Resin Acids. II. Cationic Cyclization of Isopimaric Acid Derivatives. Partial Synthesis of Isohibane*,[1]

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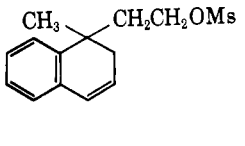
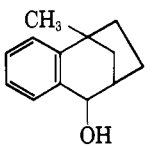
The partial synthesis of dihydroisohibaic acid (**22b**) and isohibane (**22f**) from isopimaric acid is described. The stereochemistry of the intermediates has been elucidated. Cationic cyclization of methyl 20-hydroxy-Δ^7- and -Δ^8-dihydroisopimarate alkyl and arylsulfonates (**8d** and **9d**) did not furnish derivatives of isohibane, but led to compounds of type **10** with rearrangement of the carbon skeleton.

The facile conversion of **1** to **2** by treatment with alumina and wet benzene[3] which involves participation of a properly situated double bond during solvolysis[4] suggested that this system might serve as a model for cationically induced cyclizations of isoprenoids leading to naturally occurring bicyclo[3.2.1]octanes.[5] More specifically, application of this transformation to suitably substituted derivatives of pimaradienes (**3**) was expected to lead to compounds based on the carbon skeleton **4** whose discovery in the realm of natural products could be anticipated,[6] although it was unknown at the inception of this research.



1



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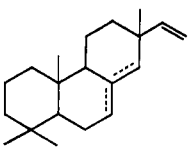

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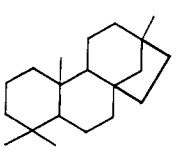
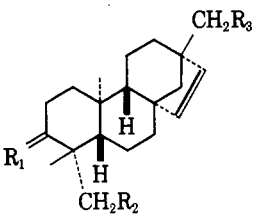
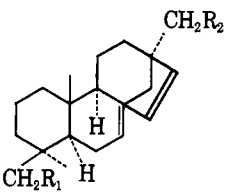


4

In fact the discovery of several compounds based on **4**[7] shortly after our work was begun lent additional impetus to the present study. Because of the recent appearance of an article in the same general area[9] which describes the partial synthesis of isohibaene (**7**) from isopimaradiene (**8a**), we would like to communicate the results of work which derived from our original objective of applying the cationic cyclization **1** → **2** to resin acid derivatives.

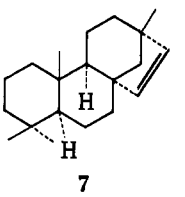


5a, R_1 = O; R_2, R_3 = H
b, R_1 = H_2; R_2, R_3 = H
c, R_1 = H, OH; R_2, R_3 = OH
d, R_1 = H_2; R_2 = OH; R_3 = H
e, R_1 = H_2; R_2 = H; R_3 = OH
f, R_1 = H_2; R_2, R_3 = OH



6a, R_1 = OH; R_2 = H
b, R_1, R_2 = OH

A logical candidate for the solvolytic experiments was methyl 20-hydroxy-Δ^7-dihydroisopimarate (**8c**) which was accessible in good yield by the selective



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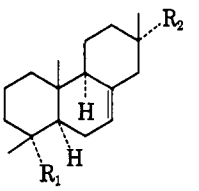


8a, R_1 = CH_3; R_2 = CH=CH_2
b, R_1 = CO_2CH_3; R_2 = CH=CH_2
c, R_1 = CO_2CH_3; R_2 = CH_2CH_2OH
d, R_1 = CO_2CH_3; R_2 = CH_2CH_2OMs
e, R_1 = CO_2H; R_2 = CH_2CH_3

hydroboration of methyl isopimarate (**8b**) using diisoamylborane[10] followed by alkaline hydrogen peroxide oxidation. Attempts to effect cyclization of its

* To Professor Louis F. Fieser.

(1) Supported in part by grants from the Petroleum Research Fund, administered by the American Chemical Society, and the National Science Foundation (GP-1962). Previous paper: N. Halbrook, R. V. Lawrence, R. L. Dressler, R. C. Blackstone, and W. Herz, *J. Org. Chem.*, **29**, 1017 (1964).

(2) Fulbright Travel Scholar, 1962–1964.

(3) W. Herz and G. Caple, *J. Am. Chem. Soc.*, **84**, 3517 (1962).

(4) For a review of previous work, see P. D. Bartlett, *Ann. Chem.*, **653**, 45 (1962).

(5) Cationic cyclizations involving double bonds in general and their applicability to biosynthetic processes have been discussed by W. S. Johnson, *Pure Appl. Chem.*, **7**, 317 (1963); see also (a) W. S. Johnson, D. M. Bailey, R. Owyang, R. A. Bell, B. Jaques, and J. K. Crandall, *J. Am. Chem. Soc.*, **86**, 1959 (1964); (b) W. S. Johnson, S. L. Gray, J. K. Crandall, and D. M. Bailey, *ibid.*, **86**, 1966; **86**, 1972 (1964); (c) W. S. Johnson and J. K. Crandall, *ibid.*, **86**, 2985 (1964); (d) W. S. Johnson and R. Owyang, *ibid.*, **86**, 5593 (1964); (e) J. A. Miller and H. C. S. Wood, *Angew. Chem.*, **76**, 301 (1964).

