Reductive Cyclization of (3-) and (4-Oxoalkyl)-9,10-anthraquinones to the Cyclopenta[a]anthraquinone and Naphthacene-5,12-dione Systems

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Abstract. Reductive cyclization of the 1-hydroxy-3-(3-oxo-alkyl)-9,10-anthraquinones **2**, **9** and **10** yields the angularly condensed cyclopenta[a]anthraquinones **3**, **21** and **22a** under neutral conditions (DMF/$Na_2S_2O_4$). By contrast, the linear cyclopenta[b]anthraquinone **23** is isolated from **10** applying the usual alkaline Marschalk conditions (aqueous methanol, NaOH, $Na_2S_2O_4$). The linearly condensed 5,12-naphthace-nequinones **24–28** of different degree of saturation are obtained in good combined yield from the corresponding 1-hydroxy-3-(4-oxoalkyl)-9,10-anthraquinones **19** and **20** under the conditions of the Marschalk reaction.

In connection with the biomimetic type synthesis of the tetracyclic angucycline antibiotics [1, 2] we investigated the attachment of oligoketide side chains on the naphthoquinone core [3, 4]. In an extension of this strategy towards the preparation of the pentacyclic pradimicin type antifungal antibiotics [5] ketide chains on the anthraquinone core were required. To this end, the reductive Claisen rearrangement [6, 7] of the anthraquinone allyl ether **1** was studied. Surprisingly, not only the expected rearrangement to **2** occurred but the cyclization product **3** could also be isolated. Upon prolonged reaction times the 1-hydroxy-3-(3-oxoalkyl)-anthraquinone **2** was converted to the cyclopenta[a]anthraquinone **3** as the only product as depicted in Scheme 1.

Sutherland *et al.* observed the cyclization of related 1,4-dihydroxy-9,10-anthraquinones (quinizarines) to lin-

early arranged pentanoanthraquinones [8, 9]. Mechanistically, these reactions can be rationalized as nucleophilic attack of the electron-rich phenolate of the anthrahydroquinones, similarly as in the alkylation of anthraquinones with aldehydes under the reducing conditions of the Marschalk reaction [10]. However, there is no precedence in the literature for the conversion of oxoalkylanthraquinones under these conditions to angularly condensed cyclopenta[a]anthraquinone systems such as **3**. Therefore, we systematically investigated the reactivity of various Phenolic (3-) (*e.g.* **1**, **9**, and **10**) and (4-oxoalkyl)-9,10-anthraquinones (**19** and **20**) under two different reductive cyclization conditions (neutral and alkaline, *vide infra*).

Starting Materials

The monobromide **4a** [11] was used as the starting material for the monoalkylated 1-hydroxy-3-(3-oxo-alkyl)-9,10-anthraquinones. Thus, alkylation of methyl acetoacetate (**5**) with the benzylic bromide **4a** yielded the monoalkylated β-ketoester **7**, and the similar reaction with methyl 5,5-diethylendioxo-3-oxo hexanoate (**6**) afforded the more complex alkylation product **8** (Scheme 2). Both compounds were subsequently saponified with 1N sodium hydroxide in ethanol to yield the phenolic decarboxylation products **9** and **10**. The phenol **10** was then alkylated with the allylic tosylate
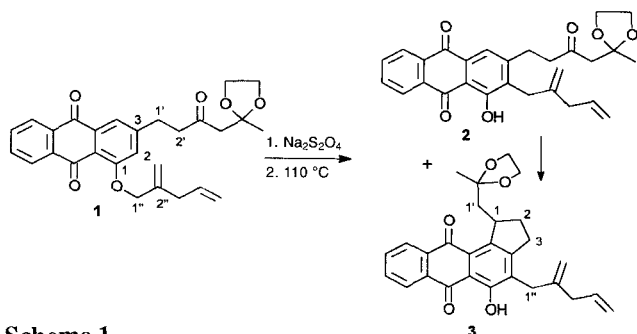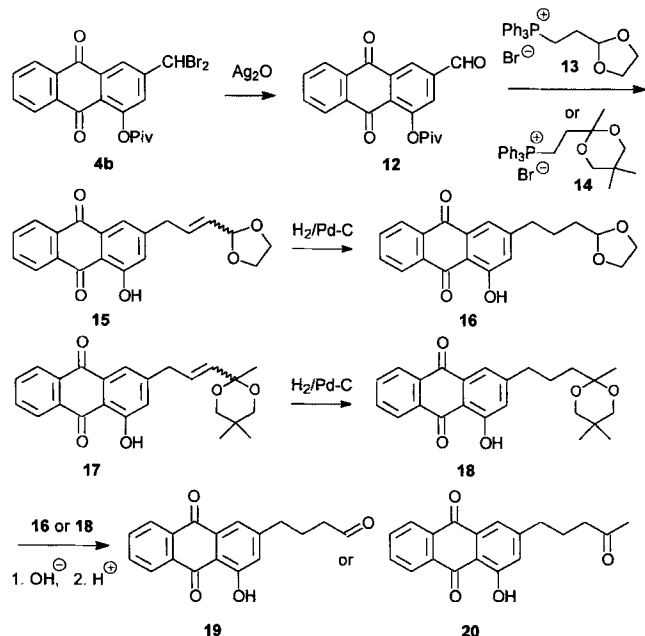

Scheme 1

11 to give the ether **1** which was required for the above-mentioned Claisen rearrangement.
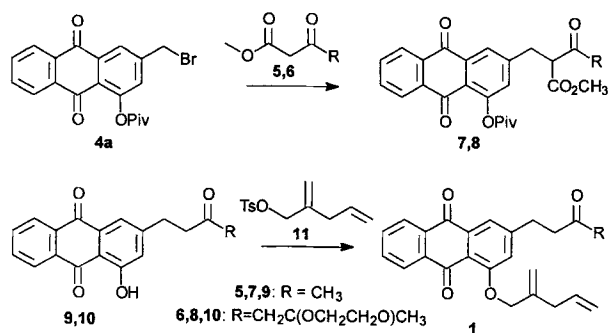
Scheme 2

It would be interesting to see if the 1-hydroxy-3-(4-oxoalkyl)-9,10-anthraquinones **19** and **20** could also be cyclized for anellation of a six-membered ring onto the anthraquinone core. The formation of either the angularly condensed benz[*a*]anthraquinones or the linear 5,12-naphthacenequinones is theoretically possible. The dibromide **4b** [11] was used as starting material to prepare the required 4-oxoalkyl-anthraquinones. First, **4b** was converted to the aldehyde **12** by treatment with silver nitrate. The chain elongations were then achieved by Wittig reactions of **12** with the triphenylphosphonium bromides **13** or **14** to yield the olefines as *E/Z*-mixtures (ca. 4:1 by NMR, Scheme 3). Hydrogenation of **15** and **17** to the saturated acetals **16** and **18** was followed by saponification with sodium hydroxide and acid-catalysed cleavage of the acetals to yield the required aldehyde **19** and the ketone **20**.

Cyclization Reactions

Two different experimental conditions were applied in our cyclization studies. Rutledge and coworkers used sodium dithionite in aqueous DMF for their Claisen rearrangement studies [6, 7]. On the other hand, in the classical alkylation reaction of phenolic anthraquinones pioneered by Marschalk [10], aqueous alkaline solution of sodium dithionite was applyed. In agreement with the reaction observed in the Claisen rearrangement shown in Scheme 1, only one type of cyclization mode was found when the ketones **9** and **10** were treated with sodium dithionite in DMF at 110 °C to afford the cyclopenta[*a*]anthraquinones **21** and **22a** in good yield (78 and 84%, respectively). The angular condensation could unambiguously be deduced from the respective COLOQ NMR experiment. The reductive elimination of the benzylic hydroxy group resulting from the nucleophilic attack of the electron-rich anthrahydroquinone on the car- bonyl group has precedence under these reducing conditions [12, review: 13].

