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Novel 1,4,5,8-Phenanthrenediquinones and Unusual Deoxygenation with Trimethylsilyl Iodide

Karsten Krohn,*[a] Abdulselam Aslan,[a] Ishtiaq Ahmed,[a] Gennaro Pescitelli,[b] and Tiziana Funaioli[b]

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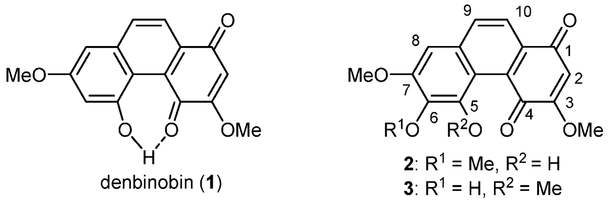
Attempt for aryl methyl ether cleavage of 5,8-dimethoxy-1,4-phenanthrenequinone (**4**) with boron trichloride or tribromide resulted in the halogenation of the quinone double bond to form **5a**,**b**. Surprisingly, reaction of dimethyl ether **4** with trimethylsilyl iodide afforded the phenanthrenediquinone **6**, whereas deoxygenation to **8** and **9** occurred by reaction of trimethylsilyl iodide with derivative **7**. The phenanthrenediquinones **6** and **10** were obtained nearly quantitatively from **4** and **7** by using ceric ammonium nitrate as the oxidant. The cyclic voltammograms of the phenanthrenediquinones **6** and **10** were studied and rationalized by Hückel Molecular Orbital calculations.

Introduction

The antitumoral, antiinflammatory, and virucidal activities of 1,4-phenanthrenequinones are known.[1] Recently, it was discovered by the group of Munoz that denbinobin (**1**) (Figure 1), a naturally occurring 1,4-phenanthrenequinone,[2] inhibits HIV-1 replication[3] and also induces apoptosis by generation of reactive oxygen species in human leukemic cells.[4] Independently, Lee et al.[5] reported on cytotoxic 1,4-phenanthrenequinones from *Calanthe arisanensis* showing that compound **2** with a phenolic hydroxy group at C-5[6] had by far the highest cytotoxic activity against a broad panel of human tumor cell lines. The corresponding 5-methoxy compound calanquinone B (**3**) was much less active. The remarkable activity of 5-hydroxy-1,4-phenanthrenequinones led to the assumption that the phenolic *peri*-hydroxy group at C-5 enhances the electrophilicity of the neighboring α,β-unsaturated enone system by hydrogen bonding with the proximate C-4 carbonyl group of the 1,4-phenanthrenequinone, as indicated in the structure of denbinobin (**1**). The increased Michael acceptor activity of **1** and **2** versus **3** might lead to enhanced addition of nucleophilic cell components and thus increase the cytotoxic activity of these phenolic phenanthrenequinones.



denbinobin (**1**)

2: R^1 = Me, R^2 = H

3: R^1 = H, R^2 = Me

Figure 1. Structures of denbinobin (**1**),[2] calanquinone A (**2**),[6] and calanquinone B (**3**).[5]

Results and Discussion

Chemistry

To verify the above hypothesis of increasing cytotoxic activity with enhanced chemical reactivity, we wanted to compare the biological activity of additional phenanthrenequinones with and without chelated phenolic hydroxy group at C-5. To this end, we tried the regioselective cleavage of some 5-methoxy-1,4-phenanthrenequinones from our previously prepared stock of 1,4-phenanthrenequinones[7] to the corresponding phenols to compare the cytotoxic activity of the respective 5-methoxy and 5-hydroxy compounds.

The common reagents for the cleavage of aryl methyl ethers are boron trichloride[8,9] or boron tribromide.[10] We hoped that these reagents might cleave the C-5 methyl ether in 5,8-dimethoxy-1,4-phenanthrenequinone (**4**) selectively by chelation with the C-4 carbonyl group. However, with both reagents a clean halogenation at C-3 of the quinoid ring to form **5a** or **5b** was observed (Scheme 1). A similar bromination of an aromatic ring was previously noted in a reaction with boron tribromide,[11] but the chlorination with boron trichloride was unexpected.

