ELSEVIER

Journal of Molecular Catalysis A: Chemical 125 (1997) 23–32

JOURNAL OF MOLECULAR CATALYSIS A: CHEMICAL

Oxidation of polycyclic aromatic hydrocarbons by an oxoferryl porphyrin π-cation radical

A. Gold *, K. Jayaraj, L.M. Ball, K. Brust

Department of Environmental Sciences and Engineering, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-7400, USA

Received 11 November 1996; accepted 25 February 1997

Abstract

Pre-formed oxoferryl tetrakis (2,6-dichlorophenyl)porphinatoiron π-cation radical at $-80°C$ in methylene chloride:methanol-d_4 is used as a low-turnover oxidant to elucidate oxidation pathways of pyrene and benzanthracene. Quantitative incorporation of the oxo oxygen in pyrene quinones and benzanthracene phenols, determined by ^{18}O-labeling experiments, indicates that a substantial proportion of the products arise via a tight complex in which the oxoferryl unit is accessible to the periphery of the polycyclic aromatic hydrocarbon. Methoxylated products indicate that one-electron transfers by an outer-sphere oxidation mechanism also occur. Thus dual reaction pathways are demonstrated. Modeling cytochrome P450-mediated oxidations by reactions of pre-formed oxoferryl porphyrin π-cation radicals under single- or low-turnover conditions appears to be a straightforward strategy for investigation of cytochrome P450 mechanisms. Nevertheless, it has rarely been exploited and, to date, reports concern only oxoferryl tetramesitylporphyrin π-cation radical epoxidation of olefins. The catalyst employed here is more active, and thus closer in behavior to cytochrome P450. © 1997 Elsevier Science B.V.

Keywords: Oxoferryl porphyrin π-cation radical; Compound I analog; Iron porphyrin catalyzed oxidation of pyrene; Iron porphyrin catalyzed oxidation of benzanthracene; Iron porphyrin catalyzed oxidation of PAH

1. Introduction

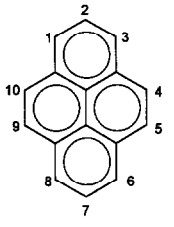
Oxoferryl porphyrin π-cation radical (compound I) transients are putative catalytic intermediates in cytochrome P450-mediated oxidations which encompass a variety of transformations [1,2]. Of these reactions, monooxygen transfer has received considerable attention because of its importance in xenobiotic metabolism as well as the potential utility of biomimetic monooxygenations in stereo- and regioselective synthetic schemes [3]. Extensive efforts have been directed at modeling catalytic activity using synthetic iron porphyrin complexes under multi-turnover conditions with various monooxygen donors, such as peroxyacids and iodosylarenes ([2–4] and references therein). By contrast, only a few studies have approached mechanistic investigations by single turnover reactions in which substrate is added to the preformed oxoferryl porphyrin π-cation radical

* Corresponding author.

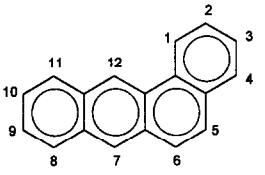
PII S1381-1169(97)00053-8

(compound I analog) [5–8]. Of the substrates investigated in model systems, polycyclic aromatic hydrocarbons (PAH) have received little attention [8–10]. Polycyclic aromatic hydrocarbons are useful as sensitive probes for regioselectivity of oxidation of π-conjugated systems, and are also of interest as precursors to carcinogenic species derived from oxidative biotransformation initiated by cytochromes P450 [1,11]. For the oxidation of PAH, a mechanistic question of considerable interest is the role of one-electron transfers [12,13].

Although the tetrakis(2,6-dichlorophenyl)porphinatoiron(III) complex has been widely used in biomimetic oxidation reactions, conditions which assure formation of the compound I analog have not been employed [4,9,14]. We have demonstrated that an oxoferryl porphyrin π-cation radical can be generated cleanly and quantitatively from triflato tetrakis(2,6-dichlorophenyl)porphinatoiron(III) by treatment with approximately 2-fold molar excess *m*-chloroperoxybenzoic acid (*m*CPBA) at $-80°$, in the presence of 10% methanol [15]. At $-80°$ with methanol-d_4 to minimize reduction by reaction with cosolvent, the compound I analog is stable for periods longer than one hour. By monitoring $\nu_{Fe=O}$ in resonance Raman studies in which the monooxygen donor was ^{18}O-labeled *m*CPBA, we have demonstrated that label from the peroxyacid is stably incorporated into the oxoferryl porphyrin π-cation radical [16]. Thus the high-valent complex can be used in single turnover studies and the transfer of oxo oxygen investigated with ^{18}O-labeled peroxyacid as monooxygen source. We describe here the generation and use of this compound I analog under approximately single turnover conditions to oxidize the PAH pyrene (**1**) and benzanthracene (**2**). We also describe the incorporation of ^{18}O from ^{18}O-oxoferryl porphyrin π-cation radical into oxidation products. In contrast to previous reports of low yields from PAH oxidations [9,10], the yields of products obtained in the oxidations described here assure that major reaction processes are being monitored.