Surprisingly, the linear cyclopenta[*b*]anthraquinone **23** resulted as the only isolable cyclization product, albeit in low yield (16%), when **10** was subjected to the Marschalk reaction conditions (aqueous methanol, NaOH, $Na_2S_2O_4$, Scheme 4). In addition, cleavage of the acetal group had occurred during acidic workup. The linear structure **23** was deduced from the coupling of one aromatic proton (singlet) with one of the quinoide carbonyls. Furthermore, a chemical evidence was provided by comparison of the ketone **22b** (obtained by cleavage of the angular ketal **22a**) with the cyclization product isolated from the Marschalk reaction of ketone **10**. The physical properties of the two compounds were
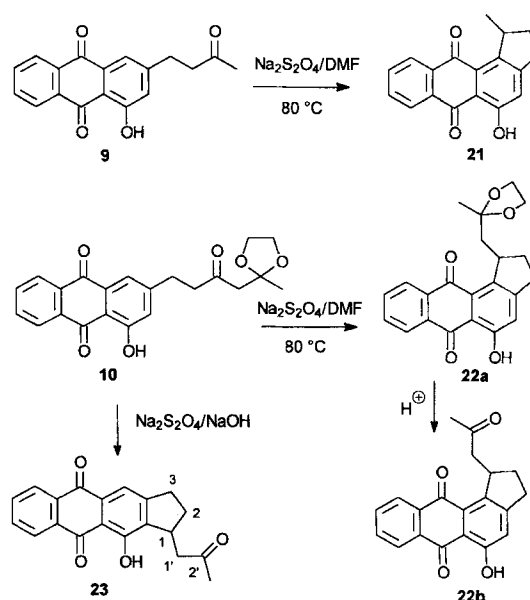
Scheme 3

Scheme 4

not identical! This interesting result can either be explained by a sodium cation mediated chelation between the phenolic group and the side chain carbonyl under the alkaline Marschalk reaction conditions. By contrast, the angular products **21** and **22a** are formed under the non-chelating neutral reactions conditions. On the other hand is the behavior in agreement with the observed reactivity of dienolates [*e.g.* α-alkylation under basic conditions, γ-alkylation under neutral conditions (reactivity of 1-siloxydienes)].

Finally, the chemical behavior of the aldehyde **19** and the 1-hydroxy-3-(4-oxoalkyl)-9,10-anthraquinone **20** was investigated under both cyclization conditions. Under neutral conditions, only the saturated 1,2,3,4-tetrahydro-5,12-naphthacenequinones **24** and **25** resulted from **19** and **20** in low yield. When the aldehyde **19** was subjected to the alkaline Marschalk conditions an unseparable mixture of **24** and the partly desaturated 3,4-dihydro-5,12-naphthacenequinone **26** resulted in 85% combined yield. The more saturated compound **24** was isolated in pure form if an excess of dithionite was employed in the reaction. A similar reactivity was found for the reaction of the ketone **20** using the Marschalk conditions. In this case, the three 5,12-naphthacenequinones **25, 27**, and **28** with different degree of saturation were isolated in 85% combined yield. Upon prolonged reaction times, the fully aromatic compound **28** was the only product. The mixture of **25** and **27** could be hydrogenated to yield the pure 1,2,3,4-tetrahydro-5,12-naphthacenequinones **25**. Inspection of models suggests that the failure of the 4-oxoalkyl-9,10-anthraquinones to yield the angular cyclization products (*e.g.* benz[*a*]anthraquinones) may be caused by sterically unfavorable chelate formation as proposed above for the related 3-oxoalkyl compounds.

19, 24, 26: R = H; 20, 25, 27: R = CH₃
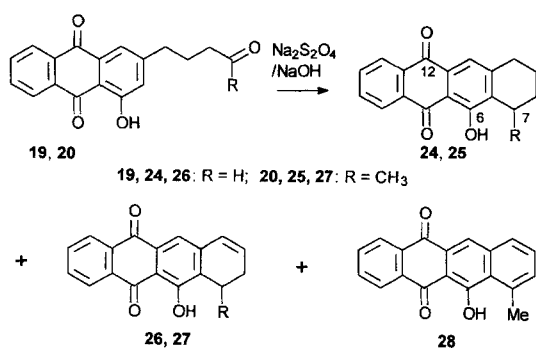
Scheme 5

In summary, a new efficient anellation method for five- and six-membered rings onto the anthraquinone core is presented. The formation of angular cyclopenta[*a*]anthraquinones or linear cyclopenta[*b*]anthraquinones from 3-oxoalkyanthraquinones can be directed by the choice of neutral or alkaline reaction conditions.

Experimental

3-[4-(2-Methyl-[1,3]dioxolane-2-yl)-3-oxo-butyl]-1-(2-methylenepent-4-enyloxy)-anthracene-9,10-dione (**1**)

A solution of anthraquinone **10** (1.00 g, 2.63 mmol) in dry acetone (40 ml) was treated with powdered K₂CO₃ (0.73 g, 5.26 mmol), KI (0.87 g, 5.26 mmol), and 2-methylenepent-4-ene-1-*O*-tosylate (**11**) (1.31 g, 5.26 mmol). The mixture was refluxed for 12 h and diluted by addition of water (50 ml). The combined organic phases were washed with water (50 ml) and brine (50 ml), dried (Na₂SO₄), filtered, and evaporated to dryness at reduced pressure. The residue was purified by chromatography on silica gel (CH₂Cl₂) to yield **1** as a yellow solid (1.05 g, 87%, *m.p.* 80–81 °C). – IR (KBr)/cm⁻¹ = 2994 (CH), 2890 (CH), 1711 (C=O, ketone), 1666 (C=O, quinone), 1599, 1593 (C=C). – UV (CH₂Cl₂): λ_{max}/nm (lg ε) = 258 (4.55), 383 (3.79). – ¹H NMR (200 MHz, CDCl₃): δ/ppm = 1.41 (s, 3H, 6"-H), 2.80 (s, 2H, 4"-H), 2.98–3.07 (m, 6H, 1"-H, 2"-H, 4'-H), 3.93–3.99 (m, 4H, OCH₂CH₂O), 4.67 (s, 2H, 1'-H), 5.11–5.25 (m, 3H, 3'-H, 6'-H), 5.52 (s, 1H, 3'-H), 5.83–6.04 (m, 1H, 5'-H), 7.19 (d, $J_{2,4}$ = 1.5 Hz, 1H, 2-H), 7.69–7.82 (m, 3H, 4-H, 6-H, 7-H), 8.21–8.31 (m, 2H, 5-H, 8-H). – ¹³C NMR (50 MHz, CDCl₃): δ/ppm = 24.87 (q, 6"-C), 30.22 (t, 1"-C), 38.05 (t, 4'-C), 44.98 (t, 2"-C), 52.25 (t, 4"-C), 65.04 (t, OCH₂CH₂O), 71.79 (t, 1'-C), 108.25 (s, 5"-C), 113.98 (t, 3'-C), 117.51 (t, 6'-C), 119.96 and 119.99 (d, 2-C and 4-C), 120.22 (s), 126.92 and 127.61 (d, 5-C and 8-C), 132.87 (s), 133.44 and 134.62 (d, 6-C and 7-C), 135.48 (s), 135.72 (d, 5'-C), 136.04 (s), 142.43 (s, 2'-C), 149.76 (s, 3-C), 159.94 (s, 1-C), 182.12 (s, 10-C), 184.08 (s, 9-C), 206.33 (s, 3"-C). – MS (EI/145 °C): *m/z* (%) = 460 (13) [M⁺], 87 (100) [C₄H₇O₂⁺].

C₂₈H₂₈O₆   Calcd.:   C 73.03   H 6.13
(460.53)   Found: C 72.85   H 6.31.

1-Hydroxy-3-[4-(2-methyl-[1,3]dioxolane-2-yl)-3-oxo-butyl]-2-(2-methylenepent-4-enyl)-anthracene-9,10-dione (**2**)

A solution of Na₂S₂O₄ (1.13 g, 5.54 mmol, 85%) in a mixture of H₂O (80 ml) and DMF (50 ml) was treated with a solution of the allyl ether **1** (1.70 g, 3.69 mmol) in DMF (30 ml). The solution was heated for 20 min at 110 °C and extracted after cooling three times with CH₂Cl₂ (50 ml). The combined organic phases were washed with water (80 ml) and brine (80 ml), dried (Na₂SO₄), filtered, and evaporated to dryness at reduced pressure. The residue was purified by chromatography on silica gel (CH₂Cl₂/cyclohexane, 80:20) to yield **2** as yellow needles (1.04 g, 92%, *m.p.* 98–99 °C). – IR (KBr)/cm⁻¹ = 3436 (OH), 2970, 2898 (CH), 1705 (C=O, ketone), 1670 (C=O, quinone), 1628, 1591 (C=C). – UV (CH₂Cl₂): λ_{max}/nm (lg ε) = 249 (4.35), 267 (4.38), 334 (3.40), 415 (3.73). – ¹H NMR (200 MHz, CDCl₃): δ/ppm = 1.45 (s, 3 H, 6"-H), 2.82 (s, 2H, 4"-H), 2.92–2.97 (m, 6H, 1"-H, 2"-H, 4'-H), 3.56 (s, 2H, 1'-H), 4.00–4.04 (m, 4H, OCH₂CH₂O), 4.40 (s, 1H, 3'-H), 4.84 (s, 1H, 3'-H), 5.12–5.23 (m, 2H, 6'-H), 5.85–6.02 (m, 1H, 5'-H), 7.71 (s, 1H, 4-H), 7.81–7.86 (m, 2H, 6-H, 7-H), 8.30–8.37 (m, 2H, 5-H, 8-H), 13.11 (s, 1H, OH). – ¹³C NMR (50 MHz, CDCl₃): δ/ppm = 24.88 (q, 6"-C), 27.46 (t, 1"-C), 32.08 (t, 1'-C), 42.04 (t, 4'-C), 44.62 (t, 2"-C), 52.23 (t,

