidation products obtained using various iron porphyrins and PFIB

Catalyst	6,7-Diols/%		6,7-Epoxide/%
	2a	**3a**	**1a**
Fe(TPFPP)Cl	2	3	26
Fe($T_{3,4,5\text{-MeO}}$PP)Cl	1	1	53
Fe(TMP)Cl	2	4	21
Fe($T_{2,4,6\text{-MeO}}$PP)Cl	1	1	33
Fe(TAP)Cl	—	—	Trace

[a] Yields calculated on CPP.

Table 2 Yields[a] of 11-MeCPP oxidation products obtained using various iron porphyrins and PFIB

Catalyst	6,7-Diols/%		6,7-Epoxide/%
	2b	**3b**	**1b**
Fe(TPFPP)Cl	7	11	31
Fe($T_{3,4,5\text{-MeO}}$PP)Cl	Trace		74
Fe(TMP)Cl	7	11	24
Fe($T_{2,4,6\text{-MeO}}$PP)Cl	4	3	49
Fe(TAP)Cl		No products	

[a] Yields calculated on 11-MeCPP.

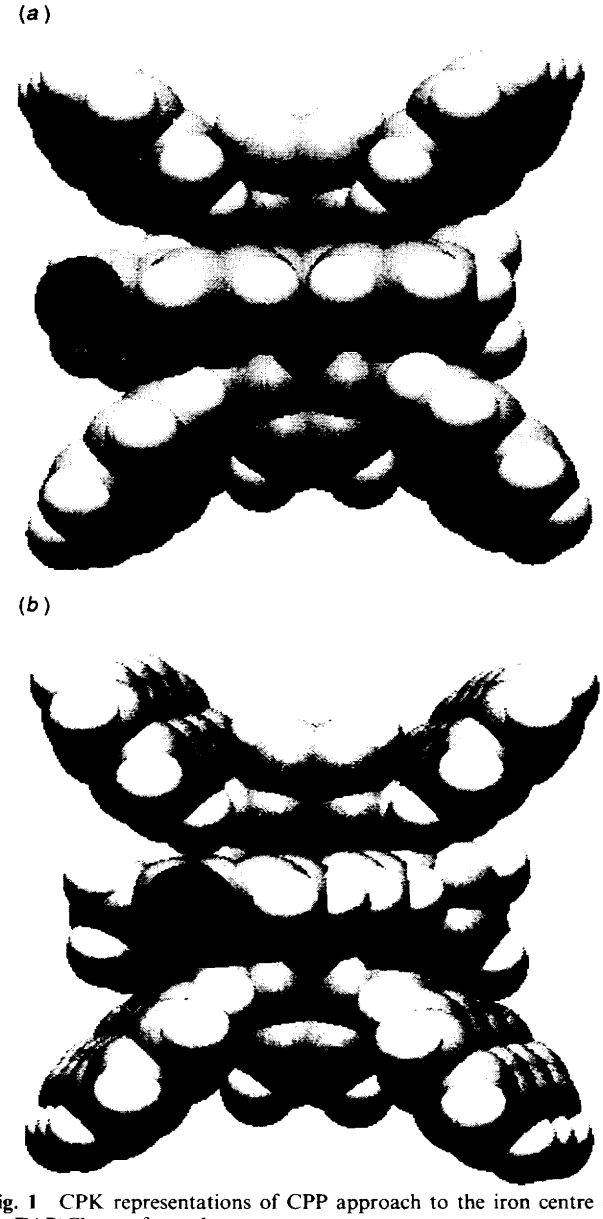


Fig. 1 CPK representations of CPP approach to the iron centre of Fe(TAP)Cl, seen from above

to produce considerably less 6,7-diols from the cyclopenta[*a*]-phenanthrenone substrates than occurs with the other catalysts. Presumably electron release from the porphyrin methoxy substituents is able largely to neutralise some acidic centre in the reaction pathway. It is notable that the peracid oxidation of the cyclopenta[*a*]phenanthrenones produces no diols, under what are essentially slightly alkaline aqueous conditions. It therefore seems reasonable that, under biomimetic oxidation, the 6,7-diols are formed from an acid-catalysed opening of the K-region epoxide.