1



2

2. Experimental section

2.1. Chemicals

Methylene chloride was distilled from calcium hydride and methanol-d_4 was used as received. Pyrene and benz[*a*]anthracene were purified by column chromatography over silica eluted with chloroform:hexane, and purity verified by HPLC. 3-Chloroperoxybenzoic acid (*m*CPBA) was dried by solution in methylene chloride followed by filtration through $MgSO_4$ and removal of solvent under reduced pressure. The titer of the resulting peroxyacid was determined by iodometric titration to be 55%. *m*CPBA ^{18}O-labeled in the peroxy oxygens (two batches, 70% and > 90% enrichment by mass spectrometric analysis) was synthesized by photolysis of a methylene chloride solution of 3-chlorobenzaldehyde in an atmosphere of $^{18}O_2$-enriched (98.8%; Isotec) dioxygen at $-20°$; the titer of the labeled acid was 55%. Pyridine was distilled from KOH. Triflato tetrakis(2,6-dichlorophenyl)porphinatoiron(III) was obtained according to published procedures [15].

2.2. Instrumentation

Mass spectra were obtained on a VG 70-250SEQ mass spectrometer operating in the EI mode, at 70 eV ionizing voltage. NMR spectra were recorded on a Bruker 500AMX spectrometer at 500 MHz and UV-vis spectra recorded on a Milton-Roy Spectronic 1201 spectrophotometer.

2.3. Analysis of products

Oxidation products were quantitated by ^{1}H NMR spectrometry of fractions isolated by HPLC; dioxane was added as an internal standard and the integral of the dioxane singlet (3.65 ppm) compared with that of a well resolved proton signal attributed to the product. Incorporation of ^{18}O in labeling studies was determined by mass spectrometry from isotope distributions of molecular ions averaged over 10 scans.

2.4. Oxidation reactions

Reactions were carried out under argon. Formation of the oxoferryl tetrakis (2,6-dichlorophenyl)porphyrin π-cation radical was accomplished by dissolving the triflato complex of the ferric porphyrin in methylene chloride at a concentration of 1.4–1.8 mg/ml, cooling to $-80°$ (dry ice–acetone) and adding to the stirred mixture *m*CPBA dissolved in sufficient methanol-d_4 to make a 9:1 methylene chloride:methanol-d_4 solution. At least 2-fold molar excess *m*CPBA is necessary for complete conversion of the porphyrin to the compound I analog [15]. The reaction mixture was stirred ~ 10 min (a deep green color develops as the compound I analog forms) and then a solution of the hydrocarbon (20 to 40-fold molar excess over catalyst) in a minimum volume of methylene chloride was added slowly down the side of the reaction flask to avoid warming the solution. The green color rapidly changed to red–brown, indicating reduction of the compound I analog to ferric complex. The reaction was maintained at $-80°$ for 45 min and then allowed to come to room temperature. The reaction mixture was then diluted with three volumes of methylene chloride, washed twice with equal volumes of saturated sodium bicarbonate and once with distilled water. The organic layer was dried over sodium sulfate and the solvent removed on a rotary evaporator. Oxidations with ^{18}O-*m*CPBA were conducted in the same manner.

2.5. Work-up of pyrene oxidation reactions

Aliquots of the pyrene reaction mixture were dissolved in 4:1 methanol:water and separated by isocratic semipreparative scale HPLC, on a 9.4 × 250 mm ODS column with 80:20 methanol:water eluant at a flow rate of 2 ml/min. Recovery of pyrene from HPLC collection was established gravimetrically as 72%, and this recovery factor was applied to all HPLC fractionations.

2.6. Work-up of benzanthracene oxidation reactions

The major products of benz[*a*]anthracene oxidation (8- and 11-benzanthracene phenols and 7-[methoxy-d_3]-benzanthracene) were quantitated following acetylation of the reaction mixture (solution in 1:1 v/v pyridine:acetic anhydride). The acetylated mixture was separated by TLC on 1000 μm silica plates eluted with hexane:chloroform 1:3 v/v into 4 bands. The band of highest mobility contained unreacted benzanthracene; following bands contained 7-methoxybenzanthracene then acetylated phenols. The lowest mobility TLC band appeared to contain a mixture of derivatized k-region dihydrodiols (vide infra) and was further resolved by semipreparative HPLC on the 9.4 × 250 mm ODS column using the following gradient program: 10 min at 75:25 methanol:water, increasing to 100% methanol over 10 min at 2 ml/min. Fractions with retention times of 19, 23 and 30 min were resolved. The 19 and 23 min fractions were isomeric C5–C6 dihydro acetoxy[methoxy-d_3] benzanthracenes and the 30 min fraction contained coupled benzan-

thracene dimers. The yield of dimers was estimated from the HPLC chromatogram (with UV detector at 350 nm) using benzanthracene as a standard under the assumption that the extinction coefficients of benzanthracene and of the dimers were similar.