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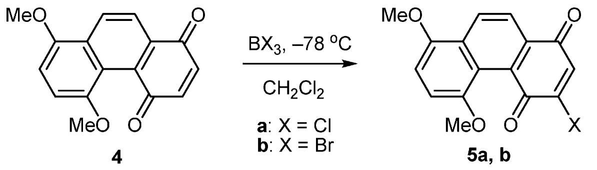
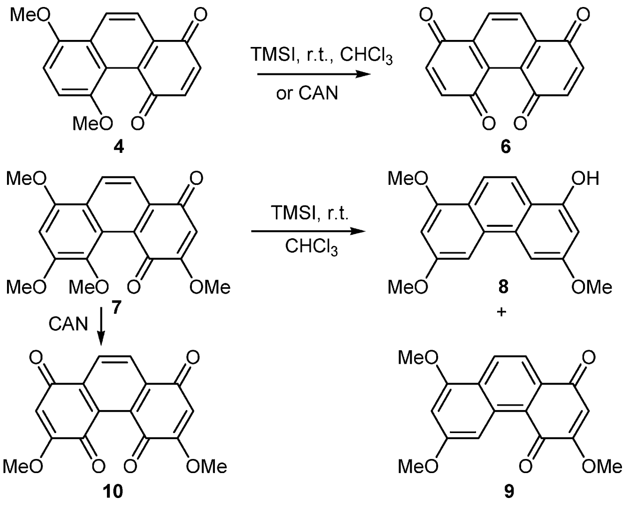
[a] Department Chemie, Universität Paderborn,
33098 Paderborn, Germany
Fax: +49-525-160-3245
E-mail: k.krohn@uni-paderborn.de
[b] Dipartimento di Chimica e Chimica Industriale, Università di Pisa
Via Risorgimento 35, 56126 Pisa, Italy



Scheme 1. Reaction of 5,8-dimethoxy-1,4-phenanthrenequinone (**4**) with BCl_3 and BBr_3, leading to the halides **5a** and **5b**, respectively.

With the boron trihalides being inefficient in the desired aryl methyl ether cleavage, we next tried the reaction of **4** with trimethylsilyl iodide, a reagent known to provide quantitative dealkylation of alkyl ethers.[12,13] However, the use of this reagent also met with surprise. In a small-scale reaction of trimethylsilyl iodide with 5,8-dimethoxy-1,4-phenanthrenequinone (**4**), we observed the conversion to the yet unknown 1,4,5,8-phenanthrenediquinone (**6**) (Scheme 2). Although initial formation of the corresponding monohydroquinone followed by air oxidation to **6** cannot be excluded, this seems rather improbable in the slightly acidic solution.[14] Although the reaction did not furnish the required monophenol, the isolation of the diquinone **6** gave us the opportunity to study the properties of this rather unknown class of diquinones. Notably, the interaction of the two quinone moieties and the redox behavior of **6** were of special interest. In fact, to the best of our knowledge, the only reported example of this class of diquinones is 2,6-dimethoxy-1,4,5,8-phenanthrenediquinone, isolated in traces from the stems of *Dendrobium moniliforme*.[15]



Scheme 2. Reaction of methoxy-1,4-phenanthrenequinones **4** and **7** with trimethylsilyl iodide (TMSI) or ceric ammonium nitrate (CAN).

A similar treatment of 3,5,6,8-tetramethoxy-1,4-phenanthrenequinone (**7**)[7] with trimethylsilyl iodide was expected to lead to symmetric diquinones ideally suited for comparison of the redox behavior with the related less electron-rich unsubstituted parent diquinone **6**. However, this reaction provided another surprise. Instead of the expected diquinones or hydroquinones, we isolated the doubly deoxygenated phenanthrene **8** together with the demethoxylated quinone **9** in a ratio of 1:9.6 in 96% combined yield (Scheme 2). The deoxygenation of reactive α-ketols by trimethylsilyl iodide to the parent ketones has been described before,[16,17] but the demethoxylation of aryl methyl ethers or the deoxygenation of quinones is unprecedented.