The mechanism of oxidation can be considered as one where the substrate must directly approach the iron centre above the porphyrin plane.[19] The detailed mechanism remains highly controversial, particularly the fundamental nature of the metal-oxo complex in iodosylbenzene-mediated reactions.[27] The interaction of the metal-oxo complex with the substrate is considered to be either concerted, stepwise *via* a carbocation or stepwise *via* a metalloxetane. A stepwise radical addition mode has been rigorously excluded[28] and hole-transfer mechanisms are considered improbable.[29] In this work, after the oxidation of ^{3}H-CPP, all the label could be accounted for in the products and remaining substrate. Importantly, the implication is that

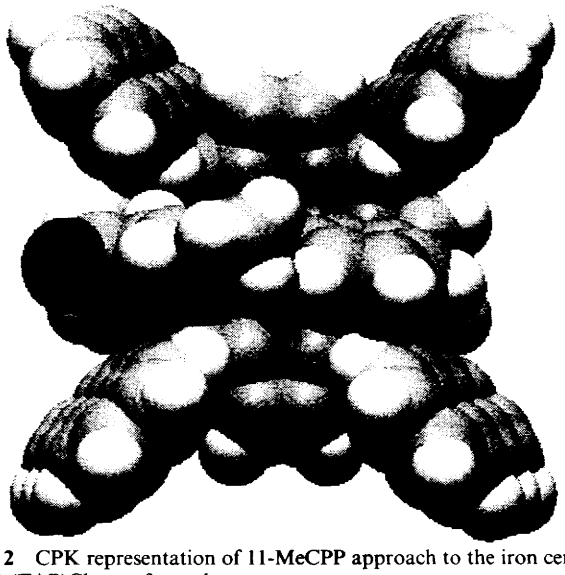


Fig. 2 CPK representation of 11-MeCPP approach to the iron centre of Fe(TAP)Cl, seen from above

CPP is exclusively oxidised *via* either a concerted process or metalloxetane. Structural considerations of the Fe(TAP)Cl-catalysed oxidation of the cyclopenta[*a*]phenanthrenones supports the conclusion that more than simply a steric control of the porphyrin periphery is required to induce terminal (A or D) ring oxidation. The approach of CPP both to produce A-ring oxidation (as per P-450) and K-region epoxidation has been examined by molecular models (Fig. 1). The representation of activated Fe(TAP)Cl was constructed using the program MacroModel[30] under Unix,[31] based upon the coordinates of Fe(TPP)Br[32] sourced from the CSD.[33] The atomic coordinates of (essentially planar) CPP and 11-MeCPP were obtained from the literature.[34] With the implementation of the MM2 force-field, the CPP guest consistently sank into the cavity taking up an 'equatorial' position which presents the most reactive 6,7-double bond to the plane of the porphyrin (Fig. 1a). Manually manipulating CPP to approach with the 3,4-double bond towards the centre of the porphyrin, produces an equally feasible result [Fig. 1(*b*)], with considerably less visible possibilities for steric hindrance of this latter approach. No repulsive nonbonded overlaps between the CPP or porphyrin periphery were seen in either case (separation > sum VDW) under 'BumpCheck'. It is therefore evident that the A-ring is essentially unreactive towards the iron active site, since terminal-ring oxidation products should have dominated for Fe(TAP)Cl catalysis.

The 11-MeCPP 6,7-double bond interaction is less favourable in this hindered catalyst due to nonbonding overlaps between the distorted A- and D-rings with the porphyrin periphery (Fig. 2): A-ring (sum VDW > separation > 0.85 sum VDW), B-ring (sum 0.85 VDW > separation > 0.70 sum VDW). The distortion[34] of the (essentially planar) CPP bay region induced by the 11-methyl substituent is therefore of importance. The increase in steric restraints is suggested as an explanation for the complete absence of oxidation products from 11-MeCPP with Fe(TAP)Cl compared with (albeit minor) oxidation of CPP (see Tables 2 and 3). However, in the comparatively unhindered iron porphyrins the more strained 11-MeCPP may be more susceptible to oxidation, as also indicated in the aforementioned tables.

The current controversy surrounding the mechanism[18] of alkene epoxidation does not help to rationalise the situation existing in PAH oxidation. It is difficult to see how efficient orbital interactions, proposed between an alkene and the active iron porphyrin, can be applied to an aryl substrate approaching

Table 3 Yields[a] of cyclohexene epoxide obtained from the oxidation of cyclohexene using various iron porphyrins and PhIO

Catalyst	Yield[a] (%)
Fe(TPFPP)Cl	79
Fe(TMP)Cl	56
Fe($T_{2,4,6\text{-MeO}}$PP)Cl	52
Fe(TAP)Cl	50
Fe($T_{3,4,5\text{-MeO}}$PP)Cl	48
Fe(T_{PIV}PP)Cl	18
Fe($T_{4\text{-MeO}}$PP)Cl	16
Fe(TTPPP)I	8

[a] Yield based on the consumption of PhIO.

