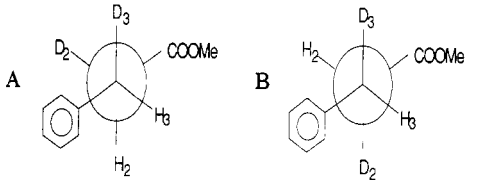

A (RR/SS) B (RS/SR)

Figure 2.

(CDOH, 3) ppm. ^{13}C ($CDCl_3$): 9.95 (1); 31.56, 31.32* (2); 75.73, 75.27* (3); 144.48 (4); 125.88 (5); 128.14 (6); 127.33 (7) ppm.

***trans*-2,3-Dideuterio-4-isopropyl-1-cyclohexanol (3a)**: colorless oil. IR (neat): 3330, 2940, 2150, 1440, 1380, 1360, 1050 cm^{-1}. NMR: ^1H ($CDCl_3$) 3.45 (*CH*OH ax, 1); 1.14 (H ax, 2,6); 1.88 (H eq, 2,6); 0.88 (H ax, 3,5); 1.63 (H eq, 3,5); 0.93 (H ax, 4); 1.35 (H, 7); 0.79 (CH_3, 8) ppm. ^2H (C_6D_6): 3.40 (D ax, 1); 1.21 (D ax, 2); 1.95 (D eq 2); 0.84 (D ax, 3); 1.54 (D eq, 3) ppm. ^{13}C ($CDCl_3$): 70.80 (1); 35.40, 34.95* (2); 27.64, 27.28* (3); 42.84 (4); 27.64 (5); 35.40 (6); 32.25 (7); 19.78 (8) ppm.

Methyl 2,3-dideuterio-3-phenyl-1-propanoate (4a): colorless oil. IR (neat): 3040, 2950, 2150, 1740, 1600, 1490, 1430, 1260, 1200, 740, 706 cm^{-1}. NMR: ^1H ($CDCl_3$) 3.66 (OCH_3); 2.61 (CHD, CH_2, 2); 2.94 (CHD, CH_2, 3); 7.29 (phenyl, 6,7,8) ppm. ^2H ($CDCl_3$): 2.52 (CHD, 2); 2.84 (CHD, 3) ppm. ^{13}C ($CDCl_3$): 51.35 (1); 173.07 (2); 30.67, 30.35* (3); 35.40, 35.11* (4); 140.27 (5); 128.06 (7); 126.06 (8) ppm.

Determination of the Stereochemistry. In ^2H NMR the two nuclei D_2 and D_3 exhibit a quadruplet (J = 1.8 and 1.3 Hz) and a triplet (J = 2.2 Hz), respectively. Among the two possible configurations, *RR/SS* (threo) and *RS/SR* (erythro) in their most stable conformation (*A* and *B*, respectively, in Figure 2), only the threo isomer could give such a pattern corresponding to $^3J_{D3H3}$(trans) $\approx$ 1.8 Hz and $^2J_{D2H2} \approx$ 3.1 Hz for D_2 and to $^3J_{D3H2}$(trans) $\approx {}^2J_{D3H3} \approx$ 2.2 Hz for D_3. Conversely, the erythro (*B*) would give only a doublet of $\approx$ 3.1 Hz ($^2J_{D2H2}$) for D2 and of $\approx$ 2.2 Hz ($^2J_{D3H3}$) for D_3 (neglecting the $^3J_{DH}$ gauche and $^3J_{DD}$ trans coupling values which should be less than 0.6 Hz).

^1H NMR confirms these assignments. By selective irradiation of H2 and H3 successively, these two nuclei exhibit a complex pattern of lines with a mean half-height width ($\Delta\nu_{1/2}$) of $\approx$ 10 Hz. The threo configuration (*A*) could correspond to the experimental spectrum with $^2J_{HD} \approx$ 2–3 Hz and $^3J_{HD}$(trans) $\approx$ 2 Hz. The erythro configuration (*B*) would show a triplet for each proton corresponding to the $^2J_{HD}$ values, giving a $\Delta\nu_{1/2}$ of 4–6 Hz.

3,5,5-Trimethyl-2,3-dideuterio-1-cyclohexanol (5a): colorless oil. IR (neat): 2150, 2940, 1710, 1440, 1160, 1260, 1225 cm^{-1}. NMR: ^1H (C_6D_6) 1.44 (H ax, 2); 2.17 (H eq, 2); 1.63 (H eq, 3); 0.82 (H ax, 4); 1.14 (H eq 4); 1.74 (H ax, 6); 1.95 (H eq, 6); 0.73 (CH_3 eq, 7); 0.71 (CH_3 ax, 8); 0.80 (CH_3, 9) ppm. ^2H (C_6D_6): 1.42 (D ax, 2); 2.13 (D eq, 2); 1.57 (D ax, 3) ppm. ^{13}C (C_6D_6): 208.7 (1); 48.60, 48.36* (2); 29.47, 28.92* (3); 47.90 (4); 34.80 (5); 53.97 (6); 22.24 (7); 31.98 (8); 25.63 (9) ppm.