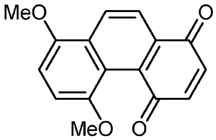
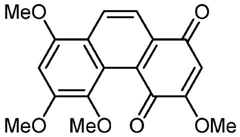
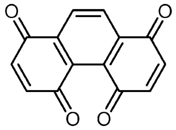
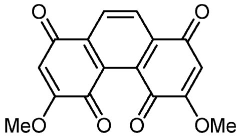
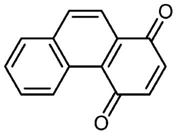
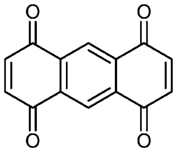
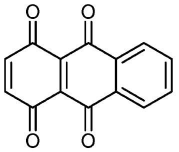
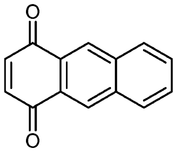
Although the reaction of **7** with trimethylsilyl iodide provided new and mechanistically interesting demethoxylation and deoxygenation reactions, we still wanted to prepare the desired 1,4,5,8-diquinone **10**. Ceric ammonium nitrate (CAN) has emerged as the reagent of choice in the oxidation of hydroquinone mono- and dimethyl ethers to the corresponding quinones.[18,19] Therefore, we tried the CAN oxidation of the dimethyl ether **4** and the tetramethyl ether **7** in aqueous acetonitrile. Gratifyingly, in both reactions, the hydroquinone ethers **4** and **7** were converted into the quinones **6** and **10** in 97 and 98% yield, respectively.

Electrochemistry

Simple quinone/hydroquinone couples are the most thoroughly studied organic redox couples.[20] The quinone structural moiety, commonly associated with reductive activation, is present in many bioreductive compounds,[21] and the selectivity of bioreductive antitumor agents has been related to redox potentials obtained by cyclic voltammetry.[21] For this reason, the cyclic voltammograms of compounds **4** and **7**, in addition to those of the two new 1,4,5,8-phenanthrenediquinones **6** and **10**, were recorded. The cyclic voltammograms of compounds **4** and **7** in anhydrous CH_3CN, 0.1 M Bu_4NPF_6, at a platinum electrode, show one reversible oxidation and two reduction processes in agreement with the data reported for similar 1,4-phenanthrenequinones[7] (Table 1): on increasing the number of methoxy groups present in the compounds, the oxidation occurs at a lower potential, whereas both reductions are shifted to more negative values.

The conjugated diquinones **6** and **10** are reduced in three successive steps (Table 1); only the first couple appears reversible (86 and 90 mV, respectively, peak-to-peak separations and nearly equal cathodic and anodic peak currents) if the sweep is reversed before the second reduction process (see Figure 2). For comparison, the diquinones 1,4,5,8-anthracenetetrone (**11**)[22] and 1,4,9,10-anthracenetetrone (**12**)[23] show two reversible couples and a more complex process at more cathodic potentials, sometimes resolved in two closely spaced couples. Moreover, the first reduction potential is shifted to less negative values with respect to monoquinone analogues, i.e. 1,4-anthracenequinone (**13**). Remarkably, the first reduction potential for phenanthrenediquinones **6** and **10** is essentially the same as that for the model monoquinone **14**. Presumably, the phenanthrene ring of **6** and **10**, that allows two oxygen atoms of the diquinone compounds to be closely spaced, behaves in a different way from the linear anthracene ring of **11** and **12** both for structural and electronic reasons.

Table 1. Electrochemical data.[a]

Compound		Oxidation process	Reduction processes		
		$E°$ [V, vs. SCE] ($E_{pa} - E_{pc}$) [mV]	$E°$ [V, vs. SCE] ($E_{pa} - E_{pc}$) [mV]	E_{pc2} [V, vs. SCE]	E_{pc3} [V, vs. SCE]
4		+1.20 (78)	–0.73 (77)	–1.70	
7		+1.05 (80)	–0.86 (95)	–1.85	
6			–0.51 (86)	–0.96	–1.57
10			–0.61 (90)	–1.20	–1.78
14			–0.59 (73)	–1.53	
11			–0.25[b]		
12			–0.08[c]		
13			–0.84[b]		

[a] Measured in CH_3CN, 0.1 M Bu_4NPF_6, scan rates: 100 mV s^{-1}. $E°$: (E_{pc} + E_{pa})/2. E_{pc2}: cathodic peak potential 2. E_{pc3}: cathodic peak potential 3. [b] From ref.[22] [c] From ref.[23]

