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Synthesis and characterization of tetramethylene-*syn*-sesterbicyclo[2.2.2]octene☆

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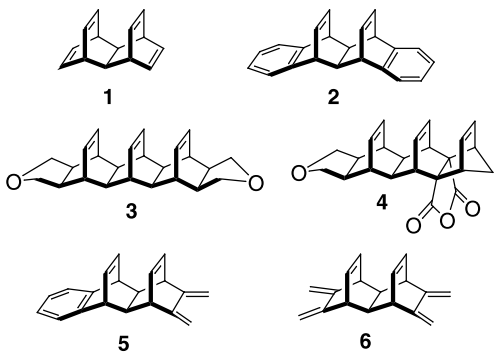
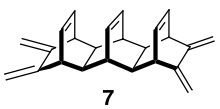
Abstract—The synthesis of *syn*-sesterbicyclo[2.2.2]octene (**7**) bilaterally grafted by an exocyclic *s-cis*-butadiene moiety is achieved from 1,8,9,10-tetrachloro-11,11-dimethoxy-*endo*-tricyclo[6.2.1.0^{2,7}]undeca-3,5,9-triene (**8**) employing repetitive Diels–Alder cycloadditions between 1,3-cyclohexadiene, generated from *p*-benzoquinone, and diethyl fumarate or maleic anhydride as the exocyclic butadienyl equivalent, followed by subsequent transformation to the conjugated diene moieties. In comparison with the corresponding sesquibicyclo[2.2.2]octene **6**, the ^{1}H NMR demonstrates the anisotropic shielding effect operating within the three parallel laticyclic double bonds. However, the UV absorption of **7** shows less effect by the increase of laticyclic conjugated ethylene units.

We have previously described the synthesis of sesqui- and sesterbicyclo[2.2.2] octene derivatives **1**–**4**[2] that are composed of bicyclo[2.2.2]octene units having all the bridged double bonds positioned on the same face in close proximity[3] and reported the results of transannular photocyclizations and brominations between the double bonds in these systems. Molecular modeling shows that these systems have carbon framework of curved topology as polynorboranes[4] and hetero-bridged [*n*]polynorbornanes.[5] The trajectory surface of bridges is suitable for the study of laticyclic orbital interactions.[6] Such compounds can also be utilized as the molecular spacer or intercalator in the donor–bridge–acceptor systems for the studies of electron transfer or energy transfer.[7] Carbocyclic molecules grafted by the exocyclic *s-cis*-butadiene units can be used as ligands for the preparation of metal complexes[8] and as building blocks for the construction of bridged polycyclic systems via Diels–Alder cycloaddition with dienophiles.[9] Along this line, we have also synthesized *syn*-sesquibicyclo-[2.2.2]octenes that are attached with one or bilaterally two exocyclic *s-cis*-butadiene units, such as **5**[2b] and **6**,[10] and shown that they reacted well with dienophiles resulting in the formation of corresponding cycloadducts in good yields.[11]

In this paper, we report our extended works on the synthesis and characterization of 17,18,19,20-tetramethylenehexacyclo[6.6.2.2^{3,6}.2^{10,13}.0^{2,7}.0^{9,14}]eicosa-4,11,15-triene (**7**), a



system related to **1**–**6**, in which the *syn*-sesterbicyclo-[2.2.2]octene ring skeleton is grafted on both sides by an exocyclic *s-cis*-butadiene unit. This polycyclic polyene is a new $C_{24}H_{24}$ hexacyclic hydrocarbon that contains two exocyclic *s-cis*-butadiene moieties spatially separated by three parallel double bonds in a rigid C_{2v}-symmetric carbon framework. The synthesis of **7** was accomplished by employing the methodology of repetitive Diels–Alder cycloaddition of the 1,3-cyclohexadiene moiety in polycyclic polyene, generated from *p*-benzoquinone, with an exocyclic butadienyl synthon, such as diethyl fumarate and maleic anhydride.



1. Results and discussion

Our synthetic approach toward the title compound **7**

☆ See Ref. 1.

Keywords: Diels–Alder reaction; bicyclo[2.2.2]octene; exocyclic *s-cis*-butadiene; polycyclic polyene.

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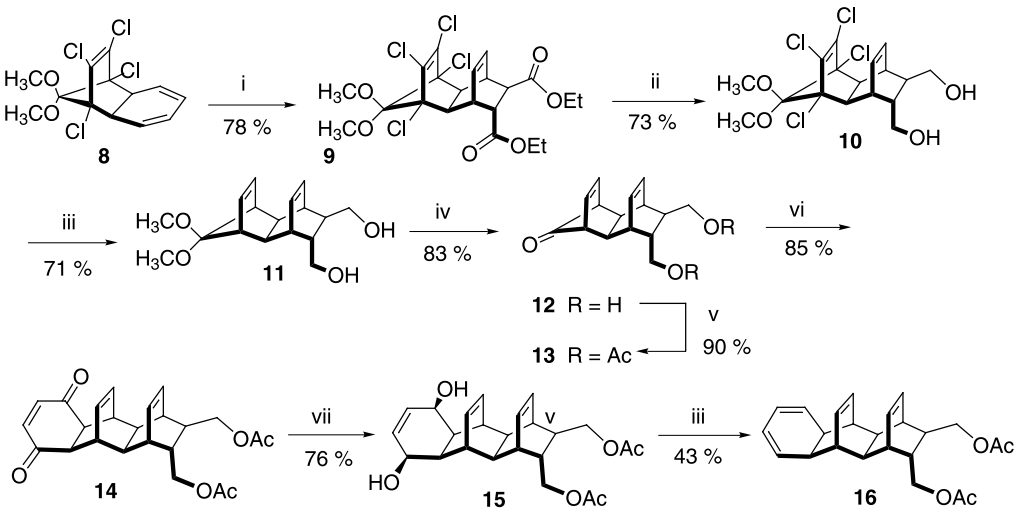
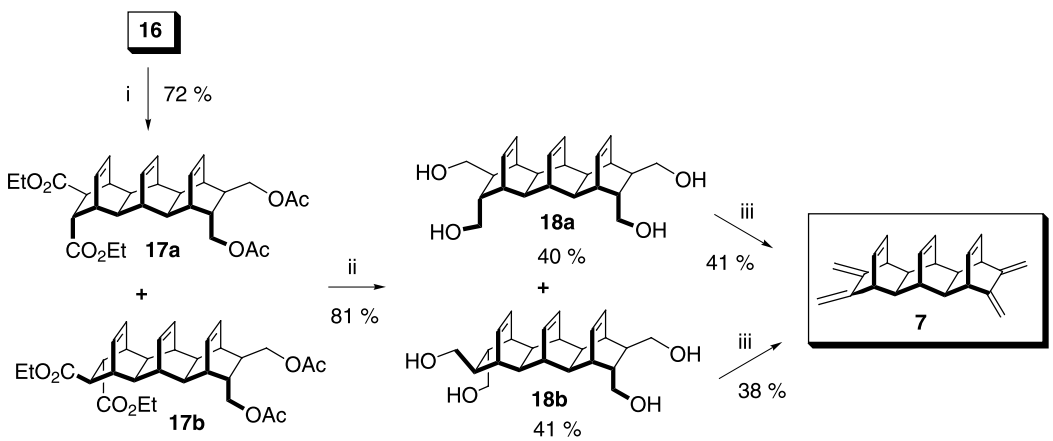
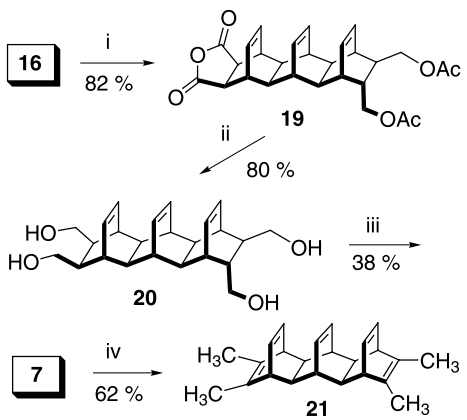