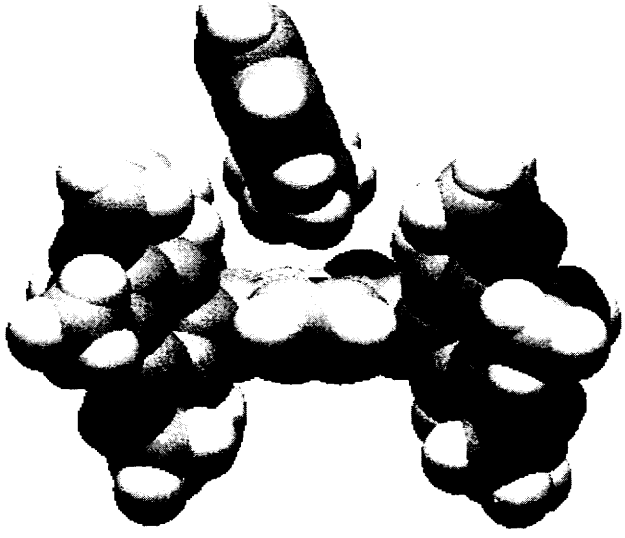


Fig. 3 CPK representation of CPP approach to the iron centre of Fe($T_{3,4,5\text{-MeO}}$PP)Cl, side view

the Fe^{V}=O centre directly from above. The results of other groups[35] support such an unfavourable aryl approach (phenanthrene and acenaphthylene), constrained by incorporating a catenane tunnel above the active iron porphyrin centre. The relative inefficiency of these hindered systems can therefore be partly explained. If a model is considered where cyclopenta[*a*]phenanthrenones approach the iron porphyrin active iron centre in such a fashion as to mimic a 'generalised' alkene epoxidation mechanism, a suggestion for the efficiency of the relatively unhindered porphyrins can be made. The most efficient catalyst for CPP oxidation, Fe($T_{3,4,5\text{-MeO}}$PP)Cl, allows completely free access for the substrate to approach the Fe^{V}=O centre as previously depicted. However, the available space within the Fe($T_{3,4,5\text{-MeO}}$PP)Cl pocket also allows an alternative approach (Fig. 3). In this representation the active porphyrin results from insertion of oxygen into the iron–nitrogen bond,[18] the CPP approaches the iron directly so as to maximise possible orbital overlap (about 70° to the porphyrin plane).

No steric interactions (separation > sum VDW) are evident on initial coordination of CPP to the iron centre and during subsequent motion of CPP towards the available oxygen. Attempts to observe such initial coordination of CPP to the iron centre spectrophotometrically, as seen in the case of alkene substrates,[36] were, however, unsuccessful due to interference from the CPP chromophore. Approach of CPP to the iron centre of Fe($T_{2,4,6\text{-MeO}}$PP)Cl, in a similar fashion, is equally unobstructed. Subsequent motion to an inserted oxygen atom incurs heavy BumpCheck violations (sum 0.70 VDW > separation > 0.55 sum VDW) between the CPP terminal rings and the porphyrin methoxy substituents. It therefore seems unlikely that such a motion could freely occur. Considering purely sterical restraints for CPP approach to Fe($T_{3,4,5\text{-MeO}}$PP)Cl and Fe($T_{2,4,6\text{-MeO}}$PP)Cl can only provide a partial explanation for the higher catalytic efficiency of the former for CPP oxidation. The pronounced efficiency of Fe(TPFPP)Cl for cyclohexene oxidation over that of CPP, suggests that contributory inducements from the porphyrin substituents for a CPP-iron-oxo intermediate are present. These inducements are the subject of further work. More quantitative MO studies are necessary in this field and, hopefully, these series of reactions will promote the interests of both theoretical and experimental chemists.