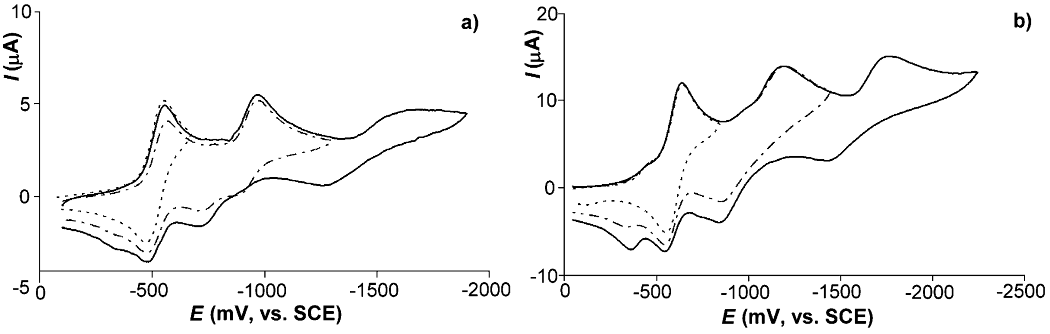


Figure 2. Cyclic voltammograms recorded at a platinum electrode in a CH_3CN solution of (a) **6** and (b) **10**. Bu_4NPF_6 (0.1 M) as supporting electrolyte. Scan rate: 100 mV s^{-1}.

In an attempt to support the experimental data for previously unknown compounds, and to rationalize the observed behaviour, the LUMO (lowest unoccupied molecular orbital) energies of compounds **6** and **10**–**14** were estimated with the Extended Hückel Molecular Orbital (EHMO) model. It is in fact recognized that polarographic half-wave reduction potentials of aromatic compounds correlate well with LUMO energies calculated with the HMO model.[24] Further reference compounds (**15**–**17**) in addition to **11**–**13**, whose data were available in the literature,[22,23] were also considered to better assess the existence and quality of the relationship between redox potentials and LUMO energies. Figure 3 demonstrates that a clear linearity between the redox potential $E°$ of the first reduction process and EH-LUMO energies exists for all substrates considered, including those described here (**6**, **10** and **14**), which indicates that the potentials measured for the latter are perfectly compatible with the polyacenequinone series. The LUMO energies of compounds **6**/**14** and **11**/**13** may be compared with those of the parent compounds, phenanthrene and anthracene, respectively, as shown in Figure 4. It emerges that the introduction of a single *p*-quinone functionality on one ring of phenanthrene (as in **14**) is sufficient to bring about a large perturbation, in terms of LUMO stabilization, which is achieved on anthracene only after the introduction of a double *p*-quinone functionality (as in **11**). In that respect, the second *p*-quinone substitution on phenanthrene (as in **6**) has little effect, as reflected in the small difference of $E°$ values measured for **6** and **14**. A more rigorous theoretical treatment of the relevant compounds, involving separate study of neutral and first ionic states with a higher-level computation,[22] was beyond the scope of this paper. Nevertheless, the very simplified calculation approach described here already gave an almost perfect correlation between experimental and calculated data, and any further improvement seemed unnecessary.

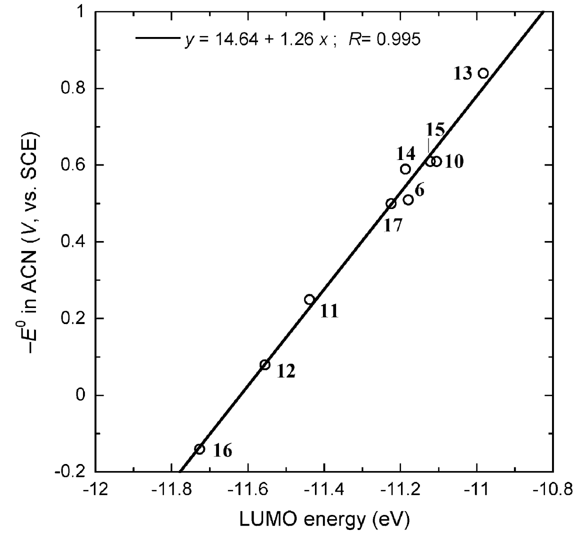


Figure 3. Correlation between the reduction potentials of anthracene- and polyacenequinones and the LUMO energies estimated with the EHMO model on AM1-optimized geometries. $E°$ values for compounds **11**–**13** and **15**–**17** were taken from the literature[22,23] (legend for compounds not included in Table 1: **15** = 1,4-naphthoquinone; **16** = 1,4,5,8-naphthalenetetrone; **17** = 1,4,7,10-naphthacenetetrone).