(5α,17β)-4,5-Dideuterio-17-hydroxy-3-androstanone (6a): white crystals, mp 180 °C (ethyl acetate). IR (KBr): 3450, 2940, 2100, 1695, 1440, 1320, 1140, 1075, 1045, 960, 915, 735 cm^{-1}. NMR: ^1H ($CDCl_3$) 2.04 (H ax, 4); 2.20 (H eq, 4); 1.50 (H ax, 5) ppm. ^2H ($CDCl_3$): 2.46 (D ax, 4); 2.65 (D eq, 4); 1.89 (D ax, 5) ppm. ^{13}C ($CDCl_3$): 209.0 (3); 44.59, 44.12* (4); 46.77, 46.31* (5) ppm.

(5β,17β)-4,5-Dideuterio-17-hydroxy-3-androstanone (6b): separated from 5α on a silica gel column, (230–400-mesh Merck) eluted with methylene chloride/ethyl acetate (85–15); white crystals, mp 140.5 °C (ethyl acetate). IR (KBr): 3450, 2940, 2100, 1700, 1440, 1370, 1260, 1060, 910, 735 cm^{-1}. NMR: ^1H ($CDCl_3$) 1.98 (H ax, 4); 2.60 (H eq, 4); 1.77 (H ax, 5) ppm. ^2H ($CDCl_3$): 2.01 (D ax, 4); 2.65 (D eq, 4); 1.78 (D ax, 5) ppm. ^{13}C ($CDCl_3$): 212.9 (3); 42.22, 41.87* (4); 44.24, 43.97* (5) ppm.

Registry No. 1, 98-53-3; **1a**, 30461-16-6; **1b**, 30461-17-7; **2**, 93-55-0; **2a**, 124267-81-8; **3**, 64233-68-7; **3a**, 124267-82-9; **4**, 1754-62-7; **4a**, 39196-55-9; **5**, 78-59-1; *cis*-**5a**, 124267-83-0; *trans*-**5a**, 124267-84-1; **6**, 58-22-0; (4β,5α,17β)-**6a**, 124267-85-2; (4α,5α,17β)-**6a**, 31285-38-8; (4α,5β,17β)-**6b**, 124267-86-3; (4β,5β,17β)-**6b**, 124267-87-4; Zn, 7440-66-6; $NiCl_2$, 7718-54-9; D_2O, 7789-20-0.

Some Transformations of Adducts of Dichlorocarbene and 7-Substituted Benzonorbornadienes

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Introduction

The addition of dichlorocarbene to norbornene (**1**),[1] norbornadiene (**2**),[1] and benzonorbornadiene (**3**)[2] provides the most direct route to compounds containing the bicyclo[3.2.1]octyl ring system. The reaction involves addition of the carbene to the exo face of the bicyclic alkene to give initially a *gem*-dichlorocyclopropane, which under the rection conditions usually undergoes ring opening to afford a rearranged, ring-expanded dihalide, e.g. **6**. In the reaction involving norbornene (**1**), the initial adduct **4** has been isolated, but in the case of norbornadiene (**2**) and benzonorbornadiene (**3**), the ring-expanded products have been obtained directly.[1,2]

The stereochemical outcome of *gem*-dihalocyclopropane ring opening has been rationalized in terms of orbital symmetry constraints.[3] The reaction involves cyclopropyl to allyl cation interconversion with participation of the cyclopropyl bonding electrons from the face of the cyclopropyl ring opposite to that of the departing halide ion. Collapse of the resulting ion pair, e.g. **5**, then affords the allylic halide, e.g. **6**, of defined stereochemistry. In a converse argument, for those cases in which the *gem*-dihalocyclopropane cannot be isolated or detected, the stereochemistry of the allylic halide defines the stereochemistry of carbene addition: exo halogen orientation implies exo addition of dihalocarbene. This paper concerns the addition of dichlorocarbene to two substituted benzonorbornadienes in which a substituent shields the exo face of the double bond.

Results and Discussion

Addition of dichlorocarbene, generated from $CHCl_3$ and NaOH under phase-transfer conditions, to *anti*-7-*tert*-butoxybenzonorbornadiene (**7**) afforded the *endo*-chloro derivative **8** and the *exo*-chloroderivative **9** in a ratio of ca. 9:1 in a total yield of 58% (based on unrecovered starting material after two sequential reactions). The endo (or β) orientation of the chloro substituent in **8** was apparent from the value $J_{5,6}$ = 5.0 Hz for the bridgehead H5 to chloromethine H6 coupling constant.[4] The corre-

(1) (a) Jefford, C. W. *Proc. Chem. Soc.* **1963**, 1753. (b) Ghosez, L.; Laroche, P.; *Proc. Chem. Soc.* **1963**, 90. (c) Moore, W. R.; Moser, W. R.; La Prade, J. E. *J. Org. Chem.* **1963**, *28*, 2200. (d) De Selms, R. C.; Combs, C. M. *J. Org. Chem.* **1963**, *28*, 2206. (d) Bergman, E. *J. Org. Chem.* **1963**, *28*, 2210. (e) Jefford, C. W.; Mahajan, S.; Waslyn, J.; Waegell, B. *J. Am. Chem. Soc.* **1965**, *87*, 2183. (f) Ghosez, L.; Slinckx, G.; Glineur, M.; Hoet, P.; Laroche, P. *Tetrahedron Lett.* **1967**, 2773. (g) Jefford, C. W.; Bernardinelli, G.; Rossier, J.-C.; Zuber, J. A. *Helv. Chim. Acta* **1972**, *65*, 1467. (h) Dehmlow, E. V. *Tetrahedron* **1972**, *28*, 175.