4"-C), 65.06 (t, OCH$_2$CH$_2$O), 108.26 (s, 5"-C), 110.94 (t, 3'-C), 114.21 (s), 117.21 (t, 6'-C), 120.32 (d, 4-C), 127.27 and 127.68 (d, 5-C and 8-C), 131.62 (s), 133.76 (s), 134.04 (s), 134.40 (s), 134.48 and 134.86 (d, 6-C and 7-C), 136.30 (d, 5'-C), 145.77 (s, 2'-C), 150.70 (s, 3-C), 161.70 (s, 1-C), 182.90 (s, 10-C), 188.69 (s, 9-C), 206.24 (s, 3"-C). – MS (EI/100 °C): *m/z* (%) = 460 (14) [M$^+$], 87 (100) [C$_4$H$_7$O$_2$$^+$].

C$_{28}$H$_{28}$O$_6$ Calcd.: C 73.03   H 6.13
(460.53)   Found: C 72.85   H 5.98.

5-Hydroxy-1-(2-methyl-[1,3]dioxolane-2-ylmethyl)-4-(2-methylenepent-4-enyl)-2,3-dihydro-1H-cyclopenta[a]anthracene-6,11-dione (**3**)

A solution of Na$_2$S$_2$O$_4$ (90 mg, 0.44 mmol, 85%) in H$_2$O (5 ml) was heated to 90 °C and and treated with a solution of the ketone **1** (100 mg, 0.22 mmol) in DMF (5 ml). The temperature was increased to 110 °C and Na$_2$S$_2$O$_4$ (3–5 equiv.) was added successively. Heating was continued until the starting material **1** and the Claisen product **2** were consumed (ca. 2 h, tlc control, CH$_2$Cl$_2$). Usual workup (see **2**) afforded **3** as yellow needles (79 mg, 82%, *m.p.* 86 °C). – IR (KBr)/cm^{-1} = 3435 (OH), 2982, 2960, 2880 (CH), 1662 (C=O, quinone) 1624, 1593, 1577 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 251 (4.56), 268 (4.38), 326 (3.48), 439 (3.88). – ^{1}H NMR (200 MHz, CDCl$_3$): δ/ppm = 1.62 (s, 3H, 6"-H), 1.62–1.66 (m, 1H, 4"-H), 1.86–2.04 (m, 2H, 4"-H, 2"-H), 2.54–2.63 (m, 1H, 2"-H), 2.83–2.91 (m, 4H, 1"-H, 4'-H), 3.51 (s, 2H, 1'-H), 4.00–4.12 (m, 4H, OCH$_2$CH$_2$O), 4.21–4.29 (m, 1H, 3"-H), 4.52 (s, 1H, 3'-H), 4.83 (s, 1H, 3'-H), 5.09–5.18 (m, 2H, 6'-H), 5.81–5.98 (m, 1H, 5'-H), 7.72–7.79 (m, 2H, 6-H, 7-H), 8.24–8.28 (m, 2H, 5-H, 8-H), 13.68 (s, 1H, OH). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 24.30 (q, 6"-C), 29.37 (t, 2"-C), 29.66 (t, 1"-C), 33.65 (t, 1'-C), 44.25 (t, 4"-C), 41.67 (t, 4'-C), 41.79 (d, 3"-C), 64.35 and 65.22 (t, OCH$_2$CH$_2$O), 110.92 (s, 5"-C), 111.18 (t, 3'-C), 114.81 (s), 116.93 (t, 6'-C), 125.96 (s), 126.81 and 127.60 (d, 5-C and 8-C), 131.81 (s), 133.39 (s), 133.84 and 134.56 (d, 6-C and 7-C), 134.50 (s), 136.46 (d, 5'-C), 144.44 (s), 144.90 (s), 156.69 (s, 3-C), 161.91 (s, 1-C), 183.47 (s, 10-C), 188.98 (s, 9-C). – MS (EI/120 °C): *m/z* (%) = 444 (6) [M$^+$], 87 (100) [C$_4$H$_7$O$_2$$^+$].

C$_{28}$H$_{28}$O$_5$ Calcd.: C 75.65   H 6.35
(444.53)   Found: C 75.41   H 6.23.

2-[4-(2,2-Dimethyl-propionyloxy)-9,10-dioxo-9,10-dihydro-anthracene-2-ylmethyl]-3-oxobutanoic methyl ester (**7**)

A suspension of NaH (33 mg, 1.10 mmol, 80%) in dry THF (5 ml) was treated dropwise under Ar at 0 °C with a solution of methyl acetoacetate (**5**) (128 mg, 1.10 mmol) in dry THF (5 ml). After 15 min of stirring a solution of the monobromide **4a** [11] (220 mg, 0.55 mmol) in dry THF (10 ml) was added. The mixture was allowed to warm to room temperature, stirring was continued for 30 min, and 1N HCl was added to neutralize the solution. The mixture was extracted three times with CH$_2$Cl$_2$ (40 ml), the combined organic phases were washed with water (50 ml) and brine (50 ml), dried (Na$_2$SO$_4$), filtered, and evaporated to dryness at reduced pressure. The residue was purified by chromatography on silica gel (CH$_2$Cl$_2$/MeOH, 99.5:0.5) to yield **7** as a yellow solid (216 mg, 90%, *m.p.* 104.5–105.5 °C). – IR (KBr)/cm^{-1} = 2966 (CH), 1754 (C=O, Ester), 1731 (C=O, Ester), 1719 (C=O, ketone), 1674 (C=O,

quinone), 1606, 1592 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 258 (4.77), 334 (3.85). – ^{1}H NMR (200 MHz, CDCl$_3$): δ/ppm = 1.52 (s, 9H, C(CH$_3$)$_3$), 2.30 (s, 3H, 4'-H), 3.32 (d, $J_{1',2'}$ = 8.0 Hz, 1H, 1'-H), 3.33 (d, $J_{1',2'}$ = 7.0 Hz, 1H, 1'-H), 3.76 (s, 3H, CO$_2$CH$_3$), 3.94 (dd, $J_{2',1'}$ = 7.0 Hz and 8.0 Hz, 1H, 2'-H), 7.24 (d, $J_{2,4}$ = 1.8 Hz, 1H, 2-H), 7.77–7.82 (m, 2H, 6-H, 7-H), 8.11 (d, $J_{4,2}$ = 1.8 Hz, 1H, 4-H), 8.22–8.30 (m, 2H, 5-H, 8-H). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 27.68 (q, C(CH$_3$)$_3$), 30.12 (q, 4'-C), 33.89 (t, 1'-C), 39.64 (s, C(CH$_3$)$_3$), 53.25 (q, CO$_2$CH$_3$), 60.49 (d, 2'-C), 124.35 (s), 125.95 (d, 2-C), 127.30 and 127.68 (d, 5-C and 8-C), 130.82 (d, 4-C), 132.95 (s), 134.19 and 134.74 (d, 6-C and 7-C), 134.61 (s), 135.69 (s), 146.68 (s, 3-C), 151.38 (s, 1-C), 169.33 (s, CO$_2$CH$_3$), 177.13 (s, CO$_2$Piv), 181.61 and 182.99 (s, 9-C and 10-C), 201.50 (s, 3'-C). – MS (EI/100 °C): *m/z* (%) = 436 (13) [M$^+$], 352 (26), 310 (100), 278 (48).

C$_{25}$H$_{24}$O$_7$ Calcd.: C 68.80   H 5.54
(436.46)   Found: C 68.63   H 5.33.

