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Chemistry of Isodrin Derivatives. The Syntheses of 11- and 12-Hydroxy-1,4,4a,9,9a,10-hexahydro-*endo*,*endo*-1,4;9,10-dimethanoanthracenes

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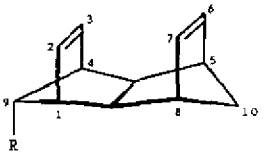
The titled compounds are synthesized through multi-step sequences involving consecutive $[_{\pi}4_s + _{\pi}2_s]$ cycloadditions of norbornadiene with two units of chlorinated cyclopentadiene. A dyotropic double hydrogen migration was observed between two closely located double bonds during the process of aromatization of a cyclohexadiene moiety. A hydroxyl group is introduced onto either of the two methylene bridges in order to provide products suitable for solvolytic analyses.

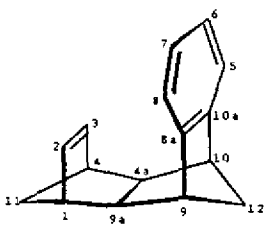
INTRODUCTION

One of the most well-known observations of anchimeric assistance by double bond is the 10^{11} fold rate enhancement in solvolysis of anti-7-norbornenyl (NBE) esters with respect to the corresponding 7-norbornyl (NBN) esters.[1] A related system based on **1b** has been reported to show a further 10^3 rate enhancement over NBE.[2] This rate enhancement was attributed to an extended delocalization of the cationic center, involving both double bonds of the intermediate.[3] Over the years there have been some arguments concerning the nature of π-electron participation of the remote C(6)=C(7) bond by relay through C(2)=C(3) bond in such a ring system.[4] In **1a** the narrow distance between C(6)=C(7) and C(2)=C(3) induces an energy splitting between a pair of symmetrical π-bonds.[5] Such through-space π-π interaction is the basis of the highly efficient $[2_{\pi} + 2_{\pi}]$ photocyclization of **1a** and **2**.[6] In solvolysis the significance of such interaction is not yet totally clear; direct orbital overlapping (e.g. through-space type) between the two π-bonds of **1b** cannot fully account for the observed rate enhancement on solvolysis.[4a]

Substituent effects manifested by linear free energy relationship have been utilized as a criterion for the estimation of charge delocalization in solvolysis.[7] Hydroxyl derivatives of **2** are synthesized in this regard where the substituents can be converted to appropriate leaving groups for solvolysis studies which would shet light on the intriguing question of through space participation of a remote π-orbital.



1 a) R = H
b) R = OH



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RESULTS AND DISCUSSION

It has been observed that the cycloaddition between hexachlorocyclopentadiene (HCCP) with 7-*tert*-butoxynorbornadiene is stereoselective leading to an endo-adduct, i.e. **7**.[8] This strategy was employed for construction of the basic skeleton of **1a**. For building up the benzene moiety in **2**, a successive cycloaddition with 1,1-dimethoxy-2,3,4,5-tetrachlorocyclopentadiene (DTCP) was carried out where an *endo*-selectivity was again observed. Hydrolysis and dechlorination led to **10a** in a straightforward manner. The route for the preparation of positional isomer **6a** required adjustment to put the hydroxyl group on the other side. Stepwise operations are described as follows.

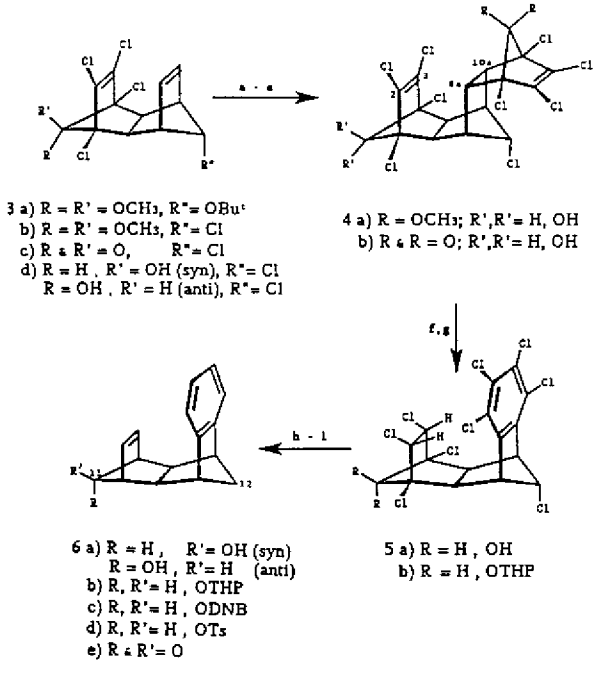
Syntheses of 11-Hydroxyl Derivatives 6a-*A*,*S* (Scheme I)

The cycloaddition of 7-*tert*-butoxynorbornadiene with DTCP for the formation of **3a** is well documented in literature.[8c] The *tert*-butoxyl group of **3a** was converted to a chloride (**3b**) by an acid catalyzed substitution reaction. Hydrolysis of the dimethylketal of **3b** with concentrated H_2SO_4

This work was initiated at The University of Utah by the late Professor Evan L. Allred, to whom this article is dedicated.