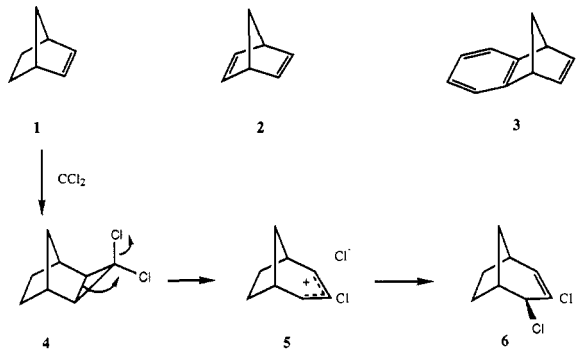
(2) (a) Tanida, H.; Tori, K.; Kitahonoki, K. *J. Am. Chem. Soc.* **1967**, *89*, 3212. (b) Hahn, R. C.; Rothman, L. J. *J. Am. Chem. Soc.* **1969**, *91*, 2409. (c) Goldschmidt, Z.; Gutman, U. *Tetrahedron* **1974**, *30*, 3327. (d) Johnson, R. P.; Exarchou, A.; Jefford, C. W.; Hahn, R. C. *J. Org. Chem.* **1977**, *42*, 3758. (e) Parvulescu, L.; Gheorhiu, M. D. *Rev. Roum. Chim.* **1977**, *22*, 1089. (f) Sustmann, R.; Gellert, R. W. *Chem. Ber.* **1978**, *111*, 42.

(3) Woodward, R. B.; Hoffmann, R. *The Conservation of Orbital Symmetry*; Verlag Chemie, Academic Press: Weinheim, 1970; pp 46–48.

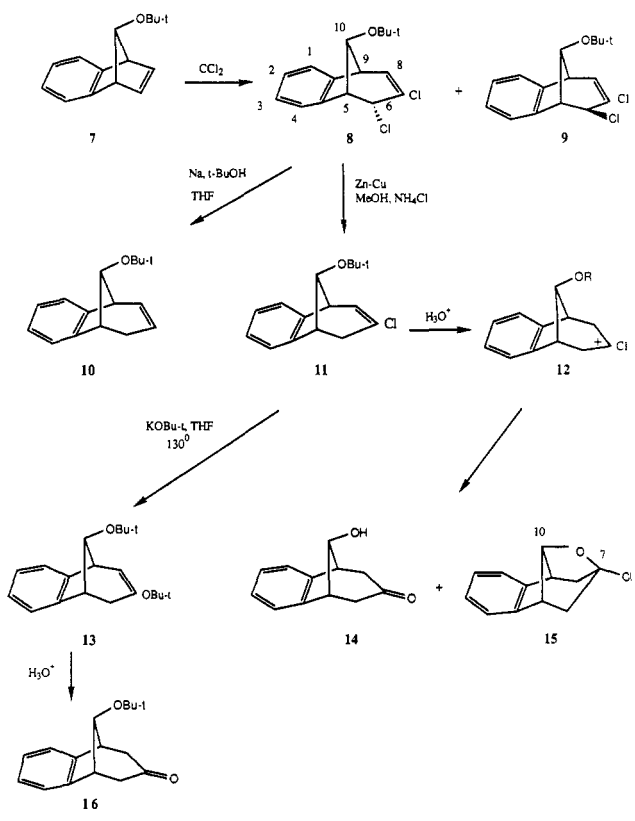
(4) The analogous coupling constant for the stereochemically related 6β-acetoxy-7-chloro-6,9-dihydro-5α,9α-methano-5*H*-benzocycloheptene is reported to be 5 Hz: Cristol, S. J.; Strom, R. M. *J. Am. Chem. Soc.* **1979**, *101*, 5707.

0022-3263/90/1955-1667$02.50/0

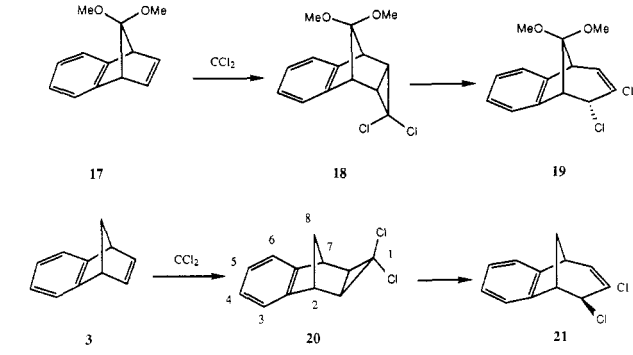
Scheme I



Scheme II



Scheme III



sponding coupling constant for the minor isomer **9**, possessing the exo (or α) chloro substituent, was 1.5 Hz, in line with the value observed for the exo chloro derivative obtained from dichlorocarbene addition to the parent benzonorbornadiene (Scheme III, see later). Dichloride **8** could be fully dechlorinated with Na in *t*-BuOH–THF to give the *tert*-butyl ether **10** while removal of the allylic chloro substituent in **8** and **9** was readily effected using Zn–Cu couple in MeOH containing NH_4Cl.[5] This reagent appears to be a useful alternative to $LiAlH_4$, which is normally used for this sort of dechlorination.