2-[4-(2,2-Dimethylpropionyloxy)-9,10-dioxo-9,10-dihydroanthracene-2-ylmethyl]-4-(2-methyl-[1,3]dioxolane-2-yl)-3-oxobutanoic methyl ester (**8**)

A suspension of NaH (0.51 g, 17.0 mmol, 80%) in dry THF (20 ml) was treated dropwise under argon at 0 °C with a solution of ester **6** [3] (3.43 g, 17.0 mmol) in dry THF (15 ml). After 15 min a solution of the monobromide **4a** [11] (3.50 g, 8.5 mmol) in dry THF (60 ml) was added slowly at 0 °C. The mixture was allowed to warm to room temperature, stirring was continued for 30 min, and 1N HCl was added to neutralize the solution. The mixture was extracted three times with CH$_2$Cl$_2$ (40 ml), the combined organic phases were washed with water (50 ml) and brine (50 ml), dried (Na$_2$SO$_4$), filtered, and evaporated to dryness at reduced pressure. The residue was purified by chromatography on silica gel (CH$_2$Cl$_2$/MeOH, 98:2) to yield **8** as a yellow oil (3.95 g, 89%). – IR (KBr)/cm^{-1} = 2960, 1751 (COOR), 1726 (C=O, ketone); 1672 (C=O, quinone), 1604, 1591 (C=C). – UV (CH$_2$Cl$_2$):λ_{max}/nm (lg ε) = 258 (4.77), 334 (3.58). – ^{1}H NMR (200 MHz, CDCl$_3$): δ/ppm = 1.36 (s, 3H, 6'-H), 1.52 (s, 9H, C(CH$_3$)$_3$), 2.85 (d, J_{gem} = 13.6 Hz, 1H, 4'-H), 3.05 (d, J_{gem} = 13.6 Hz, 1H, 4'-H), 3.29–3.34 (m, 2H, 1'-H), 3.75 (s, 3H, CO$_2$CH$_3$), 3.91–3.95 (m, 4H, OCH$_2$CH$_2$O), 4.21 (t, $J_{2',1'}$ = 7.3 Hz, 1H, 2'-H), 7.26 (d, $J_{2,4}$ = 1.4 Hz, 1H, 2-H), 7.76–7.81 (m, 2H, 6-H, 7-H), 8.14 (d, $J_{4,2}$ = 1.4 Hz, 1H, 4-H), 8.22–8.30 (m, 2H, 5-H, 8-H). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 24.82 (q, 6'-C), 27.68 (q, C(CH$_3$)3), 32.72 (t, 1'-C), 39.62 (s, C(CH$_3$)$_3$), 51.49 (t, 4'-C), 53.18 (q, CO$_2$CH$_3$), 60.65 (d, 2'-C), 64.94 and 65.15 (t, OCH$_2$CH$_2$O), 108.29 (s, 5'-C), 124.28 (s), 126.21 (d), 127.27 (d), 127.68 (d), 130.96 (d), 132.99 (s), 134.15 (d), 134.65 (s), 134.68 (d), 135.54 (s), 147.08 (s, 3-C), 151.31 (s, 1-C), 169.20 (s, CO$_2$CH$_3$), 177.06 (s, CO$_2$Piv), 181.62 and 183.02 (s, 9-C and 10-C), 200.70 (s, 3'-C). – MS (EI/150 °C): *m/z* (%) = 522 (0.5) [M$^+$], 507 (9), 423 (11) [M$^+$–C$_5$H$_7$O$_2$], 87 (100) [C$_4$H$_7$O$_2$$^+$].

C$_{29}$H$_{30}$O$_9$ Calcd.: C 66.66   H 5.79
(522.55)   Found: C 66.49   H 5.66.

1-Hydroxy-3-(3-oxobutyl)-anthracene-9,10-dione (**9**)

A solution of ester **7** (150 mg, 0.34 mmol) in EtOH (10 ml) was treated under Ar with 1N NaOH (7 ml) and the solution

was stirred at 20 °C for 6 h. The mixture was acidified by addition of 1N HCl (10 ml) and extracted three times with CH_2Cl_2 (15 ml). The combined organic phases were washed with water (50 ml) and brine (100 ml), dried (Na_2SO_4), filtered, and evaporated to dryness at reduced pressure. The residue was heated for 20 min at 150 °C and then purified by chromatography on silica gel (CH_2Cl_2/MeOH, 99.5:0.5) to yield 9 as yellow solid (87 mg, 87%, m.p. 173–175 °C). – IR (KBr)/cm^{-1} = 3429 (OH), 2925 (CH), 1707 (C=O, ketone), 1671 (C=O, quinone), 1637, 1606, 1591 (C=C). – UV (CH_2Cl_2): λ_{max}/nm (lg ε) = 261 (4.36), 329 (3.38), 406 (3.69). – ^1H NMR (200 MHz, CDCl$_3$): δ/ppm = 2.22 (s, 3H, 4'-H), 2.83–3.05 (m, 4H, 1'-H, 2'-H), 7.12 (d, $J_{2,3}$ = 1.6 Hz, 1H, 2-H), 7.64 (d, $J_{4,2}$ = 1.6 Hz, 1H, 4-H), 7.77–7.85 (m, 2H, 6-H, 7-H), 8.23–8.31 (m, 2H, 5-H, 8-H), 12.54 (s, 1H, OH). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 30.29 (t, 1'-C), 30.47 (q, 4'-C), 44.02 (t, 2'-C), 114.87 (s), 120.16 (d, 2-C), 123.97 (d, 4-C), 127.22 and 127.79 (d, 5-C and 8-C), 133.60 (s), 133.78 (s), 133.93 (s), 134.60 and 134.94 (d, 6-C and 7-C), 151.89 (s, 3-C), 163.19 (s, 1-C), 182.86 (s, 10-C), 188.42 (s, 9-C), 207.05 (s, 3'-C). – MS (EI/°C): m/z (%) = 294 (24) [M$^+$], 252 (100) [M$^+$ – C_2H_2O], 251 (84) [M$^+$ – C_2H_3O], 43 (27) [$C_2H_3O^+$].
$C_{18}H_{14}O_4$ Calcd.:   C 73.46   H 4.79
(294.31)   Found: C 73.29   H 4.54.

1-Hydroxy-3-[4-(2-methyl-[1,3]dioxolane-2-yl)-3-oxobutyl]-anthracene-9,10-dione (10)

A solution of ester 8 (2.80 g, 5.36 mmol) in EtOH (70 ml) was treated under Ar with 1N NaOH (100 ml) and the solution was stirred at 20 °C for 6 h. The mixture was acidified by addition of 1N HCl (110 ml) and extracted three times with CH_2Cl_2 (75 ml). The combined organic phases were washed with water (50 ml) and brine (100 ml), dried (Na_2SO_4), filtered, and evaporated to dryness at reduced pressure. The residue was heated for 20 min at 150 °C and then purified by chromatography on silica gel (CH_2Cl_2/MeOH, 98:2) to yield 10 as yellow needles (1.35 g, 66%, m.p. 115–116 °C). – IR (KBr)/cm^{-1} = 3431 (OH), 3072 (CH), 2965 (CH), 1711 (C=O, ketone), 1676 (C=O, quinone), 1635, 1593 (C=C), 1378. – UV (CH_2Cl_2): λ_{max}/nm (lg ε) = 262 (4.46), 327 (3.50), 406 (3.81). – ^1H NMR (200 MHz, CDCl$_3$): δ/ppm = 1.42 (s, 3H, 6'-H), 2.80 (s, 2H, 4'-H), 2.97 (s, 4H, 1'-H, 2'-H), 3.97 (s, 4H, OCH$_2$CH$_2$O), 7.12 (d, $J_{2,4}$ = 1.6 Hz, 1H, 2-H), 7.63 (d, $J_{4,2}$ = 1.6 Hz, 1H, 4-H), 7.77–7.82 (m, 2H, 6-H, 7-H), 8.23–8.29 (m, 2H, 5-H, 8-H), 12.52 (s, 1H, OH). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 24.87 (q, 6'-C), 30.16 (t, 1'-C), 44.66 (t, 2'-C), 52.22 (t, 4'-C), 60.40 (t, OCH$_2$CH$_2$O), 108.26 (s, 5'-C), 114.79 (s), 120.26 (d, 2-C), 123.99 (d, 4-C), 127.19 and 127.76 (d, 5-C and 8-C), 133.60 (s), 133.69 (s), 133.93 (s), 134.56 and 134.90 (d, 6-C and 7-C), 152.10 (s, 3-C), 163.16 (s, 1-C), 182.84 (s, 10-C), 188.39 (s, 9-C), 206.10 (s, 3'-C). – MS (EI/150 °C): m/z (%) = 380 (2) [M$^+$], 365 (7), 279 (11) [M$^+$ – $C_5H_9O_2$], 87 (100) [$C_4H_7O_2^+$].
$C_{22}H_{20}O_6$ Calcd.:   C 69.47   H 5.30
(380.40)   Found: C 69.30   H 5.49.