Scheme 1. *Reagents and conditions*: (i) diethyl fumarate, 80°C, 12 h; (ii) $LiAH_4$, THF, room temperature, 1 h then reflux, 1 h; (iii) Na, *t*-BuOH, THF, reflux, 48 h; (iv) 20% H_2SO_4, CH_2Cl_2, 0°C, 6 h; (v) Ac_2O, Et_3N, room temperature, 18 h; (vi) *p*-benzoquinone, tolune, 100°C, 18 h; (vii) $NaBH_4$, $CeCl_3{\cdot}7H_2O$, MeOH, 0°C, 1 h; (viii) (1) MsCl, Et_3N, CH_2Cl_2, −40°C, 1 h, (2) NaI, acetone, 50°C, 24 h.

basically adopted the strategy that was employed to synthesize tetrahydrofuran-grafted *syn*-sesterbicyclo-[2.2.2]octene systems,[2c,11] starting from readily available 1,8,9,10-tetrachloro-11,11-dimethoxy-*endo*-tricyclo[6.2.1.$0^{2,7}$]undeca-3,5,9-triene (**8**).[12] In the endeavor, *p*-benzoquinone was introduced to serve as a synthon of 1,3-cyclohexadiene moiety by the Diels–Alder cycloaddition, setting up for the construction of bicyclo[2.2.2]-octene skeleton by another Diels–Alder cycloaddition with dienophiles that might serve as the synthon of exocyclic *s-cis*-butadiene unit. As illustrated in Scheme 1, the Diels–Alder cycloadduct **9** obtained from the reaction of **8** with diethyl fumarate was reduced by lithium aluminum hydride to give the corresponding diol **10** in 73% yield. A three-step process was then employed to unmask the fused 1,3-cyclohexadiene moiety in diol **10** for subsequent connecting another 1,4-cyclohexenedione moiety. Thus, the tetracyclic diol **10** was subjected to a reductive dechlorination with Na–Bu^{t}OH in THF, followed by hydrolysis of the ketal functionality in **11** with 20% sulfuric acid at 0°C to afford ketodiol **12** in 59% yield (two steps). Decarbonylation of **12** was brought about in refluxing toluene to deliver 1,3-cyclohexadiene moiety and in the presence of *p*-benzoquinone to produce the corresponding Diels–Alder cycloadduct. This cycloadduct was found to be poorly soluble in methanol, making the subsequent cerium chloride-mediated reduction of its enedione functional group with sodium borohydride very difficult. To avoid the solubility problem that impeded this reduction and possibly the reactions in the later stage, ketodiol **12** was converted to the corresponding bis-acetate **13** beforehand. Decarbonylation of **13** in toluene at 100°C in the presence of one equivalent of *p*-benzoquinone furnished enedione cycloadduct **14** in 85% yield after recrystallization from ether. In the structure of cycloadduct **14**, the *syn* orientation of two bridge double bonds is preserved and the newly introduced cyclohexenedione moiety is expected to have the *endo*-configuration, based on the nature of reaction course (*exo*-addition of *p*-benzoquinone to 1,3-cyclohexadiene moiety generated from **13**)[2,12] and the Alder rule of the Diels–Alder cycloaddition, and further supported by its ^{1}H NMR spectrum. The enedione **14** was now subjected to the reduction with sodium borohydride/cerium chloride in methanol, thereby affording the enediol **15** in 76% yield.



Scheme 2. *Reagents and conditions*: (i) diethyl fumarate, 100°C, 12 h; (ii) $LiAlH_4$, THF, 0°C, 3 h then 50°C, 1 h; (iii) (1) TsCl, pyridine, 0°C, 4 h then 25°C, 6 h, (2) *t*-BuOK, DMSO, 50°C, 18 h.



Scheme 3. *Reagents and conditions*: (i) maleic anhydride, benzene, 80°C, 12 h; (ii) $LiAlH_4$, THF, 0°C, 3 h then 50°C, 1 h; (iii) (1) TsCl, pyridine, 0°C, 4 h then 25°C, 6 h, (2) *t*-BuOK, DMSO, 50°C, 18 h; (iv) Na, $NH_{3(l)}$, *t*-BuOH, THF, −30°C.

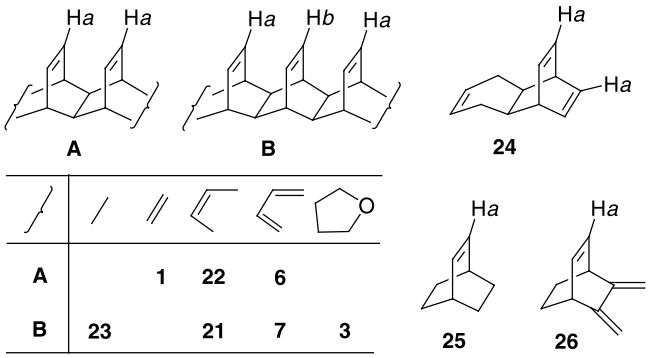
Conversion of enediol **15** to the cyclohexadiene-containing bis-acetate **16** was carried out by bis-mesylation and subsequent iodide-promoted 1,4-elimination reaction. In the bis-mesylation of enediol **15**, it was required that reaction temperature be kept at −40°C in order to avoid the formation of benzene ring via 1,2-elimination.

With cyclohexadiene-fused *syn*-sesquibicyclo[2.2.2]octene **16** in hand, it came to introduce a synthon of exocyclic *s-cis*-butadiene unit. Heating a solution of **16** in toluene at 100°C with diethyl fumarate resulted in the formation of a 1:1 mixture of cycloadduct **17a** and its diastereomer **17b** (Scheme 2). Several attempts to separate this mixture by column chromatography and crystallization were unsuccessful. However, we were able to separate the tetraols **18a** and **18b** by silica gel chromatography, which were obtained from the reduction of the mixture of **17a** and **17b** with lithium aluminum hydride in THF at 0°C. Following the standard procedure,[10,11] the 1,4-hydroxyl functionality of **18a** and **18b** was converted to the corresponding 1,3-butadiene by treatment with *p*-toluenesulfonyl chloride in dry pyridine, followed by subsequent 1,2-elimination in the presence of potassium *t*-butoxide, thereby furnishing the title heptaene **7** in a yield of 41%.

An alternative route to the title heptaene **7** from **16** was by the utility of maleic anhydride as the synthon of exocyclic *s-cis*-butadiene unit (Scheme 3). Thus, the cycloadduct **19** obtained in 80% yield from the Diels–Alder reaction of cyclohexadiene **16** and maleic anhydride was transformed by the similar reaction sequence (reduction, mesylation and elimination) to afford the title heptaene **7** in satisfactory yield.