It was of interest to determine whether the vinyl chloride functionality of **11** could be transformed into a carbonyl group, since the resulting compound would then possess functionality suitable for further elaboration in both the one- and three-atom bridges. Treatment of **11** with aqueous CF_3SO_3H under reflux afforded the expected hydroxy ketone **14** together with the novel cyclic ether **15**. The structure of **15** was evident from its spectroscopic properties, particularly its ^{13}C NMR spectrum which showed signals for only seven chemically distinct carbon atoms, including a singlet at δ 100.0 for the bridgehead atom C7 which bears both oxygen and chlorine substituents. The ^1H NMR spectrum exhibited a clean triplet for the oxymethine at C10, but the pattern due to the bridgehead and methylene protons gave rise to a complex AA'BB'MM' spin pattern. The formation of **15** presumably involves intramolecular capture by the oxy function at C10 of the carbocation centre in intermediate **12**. Although **15** is an α-chloro ether, and as such would normally be very reactive toward hydrolysis, the fact that the chloro substituent is at a bridgehead position prevents further hydrolysis. Indeed, **15** was observed to be stable to the reaction conditions, indicating that **14** and **15** arise from partitioning of intermediate **12** between two reaction pathways (Scheme II).

Treatment of the vinylic chloride **11** with KOBu-*t* in THF at 130 °C in a sealed tube[6] afforded the di-*tert*-butyl ether **13**. Mild acid-catalyzed hydrolysis of this material gave the keto ether **16** while more vigorous hydrolysis again provided the hydroxy ketone **14**.

The addition of dichlorocarbene to 7,7-dimethoxybenzonorbornadiene **17** was also briefly investigated. The dichloride **19** was isolated as the only product (Scheme III), and the β or endo orientation of the allylic chloro substituent again follows, as in the case of **8**, from the magnitude of the chloromethine-bridgehead proton coupling constant. It is thus evident that, in the addition of dichlorocarbene to the 7-substituted benzonorbornadienes **7** and **17**, attack of the carbene occurs predominantly (in the case of **7**) and exclusively (in the case of **17**) at the endo face of the π-bond, leading to an adduct, e.g. **18**, which suffers stereoelectronically controlled ring opening under the reaction conditions to give the 6β-chlorides **8** or **19**. This predominant endo addition is a consequence of shielding of the exo face by the substituent at C7. It may be noted that Klumpp and co-workers have also observed endo attack on the syn double bond in the addition of dichlorocarbene to 7-*tert*-butoxynorbornadiene[7] and other 7-substituted norbornadienes.[8] The situation with those substrates is further complicated by the occurrence of "normal" exo addition to the unhindered anti double bond and homo-1,4-addition.

Although the endo additions reported in the present work take place in only modest yield, they do have some preparative value in that they provide ready access to ring-expanded derivatives of benzonorbornadiene con-

(5) This reagent is efficient for the debromination of α-bromo ketones: Takaya, H.; Makino, S.; Hayakawa, Y.; Noyori, R. *J. Am. Chem. Soc.* **1978**, *100*, 1765.

(6) For the analogous reaction in the parent system, see: Balci, M.; Harmandar, M. *Tetrahedron Lett.* **1984**, *25*, 237.

(7) Kwantes, P. M.; Klumpp, G. W. *Tetrahedron Lett.* **1976**, 707.

(8) Klumpp, G. W.; Kwantes, P. M. *Tetrahedron Lett.* **1981**, *22*, 831.

taining functional groups, suitable for further elaboration, in both the one- and three-carbon bridges. Finally, it was observed in the present study that the addition of dichlorocarbene to benzonorbornadiene (**3**) under phase-transfer catalysis conditions permitted the isolation of the exo adduct **20**, which underwent isomerization to the exo allylic chloride **21** only upon prolonged storage, or upon distillation. All previous reports of the addition of dichlorocarbene to **3** have only recorded the direct isolation of the rearranged material **21**.[2]

Experimental Section

General Methods. NMR spectra were recorded in $CDCl_3$ containing TMS as internal standard using a Perkin Elmer R24B, Bruker WP80 or Bruker HX90 instrument. Where possible, ^1H assignments were made with the aid of spin decoupling. Mass spectra were obtained with a Hewlett-Packard 5986 instrument operating in the GC–MS mode. Microanalyses were by the Australian Microanalytical Service, Melbourne. Radial chromatography was performed with a Chromatotron Model 7924 system, using 2-mm silica gel plates. All solvent extracts were dried over anhydrous $MgSO_4$ and evaporated using a rotary evaporator. Benzonorbornadiene,[9] *anti*-7-*tert*-butoxybenzonorbornadiene,[10] and 7,7-dimethoxybenzonorbornadiene[11] were prepared as reported.