3-Formyl-1-(2,2-dimethylpropionyloxy)-9,10-anthraquinone (12)

A solution of the dibromide 4b [11] (1.00 g, 2.08 mmol) in THF (10 ml) was treated with a solution of AgNO$_3$ (0.88 g,

5.18 mmol) in H$_2$O (3 ml). the mixture was refluxed for 24 h under exclusion of light. The suspension was filtered and the filtrate evaporated at reduced pressure to dryness. The residue was solved in CH_2Cl_2 (50 ml), washed with H$_2$O (25 ml) and brine (25 ml), dried (Na_2SO_4), filtered, and again evaporated to dryness to afford the aldehyde 12 (0.60 g, 85%, m.p. 179–181 °C).– IR (KBr)/cm^{-1} = 3074 (CH), 2977, 2875 (CH), 1754 (COOR), 1699 and 1678 (CHO and C=O), 1592 (C=C). – UV (CH_2Cl_2): λ_{max}/nm (lg ε) = 229 (4.35), 261 (4.62), 339 (3.82). – ^1H NMR (200 MHz, CDCl$_3$): δ/ppm = 1.55 (s, 9H, C(CH$_3$)$_3$), 7.82–7.87 (m, 2H, 6-H, 7-H), 7.89 (d, $J_{2,4}$ = 1.6 Hz, 1H, 2-H), 8.25–8.35 (m, 2H, 5-H, 8-H), 8.77 (d, $J_{4,2}$ = 1.6 Hz, 1H, 4-H), 10.21 (s, 1H, CHO). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 27.63 (q, C(CH$_3$)$_3$), 39.73 (s, C(CH$_3$)$_3$), 127.56 (d), 127.63 (d), 127.97 (d), 128.86 (d), 129.39 (s), 132.79 (s), 134.53 (s), 134.70 and 135.14 (d, 6-C and 7-C), 136.56 (s), 140.57 (s, 3-C), 152.04 (s, 1-C), 176.98 (s, COOR), 181.49 and 182.08 (s, 9-C and 10-C), 190.19 (d, CHO). – MS (EI/100 °C): m/z (%) = 336 (6) [M$^+$], 308 (7) [M$^+$– CO], 252 (100) [M$^+$–CO – C$_4$H$_8$], 223 (10), 139 (10), 85 (7), 57 (13).
$C_{20}H_{16}O_5$ Calcd.:   C 71.42   H 4.79
(336.34)   Found: C 71.26   H 4.69.

3-(Z)- and (E)-3-[1,3]Dioxolane-2-ylpropenyl]-1-hydroxy-anthracene-9,10-dione (15)

A suspension of (2-(2-Bromoethyl)-1,3-dioxolanyl)triphenyl-phosphoniumbromide 13 [14] (0.39 g, 0.88 mmol) in dry THF (10 ml) was treated at –40 °C with n-BuLi (0.55 ml, 0.88 mmol, 1.6M in n-hexane). The mixture was stirred for 15 min at –40 °C and was then added to the solution of the aldehyde 12 (0.29 g, 0.88 mmol) in dry THF (5 ml). The mixture was allowed to warm to room temperature and 1N NaOH (10 ml) was added after 30 min. The solution was then acidified by addition of 1N HCl (15 ml). Usual workup afforded a ca. 4:1 mixture of the (E)/(Z)-isomeres of the olefin 15 as a yellow solid (0.14 g, 49%, m.p.$_{(E)}$ 113–114 °C, m.p.$_{(Z)}$ 135–136 °C).

3-(3-[1,3]Dioxolane-2-yl-propyl)-1-hydroxy-anthracene-9,10-dione (16)

A solution of the E/Z olefins 15 (50 mg, 0.15 mmol) in EtOAc (5 ml) was hydrogenated with palladium on charcoal (3 mg, 10%) for 3 h. The suspension was filtered (Celite) and the solvent removed at reduced pressure. Chromatography on silica gel (CH_2Cl_2/MeOH, 99.5:0.5) afforded the saturated acetal 16 as a yellow solid (43 mg, 85%, m.p. 101–102 °C). IR (KBr)/cm^{-1} = 3440 (OH), 2939, 2876 (CH), 2362, 2341, 1670 (C=O, quinone), 1637, 1593, (C=C). – UV (CH_2Cl_2): λ_{max}/nm (lg ε) = 248 (4.50), 262 (4.52), 331 (3.52), 410 (3.88). – ^1H NMR (200 MHz, CDCl$_3$): δ/ppm = 1.68–1.92 (m, 4H, 2'-H, 3'-H), 2.76 (t, $J_{1',2'}$ = 7.2 Hz, 2H, 1'-H), 3.83–4.03 (m, 4H, OCH$_2$CH$_2$O), 4.90 (t, $J_{4',3'}$ = 4.4 Hz, 1H, 4'-H), 7.12 (d, $J_{2,4}$ = 1.5 Hz, 1H, 2-H), 7.65 (d, $J_{4,2}$ = 1.5 Hz, 1H, 4-H), 7.75–7.84 (m, 2H, 6-H, 7-H), 8.22–8.30 (m, 2H, 5-H, 8-H), 12.56 (s, 1H, OH). – ^{13}C-NMR (50 MHz, CDCl$_3$): δ/ppm = 25.08 (t, 2'-C), 33.57 (t, 3'-C), 36.50 (t, 1'-C), 65.33 (t, OCH$_2$CH$_2$O), 104.53 (d, 4'-C), 114.72 (s), 120.58 (d, 2-C), 123.99 (d, 4-C), 127.17 and 127.76 (d, 5-C and 8-C), 133.62 (s), 133.64 (s), 133.97 (s), 134.52 and 134.85 (d, 6-C and 7-C), 153.17 (s, 3-C), 163.17 (s, 1-C), 183.02 (s, 10-C), 188.43 (s, 9-C). – MS

(EI/100 °C): m/z (%) = 338 (100) [M$^+$], 250 (54), 99 (72) [C$_5$H$_7$O$_2^+$], 73 (98) [C$_3$H$_5$O$_2^+$].

C$_{20}$H$_{18}$O$_5$ Calcd.: C 71.00   H 5.36
(338.36)   Found: C 70.81   H 5.49.

3-(E)- and [1-Hydroxy-3-(Z)-3-(2,5,5-trimethyl-[1,3]dioxan-2-yl)-propyl]-anthracene-9,10-dione (17)

The Wittig reaction with the aldehyde 12 (0.30 g, 0.89 mmol) and [2-(2-bromoethyl)-2,5,5-trimethyl-1,3-dioxanyl]triphenyl-phosphonium bromide 14 (0.48 g, 0.98 mmol) [prepared from 2-(2-bromoethyl)-2,5,5-trimethyl-1,3-dioxane] proceeded as described for 15 to afford the mixture of E/Z olefin 17 (0.21 g, 61%, m.p.$_{(E)}$ 135–136 °C, m.p.$_{(Z)}$ 129–130 °C).

1-Hydroxy-3-[3-(2,5,5-trimethyl-[1,3]dioxan-2-yl)-propyl]-anthracene-9,10-dione (18)

The olefin 17 (0.21 g, 0.52 mmol) was hydrogenated as described for 16 to yield the saturated acetal 18 as a yellow solid (0.18 g, 87%, m.p. 117–118 °C). – IR (KBr)/cm^{-1} = 3463 (OH), 2947, 2869 (CH), 1671 (C=O, quinone), 1635, 1592 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 248 (4.53), 261 (4.55), 285 (4.25), 329 (3.58), 409 (3.91). – ^{1}H NMR (200 MHz, CDCl$_3$): δ/ppm = 0.87 (s, 3H, CH$_3$), 1.05 (s, 3H, CH$_3$), 1.38 (s, 3H, CH$_3$), 1.69–1.93 (m, 4H, 2'-H, 3'-H), 2.72 (t, $J_{1',2'}$ = 7.2 Hz, 2H, 1'-H), 3.41 (d, J_{gem} = 11.4 Hz, 2H, OCH$_2$CR$_2$CH$_2$O), 3.59 (d, J_{gem} = 11.4 Hz, 2H, OCH$_2$CR$_2$CH$_2$O); 7.10 (d, $J_{2,4}$ = 1.4 Hz, 1H, 2-H), 7.63 (d, $J_{4,2}$ = 1.4 Hz, 1H, 4-H), 7.72–7.81 (m, 2H, 6-H, 7-H), 8.19–8.26 (m, 2H, 5-H, 8-H), 12.52 (s, 1H, OH). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 20.16 (q, CH$_3$), 22.83 (q, CH$_3$), 23.32 (q, CH$_3$), 24.63 (t, 2'-C), 30.35 (s, OCH$_2$CR$_2$CH$_2$O), 36.93 and 38.89 (t, 1'-C and 3'-C), 70.78 (t, OCH$_2$CR$_2$CH$_2$O), 99.06 (s, 4'-C), 114.63 (s), 120.59 (d, 2-C), 123.92 (d, 4-C), 127.12 and 127.70 (d, 5-C and 8-C), 133.55 (s), 133.62 (s), 133.96 (s), 134.44 and 134.77 (d, 6-C and 7-C), 153.51 (s, 3-C), 163.16 (s, 1-C), 182.90 (s, 10-C), 188.34 (s, 9-C). – MS (EI/220 °C): m/z (%) = 394 (15) [M$^+$], 308 (26) [M$^+$– C$_5$H$_{10}$O], 290 (23), 165 (16), 152 (20), 129 (100) [C$_7$H$_{13}$O$_2^+$].