The bilaterally exocyclic butadiene-fused hexacyclic heptaene **7** was characterized by analysis and comparison of its spectroscopic data with compounds of similar frameworks previously prepared in this laboratory. The presence of exocyclic butadiene units was further indicated by the transformation of **7** to the corresponding tetramethyl derivative **21** by Birch reduction (Scheme 2). Seven types of hydrogen absorptions in the ^1H NMR spectrum and the seven lines in the ^{13}C NMR spectrum apparently confirmed the C_{2v}-symmetry of heptaene **7**. The absorption signals for the vinyl hydrogens on three etheno-bridges in heptaene **7** appear at δ 5.71, 5.33 and 5.71, indicating that they are on the mutually shielded double bonds and those on the central double bond are further shielded by two flanking double bonds. This anisotropic shielding effect is evidently demonstrated by the carbocyclic system composed of *syn*-fused bicyclo[2.2.2]octene units, in which double bonds are

Table 1. Vinylic hydrogen chemical shift values (δ) of *syn*-fused bicyclo[2.2.2]octenes



=CH	1[a]	3[b]	6[c]	7	21	22	23[d]	24[e]	25[f]	26[g]
H*a* (flanking)	5.93	5.65	5.84	5.71	5.79	5.90	5.62	6.36	6.25	6.17
H*b* (central)		5.28		5.33	5.14		5.24			
$(CH_2{=}C)_2$ or	6.46		5.12	5.06						
=CH			4.78	4.70						

Chemical shift in ppm downfield from Me_4Si was measured (300 MHz) in $CDCl_3$ at ambient temperature (25±2°C).
[a] Taken from Ref. 2a.
[b] Taken from Ref. 2c.
[c] Taken from Ref. 9.
[d] Taken from Ref. 3b.
[e] Taken from Ref. 3a.
[f] Taken from Ref. 13.
[g] Taken from Ref. 14.

positioned face-to-face in close proximity with laticyclic topology. Examples of the absorption signals for the vinyl hydrogens on etheno-bridges in this system are indicated in Table 1.

The heptaene **7** in cyclohexane exhibits UV absorption at λ_{max}=246 nm (log ε=4.39) with a second band at λ_{max}=208 nm (log ε=4.15), and is similar to that of hexaene **6** [λ_{max}=243 nm (log ε=4.41); λ_{max}=212 nm (log ε=4.08)].[10] It seems that interaction between two exocyclic 1,3-butadiene chromophores is not very much effected by the increase of laticyclic conjugation through etheno-bridges.

In summary, we have achieved the synthesis of *syn*-sesterbicyclo[2.2.2]octene derivatives **7** and **21** by the approach of repetitive Diels–Alder cycloaddition from readily available starting material **8**, *p*-benzoquinone and diethyl fumarate or maleic anhydride. The stereoselective cycloaddition of *p*-benzoquinone from the *exo* face of a 1,3-cyclohexadiene moiety grafted onto bicyclo[2.2.2]-octene ring skeleton would become the general route applicable to the synthesis of laticyclic conjugated polyenes having *syn*-oriented etheno-bridges of higher order.

2. Experimental

2.1. General

Melting points were determined in open capillaries (Thomas Hoover) and were uncorrected. Analytical thin-layer chromatography (TLC) was performed on E. Merck silica gel 60 F_{254} plate (0.20 mm), and components were visualized by UV light or by iodine vapor or by heating the plates after treatment with a phosphomolybdic acid reagent (1:1 in ethanol). Flash chromatography was performed on E. Merck silica gel (230–400 mesh). ^{1}H NMR spectra were measured at 300 MHz and ^{13}C NMR at 75 MHz, respectively. Chemical shifts are referenced to TMS or to the residual H in perdeuterated solvents (7.26 ppm for $CDCl_3$). ^{13}C NMR multiplicities were determined using DEPT pulse sequences. MS spectra were determined at 70 eV in the EI mode unless otherwise stated. IR spectra in KBr were determined by FT-IR. Microanalyses were performed by Analytical Center of National Cheng Kung and Taiwan Universities, Taiwan.

2.1.1. Diethyl *trans*-(1α,2β,3α,6α,7β,8α,9α,10β)-3,4,5,6,-tetrachloro-13,13-dimethoxytetracyclo[6.2.2.1^{3,6}.0^{2,3}]trideca-4,11-diene-9,10-dicarboxylate (9). A solution of compound **8** (2.00 g, 5.85 mmol) and diethyl furmarate (1.00 g, 5.81 mmol) in a 10-mL round-bottom flask was heated at 80°C for 12 h. The residue was purified by flash column chromatography (SiO_2, hexane) to give **9** (2.34 g, 78% yield) as a white solid: mp 83–84°C (ether); R_f 0.28 (1:9 EtOAc/hexane); IR (KBr) 2982, 1729, 1291, 1191, 1032 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.23 (t, 3H, J=6.9 Hz), 1.30 (t, 3H, J=6.9 Hz), 2.62 (dd, 1H, J=1.5, 9.6 Hz), 2.82 (dd, 1H, J=2.4, 9.9 Hz), 2.89 (dd, 1H, J=2.1, 3.0 Hz), 3.13–3.19 (m, 2H), 3.24–3.27 (m, 1H), 3.48 (s, 3H), 3.55 (s, 3H), 4.07–4.36 (m, 4H), 5.95 (dd, 1H, J=6.3, 7.5 Hz), 6.09–6.14 (m, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 14.06 (q), 14.20 (q), 32.32 (d, two peaks), 46.21 (d), 46.57 (d), 46.93 (d), 49.59 (d), 51.45 (q), 52.59 (q), 61.04 (t), 61.06 (t), 77.07 (s), 77.21 (s), 113.69 (s), 127.34 (d), 127.63 (s), 128.00 (s), 129.33 (d), 172.52 (s), 172.64 (s); MS (EI, 70 eV) *m*/*z* (relative intensity) 514 (M^++2, 0.37), 512 (M^+, 0.28), 479 (21), 477 (22), 255 (96), 253 (100), 209 (10), 207 (11), 151 (23); HRMS *m*/*z* calcd for $C_{21}H_{24}O_6Cl_4$: 512.0329; obsd 512.0331. Anal. calcd for $C_{21}H_{24}O_6Cl_4$: C, 49.05; H, 4.70. Found: C, 49.15; H, 4.78.