Incorporation of ^{18}O in the phenol mixture from the oxidation of benz[*a*]anthracene was determined on the underivatized compounds after separation from the reaction by semipreparative HPLC. The column described above was used with the following gradient elution program: 5 min at 75:25 methanol:water increasing to 100% methanol over 15 min, at 2 ml/min. The phenol mixture was collected as a single, broad peak at 22 min.

3. Results

HPLC separation of pyrene oxidation products gave three fractions which were identified as pyrene-1,6-quinone (**3**) (12.8 min), pyrene-1,8-quinone (**4**) (13.9 min) and a mixture of

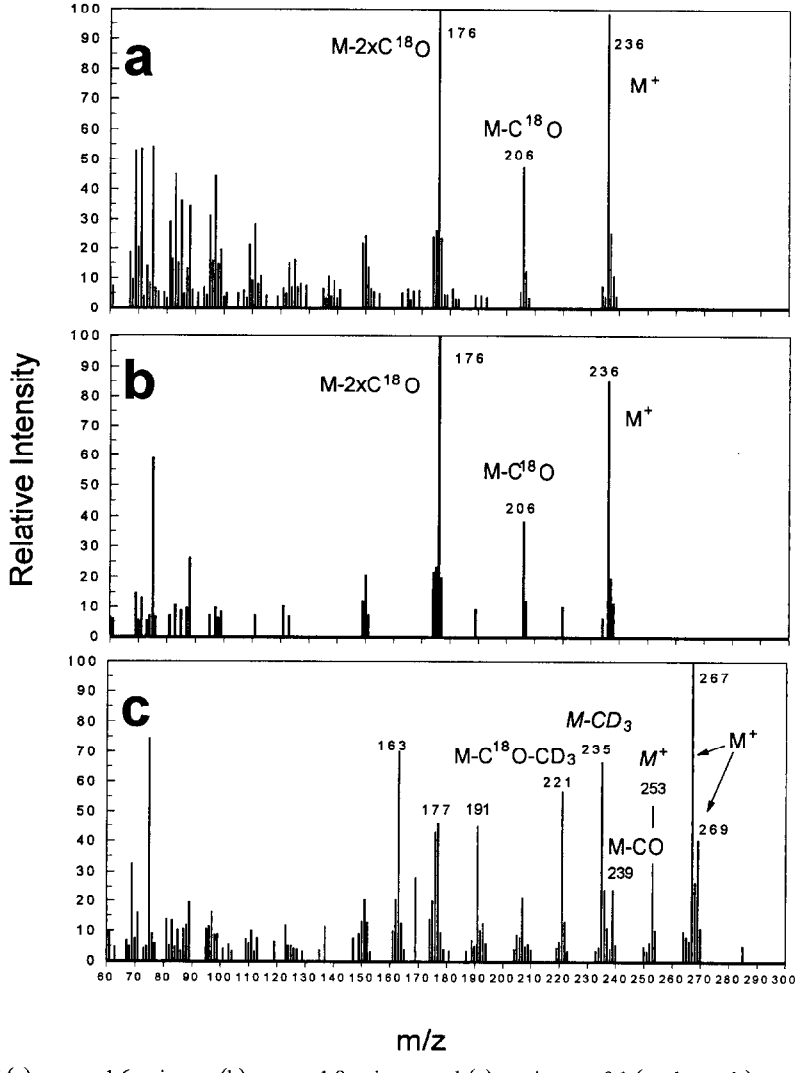
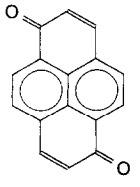
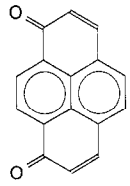


Fig. 1. Mass spectra of (a) pyrene-1,6-quinone, (b) pyrene-1,8-quinone and (c) a mixture of 1-(methoxy-d_3)pyrene-1,6- and 1,8-quinones isolated from pyrene oxidation by the compound I analog generated with *m*CPBA having > 90% ^{18}O-enrichment of the peroxy oxygens. Ions in panel c identified by italic type represent [^{18}O]-hydroxymethoxy pyrenes.