(6) E. Wenkert, *Chem. Ind.* (London), 282 (1955). Isosteviol which has carbon skeleton **4** is an artifact: F. Dolder, H. Lichti, P. Quitt, and E. Mosettig, *J. Am. Chem. Soc.*, **82**, 246 (1960); E. Mosettig, U. Beglinger, F. Dolder, H. Lichti, P. Quitt, and J. S. Waters, *ibid.*, **85**, 2305 (1963).

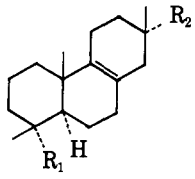
(7) Stachenone (**5a**) and its relatives from *Spirostachys africana* Son: W. H. Baarscher, D. H. S. Horn, and L. F. Johnson, *J. Chem. Soc.*, 4046 (1962); stachene (**5b**), alcohol A (**5d**), alcohol B (**5e**), and the diol **5f** from *Erythroxylon monogynum* Roxb.: R. D. H. Murray and R. McCrindle, *Chem. Ind.* (London), 500 (1964)[8]; beyerol (**5c**) from *Beyeria leschenaultii* (DC) Baill. *var. Drummondii* (Muell. Arg.) Gruning: P. R. Jefferies, R. S. Rosich, D. E. White, and M. C. Wood, *Australian J. Chem.*, **15**, 521 (1962); P. R. Jefferies, R. S. Rosich, and D. E. White, *Tetrahedron Letters*, 1793 (1963); hibaene (**5b**); Y. Kitahara and A. Yoshikoshi, *ibid.* **No. 26**, 1771 (1964); *Bull. Chem. Soc. Japan*, **37**, 890 (1964); L. H. Briggs, R. C. Cambie, P. S. Rutledge, and D. W. Stanton, *Tetrahedron Letters*, 2223 (1964).

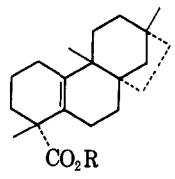
(8) Basing their conclusions on evidence which seemed equally compelling, A. H. Kapadi and S. Dev [*ibid.*, 1171 (1964)] originally assigned the opposite stereochemistry (**6a** and **6b**) to monogynol, apparently identical with Murray and McCrindle's diol, from *E. monogynum*. For comments on this discrepancy, see J. D. Connolly, R. McCrindle, R. D. H. Murray, K. H. Overton, and A. Melera, *ibid.*, 1859 (1964). This matter has now been resolved in favor of **5d** and **5f** [A. H. Kapadi and S. Dev, *ibid.*, 2751 (1964)] and settled by the partial synthesis of monogynol (**5d**) from isosteviol [J. R. Hanson, *Chem. Ind.* (London), 1579 (1964)].

(9) E. Wenkert, P. W. Jeffs, and J. R. Mahajan, *J. Am. Chem. Soc.*, **86**, 2218 (1964).

(10) H. C. Brown and G. Zweifel, *ibid.*, **82**, 3222, 3223 (1960); **83**, 1241 (1961).

methanesulfonate (**8d**) by the mild method which had proved effective for **1** were abortive[11] and recourse was had to the more usual solvolytic conditions. Acetolysis of **8d** in the presence of 1 mole equiv. of sodium acetate at 118° followed by extensive chromatography over alumina resulted in the isolation of three compounds A, B, and C which were obtained in 30, 23, and 40% yields. B and C were identified as **9a** and **9b**,



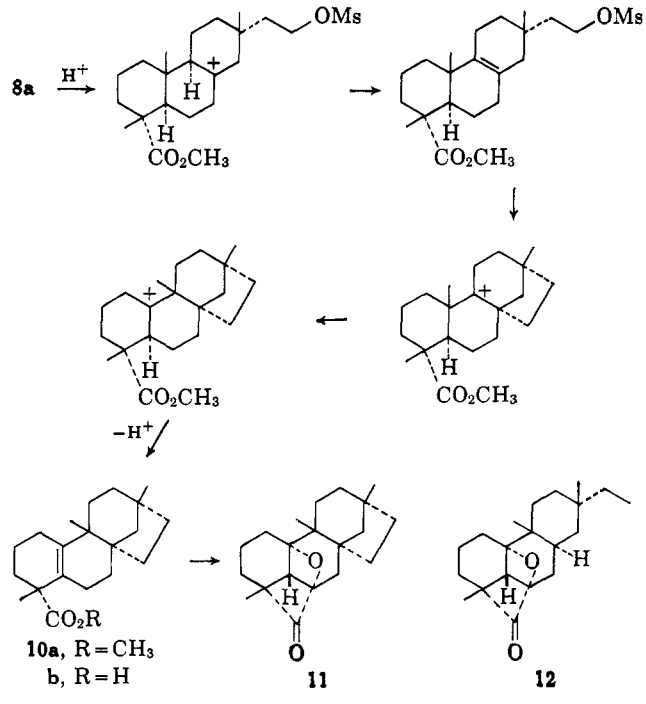


9a, $R_1 = CO_2CH_3$; $R_2 = CH_2CH_2OAc$ **10a**, R = CH_3
b, $R_1 = CO_2CH_3$; $R_2 = CH_2CH_2OH$ **b**, R = H
c, $R_1 = CO_2CH_3$; $R_2 = CH_2CH_2OMs$
d, $R_1 = CO_2CH_3$; $R_2 = CH_2CH_2OBs$

respectively (see Experimental), double-bond isomerization under acid conditions[12] being accompanied by nucleophilic displacement.[13]