Experimental

Biomimetic oxidation

The biomimetic oxidations were typically carried out as follows: CPP (3.0 mg, 13.0 μmol) and Fe(TPFPP)Cl (1.30 mg, 1.25 μmol) were placed in freshly distilled dichloromethane (2 cm^3) contained within a septum-sealed vial. Methanolic PFIB (0.5 cm^3, 9.9 mg cm^{-3}, 16 μmol) was injected into the vial and the solution stirred overnight, protected from light, at room temperature. It should be noted that the oxidations were not performed under strictly anhydrous conditions. Products were isolated, purified and quantified by HPLC. Cyclohexene (0.5 mol dm^{-3}) was oxidised by PhIO (1×10^{-3} mol dm^{-3}) in CH_2Cl_2–MeOH–H_2O (80:18:2, v/v) catalysed by various iron porphyrins (9×10^{-6} mol dm^{-3}) at 25 °C, and the reaction was complete after *ca.* 30 mins (PhIO consumption monitored at 285 nm[20]).

Peracid oxidation

The cyclopenta[*a*]phenanthrenone (1.0 mmol) and MCPBA (5 mmol) were stirred vigorously in a mixture of CH_2Cl_2 (25 cm^3) and saturated aqueous sodium hydrogen carbonate (25 cm^3) at 38 °C for 3 h, in accordance with the procedure described for the peracid oxidation of phenanthrene.[37] Subsequent to the described sodium thiosulphate quench, CH_2Cl_2 extraction and evacuation, the epoxides were purified by HPLC (Whatman Partisil M9 10/50 ODS-2) using a linear MeOH–water gradient (30–100% MeOH over 45 min).

Analysis

HPLC analyses and preparative purification were carried out using two Waters 6000A pumps, U6K injector, with detection at 254 nm (440 Detector) quantified with a Spectra Physics Minigrator. Product analysis was typically carried out using an Altex Ultrasphere ODS column (4.6 × 250 mm, 5 μm) with 15–100% MeOH in water over 80 min (linear gradient). Preparative separation utilised a Whatman Partisil M9 10/50 ODS-2 with a MeOH–water gradient (15–100% MeOH linearly over 3 h). GC analysis (cyclohexene oxidation) was performed using a Perkin-Elmer Sigma 3B chromatograph, coupled to a Spectra Physics Minigrator, with 10% Carbowax on WHP 100–120 mesh, 3 mm i.d., 2 m length. A Philips PU8700 spectrophotometer provided UV–VIS data. NMR spectra were obtained using a Bruker AC300-E spectrometer (^{1}H 300.13 MHz, Me_4Si reference, ^{3}H 320.13 MHz), Aspect 3000 processing. Resonance assignments for the cyclopenta[*a*]phenanthrenones were made primarily on sequential NOE experiments.

Materials

All materials were commercially available from Aldrich Chemical Co., unless otherwise stated.

Cyclopenta[*a*]phenanthrenones. Both CPP and 11-MeCPP were available in a pure state as a result of previously reported syntheses.[38]

Iodosylbenzenes. PhIO was prepared from the hydrolysis of

iodosylbenzene diacetate,[39] PFIB was obtained from pentafluoroiodobenzene *via* the bistrifluoroacetate.[40]

Iron porphyrins. The free porphyrins $TPFPPH_2$, $T_{3,4,5\text{-}MeO}PPH_2$, $T_{2,4,6\text{-}MeO}PPH_2$ and $TAPH_2$ were prepared by condensation of their respective benzaldehydes (9-anthraldehyde from Lancaster Synthesis) with pyrrole according to established procedures[41] (yields 7–11%). Subsequent metallation[42] with iron(II) chloride in refluxing DMF produced the respective chloro-*meso*-iron(III) porphyrins. The extremely hindered free $TTPPPH_2$ was prepared as above (yield 1%) prior to metallation with pentacarbonyl iron.[43] The precursor 2,4,6-triphenylbenzaldehyde was prepared from 2,4,6-triphenylbenzene *via* 2,4,6-tribromobenzene.[44] The Rothemunde zinc-template method[45] was used to prepare $TMPH_2$ (yield 3%), prior to metallation with iron(II) chloride to give Fe(TMP)Cl.[46] $Fe(T_{4\text{-}MeO}PP)Cl$ was purified by HPLC before use (Phenomonex C_{18}, 5 μm, 250 × 4.6 mm; 15–100% acetonitrile in water linearly over 80 min). $Fe(T_{PIV}PP)Br$ was obtained from a previously reported synthesis,[47] and the α^4-isomer was separated by differential binding to silica gel.