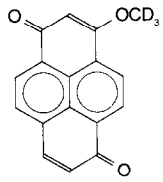
3-methoxy-d_3-1,6- and 1,8-quinones (**5,6**) (17 min), by comparison of UV-vis, ^{1}H NMR and mass spectra with those of samples characterized previously [7]. Compound I generated from *m*CPBA > 90% ^{18}O-enriched in the peroxy oxygens gave 1,6- and 1,8-pyrenequinones in which both oxo oxygens were labeled (Fig. 1a, b). Quantitative incorporation of two atoms of ^{18}O is indicated by the appearance of the molecular ions at $m/z = 236$, 4 mass units higher than the molecular ion of the natural abundance isotopomer, and the absence of ions corresponding to the natural abundance isotopomer ($m/z = 232$) or incorporation of a single ^{18}O label ($m/z = 234 < 10\%$ of $m/z = 236$). Mass spectrometric analysis of the methoxyquinone mixture (Fig. 1c) showed molecular ions of isotopomers at m/z 267 and 269 in a 2:1 ratio, corresponding to incorporation of one and two ^{18}O labels, respectively. No unlabeled methoxy quinones are observed. Comparison of chromatograms of ions at $m/z = 269$, 267, 253 and 235 indicate that the ions at $m/z = 253$ and 235 (Fig. 1c) arise from a second component of the methoxyquinone fraction. In the ^{1}H NMR spectrum of the methoxyquinone fraction, a trace constituent with doublets at 7.48 and 7.42 ppm integrates (assuming 1 proton each) to < 5% of the total methoxyquinones. These chemical shifts are in accord with aromatic protons adjacent to a hydroxy or methoxy substituent and, along with the ions at $m/z = 253$ and 235, are compatible with 6- or 8-[^{18}O]-hydroxy-1-[^{16}O]-methoxy pyrene (M^+, m/z 253; $M-CD_3$, m/z 235). (Note that the electron impact mass spectrum reflects the relative volatilities of components and is not a quantitative measure of sample composition.)



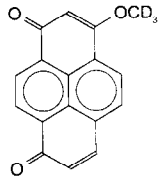
3



4



5



6

Reactions were carried out over a range of [*m*CPBA]/[porphyrin] and [pyrene]/[porphyrin] ratios (Table 1). Yield calculations (vide infra) were based on active *m*CPBA added, and assumed 3 mol *m*CPBA consumed per mole of quinone and 2.67 moles of *m*CPBA per mole of methoxy quinone. Yields were constant, at 27 ± 4%, and product ratios vary only slightly with reaction parameters.

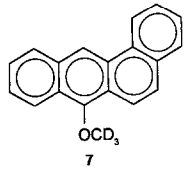
Methoxybenzanthracene (**7**) could not be separated from unreacted benzanthracene by HPLC, but was readily resolved by TLC on silica. For quantitation, therefore, the benz[*a*]anthracene oxidation mixture was separated by TLC following acetylation to stabilize hydroxylated products. 7-(Methoxy-d_3)benzanthracene was identified by comparison of spectroscopic data with previously authenticated samples [7]. A co-eluting mixture of acetylated 8- and 11-phenols (**8**, **9**) was confirmed by mass spectrometry

Table 1
Distribution of products from oxidation of pyrene by the oxoferryl tetrakis(2,6-dichlorophenyl)porphyrin π-cation radical

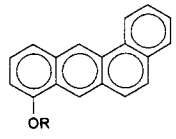
Stoichiometry			Product ratios [a]		
[*m*CPBA [b]]/[porphyrin]	[pyrene]/[porphyrin]	[porphyrin] (μmol/ml)	1,6-quinone	1,8-quinone	methoxy quinone
2.28	18.6	1.49	3.71	1.43	1.00
3.48	23.8	1.77	2.88	1.51	1.00
3.48	24.6	1.45	2.12	1.00	1.86
3.57	20.1	1.40	1.79	1.00	2.63
8.14	22.1	1.69	2.38	1.12	1.00
11.65	37.0	1.67	2.27	1.00	1.82

[a] Yields are identical for all reactions, 27 ± 4%.
[b] Active *m*CPBA.

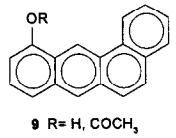
(M^+, m/z 286) and the presence of two acetoxy methyl signals in a 1.4:1 ratio in the ^1H NMR spectrum (Fig. 2). The regiochemistry of substitution was established by comparing the ^1H NMR spectrum of the mixture with that of benzanthracene. The absence of a signal from H8 in one product and from H11 in the other is evident by the appearance of two well-separated one-proton doublet resonances in a ratio of 1.4:1 at 8 and 7.9 ppm, where the resonances of H11 and H8, respectively, are expected.