C$_{24}$H$_{26}$O$_5$ Calcd.: C 73.08   H 6.64
(394.47)   Found: C 72.86   H 6.44.

4-(4-Hydroxy-9,10-dioxo-9,10-dihydroanthracene-2-yl)-bu-tyraldehyde (19)

A solution of the acetal 16 (40 mg, 0.12 mmol) in THF (3 ml) was treated with 1N HCl (3 ml), and the mixture was refluxed for 1 h. Usual workup afforded the aldehyde 19 as an orange solid (32 mg, 92%, m.p. 113–114 °C). – IR (KBr)/cm^{-1} = 3435 (OH), 2949, 2838 (CH), 2362, 2340, 1709 (C=O, Aldehyd), 1670 (C=O, quinone), 1635, 1591 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 241 (6.07), 406 (4.33). – ^{1}H NMR (300 MHz, CDCl$_3$): δ/ppm= 1.96–2.17 (m, 2H, 2'-H), 2.53 (dt, $J_{3',2'}$ = 7.2 Hz, $J_{3',4'}$ = 1.2 Hz, 2H, 3'-H), 2.75 (t, $J_{1',2'}$ = 7.7 Hz, 2H, 1'-H), 7.10 (d, $J_{2,4}$ = 1.5 Hz, 1H, 2-H), 7.64 (d, $J_{4,2}$ = 1.5 Hz, 1H, 4-H), 7.76–7.82 (m, 2H, 6-H, 7-H), 8.24–8.31 (m, 2H, 5-H, 8-H), 9.80 (t, $J_{4',3'}$ = 1.2 Hz, 1H, 4'-H), 12.54 (s, 1H, OH). – ^{13}C NMR (75 MHz, CDCl$_3$): δ/ppm = 22.42 (t, 2'-C), 35.18 (t, 1'-C), 42.73 (t, 3'-C), 114.34 (s), 119.71 (d, 2-C), 123.34 (d, 4-C), 126.61 and 127.19 (d, 5-C and 8-C), 133.03 (s), 133.22 (s), 133.37 (s), 133.97 and 134.32 (d, 6-C and 7-

C), 151.53 (s, 3-C), 162.64 (s, 1-C), 182.30 (s, 10-C), 187.86 (s, 9-C), 201.19 (d, 4'-C). – MS (EI/220 °C): m/z (%) = 294 (31) [M$^+$], 266 (70) [M$^+$– CO], 250 (81) [M$^+$– C$_2$H$_4$O], 237 (78), 164 (41), 152 (100).

C$_{18}$H$_{14}$O$_4$ Calcd.: C 73.46   H 4.79
(294.31)   Found: C 73.31   H 4.86.

1-Hydroxy-3-(4-oxopentyl)-anthracene-9,10-dione (20)

The acetal 18 (0.18 g, 0.46 mmol) was cleaved as described for 19 to yield the ketone 20 as a yellow solid (0.14 g, 97%, m.p. 128.5–129.5 °C). – IR (KBr)/cm^{-1} = 3447 (OH), 2954, 2943 (CH), 1705 (C=O, ketone), 1671 (C=O, quinone), 1636, 1592 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 248 (4.58), 261 (4.61), 330 (3.63), 409 (3.96). – ^{1}H NMR (300 MHz, CDCl$_3$): δ/ppm = 1.88–1.98 (m, 2H, 2'-H), 2.13 (s, 3H, 5'-H), 2.47 (t, $J_{3',2'}$ = 7.2 Hz, 2H, 3'-H), 2.67 (t, $J_{1',2'}$ = 7.7 Hz, 2H, 1'-H), 7.02 (d, $J_{2,4}$ = 1.4 Hz, 1H, 2-H), 7.55 (d, $J_{4,2}$ = 1.4 Hz, 1H, 4-H), 7.72–7.76 (m, 2H, 6-H, 7-H), 8.16–8.21 (m, 2H, 5-H, 8-H), 12.45 (s, 1H, OH). – ^{13}C NMR (75 MHz, CDCl$_3$): δ/ppm = 24.05 (t, 2'-C), 29.97 (q, 5'-C), 35.34 (t, 1'-C), 42.45 (t, 3'-C), 114.31 (s), 119.88 (d, 2-C), 123.41 (d, 4-C), 126.67 and 127.24 (d, 5-C and 8-C), 133.10 (s), 133.20 (s), 133.44 (s), 134.04 and 134.39 (d, 6-C and 7-C), 152.09 (s, 3-C), 162.70 (s, 1-C), 182.31 (s, 10-C), 187.87 (s, 9-C), 207.87 (s, 4'-C). – MS (EI/220 °C): m/z (%) = 308 (37) [M$^+$], 275 (21), 250 (100) [M$^+$– C$_3$H$_6$O], 223 (40) [M$^+$– C$_5$H$_9$O], 195 (41), 166 (95), 153 (91), 77 (20) [C$_6$H$_5^+$].

C$_{19}$H$_{16}$O$_4$ Calcd.: C 74.01   H 5.23
(308.33)   Found: C 73.88   H 5.11.

5-Hydroxy-1-methyl-2,3-dihydro-1H-cyclopenta[a]anthra-cene-6,11-dione (21)

The cyclization of ketone 9 (50 mg, 0.17 mmol) proceeded as described for 3. Usual workup and chromatography on silica gel (CH$_2$Cl$_2$/cyclohexane, 60:40) afforded 21 as yellow needles (37 mg, 78%, m.p. 135–137 °C). – IR (KBr)/cm^{-1} = 3441 (OH), 2944 (CH), 1662 (C=O, quinone), 1633, 1595 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 250 (4.54), 277 (4.21), 328 (3.50), 422 (3.89), 433 (3.89). – ^{1}H NMR (200 MHz, CDCl$_3$): δ/ppm = 1.26 (d, $J_{4',3'}$ = 6.9 Hz, 3H, 4'-H), 1.91–2.01 (m, 1H, 2'-H), 2.20–2.32 (m, 1H, 2'-H), 2.82–2.95 (m, 1H, 1'-H), 3.02–3.17 (m, 1H, 1'-H), 4.09–4.23 (m, 1H, 3'-H), 7.19 (s, 1H, 4-H), 7.77–7.84 (m, 2H, 6-H, 7-H), 8.25–8.37 (m, 2H, 5-H, 8-H), 13.29 (s, 1H, OH). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 19.17 (q, 4'-C), 31.08 (t, 2'-C), 33.83 (t, 1'-C), 39.76 (d, 3'-C), 115.08 (s), 120.66 (d, 2-C), 126.93 and 127.60 (d, 5-C and 8-C), 127.49 (s), 133.52 (s), 134.09 and 134.72 (d, 6-C and 7-C), 134.47 (s), 145.97 (s, 4-C), 157.06 (s, 3-C), 163.54 (s, 1-C), 184.01 (s, 10-C), 188.80 (s, 9-C). – MS (EI/ 130 °C): m/z (%) = 278 (83) [M$^+$], 263 (100) [M$^+$– CH$_3$].

C$_{18}$H$_{14}$O$_3$ Calcd.: C 77.68   H 5.07
(278.31)   Found: C 77.52   H 5.00.