(98%) suspended in CH_2Cl_2 at 25 °C yielded ketone **3c**, which shows a carbonyl stretch at 1830 cm^{-1}. Reduction of **3c** with lithium aluminum hydride yielded a mixture of isomeric alcohols, i.e. one with a hydroxyl group *syn* to the double bonds (**3d**-*S*, in 25% yield) and another with a hydroxyl group *anti* to the double bonds (**3d**-*A*, 56%). The two compounds were separated by column chromatography. The stereochemistry of **3d**-*A* was confirmed by comparison of its dechlorinated derivative with an authentic sample. Dechlorination of **3d**-*A* was accomplished through a three-step sequence similar to that of the conversion from **5a**-*A* to **6a**-*A*, where protection of the hydroxyl group was required before reduction.

Scheme I



Key: [3a] -> 3b: LiCl,HCl(g), MeOH, rt, 5 h; [3b] -> 3c: 98% H_2SO_4, CH_2Cl_2, rt, 3 d; [3c] -> 3d: $LiAlH_4$, ether, 0°C; [3a] -> 4a: $C_5Cl_4(OCH_3)_2$, xylene reflux; [4a] -> 4b: 98% H_2SO_4, CH_2Cl_2, rt; [4b] -> 5a: toluene reflux, 4 h; [5a] -> 5b: DHP, TsOH, CH_2Cl_2, rt; [5b] -> 6b: Na, Bu^tOH, THF reflux; [6b] -> 6a: 2% HCl(aq), THF, rt; [4a] -> 6c: 3,5-$(NO_2)_2C_6H_3COCl$, Py, 0°C; [6a] -> 6d: p-$CH_3C_6H_4SO_2Cl$, Py, 0°C; [6a] -> 6e: CrO_3.2Py, CH_2Cl_2, 0°C.

A procedure analogous to the preparation of **3b** and **3c** was used for accessing **4a** and **4b**. Cycloaddition reactions of **3d**-*A*,*S* with DTCP proceeded at ca. 140 °C to give stereoselective products **4a**-*A* and **4a**-*S* according to the *endo* rule.[9] Hydrolysis of the ketals with concentrated H_2SO_4 (98%) suspended in CH_2Cl_2 led to **4b**-*A*,*S* with similar yields. Subsequently, extrusion of carbon monoxide was accomplished in high yields by heating **4b**-*A*,*S* in toluene to reflux for a few hours. The decarbonylation was followed by a synchronous double hydrogen jumping across the ethylene bridges to form **5a**-*A*,*S*. This process has been found in a few classes of compounds in which appropriate alignment exists between the two bridges.[10,11] In the cases of **4b**-*A*,*S* the energy of aromatization provided substantial driving force for these processes. At moderate temperature (ca. 70 °C) the intermediate cyclohexadiene compounds can be isolated;[10a,b] yet at higher temperatures (e.g. 110 °C) the hydrogen jumping proceeded readily. Through the above-mentioned sequences **5a**-*A*,*S* were collected from **3d**-*A*,*S* in 41% and 34% yields respectively.

Dechlorination of **5a**-*A*,*S* by sodium in ethanol did not give good results. After protection of the hydroxyl group with dihydropyran, the reduction was successful using sodium/*tert*-butanol in THF. This reaction not only removed all the chlorine atoms but also regenerated a double bond between C(2) and C(3),[11] as shown by a triplet signal at δ 4.60 in ^1H NMR spectrum of **6b**-*A*, and a multiplet at δ 4.72 in the spectrum of **6b**-*S*. Deprotection was followed by hydrolysis in dilute acid to give **6A**-*A*,*S*.

Transformation of **6a**-*S* to **6a**-*A* can be achieved by going through ketone **6e**, followed by a stereoselective reduction with $LiAlH_4$, during which the aluminium atom was coordinated with the π-bond so that the hydride attacked the carbonyl carbon from the same face. Note that in the reduction of **3c** to **3d** the reagent showed no selectivity probably because the chlorine atoms substituted around the double bond hindered their coordination with aluminium.