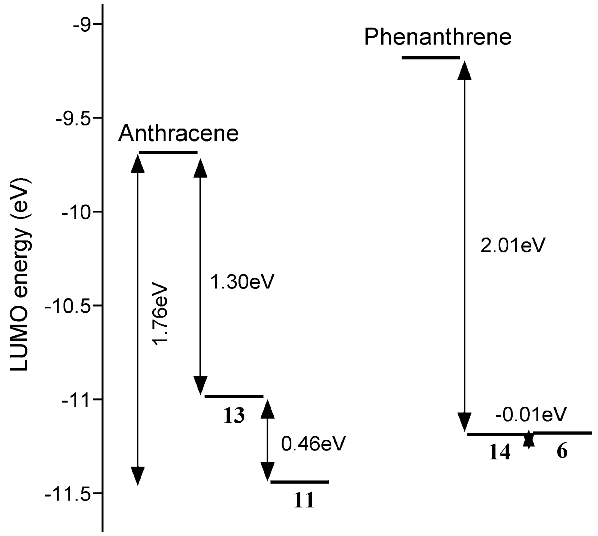


Figure 4. Differences in LUMO energies estimated with the HMO model on AM1-optimized structures for the analogous series of anthracene and phenanthrene derivatives.

Conclusion

Attempted aryl methyl ether cleavage on methoxy-1,4-phenanthrenequinones showed that side reactions such as halogenation, oxidation or deoxygenation may occur with BCl_3, BBr_3 or TMSI. By contrast, CAN converted 5,8-dimethoxy-1,4-phenanthrenequinones almost quantitatively into the corresponding 1,4,5,8-phenanthrenediquinones, prepared for the first time. The simple 1,4-phenanthrenequinones only showed one reversible oxidation and two reduction processes in cyclic voltammograms, whereas the conjugated diquinones are reduced in three successive steps; only the first couple appears reversible. Calculations with the simple Extended Hückel Molecular Orbital (EHMO) model showed almost perfect correlation between experimental and calculated data, including values from the literature for related quinones.

Experimental Section

General Materials and Methods: Melting points were determined with a Büchi SMP-20 melting point apparatus and are uncorrected. UV spectra were measured with a UV-210 PC UV. IR spectra were recorded with a Shimadzu FTIR-8400S spectrometer in KBr disks. EI-MS (ionization voltage 70 eV) and HR-EI-MS data were recorded with a Finnigan MAT double-focusing spectrometer model 8230. ^1H and ^{13}C NMR spectra were recorded with a Bruker Avance 500 MHz spectrometer in $CDCl_3$ or $CDCl_3/CD_3OD$. Chemical shifts are given relative to TMS (δ = 0 ppm) as internal standard, and coupling constants J are reported in Hz. Column chromatography (CC) was carried out on silica gel 60 F_{254} (Merck) or silica 100. Precoated plates of silica gel 60 GF_{254} were used for analytical purposes, and the spots were detected with a UV lamp at

254 and 366 nm and by spraying with 50% H_2SO_4 or ceric sulfate, followed by heating. For preparative layer chromatography silica gel plates (1 mm) (Macherey-Nagel GmbH & Co. KG) were used.

Solvents and Salts: HPLC grade acetonitrile (Carlo Erba) was stored under argon over molecular sieves (3 Å). Tetrabutylammonium hexafluorophosphate (Bu_4NPF_6, Fluka, electrochemical grade) was used as purchased.

Voltammetry: Cyclic voltammograms were performed with a Princeton Applied Research (PAR) 273A Potentiostat/Galvanostat, interfaced to a personal computer, by employing PAR M270 Electrochemical Software. All measurements were carried out in a three-electrode home-built cell, equipped with an aluminium oxide drying tube. The working and the counter electrode consisted of a platinum disk electrode and a platinum wire spiral, respectively, both sealed in a glass tube. A quasi-reference electrode of platinum was employed as reference. The Schlenk-type construction of the cell maintained anhydrous and anaerobic conditions. The cell was predried by prolonged heating under vacuum and filled with argon. A 0.1 M CH_3CN solution of tetrabutylammonium hexafluorophosphate under Ar was placed into the cell and dried by passing twice through the column of aluminium oxide (Sigma, Type WN-6, neutral Super I) at 0 °C. The working electrode was cycled between the anodic and the cathodic limits of interest until there was no change in the charging current. The substrate was then introduced, and voltammograms were recorded at a sweep rate of 100 mV s^{-1}. After several voltammograms were obtained on the substrate solution, a small amount of ferrocene was added, and the voltammogram was repeated. The $E°$ values of the compounds (see Table 1) were then determined by placing the ferrocene couple [E_{redox} calculated as $(E_{\text{pc}} + E_{\text{pa}})/2$] at +0.40 V vs. SCE.