7



8 R=H, $COCH_3$



9 R= H, $COCH_3$

The TLC band characterized as a mixture of 5,6-dihydrodiol derivatives by preliminary UV-vis and ^1H NMR analysis, was further resolved by semipreparative HPLC into three fractions with elution times of 19, 23 and 30 min. By UV-vis and mass spectrometry (M^+, m/z = 321), the 19 and 23 min fractions contained 5,6-dihydro-5,6-(methoxy-d_3)acetoxybenzanthracene derivatives. The ^1H NMR spectrum of the 19 min fraction is consistent with a mixture of trans 5,6-dihydro-5-(methoxy-d_3)-6-acetoxy- and trans 5,6-dihydro-5-acetoxy-6-(methoxy-d_3)benzanthracene isomers (**10a, b**) on the basis of 4.3 Hz coupling of methinyl protons. Methinyl proton couplings of 2.9 Hz indicate that the 23 min fraction is a mixture of the two derivatized *cis* 5,6-dihydrodiols (**11a, b**). Thus, the four possible geometric isomers of the dihydrodiol derivatives were generated. The

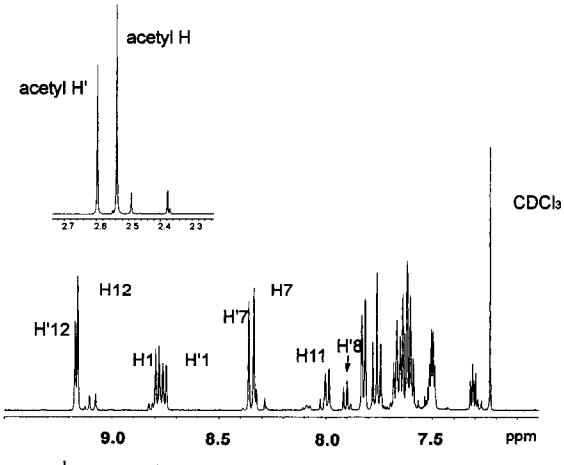
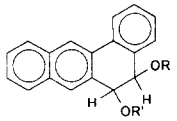


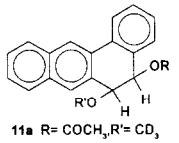
Fig. 2. ^1H NMR (500 MHz, chloroform-*d*) of the mixture of 8- and 11-acetoxybenzanthracenes. Resonances associated with the 11-acetoxy derivative are indicated on trace by primed labels.

30 min HPLC fraction displayed a benzanthracene chromophore by UV-vis, acetyl methyl groups by ^{1}H NMR and high molecular weight components with molecular ions of odd mass: $m/z = 487$, 529 and 571. These molecular ions correspond to coupling products of [methoxy-d_3]-benzanthracene with benzanthracene ($m/z = 487$), along with mono- ($m/z = 529$) and diacetylated ($m/z = 571$) derivatives.



10a R= $COCH_3$, R'= CD_3

10b R= CD_3, R'= $COCH_3$



11a R= $COCH_3$, R'= CD_3

11b R= CD_3, R'= $COCH_3$

As in the case of the pyrene oxidation, yield calculations are based on active *m*CPBA added. One mole of *m*CPBA was assumed to be consumed per mole of phenol, 7-methoxybenzanthracene and dihydrodiol and two moles per mole of coupled dimer. Products and yields from the oxidation of benzanthracene are given in Table 2.

Quantitative incorporation of ^{18}O into phenols generated from compound I was observed using *m*CPBA 70%-enriched in the peroxy oxygens as oxygen source for the compound I analog. Molecular ions corresponding to 70% ^{18}O enrichment of the phenols appear at $m/z =$ 244, 246. The absence of any ^{18}O label in the acetylated dimers from the labeling experiments indicates that initially formed phenolic products were not coupled and that acetylation was an artifact of the work-up procedure. The dihydrodiol derivatives were not obtained in sufficient purity from the labeling experiments to be reliably analyzed for ^{18}O incorporation.

Table 2
Products and yields from oxidation of benzanthracene by the oxoferryl tetrakis(2,6-dichlorophenyl)porphyrin π-cation radical

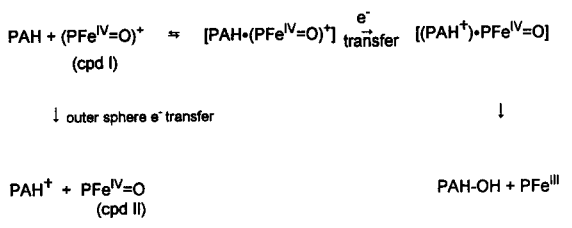
Product	μmol	Oxidant equivalents [a]	% yield
8- and 11-hydroxylated benzanthracenes	40.1	40.1	24.8
7-(methoxy-d_3)benzanthracene	5.2	5.2	3.2
5,6-dihydrodiol derivatives	2.5	2.5	1.5
Coupling products [a]	2.5	5.0	3.0
Total		52.8	32.5

[a] Stoichiometry of reactants (μmol): benzanthracene, 177; active *m*CPBA, 162 and porphyrin, 50.