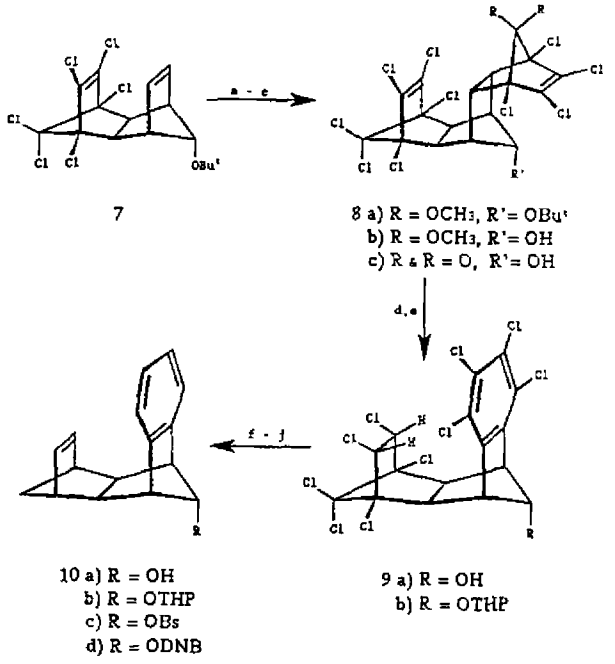
Alcohol derivatives **6c**-*S* and **6d**-*S* were also prepared, whereas the latter was provided as an effective intermediate for separating **6a**-*S* from side products. 3,5-Dinitrobenzoate **6c**-*A* is suitable for use in later kinetic analysis.

Synthese of 12-Hydroxyl Derivatives 10a-*A*,*S* (Scheme II)

Compound **7** was prepared from cycloaddition of HCCP and 7-*tert*-butoxynorbornadiene as described in literature.[8a] Heating of **7** with DTCP at 160 °C (4 d) produced a cycloadduct **8a** in 65% yield, which was recrystallized from hexane (mp 208-210 °C). Hydrolysis of **8a** was accomplished in two steps: **8b** was obtained first by heating a THF solution containing 90% H_2SO_4. Subsequent stirring of **8b** in CH_2Cl_2 suspended in 98% H_2SO_4 at room temperature led to **8c**.

Decarbonylation of **8c** followed by double hydrogen migration were accomplished in one pot by heating it in toluene to reflux. For a successful dechlorination the hydroxyl group of **9a** had to be protected by THP. Reaction of **9b** with Na/*tert*-butanol in THF produced **10b** in 52% yield.

Scheme II



Key: '7 -> 8a: $C_3Cl_4(OCH_3)_2$, 1,3,5-trimethylbenzene reflux; '8a -> 8b: 90% H_2SO_4, THF reflux; '8b -> 8c: 98% H_2SO_4, CH_2Cl_2, rt; '8c -> 9a: toluene reflux; '9a -> 9b: DHP, TsOH, CH_2Cl_2; '9b -> 10b: Na, Bu'OH, THF reflux, 18 h; '10b -> 10a: 2% $HCl_{(aq)}$, THF, rt; '10a -> 10c: p-BrC_6H_4COCl, Py, 0°C; '10c -> 10a: H_2O, THF (20:80), 55°C; '10a -> 10d: 3,5-$(NO_2)_2C_6H_3COCl$, Py, 0°C.

The olefinic hydrogens of **10b** absorb at δ 4.80 in ^{1}H NMR spectrum. Hydrolysis of **10b** in dilute acid yielded **10a** successfully. The product isolated from a column chromatograph contained a small amount of impurities which was rather difficult to remove. Further purification of **10a** was done by first converting it to a brosylate ester **10c**, after separation from impurities, it was then hydrolyzed back to **10a** in high purity.

EXPERIMENTAL SECTION

Melting points were uncorrected. ^{1}H NMR spectra were obtained with either a Varian EM-390 or a EM-360 spectrometer using TMS as an internal standard. Elemental analyses were performed by M-H-W Laboratories, Phoenix, AZ, USA.

1,2,3,4,10-Pentachloro-1,4,4a,5,8,8a-hexahydro-9-oxo-*endo,endo*-1,4;5,8-dimethanonaphthalene (3c)

To the ketal **3a**[8c] (12.0 g, 31 mmol) in a solution of chloroform (12 mL) and methanol (100 mL) was added a methanol solution (50 mL) of lithium chloride (12 g) in a round-bottom flask (250 mL). Dry HCl gas was bubbled through the rapidly stirred mixture for 4 h, during which period white precipitate appeared. The mixture was allowed to stay at room temperature for another 1 h with stirring, cooled in an ice bath and filtered. The filtrate was neutralized with saturated $NaHCO_3$ (2 L) and extracted with ether. The etheral solution was washed with distilled water and brine, dried over anhydrous $MgSO_4$, and evaporated *in vacuo*. The pentachloride **3b** was obtained as an oil (10.3 g). A portion of **3b** (2.30 g, 5.9 mmol) was dissolved in CH_2Cl_2 (50 mL) in a round-bottom flask (100 mL), treated with 98% sulfuric acid (10 mL), and stirred at room temperature for 3 d. The resulting mixture was poured onto crushed ice (100 g) and was extracted three times with ether. The ether layers were combined and washed with saturated $NaHCO_3$ and NaCl solutions, dried over anhydrous $MgSO_4$, filtered and evaporated *in vacuo*. The white solid was recrystallized from hexane to yield **3c** (1.70 g, 84%), mp 125-126 °C; IR (CCl_4) ν 1830, 1580 cm^{-1}; ^{1}H NMR (90 MHz, $CDCl_3$) δ 6.15 (2H, t, J = 2 Hz, olefinic), 3.80 (1H, m), 3.30 (2H, m), 3.15 (2H, m).