2.1.2. *trans*-(1α,2β,3α,6α,7β,8α,11α,12β)-3,4,5,6,-Tetrachloro-11,12-bis(hydroxymethyl)-13,13-dimethoxytetracyclo[6.2.2.1^{3,6}.0^{2,3}]trideca-4,9-diene (10). To a suspension of lithium aluminum hydride (0.32 g, 8.43 mmol) in dry THF (10 mL) was added dropwise a solution of **9** (2.20 g, 4.28 mmol) in dry THF (10 mL) at 0°C under an atmosphere of nitrogen. The reaction mixture was stirred at room temperature for 1 h and then refluxed for another 1 h. After cooling, the reaction mixture was quenched with wet THF (0.3 mL, 50%), 15% NaOH (0.3 mL), and water (0.9 mL). The collected white solid from the quenched solution was dissolved in 10% HCl and extracted with CH_2Cl_2 (3×60 mL). The combined organic layers were washed with water (30 mL), saturated $NaHCO_3$ (30 mL) and brine (30 mL), and dried over $MgSO_4$. Concentration of the organic solution and purification of crude product by flash chromatography (SiO_2, gradient CH_2Cl_2/hexane) gave diol **10** (1.34 g, 73% yield) as a white solid: mp 172–173°C (CH_2Cl_2); R_f 0.35 (EtOAc); IR (KBr) 3366, 3293, 2951, 2877, 1606, 1461, 1190 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.29–1.37 (m, 1H), 1.52–1.59 (m, 1H), 2.69–2.74 (m, 4H), 3.13 (t, 1H, J=9.3 Hz), 3.20–3.40 (br, 2H), 3.48 (s, 3H), 3.49–3.56 (m, 1H), 3.57 (s, 3H), 3.66–3.69 (m, 2H), 5.88 (dd, 1H, J=7.2, 7.8 Hz), 6.12 (ddd, 1H, J=1.2, 7.2, 8.1 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 31.67 (d), 31.86 (d), 45.44 (d), 46.13 (d), 47.73 (d), 51.12 (d), 51.55 (q), 52.74 (q), 64.76 (t), 66.30 (t), 77.49 (s), 77.42 (s), 113.74 (s), 126.55 (d), 128.10 (s), 128.15 (s), 130.20 (d); MS (EI, 70 eV) *m*/*z* (relative intensity) 432 (M^++4, 0.16), 430 (M^++2, 0.3), 428 (M^+, 0.24), 397 (4.7), 395 (14), 393 (14), 255 (97), 253 (100), 209 (9), 207 (9); HRMS *m*/*z* calcd for $C_{17}H_{20}O_4Cl_4$: 428.0118; obsd 428.0119. Anal. calcd for $C_{17}H_{20}O_4Cl_4$: C, 47.46; H, 4.68. Found: C, 47.48; H, 4.75.

2.1.3. *trans*-(1α,2β,3α,6α,7β,8α,11α,12β)-11,12-Bis(hydroxymethyl)-13,13-dimethoxytetracyclo[6.2.2.1^{3,6}.0^{2,3}]-trideca-4,9-diene (11). To a solution of **10** (2.20 g, 5.11 mmol) and *tert*-butyl alcohol (6.81 g, 92.1 mmol) in dry THF (40 mL) was added sodium (5.29 g, 230 mmol) in small pieces over a period of 30 min under an atmosphere of nitrogen. The mixture was vigorously stirred under reflux for 48 h. The reaction mixture was cooled to room temperature, and filtered to remove unreacted sodium. The filtrate was then poured into ice–water (20 mL) and extracted with dichloromethane (3×50 mL). The combined extracts were washed with brine (30 mL), dried, and concentrated. The resulting residue was subjected to chromatography on silica gel (gradient elution with 0–20% CH_2Cl_2 in hexane) to afford diol **11** (1.06 g, 71%) as a white solid: mp 84–85°C (CH_2Cl_2/hexane); R_f 0.23 (CH_2Cl_2); IR (KBr) 3368, 2934, 1457, 1274, 1119, 710 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.20–1.24 (m, 1H), 1.58–1.62 (m, 1H), 2.42–2.56 (m, 4H), 2.75–2.82 (m, 4H), 3.06 (s, 3H), 3.10–3.14 (m, 1H), 3.21 (s, 3H), 3.49 (dd,

1H, *J*=5.1, 9.3 Hz), 3.74–3.79 (m, 2H), 5.50–5.54 (m, 3H), 5.73 (dd, 1H, *J*=6.9, 7.2 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 34.01 (d), 35.22 (d), 35.54 (d), 39.99 (d), 46.83 (d), 48.84 (d), 49.02 (d), 49.39 (d), 49.73 (q), 51.89 (q), 65.44 (t), 66.80 (t), 119.92 (s), 129.62 (d), 130.92 (d), 131.03 (d), 133.36 (d); MS (EI, 70 eV) *m/z* (relative intensity) 292 (M^+, 13), 261 (21), 152 (53), 151 (100), 121 (54), 91 (55); HRMS *m/z* calcd for $C_{17}H_{24}O_4$: 292.1675; obsd 292.1678. Anal. calcd for $C_{17}H_{24}O_4$: C, 69.83; H, 8.27. Found: C, 69.77; H, 8.17.

2.1.4. *trans*-(1α,2β,3α,6α,7β,8α,11α,12β)-11,12-Bis(hydroxymethyl)tetracyclo[6.2.2.1^{3,6}.0^{2,3}]trideca-4,9-diene-13-one (12). To a solution of **11** (2.05 g, 7.01 mmol) in CH_2Cl_2 (20 mL) was added 20% H_2SO_4 (12 mL) with ice-cooling. The mixture was stirred for 6 h and then diluted with cold water (12 mL). The organic phase was separated and the aqueous layer extracted with CH_2Cl_2 (3×20 mL). The combined organic fractions were washed with 10% HCl (10 mL), saturated $NaHCO_3$, (10 mL) and brine (10 mL), and dried over $MgSO_4$. Removal of the solvent with rotary evaporator and purification of the residue by chromatography on silica gel (gradient elution with 0–30% CH_2Cl_2 in hexane) afforded ketodiol **12** (1.44 g, 83%) as a colorless oil: R_f 0.11 (CH_2Cl_2); IR (KBr) 3368, 2924, 1769, 1033, 707 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.22–1.28 (m, 1H), 1.54–1.62 (m, 1H), 2.44–2.71 (m, 6H), 2.94–3.00 (m, 2H), 3.11 (d, 1H, *J*=9.0, 9.3 Hz), 3.44 (dd, 1H, *J*=5.7, 9.6 Hz), 3.71 (s, 1H), 3.74 (s, 1H), 5.62 (ddd, 1H, *J*=0.3, 7.5, 7.5 Hz), 5.78–5.83 (ddd, 1H, *J*=0.9, 7.5, 7.5 Hz), 5.92–5.94 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 31.84 (d), 34.73 (d), 34.96 (d), 37.45 (d), 46.42 (d), 48.48 (d), 51.54 (d), 51.82 (d), 65.02 (t), 66.27 (t), 128.57 (d), 128.89 (d), 130.42 (d), 133.89 (d), 199.99 (s); MS (EI, 70 eV) *m/z* (relative intensity) 246 (M^+, 0.6), 228 (1.0), 200 (3.2), 181 (0.6), 169 (3.1), 140 (8.4), 128 (14), 122 (9.0), 92 (100), 79 (90); HRMS *m/z* calcd for $C_{15}H_{18}O_3$: 246.1256; obsd 246.1260. Anal. calcd for $C_{15}H_{18}O_3$: C, 73.14; H, 7.36. Found: C, 72.93; H, 7.37.