Addition of Dichlorocarbene to *anti*-7-*tert*-Butoxybenzonorbornadiene (7). A mixture of the benzonorbornadiene (7.7 g), $CHCl_3$ (30 mL), 50% NaOH solution (40 mL), and cetyltrimethylammonium bromide (1.0 g) was vigorously stirred at 60 °C for 6 h. The mixture was diluted with water and thoroughly extracted with ether, and the combined extracts were washed with water, dried, and evaporated. Unreacted alkene (**7**) was recovered by distillation (Kugelrohr, ~80 °C/0.1 mm), and the distillation residue was saved. The recovered alkene **7** was resubmitted to the reaction conditions, using the same quantities of $CHCl_3$, NaOH, and phase-transfer catalyst. Workup as before and distillation afforded unchanged *anti*-7-*tert*-butoxybenzonorbornadiene (4.42 g). The combined distillation residues were submitted to rapid silica filtration using silica gel (400 g) and eluting with 10–40% CH_2Cl_2–hexane. Early fractions yielded pure *anti*-10-*tert*-butoxy-6β,7-dichloro-6,9-dihydro-5α,9α-methano-5*H*-benzocycloheptene (**8**) (2.15 g), which crystallized from pentane as colorless plates, mp 99–100 °C: MS *m/z* 177 (12), 175 (37), 57 (100), 41 (17); ^1H NMR (90 MHz) δ 7.45–7.05 (m, 4 H, aryl), 6.18 (ddd, $J_{8,9}$ = 7.0 Hz, $J_{8,6}$ = 1.2 Hz, $J_{8,10}$ = 1.0 Hz, 1 H, vinyl H8), 4.94 (dd, $J_{6,5}$ = 5.0 Hz, $J_{6,8}$ = 1.2 Hz, 1 H, H6), 4.27 (ddd, $J_{10,5}$ = 4.5 Hz, $J_{10,9}$ = 4.5 Hz, $J_{10,8}$ = 1.0 Hz, 1 H, H10), 3.42 (ddd, $J_{5,10}$ = 4.5 Hz, $J_{5,6}$ = 5.0 Hz, $J_{5,9}$ = 1.0 Hz, 1 H, H5), 3.29 (ddd, $J_{9,8}$ = 7.0 Hz, $J_{9,10}$ = 4.5 Hz, $J_{9,5}$ = 1.0 Hz, 1 H, H9), 1.23 (s, 9 H, *tert*-butyl); ^{13}C NMR δ 28.4 (q), 46.5 (d), 53.0 (d), 59.7 (d), 74.5 (s), 78.9 (d), 121.8 (d), 126.7 (d), 127.8 (d), 128.0 (d), 129.6 (s), 130.1 (d), 138.5 (s), 147.8 (s).

Anal. Calcd for $C_{16}H_{18}Cl_2O$: C, 64.66; H, 6.10. Found: C, 64.99; H, 6.03.

Later fractions were mixtures. These were submitted to radial chromatography using 10% CH_2Cl_2–hexane to afford from the faster running band a further quantity of dichloride **8** (220 mg). The total yield of **8** was thus 2.37 g (52% based on unrecovered starting material). The slower running band yielded 10-*anti*-*tert*-butoxy-6α,7-dichloro-6,9-dihydro-5α,9α-methano-5*H*-benzocycloheptene (**9**) 275 mg, 6% based on unrecovered starting material), which crystallized from hexane as plates, mp 144–5 °C. The MS was very similar to that of **8**: ^1H NMR (90 MHz) δ 7.40–7.07 (m, 4 H, aryl), 6.26 (ddd, $J_{8,9}$ = 7.0 Hz, $J_{8,6}$ = 0.8 Hz, $J_{8,10}$ = 0.8 Hz, 1 H, H8), 4.32 (dd, $J_{6,5}$ = 1.5 Hz, $J_{6,8}$ = 0.8 Hz, 1 H, H6), 4.24 (ddd, $J_{10,9}$ = 4.4 Hz, $J_{10,5}$ = 4.4 Hz, $J_{10,8}$ = 0.8 Hz, 1 H, H10), 3.56 (ddd, $J_{5,10}$ = 4.4 Hz, $J_{5,6}$ = 1.5 Hz, $J_{5,9}$ = 1.0 Hz, 1 H, H5), 3.37 (ddd, $J_{9,8}$ = 7.0 Hz, $J_{9,10}$ = 4.4 Hz, $J_{9,5}$ = 1.0 Hz, 1 H, H9), 1.28 (s, 9 H, *tert*-butyl); ^{13}C NMR δ 28.0 (q), 46.7 (d), 51.5 (d), 59.2 (d), 74.2 (d), 74.6 (s), 122.2 (d), 125.5 (d), 127.4 (d), 127.7 (d), 130.0 (s), 131.3 (d), 140.3 (s), 148.1 (s).

Anal. Calcd for $C_{16}H_{18}Cl_2O$: C, 64.66; H, 6.10. Found: C, 64.42; H, 6.15.

Dechlorination of Dichloride 8. A solution of **8** (304 mg, 1.1 mmol) in THF (7 mL) and *t*-BuOH (2 mL) was treated with Na pieces (480 mg, 21 mmol), and the mixture was refluxed under N_2 for 3 h. The mixture was diluted with ether, which was decanted, and washed with water, dried, and evaporated. The residue was distilled (Kugelrohr, ~70 °C/0.1 mm) to afford 10-*anti*-*tert*-butoxy-6,9-dihydro-5,9-methano-5*H*-benzocycloheptene (**10**) as a clear oil (185 mg, 74%): MS *m/z* 228 (M, 8), 172 (53), 155 (16), 154 (12), 153 (28), 152 (11), 144 (78), 143 (100), 142 (18), 141 (47), 129 (33), 128 (65), 127 (14), 116 (16), 115 (30), 57 (95), 41 (21); ^1H NMR (90 MHz) δ 7.30–7.00 (m, 4 H, aryl), 5.89 (m, 1 H, H8), 5.34 (m, 1 H, H7), 4.22 (ddd, $J_{10,5}$ ~$J_{10,9}$ = 5.0 Hz, $J_{10,8}$ = 1.0 Hz, 1 H, H10), 3.10 (dd, $J_{9,8}$ = 6.0 Hz, $J_{9,10}$ = 5.0 Hz, 1 H, H9), 2.96 (m, 1H, H5), 2.63 (dm, J_{gem} = 17.0 Hz, 1 H, H6-exo), 1.86 (dm, J_{gem} = 17.0 Hz, 1 H, H6-endo).