5,10,15,20-*Tetra*(9-*anthryl*)*porphyrinatoiron*(III) *chloride* Fe(TAP)Cl.—Black solid after flash chromatographic treatment. (Found: C, 83.2; H, 4.2; N, 5.0. $C_{76}H_4ClFeN_4$ requires C, 82.65; H, 4.02; N, 5.07%); $\lambda_{max}(C_6H_6\text{–}CH_2Cl_2)$/nm 250 (ε/dm^3 mol^{-1} cm^{-1} 400 500), 256 (405 400), 352 (52 300), 370 (66 320) and 390 (64 730); $\delta_H(CDCl_3)$ (0.01 mol dm^{-3}) 79.5 (s, br, pyr-H) and 7.6–8.6 (br m, phenyl-H).

[G-^{3}H]-15,16-*Dihydrocyclopenta*[*a*]*phenanthren*-17-*one*.—CPP (10 mg, 0.04 mmol) and pre-reduced PtO_2 (20 mg) were taken up in acetic acid (200 mm^3, 70%) and H[^{3}H]O (3 mm^3, 50 Ci cm^3) was added to the mixture. The tube containing the mixture was frozen in liquid nitrogen, prior to evacuation and sealing. The contents were heated at 140 °C for 60 h, extracted into methanol (5 cm^3) removed in vacuo. A further addition and evacuation of methanol (5 ml) removed the final labile tritium. Final purification was achieved by HPLC as below (30–100% MeOH in water linearly over 2 h). Yield (4 mg, 0.02 mmol) specific activity 165 mCi mmol^{-1}; $\delta_T(CDCl_3)$ 2.30 (33%, s, 16-CT_2), 2.61 (5.9%, s, 15-CT_2), 7.43 (28.2%, s, 2,3-T), 7.61, 7.71 (10.9% ea, s, 6,7-T), 8.03 (6.6%, s, 4-T) and 8.40 (3.3%, s, 1,11-T).

Characterisation of the cyclopenta[*a*]phenanthrenones. NMR data are presented to supplement previous characterisation.[13]

15,16-*Dihydrocyclopenta*[*a*]*phenanthren*-17-*one*[13] (*CPP*) **I**.—$\delta_H(CDCl_3)$ 2.84 (2 H, t, 16-CH_2), 3.44 (2 H, t, 15-CH_2), 7.69 (2 H, m, 2,3-H), 7.88 (4 H, m, 4,6,7,12-H), 8.65 (1 H, d, 11-H) and 8.71 (1 H, cd, 1-H); $\lambda_{max}(CH_2Cl_2)$/nm 265 (ε/dm^3 mol^{-1} cm^{-1} 78 000), 284 (33 100), 297 (24 200), 350 (2500) and 367 (20 800).

11-*Methyl*-15,16-*dihydrocyclopenta*[a]*phenanthren*-17-*one*[13] (11-*MeCPP*) **II**.—$\delta_H(CDCl_3)$ 2.84 (2 H, t, 16-CH_2), 3.15 (3 H, s, 11-CH_3), 3.43 (2 H, t, 15-CH_2), 7.69 (2 H, m, 2,3-H), 7.78 (1 H, s, 12-H), 7.89 (2 H, d, 6,7-H), 7.98 (1 H, m, 4-H) and 8.95 (1 H, m, 1-H); $\lambda_{max}(CH_2Cl_2)$/nm 263 (ε/dm^3 mol^{-1} cm^{-1} 68 000), 288 (30 000), 304 (1300), 358 (2400) and 380 (2700).

cis-6,7-*Epoxy*-6,7,15,16-*tetrahydrocyclopenta*[a]*phenanthren*-17-*one* **1a**.—$\delta_H(CDCl_3)$ 2.83 (2 H, t, 16-CH_2), 3.42 (2 H, dd, 15-CH_2), 4.62 (1 H, d, 6-H), 4.76 (1 H, d, 7-H), 7.49 (1 H, m, 2-H), 7.54 (1 H, m, 3-H), 7.73 (1 H, d, 4-H), 7.85 (1 H, d, 12-H) and 8.18 (2 H, t, 1,11-H); λ_{max}(MeOH)/nm 303 (ε/dm^3 mol^{-1} cm^{-1} 24 300), 307sh (23 820) and 325 (20 420); yield 81%.