2.1.5. *trans*-(1α,2β,3α,6α,7β,8α,11α,12β)-11,12-Bis(acetoxylmethyl)tetracyclo[6.2.2.1^{3,6}.0^{2,3}]trideca-4,9-diene-13-one (13). A mixture of **12** (1.50 g, 6.09 mmol), triethylamine (8 mL) and acetic anhydride (4 mL) was stirred at room temperature for 18 h and then quenched with ice–water (20 mL). The resulting mixture was extracted with CH_2Cl_2 (3×30 mL). The combined organic layers were washed with water (2×30 mL) and brine (30 mL), and dried over $MgSO_4$. After removal of the solvent, the residue was chromatographed on a column of silica gel, using hexane as eluent to obtain **13** (1.81 g, 90% yield) as a white solid: mp 103–105°C (CH_2Cl_2/hexane); R_f 0.26 (3:7 EtOAc/hexane); IR (KBr) 2988, 1770, 1734, 1259, 1042 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.15–1.23 (m, 1H), 1.51–1.58 (m, 1H), 2.04 (s, 3H), 2.07 (s, 3H), 2.42–2.48 (m, 1H), 2.60–2.70 (m, 3H), 2.96–3.02 (m, 2H), 3.65 (dd, 1H, *J*=9.0, 10.8 Hz), 3.72 (dd, 1H, *J*=6.3, 12.6 Hz), 4.10 (dd, 1H, *J*=9.3, 11.4 Hz), 4.23 (dd, 1H, *J*=6.3, 11.1 Hz), 5.65 (dd, 1H, *J*=7.2, 7.8 Hz), 5.83 (dd, 1H, *J*=6.9, 7.2 Hz), 5.94 (t, 2H, *J*=1.8 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.66 (q, two peaks), 30.96 (d), 33.18 (d), 34.01 (d), 36.93 (d), 41.76 (d), 42.95 (d), 51.21 (d), 51.59 (d), 64.41 (t), 66.16 (t), 128.42 (d), 128.74 (d), 130.24 (d), 133.78 (d), 170.65 (s), 170.71 (s), 199.14 (s); MS (FAB) *m/z* (relative intensity) 331 (M^++H, 15), 289 (7.7), 271 (9.9), 229 (28), 211 (23), 183 (27), 129 (29), 104 (100), 91 (48); HRMS *m/z* calcd for $C_{19}H_{23}O_5$: (MH^+): 331.1546; obsd 331.1540. Anal. calcd for $C_{19}H_{23}O_5$: C, 69.74; H, 6.71. Found: C, 69.82; H, 6.70.

2.1.6. *trans*-(1α,2β,7β,8α,9β,10α,13α,14β)-17,18-Bis(acetoxylmethyl)pentacyclo[6.6.2.2^{10,13}.0^{2,7}.0^{9,14}]octadeca-4,11,15-triene-3,6-dione (14). A solution of **13** (1.65 g, 4.99 mmol) and *p*-benzoquinone (0.54 g, 5.00 mmol) in toluene (8 mL) was sealed in a glass tube (2.0 cm OD×18 cm length) under vacuum. The mixture was heated at 100°C for 18 h. After removal of solvent, the resulting residue was recrystallized from ether to give **14** (1.74 g, 85%) as a yellowish solid: mp 92–93°C (ether); R_f 0.60 (1:1 EtOAc–hexane); IR (KBr): 2948, 1738, 1676, 1245, 1034 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.12–1.18 (m, 1H), 1.45–1.49 (m, 1H), 2.02 (s, 3H), 2.06 (s, 3H), 2.07–2.09 (m, 1H), 2.27–2.30 (m, 1H), 2.46–2.51 (m, 2H), 2.92–3.01 (m, 2H), 3.03–3.07 (m, 1H), 3.10–3.13 (m, 1H), 3.60 (dd, 1H, *J*=9.9, 10.2 Hz), 3.69 (dd, 1H, *J*=6.3, 10.8 Hz), 4.04 (dd, 1H, *J*=9.9, 11.1 Hz), 4.19 (dd, 1H, *J*=6.3, 11.1 Hz), 5.64 (t, 1H, *J*=7.2 Hz), 5.76 (t, 2H, *J*=3.9 Hz), 5.84 (t, 1H, *J*=7.8 Hz), 6.59 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.84 (q), 20.87 (q), 35.62 (d, two peaks), 36.64 (d), 40.28 (d), 40.56 (d), 41.10 (d), 42.48 (d), 42.94 (d), 50.58 (d), 50.72 (d), 64.83 (t), 66.69 (t), 130.02 (d), 132.10 (d), 132.37 (d), 133.67 (d), 142.17 (d), 142.27 (d), 170.95 (s), 171.06 (s), 198.59 (s), 198.71 (s); MS (EI, 70 eV) *m/z* (relative intensity) 410 (M^+, 6.2), 291 (26), 290 (100), 160 (16), 104 (29); HRMS *m/z* calcd for $C_{24}H_{26}O_6$: 410.1730; obsd 410.1732. Anal. calcd for $C_{24}H_{26}O_6$: C, 70.23; H, 6.38. Found: C, 70.21; H, 6.22.

2.1.7. *trans*-(1α,2β,7β,8α,9β,10α,13α,14β)-17,18-Bis(acetoxylmethyl)-3,6-dihydroxypentacyclo[6.6.2.2^{10,13}.0^{2,7}.0^{9,14}]-octadeca-4,11,15-triene (15). A solution of diacetate **14** (1.74 g, 4.24 mmol) and cerium(III) chloride heptahydrate (1.58 g, 4.24 mmol) in methanol (20 mL) was added sodium borohydride (0.16 g, 4.23 mmol) in portions over a period of 10 min at 0°C. The reaction mixture was stirred for 1 h at the same temperature and quenched by addition of ice–water. The aqueous layer was extracted with CH_2Cl_2 (3×60 mL). The CH_2Cl_2 layers were washed with 10% HCl (30 mL), saturated $NaHCO_3$ (30 mL) and brine (30 mL), and dried over $MgSO_4$. After removal of the solvent, the pure product **15** (1.34 g, 76% yield) was isolated by silica gel chromatography with gradient CH_2Cl_2/hexane as eluent. Recrystallization from ether gave white crystals: mp 167–168°C (CH_2Cl_2); R_f 0.18 (1:1 EtOAc/hexane); IR (KBr) 3349, 2895, 1739, 1374, 1243 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.09–1.15 (m, 1H), 1.43–1.49 (m, 1H), 1.95–1.99 (m, 1H), 2.03 (s, 3H), 2.04–2.05 (m, 2H), 2.06 (s, 3H), 2.16–2.20 (m, 1H), 2.43–2.49 (m, 5H), 2.55–2.56 (m, 1H), 3.61 (dd, 1H, *J*=9.0, 10.8 Hz), 3.71 (dd, 1H, *J*=5.4, 6.3 Hz), 4.02–4.18 (m, 4H), 5.69 (t, 1H, *J*=7.2 Hz), 5.84 (dd, 2H, *J*=3.6, 4.5 Hz), 5.89 (t, 1H, *J*=7.8 Hz), 6.34 (dd, 2H, *J*=2.7, 3.9 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.91 (q, two peaks), 36.09 (d), 37.04 (d), 37.51 (d), 38.93 (d), 39.26 (d), 41.44 (d), 43.31 (d), 44.47 (d), 47.28 (d), 47.40 (d), 65.22 (d, two peaks), 66.93 (t, two peaks), 130.05 (d), 131.12 (d), 131.19 (d), 133.85 (d), 136.29 (d), 136.33 (d), 171.04 (s), 171.15 (s); MS (EI, 70 eV) *m/z* (relative intensity) 414 (M^+, 80), 354 (7.4), 336 (6.9), 294 (40), 276

(21), 258 (18), 209 (18), 128 (40); HRMS *m/z* calcd for $C_{24}H_{30}O_6$: 414.2043; obsd 414.2051. Anal. calcd for $C_{24}H_{30}O_6$: C, 69.55; H, 7.29. Found: C, 69.67; H, 7.19.