Anal. Calcd for $C_{16}H_{20}O$: C, 84.16; H, 8.83. Found: C, 84.25; H, 9.20.

Reduction of Dichloride 8 with Zn–Cu Couple. To a solution of $CuSO_4 \cdot 5H_2O$ (600 mg) in water (20 mL) was added with stirring Zn dust (3.0 g). The resultant couple was allowed to settle, the supernatant was decanted, and the residue was washed sequentially with water and MeOH. The couple was suspended in MeOH (30 mL), which had been saturated with NH_4Cl, the chloride **8** (495 mg) was added, and the mixture was refluxed with stirring for 4 h. The mixture was filtered through Celite, and the filtercake washed with ether. The combined filtrate was diluted with water and extracted with ether. The dried ether extract was evaporated to yield essentially pure 10-*anti*-*tert*-butoxy-7-chloro-6,9-dihydro-5,9-methano-5*H*-benzocycloheptene (**11**) (410 mg, 94%), which crystallized from MeOH as needles, mp 83–83.5 °C. A similar reduction carried out on a 9:1 mixture of *endo*-chloride (**8**) and *exo*-chloride (**9**) gave **11** in 90% yield: MS *m/z* 264 (M, 0.5), 262 (M, 1.7), 206 (20), 171 (11), 153 (16), 152 (15), 142 (11), 141 (40), 115 (21), 57 (100), 41 (28); ^1H NMR (90 Mz) δ 7.32–7.02 (m, 4 H, aryl), 5.95 (dm, $J_{8,9}$ = 7.0 Hz, 1 H, H8), 4.10 (dd, $J_{10,5}$, $J_{10,9}$ = 5.0 Hz, 1 H, H10), 3.24 (dd, $J_{9,8}$ = 7.0 Hz, $J_{9,10}$ = 5.0 Hz, 1 H, H9), 3.06 (m, 1 H, H5), 2.89 (ddd, J_{gem} = 17.0 Hz, $J_{6\text{-exo},5}$ = 5.0 Hz, $J_{6\text{-exo},8}$ = 2.0 Hz, 1 H, H6-exo) 2.09 (broadened d, J_{gem} = 17.0 Hz, 1 H, H6-endo), 1.23 (s, 9 H, *tert*-butyl); ^{13}C NMR δ 28.5 (q), 35.4 (t), 44.8 (d), 46.1 (d), 73.8 (s), 74.4 (d), 121.5 (d), 124.3 (d), 125.6 (d), 126.9 (d), 130.6 (s), 142.9 (s), 148.4 (s).

Anal. Calcd for $C_{16}H_{19}ClO$: C, 73.13; H, 7.29. Found: C, 73.22; H, 7.20.

Acid-Catalyzed Hydrolysis of 11. A mixture of the chloride **11** (100 mg), water (1 mL) and CF_3SO_3H (1 mL) was heated under reflux (N_2 atmosphere) for 3 h. The mixture was diluted with water and extracted with ether, and the ether extracts were washed with $NaHCO_3$ solution and water and then dried. The ether was evaporated, and the residue was submitted to radial chromatography using 5% EtOAc–hexane as eluant. The faster running band afforded 7-chloro-7,10-epoxy-6,7,8,9-tetrahydro-5,9-methano-5*H*-benzocycloheptene (**15**) (48 mg, 60%), which crystallized from pentane as plates, mp 84–5°C: MS *m/z* 208 (M, 20), 206 (M, 57), 177 (30), 175 (14), 171 (29), 170 (15), 153 (12), 143 (41), 142 (39), 141 (100), 131 (44), 129 (25), 128 (52), 127 (17), 115 (37); ^1H NMR (90 Mz) δ 7.14 (narrow m, 4 H, aryl), 5.21 (t, J = 5.2 Hz, 1 H, H10), 3.44 (m, 2 H, H5, H9), 2.51–1.80 (m, AA'BB' part of AA'BB'XX', 4 H, methylene H6, H8); ^{13}C NMR δ 46.5 (d), 48.1 (t), 87.4 (d), 100.0 (s), 124.2 (d), 127.5 (d), 145.8 (s).

Anal. Calcd for $C_{12}H_{11}ClO$: C, 69.74; H, 5.36. Found: C, 69.86; H, 5.39.

The slower running band afforded the hydroxy ketone **14** (12 mg 17%) as colorless crystals, identical with material prepared below.

Reaction of Chloride 11 with KOBu-*t*. A mixture of the chloride **11** (1.80 g, 6.9 mmol), KOBu-*t* (2.5 g, 22.3 mmol), and THF (25 mL) was placed in a thick-walled ampoule (100 mL capacity), which was sealed and heated at 130 °C for 18 h. The dark reaction mixture was poured into water and thoroughly extracted with ether. The ether extract was washed with water, dried, and evaporated, and the residue was filtered through a pad of silica in 20% CH_2Cl_2–hexane to remove colored byproducts.