1,2,3,4,10-Pentachloro-1,4,4a,5,8,8a-hexahydro-9-hydroxy-*endo,endo*-1,4;5,8-dimethanonaphthalene (3d-*A* and 3d-*S*)

A 300 mL two-necked round-bottom flask was fitted with a dropping funnel and a nitrogen inlet/outlet. To this flask was added $LiAlH_4$ (1.0 g, 26 mmol) dispersed in anhydrous ether (200 mL) at 0 °C under a nitrogen atmosphere, and to the dropping funnel was filled with ketone **3c** (8.0 g, 23 mmol) dissolved in anhydrous ether (50 mL). The latter solution was added dropwise to the stirred LAH at 0 °C during a period of 30 min and the mixture was allowed to react for 6 h. It was quenched by wet ether, followed by saturated NH_4Cl. The aqueous solution was extracted three times with ether. The ether layers were combined and dried over anhydrous $MgSO_4$, filtered and evaporated *in vacuo*. The products were isolated by silica gel chromatography eluted with methylene chloride/hexane (v/v = 1/1). The *syn*-hydroxide **3d**-*S* was isolated in 25% yield (2.0 g), whereas the anti-hydroxide **3d**-*A* in 56% (4.5 g). Physical data of **3d**-*S*: mp 153-155 °C; ^{1}H NMR (90 MHz, $CDCl_3$) δ 6.15 (2H, t, J = 2 Hz, olefinic), 4.25 (1H, d, J = 8 Hz, changed to a singlet when treated with D_2O) 3.85 (1H, m), 3.40 (2H, m), 3.00 (2H, m), 2.65 (1H, d, J = 8 Hz, -OH). Physical data of **3d**-*A*: mp 137-141 °C (crude); ^{1}H NMR (90 MHz, CCl_4) δ 6.18 (2H, t, J = 2 Hz, olefinic), 3.90 (1H, m) 3.75 (1H, s), 3.65

(2H, m), 3.30 (1H, br, -OH), 2.85 (2H, m).

1,2,3,4,5,6,7,8,13-Nonachloro-1,4,4a,5,8,8a,9,9a,10,10a-decahydro-11-hydroxy-12,12-dimethoxy-*endo,endo,exo,endo*-1,4;5,8;9,10-trimethanoanthracene (4a-*A* and 4a-*S*)

A mixture of **3d**-*S* (500 mg, 1.44 mmol) and DTCP (950 mg, 3.60 mmol) was refluxed in xylene for 5 d, after which the solvent was distilled off at reduced pressure and the residue was applied onto a silica gel using hexane/ether (v/v = 1/1) as eluent. The solids of **4a**-*S* were recrystallized from hexane to give 420 mg (48% yield) colorless crystals: mp 237-238 °C. ^{1}H NMR (90 MHz, $CDCl_3$) δ 4.50 (1H, m) 3.83 (1H, d, J = 4Hz), 3.70 (2H, m), 3.45 & 3.55 (3H each, s, $-OCH_3$), 3.20 (1H, d, J = 4Hz, -OH), 2.75 (2H, s), 2.60 (2H, m).

The solution of **3d**-*A* (1.40 g, 4.0 mmol) and DTCP (4.5 g, 17 mmol) in xylene was heated to reflux and worked up by a similar procedure. The colorless crystals of **4a**-*A* (1.0 g, 40%) were recrystallized from hexane/methylene chloride with mp 237-240 °C. ^{1}H NMR (90 MHz, $CDCl_3$) δ 4.50 (1H, m), 3.85 (1H, s), 3.70 (2H, m), 3.50 & 3.60 (3H each, s, $-OCH_3$), 3.30 (1H, br, -OH), 2.80 (2H, s), 2.60 (2H, m). Anal. Calcd for $C_{19}Cl_9H_{15}O_3$: C, 37.39; H, 2.48%. Found: C, 37.23; H, 2.73%.

1,2,3,4,5,6,7,8,13-Nonachloro-1,4,4a,5,8,8a,9,9a,10,10a-decahydro-11-hydroxy-12-oxo-*endo,endo,exo,endo*-1,4;5,8;9,10-trimethanoanthracene (4b-*A* and 4b-*S*)

The ketal **4a**-*S* (130 mg, 0.21 mmol) was dissolved in CH_2Cl_2 (10 mL) and treated with 98% sulfuric acid (1 mL). The two-phase mixture was stirred **6d** at room temperature and quenched by pouring onto crushed ice. It was worked up by standard procedures. The colorless solid of **4b**-*S* was recrystallized from chloroform (110 mg, 90%): mp 130-133 °C (decomp.); IR ($CDCl_3$) ν 3400, 1840, 1820, 1600 cm^{-1}; ^{1}H NMR (90 MHz, $CDCl_3$) δ 4.65 (1H, m), 4.45 (1H, s), 4.00 (1H, br, -OH), 3.55 (2H, m), 3.05 (2H, m), 2.90 (2H, s).