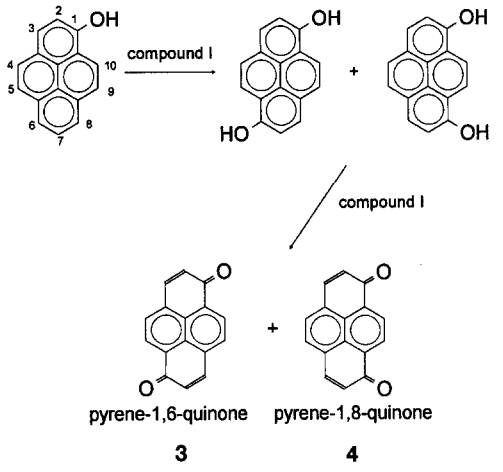
4. Discussion

The anthracene cation radical is attacked by nucleophiles at C9 and/or C10 [17–20], and similar chemistry at C7 would be predicted for the benzanthracene cation radical and at C1 for the pyrene cation radical. The formation of methoxylated derivatives of both pyrene and benzanthracene thus provides evidence that one-electron oxidation processes are operative. The presence of coupled dimers among the products of benzanthracene oxidation lend additional support to this conclusion. The nucleophilic attack of methanol cosolvent to yield methoxylated products is confirmed by use of methanol-d_4 and determination that all methoxy groups are deuterated. The electron-withdrawing 2,6-dichlorophenyl substituents will raise the oxidation potential of the compound I analog above +1.45 V determined for the compound I analog of tetramesitylporphyrin [21,22]. Since this oxidation potential exceeds that of pyrene and benzanthracene (+1.2 V, vs. SCE [23]), oxidation of the PAH by one-electron transfer is expected. At the same time, oxidations using ^{18}O-*m*CPBA to generate the oxoferryl porphyrin π-cation radical demonstrate quantitative incorporation of ^{18}O label in benzanthracene 8- and 11-phenols and pyrene 1,6-

and 1,8-quinones, and incorporation of one and two ^{18}O labels in a 2:1 ratio into the methoxy pyrene quinones. Incorporation of ^{18}O by routes other than reaction with the oxoferryl porphyrin π-cation radical may be ruled out on several counts. *m*CPBA is inert towards the neutral PAH under the conditions used for the oxidations (−80°, 45 min) [14]; therefore, direct oxidation of the PAH by *m*CPBA will not occur. Reaction of initially generated PAH cation radicals with excess *m*CPBA can be discounted by the fact that the ratio of 1,6- and 1,8-pyrene quinones to methoxypyrene quinones does not show any trend with increasing *m*CPBA:porphyrin ratios (Table 1). Under conditions identical to those of the oxidations, it has been demonstrated that the compound I analogs do not exchange ^{18}O with trace water [16]. The sequence of reactions leading to the observed products is most simply accommodated by the mechanism depicted in Scheme 1. Oxidation can occur either by outer sphere 1-electron transfer, analogous to peroxidase-mediated one-electron [24] oxidations, or from a PAH:compound I complex. Because of the high oxidation potential of the compound I analog generated from tetrakis(2,6-dichlorophenyl)porphyrin, we postulate electron transfer within the complex to give a PAH cation radical:oxoferryl (compound II) complex, which then collapses to monooxygenated product and ferric porphyrin. While the oxoferryl species is not an efficient monooxygen donor and would not be expected to hydroxylate the neutral PAH [25,26], reaction with the aromatic cation radical has, indeed, been supported [27,28]. 1-Hydroxypyrene, the initial oxidation product (Scheme 2),



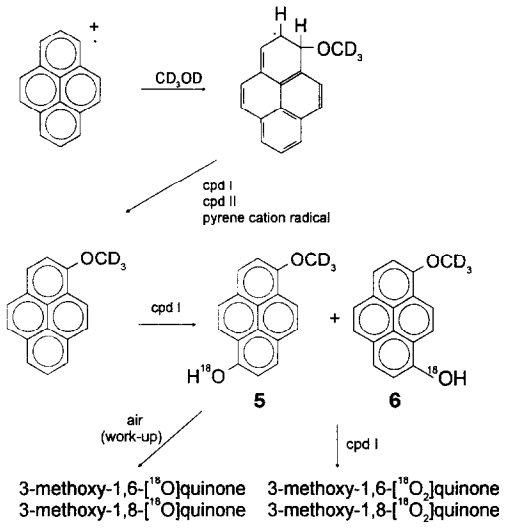
Scheme 1.



Scheme 2.

is activated towards additional hydroxylation and to a mixture of 1,6- and 1,8-dihydroxypyrenes. The dihydroxy pyrenes are even more readily oxidized, leading to the respective quinones. Although oxidation of the dihydroxy pyrenes to the quinones by dioxygen could occur during work-up, it is more likely that one of several oxidizing species present during the reaction: compound I, compound II, or pyrene cation radicals, would accomplish this. Since *m*CPBA is the source of all oxidizing equivalents present in the reaction mixture, three moles of *m*CPBA would be consumed for each mole of quinone produced.