3-Chloro-5,8-dimethoxy-1,4-phenanthrenequinone (5a): To a solution of 5,8-dimethoxy-1,4-phenanthrenequinone (**4**)[7] (53 mg, 0.198 mmol) in dry dichloromethane (5 mL) at –78 °C was added dropwise a solution of 1.0 M BCl_3 in dichloromethane (0.2 mL, 0.2 mmol). The reaction mixture was warmed to –30 °C, then quenched by addition of water (10 mL), and the mixture was stirred at room temperature for 5 h. The organic layer was separated, the aqueous layer was extracted with dichloromethane (3 × 15 mL), and the combined organic phases were dried (Na_2SO_4). After filtration, the solvent was removed under reduced pressure, and the residue was purified by flash chromatography on silica gel by using ethyl acetate and petroleum ether (1:10 to 1:3) to afford **5a** (41 mg, 68%); m.p. 175–177 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.93 (s, 3 H, OCH_3), 3.99 (s, 3 H, OCH_3), 6.94 (d, J = 8.5 Hz, 1 H, 7-H), 7.00 (d, J = 8.5 Hz, 1 H, 6-H), 7.03 (s, 1 H, 2-H), 8.05 (d, J = 8.7 Hz, 1 H, 10-H), 8.53 (d, J = 8.7 Hz, 1 H, 9-H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 56.11 (OCH_3), 56.29 (OCH_3), 107.79 (C-7), 109.74 (C-6), 121.19 (C-10), 122.05 (C-4b), 128.16 (C-9), 129.63 (C-4a), 132.40 (C-8a), 132.44 (C-2), 132.75 (C-10a), 147.54 (C-3), 149.66 (C-5), 150.75 (C-8), 179.32 (C-4), 182.80 (C-1) ppm. IR (KBr): $\tilde{\nu}$ = 2924, 1672, 1649, 1607, 1589, 1458, 1361, 1301, 1239, 1194, 1101, 837, 803 cm^{-1}. MS (EI, 70 eV): m/z (%) = 302.0 (100) [M$^+$], 287.0 (81), 258.9 (21), 253.0 (18), 237.0 (15). HRMS: m/z (%) = 302.03457 (calcd. for $C_{16}H_{11}ClO_4$ 302.03458).

3-Bromo-5,8-dimethoxy-1,4-phenanthrenequinone (5b): To a solution of 5,8-dimethoxy-1,4-phenanthrenequinone (**4**)[7] (20 mg, 0.075 mmol) in dry dichloromethane (3 mL) was added dropwise at –78 °C a solution of 1.0 M BBr_3 in dichloromethane (0.1 mL, 0.1 mmol). The reaction mixture was warmed to –30 °C. Workup was done as described for **5a** to afford **5b** (16 mg, 62%); m.p. 135–137 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.91 (s, 3 H, OCH_3), 3.98 (s, 3 H, OCH_3), 6.93 (d, J = 8.5 Hz, 1 H, 7-H), 6.98 (d, J = 8.5 Hz, 1 H, 6-H), 7.55 (s, 1 H, 2-H), 8.12 (d, J = 8.7 Hz, 1 H, 10-H), 8.50 (d, J = 8.7 Hz, 1 H, 9-H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 56.09 (OCH_3), 55.24 (OCH_3), 107.96 (C-7), 109.64 (C-6), 121.77 (C-4b), 122.11 (C-10), 127.70 (C-9), 129.79 (C-10a), 131.27 (C-8a), 133.11 (C-4a), 134.32 (C-3), 141.76 (C-2), 149.61 (C-5), 150.86 (C-8), 178.21 (C-4), 183.30 (C-1) ppm. IR (KBr): $\tilde{\nu}$ = 2960, 2919, 2360, 2340, 1671, 1647, 1605, 1591, 1519, 1507, 1458, 1402, 1301, 1263, 1239, 1201, 1192, 1099, 1208, 826 cm^{-1}. MS (EI, 70 eV): m/z (%) = 347.9 (100), 345.9 (100) [M$^+$], 332.9 (77), 302.9 (20), 236.9 (38), 208.9 (21), 148.1 (28). HRMS: m/z = 345.98406 (calcd. for $C_{16}H_{11}BrO_4$ 345.98407).