The ketal **4a**-*A* was hydrolyzed to **4b**-*A* following the same procedure as described above. Partial decarbonylation happened during the course of hydrolysis. The crude product of **4b**-*A* was not further purified but immediately used in the next reaction.

1,2,3,4,5,6,7,8,12-Nonachloro-1,2,3,4,4a,9,9a,10-octahydro-11-hydroxy-*endo,endo*-1,4;9,10-dimethanoanthracene (5a-*A* and 5a-*S*)

The ketone **4b**-*S* (280 mg, 0.50 mmol) was refluxed 4 h in toluene (30 mL). After evaporation of solvent the colorless solid was recrystallized from acetone to give **5a**-*S* (250 mg, 94%). It showed low solubilities in both CH_2Cl_2 and $CHCl_3$: mp 320-322 °C (decomp.). ^{1}H NMR (90 MHz, acetone-d_6) δ 4.55 (1H, m), 4.20 (1H, m), 3.85 (2H, m), 3.50 (4H, two peaks, s & m), 3.00 (1H, br, -OH). Anal. Calcd for $C_{16}Cl_9H_9O$: C, 35.80; H, 1.69%. Found: C, 35.83; H, 1.81%.

The crude product of **4b**-*A* collected from hydrolysis was heated in toluene under similar condition. Colorless crystals of **5a**-*A* were recrystallized from chloroform (520 mg, 85% from **4a**-*A*): mp 308-310 °C. ^{1}H NMR (90 MHz, acetone-d_6) δ 6.15 (1H, br, -OH), 4.70 (1H, br, sharpened on D_2O treatment), 4.30 (1H, m), 4.25 (2H, m), 4.00 (2H, m), 3.80 (2H, s).

1,2,3,4,5,6,7,8,12-Nonachloro-1,2,3,4,4a,9,9a,10-octahydro-11-tetrahydropyranyloxy-*endo,endo*-1,4;9,10-dimethanoanthracene (5b-*A* and 5b-*S*)

The ketal **5a**-*S* (100 mg, 0.186 mmol) was dissolved in freshly distilled CH_2Cl_2 (10 mL) and to this solution was added dihydropyran (17 mg, 0.20 mmol) and a crystal of toluenesulfonic acid (3.0 mg, 0.017 mmol). The solution, which turned from red to dark blue after stirring at room temperature overnight, was quenched by the addition of water, then worked up according to standard procedures. The nonpolar compound **5b**-*S* was isolated from silica gel chromatography using hexane/methylene chloride (v/v = 2/1) as eluent, and was recrystallized from hexane to yield 100 mg (87%): mp 280-281 °C. ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.30 (1H, m), 4.30 (1H, m), 4.00 (3H, br), 3.75 (4H, m), 3.65 (2H, m), 1.50-1.80 (6H, br). Anal. Calcd for $C_{21}Cl_9H_{17}O_2$: C, 40.60; H, 2.76%. Found: C, 40.46; H, 3.00%.

The alcohol **5a**-*A* (460 mg, 0.86 mmol) was stirred with dihydropyran (90 mg, 1.07 mmol) in methylene chloride in the presence of toluenesulfonic acid hydrate (5.0 mg, 0.03 mmol) at room temperature overnight to yield **5b**-*A* (440 mg, 83%) as colorless crystal which was recrystallized from hexane. The crystal appeared to change shape at 214-215 °C and melted with decomposition at 304-305 °C to become dark residue. ^{1}H NMR (90 MHz, CCl_4) δ 5.30 (1H, m), 4.80 (1H, s), 4.15 (3H, m), 3.90 (4H, m), 3.70 (2H, s), 1.60-1.90 (6H, br).

1,4,4a,9,9a,10-Hexahydro-11-hydroxy-*endo,endo*-1,4;9,10-dimethanoanthracene (6a-*A* and 6a-*S*)

The tetrahydropyranyl ether **6b**-*S* (30 mg, 0.097 mmol) was dissolved in THF (10 mL) which was saturated with 2% HCl. The solution was stirred at room temperature for 15 hours, added to saturated brine (50 mL), and extracted three times with ether. The ether layers were combined, washed once with saturated $NaHCO_3$, once with satu-

rated brine, dried over anhydrous $MgSO_4$, filtered and evaporated *in vacuo*. The crude product was allowed to pass through a silica gel column using methylene chloride as eluent. Compound **6a-*S*** was recrystallized to give 17 mg (78%): mp 95-96 °C; ^{1}H NMR (90 MHz, $CDCl_3$) δ 6.9-7.2 (4H, m), 4.75 (2H, m, vinyl), 3.75 (1H, m), 3.20 (2H, m), 2.80 (2H, m), 2.60 (2H, m), 2.40 (1H, m), 1.70 (2H, m).