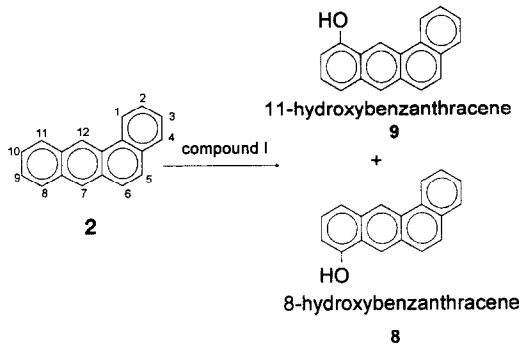
The methanol-d_4 cosolvent can attack the pyrene cation radical generated by outer sphere electron transfer (Scheme 3), and one electron oxidation of the resulting radical species gives 1-methoxypyrene. 1-Methoxypyrene, like 1-hydroxypyrene, is activated towards hydroxylation to give a mixture of 6-hydroxy-1-methoxy- and 8-hydroxy-1-methoxypyrenes. The isolation of methoxypyrene quinones with one or two ^{18}O-labels in a 2:1 ratio (Fig. 1c), indicates that the source of the second quinone oxygen is air or compound I in 2:1 ratio. As shown in Scheme 3, this may occur via oxidation of the hydroxymethoxypyrene intermediates by air during work-up or by compound I during the reaction. The 2:1 ratio of singly:doubly labeled



Scheme 3.

methoxypyrene quinones leads to the net utilization of 2.67 moles of *m*CPBA/mole of methoxypyrene quinone. Since only one-third of the methoxy quinone mixture contains two ^{18}O labels, the possibility that methoxypyrene quinones result from the oxidation of the pyrene quinones rather than initial formation of 1-methoxypyrene is ruled out by the absence of pyrene 1,6- and 1,8-quinone containing a single ^{18}O-label. The presence of small quantities of [^{18}O]-hydroxy-[^{16}O]-methoxy pyrenes provides strong support for the route proposed in Scheme 3.

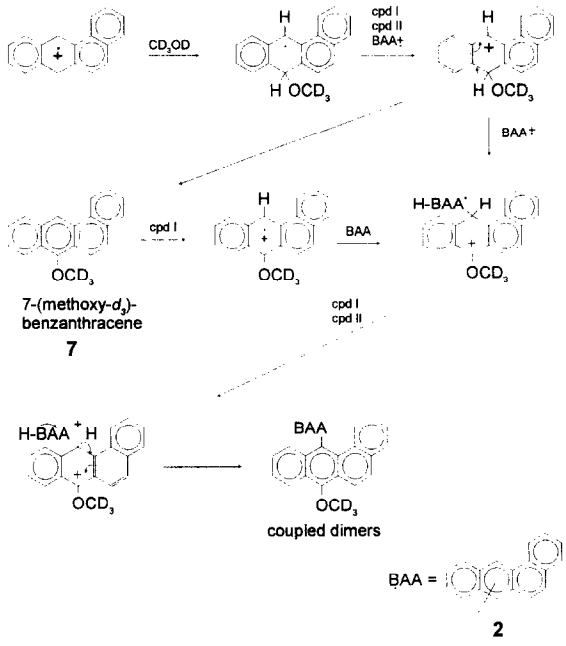
In the case of benzanthracene, the primary oxidation products do not undergo multiple oxidations (Scheme 4). Each mole of product therefore results in the consumption of one mole of *m*CPBA, and yields were calculated on this basis. By analogy to anthracene, nucleophilic attack of methanol-d_4 is predicted at C7 of the cation radical produced by outer sphere electron transfer leading, after an additional one-electron oxidation, to 7-(methoxy-d_3)benzanthracene (Scheme 5). Since the ultimate source of the second oxidizing equivalent is *m*CPBA, the oxidizing equivalent of one mole of peroxyacid is consumed in generating the 7-methoxy derivative. The coupled dimers are readily explained



Scheme 4.

by attack of the radical intermediate from methanol addition to benzanthracene or the one-electron oxidation product of 7-methoxybenzanthracene on benzanthracene or benzanthracene cation radical [29] (Scheme 5). The regiochemistry of coupling has not been established in the mixture of dimers.

The absence of benzanthracene-7,12-quinone among the oxidation products may reflect steric factors controlling access of the aromatic periphery to the oxo oxygen. However, it is noteworthy that this quinone is not a product of cytochrome P450-mediated oxidation of benzan-



Scheme 5.

thracene [30,31], and the analogous 9,10-anthraquinone is not a direct product of nucleophilic attack on the anthracene cation radical, even in the presence of water [17,20]. Hence, the product profile of benzanthracene oxidation is consistent with involvement of pathways that are known to involve one-electron transfers. Under reaction conditions that exclude high concentrations of air and water, the most likely origin of the C5–C6 hydroxymethoxy derivative mixture is methanolysis of benzanthracene-5,6-oxide.