2.1.8. *trans*-(1α,2β,7β,8α,9β,10α,13α14β)-17,18-Bis-(acetoxylmethyl)pentacyclo[6.6.2.2^{10,13}.0^{2,7}.0^{9,14}]octadeca-3,5,11,15-tetraene (16). To a solution of **15** (1.00 g, 2.41 mmol) and triethylamine (1.46 g, 14.43 mmol) in CH_2Cl_2 (20 mL) at −40°C was added a solution of methanesulfonyl chloride (1.66 g, 14.49 mmol) in CH_2Cl_2 (20 mL). The mixture was then stirred at this temperature for 1 h and then quenched with ice–water (10 mL). The layers were separated; the aqueous layer was extracted with CH_2Cl_2 (3×20 mL). The combined organic extracts were washed with 10% HCl (30 mL), saturated $NaHCO_3$ (30 mL) and brine (30 mL), and dried over $MgSO_4$. After removal of the solvent, the residue was dissolved in acetone (10 mL) and added with a solution of NaI (1.45 g, 9.67 mmol) in acetone (20 mL). The mixture was then stirred at 50°C for 24 h and then cooled to 0°C. The mixture was poured into a solution of sodium thiosulfate (3.55 g, 14.31 mmol) in water (30 mL). The aqueous layer was extracted with CH_2Cl_2 (3×20 mL), and the combined organic phases were washed with brine (20 mL), dried, and evaporated. The residue was chromatographed (silica gel, eluted with 10% CH_2Cl_2/ hexane) to afford **16** (0.32 g, 43%) as a white solid: mp 105–107°C ($CHCl_3$); R_f 0.32 (EtOAc/hexane); IR (KBr) 2912, 1734, 1247, 1237, 707 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.06–1.19 (m, 1H), 1.42–1.48 (m, 1H), 2.01 (s, 3H), 2.05 (s, 3H), 2.22–2.40 (m, 6H), 2.83–2.87 (m, 2H), 3.60 (dd, 1H, *J*=9.3, 10.8 Hz), 3.69 (dd, 1H, *J*=6.0, 10.5 Hz), 4.08 (t, 1H, *J*=9.9 Hz), 4.18 (dd, 1H, *J*= 6.6, 11.1 Hz), 5.20–5.28 (m, 2H), 5.34–5.40 (m, 2H), 5.65 (t, 1H, *J*=6.0 Hz), 5.83–5.87 (m, 1H), 5.90 (dd, 2H, *J*=3.0, 4.5 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.85 (q), 20.87 (q), 35.99 (d), 36.90 (d), 36.93 (d), 40.93 (d), 41.30 (d), 41.32 (d), 42.19 (d), 42.29 (d), 43.05 (d), 43.87 (d), 65.27 (t), 66.97 (t), 120.92 (d), 120.99 (d), 129.16 (d), 129.19 (d), 129.92 (d), 133.17 (d), 133.36 (d), 133.80 (d), 170.94 (s), 171.06 (s); MS (EI, 70 eV) *m/z* (relative intensity) 380 (M^+, 3.6), 341 (4.2), 302 (2.0), 279 (28), 258 (47), 241 (19), 185 (15), 149 (87), 128 (93), 104 (100), 58 (81); HRMS *m/z* calcd for $C_{24}H_{28}O_4$: 380.1988; obsd 380.1974. Anal. calcd for $C_{24}H_{28}O_4$: C, 75.76; H, 7.41. Found: C, 75.42; H, 7.26.

2.1.9. A mixture of diethyl *trans*,*trans*-(1α,2β,3α,6α,7-β,8α,9β,10α,13α14β)-19,20-bis(acetoxymethyl)hexacyclo[6.6.2.2^{3,6}.2^{10,13}.0^{2,7}.0^{9,14}]eicosa-11,15,17-triene-4,5-dicarboxylate (17a) and isomer 17b. A solution of **16** (0.22 g, 0.58 mmol) and diethyl fumarate (0.39 g, 2.27 mmol) was heated at 100°C for 12 h. The resulting mixture was chromatographed on a column of silica gel (hexane as elution) and recrystallized from hexane to give a mixture of inseparable isomers **17a** and **17b** (0.23 g, 72%) as a white solid: mp 129–130°C (hexane); R_f 0.43 (3:7 EtOAc/ hexane); IR (KBr) 2907, 1725, 1256, 1232, 1188 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.01–1.08 (m, 1H), 1.20 (t, 3H, *J*=7.2 Hz), 1.30 (t, 3H, *J*=7.2 Hz), 1.42–1.51 (m, 1H), 1.88–1.97 (m, 2H), 2.04 (s, 3H), 2.07 (s, 3H), 2.20–2.23 (m, 1H), 2.31–2.38 (m, 3H), 2.66 (dd, 1H, *J*=2.7, 5.7 Hz), 2.78–2.86 (m, 2H), 3.10 (dd, 1H, *J*=2.4, 5.7 Hz), 3.60 (dd, 1H, *J*=9.0, 10.8 Hz), 3.69 (dd, 1H, *J*=6.3, 11.7 Hz), 4.00–4.10 (m, 4H), 4.15–4.30 (m, 4H), 5.29 (ddd, 2H, *J*=1.5, 3.6, 3.6 Hz), 5.53–5.63 (m, 2H), 5.80 (ddd, 2H, *J*=0.9, 7.5, 14.7 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 14.14 (q), 14.23 (q), 20.94 (q), 20.96 (q), 36.10 (d), 36.91 (d), 37.87 (d), 38.03 (d), 38.48 (d), 39.91 (d), 40.01 (d), 40.59 (d), 41.73 (d), 43.45 (d), 44.39 (d), 45.3 5 (d), 47.01 (d), 47.76 (d), 60.61 (t), 60.90 (t), 65.55 (t), 67.03 (t), 129.90 (d), 130.33 (d), 131.39 (d), 131.58 (d), 133.09 (d), 134.12 (d), 171.06 (s), 171.09 (s), 173.73 (s), 173.86 (s); MS (EI, 70 eV) *m/z* (relative intensity) 552 (M^+, 19), 478 (40), 432 (44), 358 (64), 151 (60), 104 (100), 91 (53); HRMS *m/z* calcd for $C_{32}H_{40}O_8$: 552.2724; obsd 552.2733. Anal. calcd for $C_{32}H_{40}O_8$: C, 69.55; H, 7.30. Found: C, 69.53; H, 7.25.

2.1.10. *trans*,*trans*-(1α,2β,3α,6α,7β,8α,9β,10α,13α,14β)-17,18,19,20-Tetra(hydroxymethyl)hexacyclo-[6.6.2.2^{3,6}.2^{10,13}.0^{2,7}.0^{9,14}]eicosa-4,11,15-triene (18a) and isomer 18b. To a THF (10 mL) slurry of lithium aluminum hydride (0.060 g, 1.58 mmol) was added dropwise a solution of the mixture **17a** and **17b** (0.22 g, 0.40 mmol) in THF (10 mL) at 0°C. The gray suspension was stirred at 0°C for 3 h and then heat at 50°C for another 1 h. The reaction was quenched by careful addition of a mixture of THF (10 mL) and water (0.060 mL) at 0°C, followed by 15% NaOH (0.060 mL) and water (0.18 mL). The resulting mixture was then stirred vigorously at room temperature until a white solid was separated from the solution. The mixture was filtered and the residue was extracted with hot ethanol (3×20 mL). The combined organic phases were concentrated in vacuo. Purification of the crude product by silica gel chromatography (5% methanol/ethyl acetate) gave first tetraol **18b**, followed by **18a** as white solids.