The other isomer **6b-*A*** (120 mg, 0.39 mmol) was hydrolyzed in a similar manner to give **6a-*A*** (70 mg, 80%): mp 126-128 °C; ^{1}H NMR (90 MHz, $CDCl_3$) δ 7.05 (4H, m), 4.65 (2H, t, J = 2Hz, vinyl), 3.50 (1H, m), 3.20 (4H, m), 2.60 (1H, m), 2.35 (2H, m), 2.00 (2H, m). Anal. Calcd for $C_{16}H_{16}O$: C, 85.68; H, 7.19%. Found: C, 85.44; H, 7.08%.

1,4,4a,9,9a,10-Hexahydro-11-tetrahydropyranyloxy-*endo,endo*-1,4;9,10-dimethanoanthracene (6b-*A* and 6b-*S*)

To a solition of the polychloride **5b-*S*** (20 mg, 0.032 mmol) in anhydrous THF (50 mL) was added freshly chopped sodium metal (46 mg, 2.0 mmol) and dry *tert*-butanol (96 mg, 1.3 mmol). The solution was stirred and heated to reflux for 20 hours while the color became purplish. The excess metal was destroyed by slow addition of 95% ethanol, and the mixture was quenched with brine. Products were extracted four times with ether, and the combined etheral solution was washed twice with brine, dried over anhydrous $MgSO_4$, and evaporated *in vacuo*. Compound **6b-*S*** was recrystallized from hexane/ether to yield 8.0 mg (83%): mp 125-126 °C. ^{1}H NMR (90 MHz, $CDCl_3$) δ 7.00-7.25 (4H, m), 4.72 (2H, m, vinyl), 4.50 (1H, m), 3.85 (1H, m), 3.30-3.85 (2H, m), 3.20 (2H, m), 2.80 (4H, m), 1.75 (2H, m) 1.40-1.60 (6H, m). Anal. Calcd for $C_{21}H_{24}O_2$: C, 81.80; H, 7.84%. Found: C, 82.01; H, 7.73%.

The other isomer **5b-*A*** (400 mg, 0.64 mmol) was dissolved in THF along with tert-butanol (1.9 g, 26 mmol) and treated with finely chopped sodium (0.90 g, 39 mmol). It was heated to reflux overnight and worked up as described above. Product **6b-*A*** was obtained as pale yellow oil (150 mg, 76%) by silica gel chromotography using methylene chloride/hexane (1/4) as eluent. ^{1}H NMR (90 MHz, $CDCl_3$) δ 7.05 (4H, m), 4.60 (2H, t, J = 3Hz, vinyl), 4.55 (1H, m), 3.35-3.85 (2H, m), 3.30 (1H, m), 3.10 (4H, m), 2.40 (2H, m), 2.00 (2H, m), 1.40-1.60 (6H, m).

11-(3,5-Dinitrobenzoyloxy)-1,4,4a,9,9a,10-hexahydro-*endo,endo*-1,4;9,10-dimethanoanthracene (6c-*A* and 6c-*S*)

Freshly recrystallized 3,5-dinitrobenzoyl chloride (28 mg, 0.12 mmol) was added to the alcohol **6a-*S*** (17 mg, 0.076 mmol) and the mixture was heated in a small vial at 60 °C for one minute to dissolve all the solids. It was cooled to 0 °C and stored for 3 d while needle-like crystals (pyridium salt) appeared. The reaction was quenched by adding distilled water, extracted three times with ether. The combined ether layer was washed twice with saturated brine, dried over anhydrous K_2CO_3, filtered and evaporated *in vacuo*. The crude products were recrystllized twice from ether to give **6c-*S*** (23 mg, 72%) as pale greenish needles: mp 222-223 °C (decomp.). ^{1}H NMR (90 MHz, $CDCl_3$) δ 9.50 (1H, t, J = 2 Hz), 9.30 (2H, d, J = 2Hz), 7.30 (4H, m), 5.05 (1H, m), 4.95 (2H, m), 3.40 (2H, m), 3.10 (4H, m), 1.95 (2H, m).

The isomer **6c-*A*** (40 mg, 73% yield) was prepared in a similar way from **6a-*A*** (30 mg, 0.13 mmol) and 3,5-dinitrobenzoyl chloride (45 mg, 0.20 mmol) in pyridine. It was recrystallized to form yellow-greenish needles: mp 173-175 °C. ^{1}H NMR (90 MHz, $CDCl_3$) δ 9.10-9.30 (3H, m), 7.50 (4H, br), 4.75 (2H, t, J = 3 Hz, olefinic), 4.45 (1H, m), 3.15 (4H, m), 2.70 (2H, m), 1.95 (2H, m). Anal. Calcd for $C_{23}H_{18}N_2O_6$: C, 66.03; H, 4.34%. Found: C, 66.30; H, 4.16%.