cis-6,7-*Epoxy*-11-*methyl*-6,7,15,16-*tetrahydrocyclopenta*[a]-*phenanthren*-17-*one* **1b**.—$\delta_H(CDCl_3)$ 2.70 (2 H, t, 16-CH_2), 2.79 (3 H, s, 11-CH_3), 3.27 (2 H, dd, 15-CH_2), 4.58 (1 H, d, 6-H), 4.76 (1 H, d, 7-H), 7.47 (2 H, m, 2,3-H), 7.61 (1 H, s, 12-H), 7.65 (1 H, d, 4-H) and 8.18 (1 H, d, 1-H); λ_{max}(MeOH)/nm 307 (ε/dm^3 mol^{-1} cm^{-1} 14 230) and 333sh (8300); yield 85%.

trans-6,7-*Dihydroxy*-6,7,15,16-*tetrahydrocyclopenta*[a]*phenanthren*-17-*one* **2a**.—$\delta_H(CDCl_3)$ 2.79 (2 H, ct, 16-CH_2), 3.32 (2 H, m, 15-CH_2), 4.67 (1 H, d, $J_{6,7}$ 4, 6-H), 4.97 (1 H, d, 7-H), 7.45 (3 H, m, 2,3,4-H), 7.83 (1 H, d, 12-H) and 7.92 (2 H, d, 1,11-H); λ_{max}(MeOH)/nm 293 (ε/dm^3 mol^{-1} cm^{-1} 10 520) and 308 (20 770).

trans-6,7-*Dihydroxy*-6,7,15,16-*tetrahydrocyclopenta*[a]*phenanthren*-17-*one* **3a**.—$\delta_H(CDCl_3)$ 2.79 (2 H, ct, 16-CH_2), 3.32 (2 H, m, 15-CH_2), 4.43 (1 H, d, $J_{6,7}$ 9, 6-H), 5.08 (1 H, d, 7-H), 7.45 (2 H, m, 2,3-H), 7.52 (1 H, m, 4-H), 7.82 (1 H, d, 12-H) and 7.93 (2 H, t, 1,11-H); λ_{max}(MeOH)/nm 238 (ε/dm^3 mol^{-1} 10 540) and 307 (20 800).

trans-6,7-*Diacetoxy*-6,7,15,16-*tetrahydrocyclopenta*[a]*phenanthren*-17-*one* **4a**.—λ_{max}(MeOH)/nm 237, 301, 304 and 317sh.

trans-6,7-*Diacetoxy*-6,7,15,16-*tetrahydrocyclopenta*[*a*]*phenanthren*-17-*one* **5a**.—λ_{max}(MeOH)/nm 237, 301, 308 and 319sh.

6-*Hydroxy*-15,16-*dihydrocyclopenta*[a]*phenanthren*-17-*one* **6a**.—$\delta_H(CD_3OD)$ 2.83 (2 H, dt, 16-CH_2), 3.42 (2 H, dt, 15-CH_2), 7.22 (1 H, s, 7-H), 7.69 (3 H, m, 2,3,12-H), 8.42 (1 H, cd, 4-H), 8.68 (1 H, d, 11-H) and 8.79 (1 H, cd, 1-H); $\delta_H(CDCl_3$ sat.) 5.62 (1 H, s, 6-OH); λ_{max}(MeOH)[13]/nm 274 (ε/dm^3 mol^{-1} cm^{-1} 65 500), 289 (40 660), 368 (2168) and 386 (2508); anion λ_{max}(MeOH)[13]/nm 289, 348 and 427.

7-*Hydroxy*-15,16-*dihydrocyclopenta*[a]*phenanthren*-17-*one* **7a**.—$\delta_H(CD_3OD)$ 2.85 (2 H, dt, 16-CH_2), 3.48 (2 H, dt, 15-CH_2), 7.19 (1 H, s, 6-H), 7.70 (3 H, m, 2,3,12-H), 8.21 (1 H, cd, 4-H), 8.66 (1 H, d, 11-H) and 8.73 (1 H, d, 1-H); $\delta_H(CDCl_3$ sat.) 5.51 (1 H, s, 6-OH); λ_{max}(MeOH)/nm 273 (ε/dm^3 mol^{-1} cm^{-1} 65 800), 305 (19 068) and 391 (4747); anion λ_{max}(MeOH)/nm 287, 349 and 447.