Compound **18a**. 0.062 g, 40%: mp 222–223°C (CH_3OH); R_f 0.38 (1:5 CH_3OH/ EtOAc); IR (KBr) 3305, 2911, 2867, 1376, 1028, 695 cm^{-1}; ^{1}H NMR (C_5D_5N, 300 MHz) δ 1.39–1.42 (m, 2H), 1.72–1.75 (m, 2H), 1.99–2.02 (m, 2H), 2.30–2.35 (m, 4H), 2.66–2.71 (m, 4H), 3.56–3.62 (m, 4H), 4.02–4.15 (m, 4H), 5.34–5.42 (m, 6H), 5.65 (t, 2H, *J*=7.2 Hz), 5.85 (t, 2H, *J*=7.2 Hz); ^{13}C NMR (C_5D_5N, 75 MHz) δ 37.11 (d), 38.04 (d), 39.63 (d), 40.89 (d), 41.74 (d), 46.83 (d), 47.17 (d), 48.88 (d), 64.03 (t), 66.31 (t), 130.75 (d), 132.33 (d), 134.34 (d), 134.73 (d); MS (EI, 70 eV) *m/z* (relative intensity) 384 (M^+, 9.3), 366 (15), 335 (14), 317 (7.0), 287 (3.6), 245 (6.4), 195 (6.5), 155 (10), 129 (11), 84 (100), 56 (45); HRMS *m/z* calcd for $C_{24}H_{32}O_4$: 384.2302; obsd 384.2299. Anal. calcd for $C_{24}H_{32}O_4$: C, 74.96; H, 8.38. Found: C, 74.77; H, 8.47.

Compound **18b**. 0.063 g, 41%: mp 234–235°C (CH_3OH); R_f 0.40 (1:5 CH_3OH/EtOAc); IR (KBr) 3271, 2912, 2860, 1456, 1028, 700 cm^{-1}; ^{1}H NMR (C_5D_5N, 300 MHz) δ 1.39–1.41 (m, 2H), 1.68–1.72 (m, 2H), 1.89–1.92 (m, 2H), 2.08–2.09 (m, 2H), 2.27–2.31 (m, 2H), 2.65 (d, 2H, *J*= 6.0 Hz), 2.71 (d, 2H, *J*=6.6 Hz), 3.58–3.59 (m, 4H), 4.04–4.16 (m, 4H), 5.38 (t, 2H, *J*=3.9 Hz), 5.64 (t, 2H, *J*=6.9 Hz), 5.87 (t, 2H, *J*=7.2 Hz), 6.12 (br, 2H), 6.21 (br, 2H); ^{13}C NMR (C_5D_5N, 75 MHz) δ 37.03 (d), 37.98 (d), 39.49 (d), 41.27 (d), 46.82 (d), 47.01 (d), 48.90 (d), 64.11 (t), 66.29 (t), 130.68 (d), 132.31 (d), 134.78 (d); MS (EI, 70 eV) *m/z* (relative intensity) 384 (M^+, 31), 366 (49), 335 (41), 317 (20), 289 (14), 245 (19), 209 (22), 183 (26), 155 (33), 129 (34), 92 (100), 79 (73); HRMS *m/z* calcd for $C_{24}H_{32}O_4$: 384.2302; obsd 384.2296.

2.1.11. (1α,2β,3α,6α,7β,8α,9β,10α,13α,14β)-17,18,19,20-Tetramethylenehexacyclo[6.6.2.2^{3,6}.2^{10,13}.0^{2,7}.0^{9,14}]eicosa-4,11,15-triene (7). Tetraol **18a** (0.93 g, 2.42 mmol) or isomeric **18b** (0.93 g, 2.42 mmol) in anhydrous pyridine (20 mL) was added dropwise to a stirred solution of *p*-toluenesulfonyl chloride (3.88 g, 20.35 mmol) in anhydrous pyridine (10 mL) at 0°C under an atmosphere of nitrogen. The reaction mixture was stirred for 4 h in an ice-bath. The ice-bath was removed and stirring was continued at room temperature for 6 h. The reaction mixture was poured into cooled 10% HCl solution and extracted with CH_2Cl_2 (3×20 mL). The organic extracts were washed with cold $NaHCO_3$ solution (2×10 mL) and brine (15 mL) and dried. After removal of the solvent, the residue was dissolved in dimethyl sulfoxide (20 mL) and added with potassium *tert*-butoxide (2.83 g, 25.22 mmol). The reaction mixture was stirred at 50°C for 18 h. It was then cooled and diluted with ice–water, and the solution was extracted with hexane. The extracts were washed with water and saturated brine and dried. Purification of the crude product by silica gel chromatography (hexane) gave heptaene **7** (from **18a**, 0.31 g, 41%; from **18b**, 0.28 g, 38%) as white solid: mp >230°C (hexane) (decomp.); R_f 0.33 (hexane); IR (KBr) 3039, 2885, 1615, 896, 681 cm^{-1}; UV (cyclohexane) λ_{max}= 246 nm (log ε=4.39), 208 nm (shoulder, log ε=4.15); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 2.13 (s, 4H), 2.50–2.53 (m, 2H), 3.03 (t, 4H, *J*=3.9 Hz), 4.70 (s, 4H), 5.06 (d, 4H, *J*=1.2 Hz), 5.33 (dd, 2H, *J*=3.3, 4.8 Hz), 5.71 (dd, 4H, *J*= 3.3, 4.5 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 40.18 (d), 44.61 (d), 47.32 (d), 101.91 (t), 130.60 (d), 131.00 (d), 147.75 (s); MS (EI, 70 eV) *m/z* (relative intensity) 312 (M^+, 59), 286 (7.5), 241 (4.0), 212 (5.7), 193 (5.6), 166 (36), 129 (6.2), 104 (100); HRMS *m/z* calcd for $C_{24}H_{24}$: 312.1879; obsd 312.1873. Anal. calcd for $C_{24}H_{24}$: C, 92.25; H, 7.74. Found: C, 91.87; H, 7.55.