1,4,4a,9,9a,10-Hexahydro-11-(4-methylphenylsulfonyl)-*endo,endo*-1,4;9,10-dimethanoanthracene (6d-*S*)

Tosylate **6d-*S*** from **6a-*S*** was prepared accordingly by a similar procedure. Data for **6d-*S***: mp 238-240 °C. ^{1}H NMR (90 MHz, $CDCl_3$) δ 7.50 (2H, d, J = 9 Hz), 7.90 (2H, d, J = 9 Hz), 7.05-7.30 (4H, m), 4.65 (2H, m), 4.50 (1H, m), 3.30 (2H, m), 2.85 (4H, m), 2.50 (3H, s), 1.80 (2H, m).

1,4,4a,9,9a,10-Hexahydro-11-oxo-*endo,endo*-1,4;9,10-dimethanoanthracene (6e)

A chromium trioxide-dipyridine reagent was prepared by stirring a solution of CrO_3 (154 mg, 1.54 mmol) and pyridine (240 mg, 30 mmol) in 4 mL CH_2Cl_2 for 15 min. The alcohol **6a-*S*** (40 mg, 0.18 mmol) was dissolved in 1.0 mL CH_2Cl_2 and dropped gradually into the reagent solution at 0 °C. The course of the reaction was monitored by TLC. When all the starting material was consumed, the reaction was quenched by adding distilled water and the products were extracted three times with ether. The combined ether was washed with 5% HCl, twice with saturated $NaHCO_3$, once with saturated brine, then dried and evaporated *in vacuo*. Quantitative NMR analysis on the crude product (multiplet at δ 5.10 in CCl_4 for the olefinic hydrogens) indicated the presence of **6e** in 10% yield. The crude product was directly subjected to reduction with $LiAlH_4$ in anhydrous ether at 0 °C to give alcohol **6a-*A*** (4 mg, 10% yield from **6a-*S***) which was isolated from a silica gel chromatography using methylene chloride as eluent. The spectroscopic features of the product are identical to those of an

authentic sample.

13-*tert*-Butoxy-1,2,3,4,5,6,7,8,11,11-decachloro-1,4,4a,5,8,8a,9,9a,10,10a-decahydro-12,12-dimethoxy-*endo,endo,exo,endo*-1,4;5,8;9,10-trimethanoanthracene (8a)

Diene **7**[8a] (530 mg, 1.2 mmol) and DTCP (950 mg, 3.60 mmol) was heated in mesitylene at 160 °C for 4 d. Mesitylene and excess ketal were distilled off at reduced pressure and the residue was allowed to pass through a silica gel column using hexane/methylene chloride (v/v = 1/1) as eluent. The solid of **8a** was recrystallized from hexane to yield 550 mg (65% yield) crystals: mp 208-210 °C. ^{1}H NMR (90 MHz, $CDCl_3$) δ 4.50 (1H, m) 3.60 (3H, s, -OCH_3), 3.50 (3H, s, -OCH_3), 3.55 (2H, m), 2.65 (2H, s), 2.45 (2H, m), 1.15 (9H, s). Anal. Calcd for $C_{23}Cl_{10}H_{22}O_3$: C, 39.4, H, 3.16%. Found: C, 39.23, H, 3.28%.

1,2,3,4,5,6,7,8,11,11-Decachloro-1,4,4a,5,8,8a,9,9a,10,10a-decahydro-13-hydroxy-*endo,endo,exo,endo*-1,4;5,8;9,10-trimethanoanthracene derivatives, 8b (12,12-dimethoxy-) and 8c (12-oxo-)

To the ketal **8a** (465 mg, 0.66 mmol) in THF (20 mL) was added 90% sulfuric acid (5 mL), heated to reflux for 5 h and quenched by diluting with cold distilled water. The aqueous solution was extracted three times with ether. The ether layers were combined and washed with saturated $NaHCO_3$ and brine, dried and evaporated *in vacuo*. The crude product **8b** (370 mg, 87%) was not further purified. ^{1}H NMR (90 MHz, $CDCl_3$) δ 4.50 (1H, m), 3.45 (3H, s, -OCH_3), 3.60 (3H, s, -OCH_3), 3.60 (2H, m), 2.65 (2H, s), 2.50 (2H, m).

Ketal **8b** (370 mg, 0.57 mmol) was hydrolyzed to ketone **8c** (200 mg, 59%) following the same procedure as in the hydrolysis of **4a**-*S*. The oil collected was not further purified. IR (CCl_4) m 3400 (br), 1840, 1600 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 6.10 (1H, br, -OH), 4.60 (1H, m, -CHOH), 3.70 (2H, m), 2.75 (2H, m), 2.60 (2H, s).

1,2,3,4,5,6,7,8,11,11-Decachloro-1,2,3,4,4a,9,9a,10-octahydro-12-hydroxy-*endo,endo*-1,4;9,10-dimethanoanthracene (9a)

The oil of **8c** (200 mg, 0.33 mmol) was dissolved in toluene (100 mL) and heated to reflux for 5 h. The solvent was evaporated and solid was washed with chloroform and recrystallized from acetone to give pure **9a** (150 mg, 80%): mp 305-307 °C (decomp.). ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.10 (1H, s, -OH), 4.15 (1H, m), 4.05 (2H, m), 3.95 (2H, s), 3.90 (2H, m). Anal. Calcd for $C_{16}Cl_{10}H_8O$: C, 33.70; H, 1.41%. Found: C, 33.83; H, 1.68%.