1,4,5,8-Phenanthrenetetraone (6): To a 10 mL flask equipped with a magnetic stirring bar and fitted with a septum were added chloroform (2 mL) and 5,8-dimethoxy-1,4-phenanthrenequinone (**4**)[7] (11 mg, 0.041 mmol). An inert atmosphere was maintained, and iodotrimethylsilane (0.1 mL, 0.703 mmol) was added through the septum with the help of a syringe. The reaction mixture was stirred at room temperature for 48 h and diluted with methanol (5 mL). After addition of brine (10 mL), the reaction mixture was extracted with diethyl ether (3 × 15 mL). The combined organic layers were washed with sodium bisulfite and brine. The organic layer was then dried (Na_2SO_4), filtered and concentrated under reduced pressure. The residue obtained was purified by flash chromatography on a silica gel column to afford **6** (5 mg, 51%); m.p. 230–232 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 6.99 (d, J = 10.3 Hz, 2 H, 3-H, 6-H), 7.17 (d, J = 10.3 Hz, 2 H, 2-H, 7-H), 8.41 (s, 2 H, 9-H, 10-H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 130.27 (C-9, C-10), 134.00 (C-4a, C-4b), 136.44 (C-8a, C-10a), 136.52 (C-2, C-7), 140.90 (C-3, C-6), 183.00 (C-1, C-8), 183.53 (C-4, C-5) ppm. IR (KBr): $\tilde{\nu}$ = 3076, 2924, 2852, 1683, 1666, 1605, 1580, 1559, 1449, 1362, 1291, 1281, 1089, 1075, 1033, 825, 638, 457 cm^{-1}. MS (EI, 70 eV): m/z (%) = 238 (100) [M$^+$], 210 (18), 184 (50), 149 (30), 111 (18), 97 (21), 85 (22), 71 (38), 57 (51). HRMS: m/z = 238.02676 (calcd. for $C_{14}H_6O_4$ 238.02661).

1-Hydroxy-3,6,8-trimethoxyphenanthrene (8) and 3,6,8-Trimethoxy-1,4-phenanthrenequinone (9): 3,5,6,8-Tetramethoxy-1,4-phenanthrenequinone (**7**)[7] (52 mg, 0.158 mmol) was treated with iodotrimethylsilane (0.5 mL, 3.515 mmol) as described for **6** to afford after preparative layer chromatography on silica gel plates (1 mm) **8** (4 mg, 9%) and **9** (41 mg, 87%).

8: M.p. 125–127 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.98 (s, 3 H, OCH_3), 4.01 (s, 3 H, OCH_3), 4.02 (s, 3 H, OCH_3), 6.67 (d, J = 1.9 Hz, 2 H, 4-H, 5-H), 7.47 (d, J = 1.8 Hz, 1 H, 7-H), 7.53 (d, J = 1.7 Hz, 1 H, 2-H), 7.87 (d, J = 9.2 Hz, 1 H, 10-H), 8.00 (d, J = 9.2 Hz, 1 H, 9-H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 55.50 (OCH_3), 55.52 (OCH_3), 55.74 (OCH_3), 95.92 (C-2), 97.53 (C-4), 97.76 (C-7), 101.24 (C-5), 116.36 (C-10), 117.30 (C-9), 117.99 (C-10a), 119.33 (C-8a), 131.38 (C-4a, C-4b), 153.03 (C-1), 157.19 (C-8), 158.17 (C-6), 158.71 (C-3) ppm. IR (KBr): $\tilde{\nu}$ = 3436, 2924, 2852, 2360, 2342, 1652, 1636, 1586, 1577, 1465, 1457, 1275, 1233, 1205, 1155, 1046, 819, 674 cm^{-1}. MS (EI, 70 eV): m/z (%) = 284 (100) [M$^+$], 296 (40), 241 (30), 226 (20), 149 (32), 97 (18), 71 (21), 57 (30), 28 (35). HRMS: m/z = 284.10481 (calcd. for $C_{17}H_{16}O_4$ 284.10486).