5-Hydroxy-1-(2-methyl-[1,3]dioxolane-2-ylmethyl)-2,3-dihy-dro-1H-cyclopenta[a]anthracene-6,11-dione (22a)

The cyclization of ketone 10 (0.20 g, 0.53 mmol) proceeded as described for 3 to yield 22a as an orange solid (0.16 g, 84%, m.p. 145 °C). – IR (KBr)/cm^{-1} = 3437 (OH), 2984, 2943, 2873 (CH), 1670 (C=O, quinone), 1637, 1593 (C=C). – UV

(CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 251 (4.52), 279 (4.21), 329 (3.47), 433 (3.86). – ^{1}H NMR (300 MHz, CDCl$_3$): δ/ppm = 1.53 (s, 3H, 6'-H), 1.53–1.55 (m, 1H, 4'-H), 1.80 (d, J_{gem} = 13.3 Hz, 1H, 4'-H), 1.91–2.02 (m, 1H, 2'-H), 2.47–2.54 (m, 1H, 2'-H), 2.76 (dd, J_{gem} = 17.2 Hz, $J_{1',2'}$ = 8.6 Hz, 1H, 1'-H), 2.88–2.98 (m, 1H, 1'-H), 3.86–4.02 (m, 4H, OCH$_2$CH$_2$O), 4.11–4.18 (m, 1H, 3'-H), 7.08 (s, 1H, 2-H), 7.68–7.73 (m, 2H, 6-H, 7-H), 8.19–8.23 (m, 2H, 5-H, 8-H), 13.31 (s, 1H, OH). – ^{13}C NMR (75 MHz, CDCl$_3$): δ/ppm = 24.39 (q, 6'-C), 29.85 (t, 2'-C), 31.15 (t, 1'-C), 39.97 (t, 4'-C), 41.43 (d, 3'-C), 64.41 and 65.62 (t, OCH$_2$CH$_2$O), 110.88 (s, 5'-C), 115.21 (s), 120.50 (d, 2-C), 126.89 and 127.78 (d, 5-C and 8-C), 127.74 (s), 133.43 (s), 134.06 and 134.73 (d, 6-C and 7-C), 134.42 (s), 144.90 (s, 4-C), 157.59 (s, 3-C), 163.55 (s, 1-C), 183.75 (s, 10-C), 188.88 (s, 9-C). – MS (EI/100 °C): m/z (%) = 364 (4) [M$^+$], 277 (12) [M$^+$– C$_4$H$_7$O$_2$], 263 (20) [M$^+$– C$_5$H$_9$O$_2$], 87 (100) [C$_4$H$_7$O$_2$$^+$].

C$_{22}$H$_{20}$O$_5$ Calcd.:   C 72.52   H 5.53
(364.40)   Found: C 72.44   H 5.62.

5-Hydroxy-1-(2-oxo-propyl)-2,3-dihydro-1H-cyclopenta [a]anthracene-6,11-dione (22b)

A solution of acetal 22a (25 mg, 0.07 mmol) in THF (5 ml) was treated with 1N HCl (3 ml) and the mixture was refluxed for 1 h. After usual workup (see 2) crystallization (CH$_2$Cl$_2$/ cyclohexane) yielded ketone 22b as yellow needles (21 mg, 94%, m.p. 175–176 °C). – IR (KBr)/cm^{-1} = 3448 (OH), 2961 (CH), 1704 (C=O, ketone), 1657 (C=O, quinone), 1630, 1591 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm(lg ε) = 230 (4.36), 251 (4.56), 278 (4.22), 329 (3.52), 432 (3.93). – ^{1}H NMR (300 MHz, CDCl$_3$): δ/ppm = 1.98–2.05 (m, 1H, 2'-H), 2.17–2.28 (m, 1H, 2'-H), 2.31 (s, 3H, 6'-H), 2.39 (dd, J_{gem} = 15.9 Hz, $J_{4',3'}$ = 10.8 Hz, 1H, 4'-H), 2.84–3.06 (m, 3H, 1'-H, 4'-H), 4.35–4.42 (m, 1H, 3'-H), 7.17 (s, 1H, 2-H), 7.78–7.82 (m, 2H, 6-H, 7-H), 8.24–8.33 (m, 2H, 5-H, 8-H), 13.23 (s, 1H, OH). – ^{13}C NMR (75 MHz, CDCl$_3$): δ/ppm = 29.51 (q, 6'-C), 30.31 and 30.41 (t, 1'-C and 2'-C), 40.47 (d, 3'-C), 46.06 (t, 4'-C), 114.61 (s), 120.11 (d, 2-C), 126.41 and 127.04 (d, 5-C and 8-C), 127.34 (s), 132.84 (s), 133.67 and 134.21 (d, 6-C and 7-C), 142.28 (s, 4-C), 156.60 (s, 3-C), 163.16 (s, 1-C), 183.47 (s, 10-C), 188.11 (s, 9-C), 208.06 (s, 5'-C). – MS (EI/220 °C): m/z (%) = 320 (21) [M$^+$], 277 (67) [M$^+$– C$_2$H$_3$O], 263 (95) [M$^+$ –C$_3$H$_5$O], 262 (100), 231 (29), 202 (47), 189 (46), 178 (38), 176 (29), 43 (47).

C$_{20}$H$_{16}$O$_4$ Calcd.:   C 74.99   H 5.03
(320.34)   Found: C 74.78   H 4.91.

11-Hydroxy-1-(2-oxo-propyl)-2,3-dihydro-1H-cyclopen-ta[b]anthracene-5,10-dione (23)

A solution of ketone 10 (100 mg, 0.26 mmol) in a mixture of methanol (35 ml) and 1N NaOH (5 ml) was treated under Ar with a solution of Na$_2$S$_2$O$_4$ (80 mg, 0.39 mmol, 85%) in H$_2$O (10 ml). the reaction mixture was then heated to 60 °C, stirred overnight, and neutralized by addition of 2N HCl (2.5 ml). After usual workup (see 2) and chromatography on silica gel (CH$_2$Cl$_2$) the linear tetracycle 23 was isolate as yellow crystals (14 mg, 16%, m.p. 186 °C). – IR (KBr)/cm^{-1} = 3446 (OH), 2926 (CH), 1708 (C=O, ketone), 1668 (C=O, quinone), 1632, 1592 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 247 (4.53), 267 (4.68), 333 (3.63), 411 (3.94). – ^{1}H NMR (300 MHz,

CDCl$_3$): δ/ppm =1.77–1.88 (m, 1H, 2'-H), 2.22 (s, 3H, 6'-H), 2.40–2.53 (m, 1H, 2'-H), 2.58 (dd, J_{gem} = 17.3 Hz, $J_{4',3'}$ = 9.8 Hz, 1H, 4'-H), 2.91–3.13 (m, 2H, 1'-H), 3.31 (dd, J_{gem} = 17.3 Hz, $J_{4',3'}$ = 3.6 Hz, 1H, 4'-H), 3.83–3.92 (m, 1H, 3'-H), 7.70 (s, 1H, 4-H), 7.76–7.82 (m, 2H, 6-H, 7-H), 8.24–8.32 (m, 2H, 5-H, 8-H), 12.85 (s, 1H, OH). – ^{13}C NMR (75 MHz, CDCl$_3$): δ/ppm = 30.51 (q, 6'-C), 31.41 (t, 2'-C), 32.80 (t, 1'-C), 38.97 (d, 3'-C), 46.97 (t, 4'-C), 114.66 (s), 116.12 (d, 4-C), 126.54 and 127.10 (d, 5-C and 8-C), 132.86 (s), 133.14 (s), 133.52 (s), 133.78 and 134.21 (d, 6-C and 7-C), 139.87 (s, 2-C), 154.53 (s, 3-C), 159.13 (s, 1-C), 182.41 (s, 10-C), 188.54 (s, 9-C), 207.37 (s, 5'-C). – MS (EI/°C): m/z (%) = 320 (45) [M$^+$], 277 (100) [M$^+$–C$_2$H$_3$O], 262 (43) [M$^+$–C$_3$H$_6$O].

High resolution MS   Calcd.:   320.104
(C$_{20}$H$_{16}$O$_4$)   Found: 320.104 ± 2 ppm.

6-Hydroxy-7,8,9,10-tetrahydronaphthacene-5,12-dione (24) and *11-Hydroxy-7,8-dihydronaphthacene-5,12-dione* (26)

A: Marschalk-Reaktion

A solution of the aldehyde 19 (50 mg, 0.17 mmol) in a mixture of methanol (25 ml) and 1N NaOH (4 ml) was treated under Ar with a solution von Na$_2$S$_2$O$_4$ (53 mg, 0.26 mmol, 85%) in H$_2$O (10 ml). The mixture was stirred for 2 h at 60 °C and then acidified by addition of 2N HCl. After usual workup a mixture of the tetracyclic compounds 24 and 26 as an orange solid was isolated (40 mg).

B: Reduction of the double bond

A solution of the mixture (20 mg, ~ 0.07 mmol) in methanol (15 ml) and 1N NaOH (2 ml) was treated with a solution of Na$_2$S$_2$O$_4$ (50 mg, 0.28 mmol) in H$_2$O (10 ml) and heated under Ar for 1 h. After usual workup and crystallization from CH$_2$Cl$_2$/ cyclohexane the tetrahydronaphthacene-5,12-dione 24 was isolated as yellow needles (18 mg, ~ 92%, m.p. 280–281 °C).