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The eluate was evaporated to give an oil (1.56 g), which deposited crystals of 7,10-*anti*-di-*tert*-butoxy-6,9-dihydro-5,9-methano-5*H*-benzocycloheptene (**13**) (780 mg), mp 85–7 °C, on addition of cold MeOH (10 mL). The mother liquor was subjected to radial chromatography (5% EtOAc–hexane) to afford a further quantity of **13** (230 mg). The total yield thus was 1.10 g (53%). Recrystallization from MeOH gave plates, mp 88–9 °C: MS *m/z* 300 (M, 0.6), 244 (10), 188 (16), 187 (59), 142 (16), 141 (100), 57 (12); ^{1}H NMR (90 Mz) δ 7.24–7.00 (m, 4 H, aryl), 5.28 (dm, $J_{8,9}$ = 7.0 Hz, 1 H, H8), 4.05 (dd, $J_{10,5} = J_{10,9}$ = 5.0 Hz, 1 H, H10), 3.17 (dd, $J_{9,8}$ = 7.0 Hz, $J_{9,10}$ = 5.0 Hz, 1 H, H9), 3.01 (m, 1 H, H5), 2.63 (ddd, J_{gem} = 16 Hz, $J_{6,5}$ = 5.0 Hz, $J_{6,8}$ = 1.8 Hz, 1 H, H6-exo), 1.84 (ddd, J_{gem} = 16 Hz, $J_{6,5}$ = 1.8 Hz, $J_{6,8}$ = 1.0 Hz, 1 H, H6-endo), 1.24 and 1.23 (2 s, 9 H, 2 *tert*-butyl); ^{13}C NMR 28.6 (q), 29.2 (q), 33.3 (t), 44.3 (d), 44.5 (d), 73.5 (s), 74.5 (d), 77.4 (s), 112.5 (d), 121.0 (d), 124.0 (d), 126.2 (d), 126.5 (d), 143.2 (s), 149.4 (s), 149.6 (s).

Anal. Calcd for $C_{20}H_{28}O_2$: C, 79.96; H, 9.39. Found C, 80.16; H, 9.41.

Hydrolysis of the Di-*tert*-butyl Ether 13. A. A solution of the ether **13** (660 mg) in CH_2Cl_2 (20 mL) was added to a slurry of SiO_2 (5 g) and 10% aqueous oxalic acid.[12] The mixture was stirred at room temperature until TLC analysis showed that the starting material had been consumed (2 h). The mixture was treated with solid $NaHCO_3$ (5 g) and filtered, and the filtrate was evaporated. The residue was subjected to radial chromatography (10% EtOAc–hexane) to give *anti*-10-*tert*-butoxy-5,6,8,9-tetrahydro-5,9-methano-7*H*-benzocyclohepten-7-one (**16**) (515 mg, 96%) as colorless crystals, mp 52–3 °C: MS *m/z* 244 (3), 189 (11), 188 (58), 159 (10), 157 (12), 145 (19), 144 (29), 143 (11), 142 (15), 141 (12), 131 (17), 129 (45), 128 (51), 115 (13), 57 (100), 41 (15); ^{1}H NMR (90 Mz) δ 7.16 (narrow m, 4 H, aryl), 4.18 (t, J = 5 Hz, 1 H, H10), 3.17 (m, 2 H, H5, H9), 2.99 and 2.28 (m, AA'BB' part of AA'BB'MM' system, $J_{AB} \sim$ 17 Hz, 4 H, methylenes), 1.29 (s, 9 H, *tert*-butyl); ^{13}C NMR δ 28.5 (q), 43.3 (t), 44.6 (d), 74.0 (s), 74.4 (d), 124.0 (d), 127.7 (d), 143.8 (s), 210.6 (s); IR ν_{max} ($CHCl_3$) 1710 cm^{-1}.

Anal. Calcd for $C_{16}H_{20}O_2$: C, 78.65; H, 8.25. Found: C, 79.03; H, 8.52.

B. A solution of the di-*tert*-butyl ether **13** (630 mg) in THF (20 mL) containing concentrated H_2SO_4 (5 mL) and water (5 mL) was refluxed for 3 h. The mixture was diluted with water and thoroughly extracted with ether. The ether extract was washed with aqueous $NaHCO_3$ and water, dried, and evaporated. The residue crystallized from CH_2Cl_2–hexane to give *anti*-10-hydroxy-5,6,8,9-tetrahydro-5,9-methano-7*H*-benzocyclohepten-7-one (**14**) as colorless crystals (318 mg, 81%), mp 146–7 °C: MS *m/z* 189 (M + 1, 14), 188 (M, 100), 159 (14), 158 (14), 157 (12), 145 (43), 144 (37), 143 (31), 142 (36), 141 (28), 131 (42), 130 (15), 129 (88), 128 (97), 127 (26), 118 (10), 117 (43), 116 (37), 115 (74), 103 (19), 91 (24), 77 (17), 43 (12); ^{1}H NMR (90 Mz) δ 7.17 (s, 4 H, aryl), 4.35 (t, J = 4.5 Hz, 1 H, H10), 3.34 (s, 1 H, OH), 3.24 (m, 2 H, H5, H9), 2.97 and 2.31 (m, AA'BB' part of AA'BB'MM' system, $J_{AB} \sim$ 17 Hz, 4 H, methylenes); ^{13}C NMR δ 42.8 (t), 44.3 (d), 73.8 (d), 124.2 (d), 128.0 (d), 143.6 (s), 210.4 (s); IR ν_{max} ($CHCl_3$) 3690, 3610, 3420, 1712 cm^{-1}.

Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.42; H, 6.47.