In summary, the oxidation of pyrene and benzanthracene by a cytochrome P450 model has been investigated. This objective was approached by using an oxoferryl porphyrin π-cation radical (compound I analog), preformed at $-80°$ from tetrakis(2,6-dichlorophenyl)porphinatoiron(III) in a homogeneous reaction mixture by treatment with *m*CPBA. The results of labeling with ^{18}O-*m*CPBA as monooxygen donor and the observed product distributions support a scheme involving both outer sphere one-electron transfer and oxidation following formation of a PAH:compound I complex.

Acknowledgements

This work was supported in part by USPHS Grant ES03433.

References

[1] F.P. Guengerich (Ed.), Mammalian Cytochromes P450, Vol II, CRC Press, Boca Raton, FL, 1987.
[2] P.R. Ortiz de Montellano (Ed.), Cytochrome P450: Structure, Mechanism, and Biochemistry, Plenum Press, NY, 1995.
[3] B. Meunier, Chem. Rev. 92 (1992) 1411.
[4] G.J. Harden, M.M. Coombs, J. Chem. Soc. Perkin Trans. 1 (1995) 3037.
[5] J.T. Groves, R.C. Haushalter, N. Nakamura, T.E. Nemo, B.J. Evans, J. Am. Chem. Soc. 103 (1983) 2884.
[6] J.T. Groves, Y. Watanabe, J. Am. Chem. Soc. 108 (1986) 507.
[7] A. Gold, K. Brust, K. Jayaraj, R. Sangaiah, L.M. Ball, A.X. Trautwein, E. Bill, Polycyclic Aromat. Comp. 7 (1994) 27.
[8] Z. Gross, S. Nimri, J. Am. Chem. Soc. 117 (1995) 8021.
[9] C.K. Chang, F. Ebina, J. Chem. Soc., Chem. Commun. (1981) 778.
[10] J.R.L. Smith, P.R. Sleath, J. Chem. Soc. Perkin Trans. 2 (1982) 1009.
[11] R.G. Harvey, Acc. Chem. Res. 14 (1981) 218.
[12] N.V.S. RamaKrishna, E.L. Cavalieri, E.G. Rogan, G. Dolnikowski, R.L. Cerny, M.L. Gross, H. Jeong, R. Jankowiak, G.J. Small, J. Am. Chem. Soc. 114 (1992) 1863.
[13] E.L. Cavalieri, E.G. Rogan, in: R.G. Harvey (Ed.), Polycyclic Hydrocarbons and Cancer, American Chemical Society, Washington, DC, 1985, p. 289.
[14] A. Gold, K. Jayaraj, R. Sangaiah, L.M. Ball, Chem.-Biol. Interact. 68 (1988) 39.
[15] C. Mandon, R. Weiss, K. Jayaraj, A. Gold, J. Terner, E. Bill, A.X. Trautwein, Inorg. Chem. 31 (1992) 4404.
[16] K. Jayaraj, J. Terner, A. Gold, D.A. Roberts, R.N. Austin, D. Mandon, R. Weiss, E. Bill, M. Müther, A.X. Trautwein, Inorg. Chem. 35 (1996) 1632.
[17] V.D. Parker, Acta Chem. Scand. 24 (1970) 3162.
[18] O. Hammerich, V.D. Parker, Acta Chem. Scand. B 36 (1982) 519.
[19] B. Reitstöen, V.D. Parker, Acta Chem. Scand. 46 (1992) 464.
[20] F. Radner, Acta Chem. Scand. 45 (1991) 49.
[21] J.T. Groves, J.A. Gilbert, Inorg. Chem. 25 (1986) 125.
[22] T. Wolter, Ph.D. dissertation, Université Louis Pasteur, Strasbourg, FR, 1995.
[23] C.K. Mann, K.K. Barnes, Electrochemical Reactions in Nonaqueous Systems, Marcel Dekker, Inc., NY, 1970, p. 116 (Table 3–4).
[24] L.J. Marnett, T.A. Kennedy, in: P.R. Ortiz de Montellano (Ed.), Cytochrome P450: Structure, Mechanism, and Biochemistry, Plenum Press, 1995, p. 49.
[25] D.H. Chin, A.L. Balch, G.N. LaMar, J. Am. Chem. Soc. 102 (1980) 1446.
[26] J.T. Groves, Z. Gross, M.K. Stern, Inorg. Chem. 33 (1994) 5065.
[27] P. Plé, L.J. Marnett, J. Biol. Chem. 264 (1989) 13983.
[28] K. Korzekwa, W. Trager, M. Gouterman, D. Spangler, G.H. Loew, J. Am. Chem. Soc. 107 (1985) 4273.
[29] L. Everson, K. Nyberg, Acc. Chem. Res. 6 (1973) 106.
[30] C.E. Cerniglia, Adv. App. Microbiol. 30 (1984) 31.
[31] D.R. Thakker, W. Levin, H. Yagi, D. Ryan, P.E. Thomas, J.M. Karle, R.E. Lehr, D.M. Jerina, A.H. Conney, Mol. Pharmacol. 15 (1979) 139.