9: M.p. 250–252 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.94 (s, 3 H, OCH_3), 3.99 (s, 3 H, OCH_3), 4.00 (s, 3 H, OCH_3), 6.12 (s, 1 H, 2-H), 6.61 (d, J = 2 Hz, 1 H, 7-H), 8.03 (d, J = 9 Hz, 1 H, 10-H), 8.58 (d, J = 9 Hz, 1 H, 9-H), 8.67 (d, J = 2 Hz, 1 H, 5-H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 55.58 (OCH_3), 55.77 (OCH_3), 56.52 (OCH_3), 97.42 (C-5), 99.91 (C-7), 107.22 (C-2), 119.20 (C-10), 123.88 (C-10a), 125.50 (C-8a), 129.83 (C-9), 132.83 (C-4b), 133.76 (C-4a), 156.65 (C-8), 161.10 (C-3), 162.74 (C-6), 182.38 (C-4), 185.67 (C-1) ppm. IR (KBr): $\tilde{\nu}$ = 2952, 2924, 2853, 2361, 1667, 1644, 1623, 1584, 1570, 1452, 1407, 1258, 1244, 1231, 1206, 1179, 1156, 1139, 1017, 902, 836 cm^{-1}. MS (EI, 70 eV): m/z (%) = 298 (100) [M$^+$], 255 (8), 227 (12), 199 (18), 141 (3), 97 (3), 57 (4). HRMS: m/z = 298.08408 (calcd. for $C_{17}H_{14}O_5$ 298.08411).

1,4,5,8-Phenanthrenetetraone (6): To a solution of 5,8-dimethoxy-1,4-phenanthrenequinone (**4**) (20 mg, 0.075 mmol) in acetonitrile (1 mL) was added an aqueous solution of CAN [20 mg (0.036 mmol) in H_2O (0.1 mL)]. After addition of the CAN solution, the color immediately changed from violet to orange and finally to yellow. The reaction mixture was stirred at 20 °C for another 15 min. After complete conversion of the starting material, CH_2Cl_2 (20 mL) was added to the reaction mixture. The organic phase was washed with water (15 mL) and brine (15 mL). The organic layer was dried (Na_2SO_4), filtered and concentrated under reduced pressure. The residue obtained was purified by flash chromatography on a silica gel column to afford **6** as a yellow solid (17.3 mg, 97 %); m.p. 230–232 °C.

3,6-Dimethoxy-1,4,5,8-phenanthrenetetraone (10): To a solution of 3,5,6,8-tetramethoxy-1,4-phenanthrenequinone (**7**)[7] (52 mg, 0.158 mmol) in acetonitrile (3 mL) was added an aqueous solution of CAN [100 mg (0.182 mmol) in H_2O (0.5 mL)] at room temperature. After the addition of CAN solution, the color immediately changed from violet to orange and finally to yellow. The reaction mixture was stirred at room temperature for another 15 min. After complete conversion of the starting material, CH_2Cl_2 (20 mL) was added to the reaction mixture. The organic phase was washed with water (15 mL) and brine (15 mL). The organic layer was then dried (Na_2SO_4), filtered and concentrated under reduced pressure. The residue was purified by flash chromatography on a silica gel column to afford **10** as a yellow solid (46 mg, 98 %); m.p. 240–242 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.95 (s, 6 H, OCH_3), 6.18 (s, 2 H, 2-H, 7-H), 8.40 (s, 2 H, 9-H, 10-H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 56.82 (OCH_3), 108.25 (C-2, C-7), 130.45 (C-9, C-10), 133.20 (C-4a, C-4b), 136.62 (C-8a, C-10a), 162.79 (C-3, C-6), 178.82 (C-1, C-8), 182.49 (C-4, C-5) ppm. IR (KBr): $\tilde{\nu}$ = 3069, 2934, 2852, 1707, 1689, 1655, 1613, 1456, 1340, 1309, 1253, 1246, 1216, 1181, 1084, 964, 839, 715, 633, 478, 431 cm^{-1}. MS (EI, 70 eV): m/z (%) = 298 (100) [M$^+$], 283 (90), 255 (59), 240 (57), 214 (20), 199 (11), 156 (15), 69 (16). HRMS: m/z = 298.04780 (calcd. for $C_{16}H_{10}O_6$ 298.04773).

Computational Section: All calculations were run with Gaussian 03W.[25] Molecules were built with GaussView 4.1.2 and optimized with the semiempirical method[26] AM1 by using default parameters and convergence criteria. Optimized geometries had the maximum possible planar symmetry for all molecules; for compounds **6** and **10**, however, this geometry was a local and not the absolute global energy minimum. LUMO energies were obtained after single-point calculations run with the Extended Hückel Method (EHMO)[26] on AM1-optimized energies.

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