2.1.12. *trans*-(1α,2β,3α,4β,5β,6α,7β,8α,9β,10α,13α,14β)-19,20-Bis(acetoxymethyl)hexacyclo[6.6.2.2^{3,6}.2^{10,13}.0^{2,7}.0^{9,14}]eicosa-11,15,17-triene-4,5-dicarboxylic anhydride (19). A solution of **16** (0.22 g, 0.58 mmol) and maleic anhydride (0.058 g, 0.61 mmol) in benzene (1 mL) was heated at 80°C for 12 h. The reaction mixture was cooled to room temperature and concentrated under vacuum. The crude product was recrystallized from ether to give anhydride **19** (0.23 g, 82%) as a white solid: mp 184–185°C (ether); R_f 0.17 (1: 2 EtOAc/hexane); IR (KBr) 3046, 2936, 1861, 1774, 1736, 1230, 910, 705, 684 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.08–1.12 (m, 1H), 1.44–1.47 (m, 1H), 1.90–1.93 (m, 1H), 2.04 (s, 3H), 2.05–2.07 (m, 2H), 2.08 (s, 3H), 2.13–2.16 (m, 1H), 2.36–2.43 (m, 4H), 3.04–3.11 (m, 4H), 3.57–3.73 (m, 2H), 4.13–4.17 (m, 2H), 5.30–5.34 (m, 2H), 5.59 (t, 1H, *J*=7.2 Hz), 5.76–5.80 (m, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.97 (q, two peaks), 35.73 (d), 36.77 (d), 36.89 (d), 36.90 (d), 38.33 (d), 39.74 (d), 40.12 (d), 41.51 (d), 43.02 (d), 43.12 (d), 43.44 (d), 45.34 (d), 46.35 (d, two peaks), 65.14 (t), 66.89 (t), 130.18 (d), 131.09 (d, two peaks), 131.27 (d), 131.41 (d), 133.73 (d), 170.95 (s), 171.11 (s), 172.21 (s), 172.30 (s); MS (EI, 70 eV) *m/z* (relative intensity) 478 (M^+, 6.1), 376 (15), 358 (90), 208 (15), 155 (11), 129 (15), 104 (100); HRMS *m/z* calcd for $C_{28}H_{30}O_7$: 478.1992; obsd 478.1990. Anal. calcd for $C_{28}H_{30}O_7$: C, 70.26; H, 6.32. Found: C, 70.19; H, 6.54.

2.1.13. *trans*,*cis*-(1α,2β,3α,6α,7β,8α,9β,10α,13α,14β)-17,18,19,20-Tetra(hydroxymethyl)hexacyclo[6.6.2.2^{3,6}.2^{10,13}.0^{2,7}.0^{9,14}]eicosa-4,11,15-triene (20). Following the same procedure used to prepare **18a** and **18b** from a mixture of **17a** and **17b**, the carboxylic anhydride **19** (0.10 g, 0.21 mmol) was converted to tetraol **20** (0.064 g, 80%) as an amorphous solid: mp 264–265°C (CH_3OH); R_f 0.42 (1:5 CH_3OH/EtOAc); IR (KBr) 3221, 3037, 2910, 2883, 1034, 695 cm^{-1}; ^{1}H NMR (C_5D_5N, 300 MHz) δ 1.38–1.43 (m, 1H), 1.75–1.80 (m, 1H), 1.90–2.07 (m, 4H), 2.24–2.28 (m, 2H), 2.47–2.72 (m, 6H), 3.53–3.70 (m, 4H), 3.91–4.22 (m, 4H), 5.33–5.36 (m, 2H), 5.62–5.70 (m, 3H), 5.85 (dd, 1H, *J*=7.2, 7.5 Hz), 6.10–6.28 (m, 4H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 36.98 (d), 37.98 (d), 39.33 (d), 39.60 (d), 39.71 (d), 41.03 (d), 41.51 (d), 46.03 (d), 46.10 (d), 46.63 (d), 46.99 (d), 48.26 (d), 48.36 (d), 48.95 (d), 63.05 (t, two peaks), 64.15 (t), 66.29 (t), 130.78 (d), 131.79 (d), 131.87 (d), 132.04 (d), 132.11 (d), 134.60 (d); MS (EI, 70 eV) *m/z* (relative intensity) 384 (M^+, 7.9), 366 (20), 354 (16), 335 (15), 209 (11), 183 (13), 155 (23), 129 (35), 117 (28), 79 (100); HRMS *m/z* calcd for $C_{24}H_{32}O_4$: 384.2302; obsd 384.2304. Anal. calcd for $C_{24}H_{32}O_4$: C, 74.96; H, 8.38. Found: C, 74.72; H, 8.18.

2.1.14. (1α,2β,3α,6α,7β,8α,9β,10α,13α,14β)-4,5,11,12-Tetramethylhexacyclo[6.2.2.2^{3,6}.2^{10,13}.0^{2,7}.0^{9,14}]eicosa-4,11,15,17,19-pentaene (21). Ammonia (2 mL) was condensed into the flask in a dry-ice/acetone bath. Sodium metal (37.2 mg, 1.62 mmol) was added in small pieces with vigorous stirring, over 1 h. A solution of tetramethylene-hexacyclic diene **7** (10.0 mg, 0.032 mmol) and *tert*-butanol (94.8 mg, 1.28 mmol) in dry THF (1 mL) was then added over a period of 10 min. Stirring was continued at −33°C until the blue color had disappeared. After removal of ammonia, the residue was extracted with hexane (3×10 mL). The extracts were washed with water and dried over $MgSO_4$. Cautious evaporation of the solvent, the crude product was chromatographed on silica gel (hexane) to give **21** (6.3 mg, 62%) as a white solid: mp 138–139°C (pentane); R_f 0.30 (hexane); IR (KBr) 3045, 2927, 1610, 1436, 796, 719, 676 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.66 (s, 12H), 1.90 (s, 4H), 2.21–2.22 (m, 2H), 2.89 (t, 4H, *J*=3.9 Hz), 5.14 (dd, 2H, *J*=3.6, 4.5 Hz), 5.79 (dd, 4H, *J*=3.9, 4.5 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 15.65 (q), 40.85 (d), 46.30 (d), 48.62 (d), 129.62 (d), 133.11 (d), 136.57 (s); MS (EI, 70eV) *m/z* (relative intensity) 316 (M^+, 100), 210 (86), 195 (49), 132 (94), 117 (84), 91 (56), 78 (40); HRMS *m/z* calcd for $C_{24}H_{28}$: 316.2192; obsd 316.2185.

2.1.15. (1α,2β,3α,6α,7β,8α)-4,5,9,10-Tetramethyltetracyclo[6.2.2.2^{3,6}.0^{2,7}]tetradeca-4,9,11,13-tetraene (22). Following the same procedure used to prepare **21** from **7**, tetramethylenetetracyclic diene **6** (0.10 g, 0.43 mmol) was converted to tetramethyltetracyclic tetraene **22** (0.072 g, 71%) as a white solid: mp 119–120°C (pentane); R_f 0.31 (hexane); IR (KBr) 3050, 2950, 2905, 1607, 1447, 753, 692 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.67 (s, 12H), 2.15 (s, 2H), 2.79 (dd, 4H, *J*=3.9, 4.2 Hz), 5.90 (dd, 4H, *J*=3.0, 4.2 Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 15.74 (q), 46.85 (d), 48.14 (d), 132.69 (d), 137.47 (s); MS (EI, 70 eV) *m/z* (relative intensity) 238 (M^+, 31), 132 (69), 117 (95), 91 (100), 78 (28), 65 (5.9), 53 (4.5); HRMS *m/z* calcd for

$C_{18}H_{22}$: 238.1722; obsd 238.1718. Anal. calcd for $C_{18}H_{22}$: C, 90.70; H, 9.30. Found: C, 90.51; H, 9.06.

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References

1. Alternative names: 2,3,6,7-tetramethylenetetradecahydro-1,4;5,8;9,10-triethenoanthracene; 17,18,19,20-tetramethylenehexacyclo[6.6.2.2^{3,6}.2^{10,13}.0^{2,7}.0^{9,14}]eicosa-4,11,15-triene.
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