C: Cyclization under neutral conditions (Na$_2$S$_2$O$_4$ in DMF/ H$_2$O)

The cyclization of the aldehyde 19 (25 mg, 0.09 mmol) proceeded as described for 3 to afford 24 (4 mg, 15%).

Data of 24:

IR (KBr)/cm^{-1}= 3481 (OH), 2932 (CH), 1668 (C=O, quinone), 1626, 1592 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 247 (4.40), 268 (4.46), 328 (3.42), 414 (3.76). – ^{1}H NMR (200 MHz, CDCl$_3$): δ/ppm = 1.81–1.96 (m, 4H, 2-H, 3-H), 2.80–2.91 (m, 4H, 1-H, 4-H), 7.61 (s, 1H, 5-H), 7.80–7.87 (m, 2H, 8-H, 9-H), 8.30–8.37 (m, 2H, 7-H, 10-H), 13.10 (s, 1H, OH). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 22.28 and 22.54 (t, 2-C and 3-C), 23.45 (t, 1-C), 30.89 (t, 4-C), 113.28 (s), 120.97 (d, 5-C), 127.13 and 127.65 (d, 7-C and 10-C), 130.25 (s), 133.85 (s), 134.18 (s), 134.27 (s), 134.32 and 134.68 (d, 8-C and 9-C), 147.72 (s), 161.48 (s, 12-C), 183.11 (s, 6-C), 188.64 (s, 11-C).

Data of 26:

^{1}H NMR (200 MHz, CDCl$_3$): δ/ppm = 2.41–2.46 (m, 2H, 3-H), 2.76–2.95 (m, 2H, 4-H), 6.24–6.33 (dt, J = 9.8 Hz, J = 4.5 Hz, 1H, 2-H), 6.96 (d, J = 9.8 Hz, 1H, 1-H), 7.56 (s, 1H, 5-H), 7.77–7.81 (m, 2H, 8-H, 9-H), 8.24–8.31 (m, 2H, 7-H,

10-H), 12.89 (s, 1H, OH). – ^{13}C NMR (50 MHz, CDCl$_3$): δ/ppm = 22.75 (t, 3-C), 28.36 (t, 4-C), 115.12 (s), 119.69 (d), 120.85 (d), 127.16 and 127.64 (d, 7-C and 10-C), 129.54 (s), 131.36 (s), 132.07 (d), 133.66 (s), 134.12 (s), 134.29 and 134.81 (d, 8-C and 9-C), 144.97 (s), 158.09 (s, 12-C), 182.61 (s, 6-C), 188.85 (s, 11-C).

6-Hydroxy-7-methyl-7,8,9,10-tetrahydro-naphthacene-5,12-dione (**25**), *11-Hydroxy-10-methyl-7,8-dihydronaphthacene-5,12-dione* (**27**), *and 6-Hydroxy-7-methyl-naphthacene-5,12-dione* (**28**)

A: Marschalk-Reaktion

The ketone **20** (50 mg, 0.16 mmol) was treated according to the procedure given for **24**. Chromatographic separation on silica gel (CH$_2$Cl$_2$/cyclohexane, 70:30) afforded the fully aromatic naphthacenequinone **28** (14 mg, 30%, *m.p.* 255–256 °C, dark orange needles) and the mixture of the partly saturated naphthacenequinones **25** and **27** as a red solid (27 mg).

B: Reduction of the olefinc double bond

A solution of the mixture of **25** and **27** [20 mg, ~0.07 mmol) in ethyl acetate (5 ml)] was hydrogenated as described for **16** to yield the tetrahydronaphthacenequinone **25** as orange needles (15 mg, 75%, *m.p.* 196–197 °C).

C: Reaction of 20 with Na$_2$S$_2$O$_4$ in DMF/H$_2$O

The cyclization of ketone **20** (25 mg, 0.08 mmol) under neutral conditions was performed as described for **3** to yield **28** (3 mg, 12%).

Data for **25**:

IR (KBr)/cm^{-1} = 3448 (OH), 2925, 2857 (CH), 1670 (C=O, quinone), 1625, 1592 (C=C), 1571. – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 248 (4.43), 268 (4.47), 333 (3.45), 415 (3.79). – ^{1}H NMR (300 MHz, CDCl$_3$): δ/ppm = 1.29 (d, J = 7.0 Hz, 3H, CH$_3$), 1.77–1.88 (m, 4H, 3-H and 4-H), 2.73–2.92 (m, 2H, 5-H), 3.28–3.31 (m, 1H, 2-H), 7.48 (s, 1H, 6-H), 7.73–7.76 (m, 2H, 9-H, 10-H), 8.21–8.26 (m, 2H, 8-H, 11-H), 13.11 (s, 1H, OH). – ^{13}C NMR (75 MHz, CDCl$_3$): δ/ppm = 17.32 (t,), 20.07 (q, 1-C), 26.86 (d, 2-C), 29.30 (t,), 30.57 (t, 5-C), 113.09 (s), 120.65 (d, 6-C), 126.64 and 127.12 (d, 8-C and 11-C), 129.89(s,), 133.44 (s), 133.68 (s), 133.82 and 134.14 (d, 9-C and 10-C), 138.56 (s), 146.76 (s), 161.28 (s, 13-C), 182.57 (s, 7-C), 188.19 (s, 12-C). – MS (EI/70 °C): *m/z* (%) = 292 (48) [M$^+$], 277 (100) [M$^+$– CH$_3$].

High resolution MS: Calcd.: 292.109
(C$_{19}$H$_{16}$O$_3$)   Found: 292.109 ± 3 ppm.

Data for **27**:

^{1}H NMR (300 MHz, CDCl$_3$): δ/ppm = 2.21–2.23 (m, 2H, 4-H), 2.34 (s, 3H, CH$_3$), 2.73–2.92 (m, 2H, 5-H), 6.00 (br. s, 1H, 3-H), 7.56 (s, 1H, 6-H), 7.73–7.76 (m, 2H, 9-H, 10-H), 8.21–8.26 (m, 2H, 8-H, 11-H), 13.35 (s, 1H, OH). – ^{13}C NMR (75 MHz, CDCl$_3$): δ/ppm = 22.13 (t, 4-C), 22.65 (q, 1-C), 29.99 (t, 5-C), 115.02 (s), 119.14 (d, 6-C), 126.75 and 127.03 (d, 8-C and 11-C), 129.72 (d, 3-C), 130.80 (s), 131.00 (s), 132.34 (s), 133.39 (s), 133.53 (s), 133.82 and 134.23 (d, 9-C and 10-C), 147.66 (s), 160.30 (s, 13-C), 182.12 (s, 7-C), 188.52 (s, 12-C). – MS (EI/70 °C): *m/z* (%) = 290 (59) [M$^+$], 275 (57) [M$^+$– H$_2$O].

High resolution MS: Calcd.:   290.094
(C$_{19}$H$_{14}$O$_3$)   Found: 290.094 ± 3 ppm.

Data for **28**:

IR (KBr)/cm^{-1} = 3447 (OH), 2967, 2927 (CH), 1667 (C=O, quinone), 1623, 1593, 1572 (C=C). – UV (CH$_2$Cl$_2$): λ_{max}/nm (lg ε) = 259 (4.85), 458 (4.09). – ^{1}H NMR (300 MHz, CDCl$_3$): δ/ppm = 3.03 (s, 3H, CH$_3$), 7.40 (d, J = 7.3 Hz, 1H, 3-H), 7.56 (t, J = 7.7 Hz, J = 7.3 Hz, 1H, 4-H), 7.77–7.84 (m, 3H, 5-H, 9-H, 10-H), 8.23 (s, 1H, 6-H), 8.33–8.42 (m, 2H, 8-H, 11-H), 15.48 (s, 1H, OH). – ^{13}C NMR (75 MHz, CDCl$_3$): δ/ppm = 25.27 (q, 1-C), 110.10 (s), 123.13 (d, 6-C), 127.42 and 127.86 (d, 8-C and 11-C), 127.48 (s), 128.49 (s), 129.52 (d, 5-C), 131.31 (d), 132.62 (d), 134.53 and 134.62 (d, 9-C and 10-C), 134.78 (s), 134.88 (s), 138.52 (s), 140.45 (s), 168.23 (s, 13-C), 182.80 (s, 7-C), 187.81 (s, 12-C). – MS (EI/220 °C): *m/z* (%) = 288 (100) [M$^+$], 270 (19) [M$^+$– H$_2$O], 243 (31), 232 (20), 214 (43), 203 (45), 152 (21), 110 (63), 81 (47).

C$_{19}$H$_{12}$O$_3$ Calcd.: C 79.16   H 4.20
(288.30)   Found: C 78.91   H 4.08.

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