6,7,15,16-*Tetrahydrocyclopenta*[*a*]*phenanthrene*-6,7,17-*trione* **8a**.—$\delta_H(CDCl_3)$ 2.81 (2 H, ct, 16-CH_2), 3.65 (2 H, ct, 15-CH_2), 7.60 (1 H, t, 2-H), 7.80 (1 H, t, 3-H), 8.11 (2 H, d, 11,12-H), 8.14 (1 H, d, 4-H) and 8.25 (1 H, d, 1-H); λ_{max}(MeOH)[13]/nm 269 (ε/dm^3 mol^{-1} cm^{-1} 10 950), 280sh (10 238), 327 (1750) and 402 nm (1239); mp[13] 244 °C.

trans-6,7-*Dihydroxy*-11-*methyl*-6,7,15,16-*tetrahydrocyclopenta*[a]*phenanthren*-17-*one* **2b**.—$\delta_H(CDCl_3)$ 2.69 (2 H, ct, 16-CH_2), 2.78 (3 H, s, 11-CH_3), 3.42 (2 H, ct, 15-CH_2), 4.62 (1 H, d, $J_{6,7}$ 4, 6-H), 4.93 (1 H, d, 7-H), 7.40 (2 H, 2,3-H), 7.62 (1 H, s, 12-H), 7.69 (1 H, d, 4-H) and 8.11 (1 H, d, 1-H); λ_{max}(MeOH)/nm 300 (ε/dm^3 mol^{-1} cm^{-1} 19 600).

trans-6,7-*Dihydroxy*-11-*methyl*-6,7,15,16-*tetrahydrocyclopenta*[a]*phenanthren*-17-*one* **3b**.—$\delta_H(CDCl_3)$ 2.68 (2 H, t, 16-CH_2), 2.79 (3 H, s, 11-CH_3), 3.38 (2 H, ct, 15-CH_2), 4.37 (1 H, d, $J_{6,7}$ 9, 6-H), 5.05 (1 H, d, 7-H), 7.40 (2 H, m, 2,3-H), 7.64 (1 H, s, 12-H), 7.73 (1 H, d, 4-H) and 8.11 (1 H, d, 1-H); λ_{max}(MeOH)/nm 301 (ε/dm^3 mol^{-1} cm^{-1} 19 200).

trans-6,7-*Diacetoxy*-11-*methyl*-6,7,15,16-*tetrahydrocyclopenta*[a]*phenanthren*-17-*one* **4b**.—λ_{max}(MeOH)/nm 301 and 310sh.

trans-6,7-*Diacetoxy*-11-*methyl*-6,7,15,16-*tetrahydrocyclopenta*[*a*]*phenanthren*-17-*one* **5b**.—λ_{max}(MeOH)/nm 301 and 312sh.

6-*Hydroxy*-11-*methyl*-15,16-*dihydrocyclopenta*[a]*phenanthren*-17-*one* **6b**.—$\delta_H(CD_3OD)$ 2.70 (2 H, ct, 16-CH_2), 2.88 (3 H, s, 11-CH_3), 3.34 (2 H, ct, 15-CH_2), 7.25 (1 H, s, 7-H), 7.69 (2 H, m, 2,3-H), 7.81 (1 H, s, 12-H), 8.54 (1 H, cd, 4-H), 9.02 (1 H, m, 1-H); $\delta_H(CDCl_3$ sat.) 5.68 (1 H, s, 6-OH); λ_{max}(MeOH)[13]/nm 266 (ε/dm^3 mol^{-1} cm^{-1} 63 200), 288 (39 260), 365 (4980) and 382 (3516); anion λ_{max}(MeOH)[13]/nm 268sh, 289, 298sh, 350 and 425.

7-*Hydroxy*-11-*methyl*-15,16-*dihydrocyclopenta*[a]*phenanthren*-17-*one* **7b**.—λ_{max}(MeOH)/nm 265, 289 and 389; anion λ_{max}(MeOH)/nm 332 and 442.

11-*Methyl*-6,7,15,16-*tetrahydrocyclopenta*[a]*phenanthrene*-6,7,17-*trione* **8b**.—$\delta_H(CDCl_3)$ 2.69 (2 H, ct, 16-CH_2), 2.84 (3 H, s, 11-CH_3), 3.32 (2 H, ct, 15-CH_2), 7.49 (1 H, t, 2-H), 7.59 (1 H,

t, 3-H), 7.78 (1 H, s, 12-H), 7.94 (1 H, d, 4-H) and 8.23 (1 H, d, 1-H); λ_{max}(MeOH)[13]/nm 263 (ε/dm^3 mol^{-1} cm^{-1} 21 200), 346 (5660) and 413 (1236).

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