Addition of Dichlorocarbene to 7,7-Dimethoxybenzonorbornadiene (17). A mixture of **17** (1.29 g), $CHCl_3$ (10 mL), 50% NaOH solution (10 mL), and cetyltrimethylammonium bromide (150 mg) was vigorously stirred at 40 °C for 6 h. The mixture was diluted with water and worked up by ether extraction in the usual manner. Distillation (Kugelrohr, 100 °C/0.1 mm) gave unreacted alkene **17** (760 mg). The distillation residue was subjected to radial chromatography using 10% CH_2Cl_2–hexane. The slower moving band afforded additional starting material (120 mg). The faster moving band yielded 6β,7-dichloro-6,9-dihydro-10,10-dimethoxy-5α,9α-methano-5*H*-benzocycloheptene (**19**) (220 mg, 50% based on consumed starting material) as an oil, which crystallized from pentane, mp 86–7 °C: MS *m/z* 251 (M – Cl, 13), 249 (M – Cl, 39), 217 (21), 202 (22), 177 (39), 175 (100), 171 (16), 149 (15), 140 (17), 139 (80), 122 (18), 115 (26), 111 (22), 109 (53), 63 (15), 59 (20); ^{1}H NMR (90 MHz) δ 7.48 (m, 4 H, aryl), 6.30 (dd, $J_{8,9}$ = 7.2 Hz, $J_{8,6}$ = 1.2 Hz, 1 H, H8), 4.93 (dd, $J_{6,5}$ = 5.4 Hz, $J_{6,8}$ = 1.2 Hz, 1 H, H6), 3.76 (dd, $J_{5,6}$ = 5.4 Hz, $J_{5,9}$ = 1.8 Hz, 1 H, H5), 3.50 (dd, $J_{9,8}$ = 7.2 Hz, $J_{9,5}$ = 1.8 Hz, 1 H, H9), 3.26 (s, 3 H, methoxy), 3.15 (s, 3 H, methoxy).

Anal. Calcd for $C_{14}H_{14}Cl_2O_2$: C, 58.97; H, 4.95. Found: C, 58.88; H, 5.27.

Addition of Dichlorocarbene to Benzonorbornadiene (3). A mixture of benzonorbornadiene (14.2 g), $CHCl_3$ (60 mL), 50% NaOH (100 mL), and cetyltrimethylammonium chloride (1.0 g) was stirred at 0 °C for 2 h and then at room temperature overnight. The mixture was diluted with water and extracted with ether, and the ether extract was washed with water, dried, and evaporated (below 30 °C) to give (1aα,2α,7α,7aα)-1,1-dichloro-1a,2,7,7a-tetrahydro-2,7-methanocyclopropa[*b*]naphthalene (**20**) as a pale brown oil (19.6 g, 87%): ^{1}H NMR (60 MHz) δ 7.25–6.85 (AA'BB', 4 H, aryl), 3.54 (broad s, 2 H, H2, H7), 2.60 (A part of AB, further split, J_{AB} = 10 Hz, 1 H, H8), 1.81 (s, 2 H, H1a, H7a), 1.29 (B part of AB, broadened, 1 H, H8); ^{13}C NMR δ 39.5 (t), 41.7 (d), 44.8 (d), 76.8 (s), 121.4 (d), 125.5 (d), 150.1 (s). On vacuum distillation, quantitative isomerization occurred to afford 6α,7-dichloro-6,9-dihydro-5α,9α-methano-5*H*-benzocycloheptene (**21**), bp 117–120 °C/0.8 mm (lit.[2c] bp 92 °C/0.04 mm), having spectral properties identical with those reported.[2] Rearrangement of **20** to **21** also occurred upon attempted flash chromatography on SiO_2.

Registry No. **3**, 4453-90-1; **7**, 15893-89-7; **8**, 125023-43-0; **9**, 125132-87-8; **10**, 125023-44-1; **11**, 125023-45-2; **13**, 125023-46-3; **14**, 55139-53-2; **15**, 125023-47-4; **16**, 125023-48-5; **17**, 42490-91-5; **19**, 125023-49-6; **20**, 125023-50-9; **21**, 54647-00-6; CCl_2, 1605-72-7.

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Total Synthesis of Colneleic Acid

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The lipoxygenase of potato (*Solanum tuberosum*) converts endogenous linoleic acid to a mixture of 9(*S*)- and 13(*S*)-hydroperoxides.[1] The 9(*S*)-hydroperoxide **2** is transformed further by lipoxygenase preparations from potato homogenate under anaerobic conditions to colneleic acid, **1**, an unusual fatty acid which can be isolated from potato tubers.[2] Although the physiological function of colneleic acid in *S. tuberosum* is unknown, the surmise that it might be an important biochemical regulator was rendered more plausible by the finding in this laboratory that **1** is a strong competitive inhibitor of the potato lipoxygenase (K_i at 23 °C and pH 6.3 of 7 μM).[3] For example, it is not unreasonable that hte potato lipoxygenase under regulation by its own product (**1**) could function as an oxygen sensor which links metabolism and oxygen supply.

An earlier research project in our laboratory resulted in the successful development of a biomimetic synthesis of colneleic acid from linoleic acid via the 9(*S*)-hydroperoxide.[3] In this paper we report a totally different chemical route from cheap, non-fatty acid precursors which utilizes novel methodology.

The enol ester **3** was selected as the key intermediate in this synthesis. Stereoselective enolate formation followed by O-phosphorylation was expected to afford the bis enol phosphate **4**. It was anticipated that palladium-

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