1,2,3,4,5,6,7,8,11,11-Decachloro-1,2,3,4,4a,9,9a,10-octahydro-12-tetrahydropyranyloxy-*endo,endo*-1,4;9,10-dimethanoanthracene (9b)

The alcohol **9a** (70 mg, 0.12 mmol) was dissolved in CH_2Cl_2 (5 mL) and to this solution was added dihydropyran (20 mg, 0.23 mmol) and toluenesulfonic acid (3.0 mg, 0.017 mmol). The solution was stirred at room temperature for 5 h and worked up as previously described for the preparation of **5b**. Compound **9b** was isolated from silica gel chromatography using hexane as eluent, recrystallized from hexane to yield colorless crystals (65 mg, 83%): mp 224-225 °C (decomp.). ^{1}H NMR (90 MHz, $CDCl_3$) δ 4.80 (1H, m), 4.00 (4H, m), 3.90 (2H, s), 3.60-4.10 (3H, m), 1.50-1.90 (6H, m). Anal. Calcd for $C_{21}Cl_{10}H_{16}O_2$: C, 38.50; H, 2.46%. Found: C, 38.50; H, 2.69%.

1,4,4a,9,9a,10-Hexahydro-12-hydroxy-*endo,endo*-1,4;9,10-dimethanoanthracene (10a)

The tetrahydropyranyl ether **10b** was hydrolyzed according to the procedure previously used for **6a**-*S*. The alcohol **10a** could not be purified by either column chromatography or preparative GLC due to the presence of a major side product alcohol of similar polarity. A practical way for collecting pure **10a** was via its brosylate derivative **10c** which was rehydrolyzed on mild heating (55 °C, 10 h) in THF/H_2O (80/20). The brosylate derivative of the side product was stable under such condition and can be easily separated from **10a** by column chromatography. The alcohol **10a** thus purified was sublimed at room temperature under reduced pressure to yield small needles: mp 121 °C (crystals crash at 112-113 °C). ^{1}H NMR (90 MHz, CCl_4) δ 7.00-7.20 (4H, m), 4.80 (2H, m, vinyl), 3.90 (1H, m), 3.20 (2H, m), 3.00 (2H, m), 2.60 (2H, m), 2.30 (1H, br, -OH), 1.50-1.70 (2H, m).

Brosylate **10c** was prepared in a similar manner as that for **6c**-*S*. The compound is very sensitive to silica gel at room temperature and loses its brosyl group readily even in the absence of water. ^{1}H NMR (90 MHz, CCl_4) δ 7.80-8.10 (4H, m, -OBs), 6.90-7.20 (4H, m, benzo), 4.75 (2H, m, vinyl), 4.30 (1H, m), 3.30 (4H, m), 2.70 (2H, m), 1.50-1.70 (2H, m).

1,4,4a,9,9a,10-Hexahydro-12-tetrahydropyranyloxy-*endo,endo*-1,4;9,10-dimethanoanthracene (10b)

The pentachloride **9b** (65 mg, 0.10 mmol) was dissolved in anhydrous THF (30 mL) and treated with freshly chopped sodium metal (120 mg, 5.2 mmol) and dry tert-butanol (300 mg, 4.0 mmol). The solution was heated to reflux for 18 hours until the excess sodium chips clumped together. A purplish precipitate accumulated after a few hours. The

reaction was quenched by the addition of 95% ethanol until metal was consumed completely. Compound **10b** was isolated as a colorless oil (16 mg, 52%). ^{1}H NMR (90 MHz, CCl_4) δ 7.0-7.2 (4H, m), 4.80 (2H, m, vinyl), 4.75 (1H, m), 3.80 (1H, m), 3.30-3.70 (2H, m), 3.15 (4H, m), 2.55 (2H, m), 1.40-1.80 (8H, m).

12-(3,5-Dinitrobenzoyloxy)-1,4,4a,9,9a,10-Hexahydro-*endo,endo*-1,4;9,10-dimethanoanthracene (10d)

The 3,5-dinitrobenzoate **10d** was prepared following a similar procedure as that for **6c-*S***. ^{1}H NMR (90 MHz, $CDCl_3$) δ 9.45 (1H, t, J = 2 Hz), 9.25 (1H, d, J = 2 Hz), 7.15-7.25 (4H, m, benzo), 5.00 (1H, m), 4.85 (2H, m, vinyl), 3.35 (2H, m), 3.10 (4H, m), 2.85 (2H, m).

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Laticyclic topology; Isodrin; Dyatropic hydrogen migration; 7-Substituted norbornadiene; Hexachlorocyclopentadiene; Cycloaddition; Decarbonylation.

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