Acetolysis of **8d** in the absence of sodium acetate furnished in 89% yield only compound A, $C_{21}H_{32}O_2$, whose structure **10a** follows from the following observations. In the infrared, A exhibited no hydroxyl or double-bond absorption, but the presence of a tetrasubstituted double bond was indicated by strong end absorption in the ultraviolet and a positive tetranitromethane test. The n.m.r. spectrum was devoid of signals characteristic of vinyl hydrogens or of protons α to oxygenated functions (other than the singlet of the carbomethoxy group) and the singlets previously associated with C-10 and C-13 methyl had shifted downfield from 0.79 and 0.88 to 0.97 p.p.m.

The existence of a tetrasubstituted double bond was supported by oxidation of **10a** to a mixture exhibiting α,β-unsaturated ketone absorption at 248 mμ (see Experimental) which when coupled with the elemental analysis required the presence of four rings. Mechanistic considerations (**8d** → **10a**)[14,15] then led to formula **10a** which was confirmed in the following manner. Hydrolysis of **10a** furnished an amorphous acid **10b** (methyl singlets at 0.98, 0.98, and 1.28 p.p.m.) which on treatment with concentrated sulfuric acid at −10°[12] afforded a γ-lactone **11** (infrared band at 1780 cm.$^{-1}$). The n.m.r. spectrum of **11** (methyl singlets at 0.99, 0.99, and 1.10 p.p.m.) indicated the absence of low-field protons (lactone closed to tertiary position); lactonization was accompanied by an upfield shift of the C-4 methyl signal which is also observed during the conversion of **8e** (methyl singlets at 0.70, 0.90, and 1.26 p.p.m.) to **12** (methyl singlets at 0.82, 0.87, and 1.12 p.p.m.).[16]



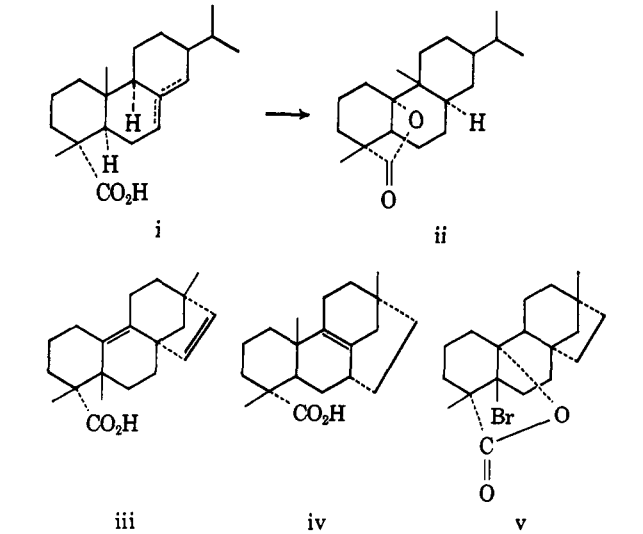
(11) Stirring with alumina and wet benzene at 0 and 60° resulted in a 92% recovery of **8d**.

(12) O. E. Edwards and R. Howe, *Can. J. Chem.*, **37**, 760 (1959).

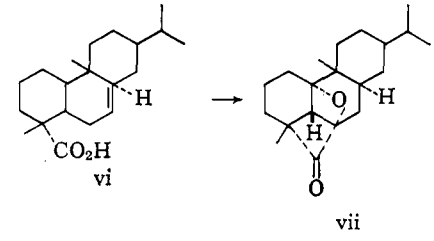
(13) The formation of primary alcohol **9b** is probably due to prolonged exposure of **9a** to alumina on the chromatographic column: W. F. Johns and D. M. Jerina, *J. Org. Chem.*, **28**, 2922 (1963).

(14) *Cf.* the conversion of the dihydrobietic acids (i)[15] and of dihydroisopimaric acid (**8e**) to the lactones ii and **12**: D. H. R. Barton, *Chem. Ind.* (London), 638 (1948); L. A. Subluskey and T. F. Sanderson, *J. Am. Chem. Soc.*, **76**, 3512 (1954); L. Velluz, G. Muller, A. Petit, and J. Mathieu, *Bull. soc. chim. France*, 401 (1954); Le-Van-Thoi and J. Ourgaud, *ibid.*, 202 (1956). The depiction of discrete carbonium ion intermediates is a matter of convenience only and is not intended to exclude the more likely[5d] possibility of a synchronous cyclization *cum* rearrangement. In the pimaric acid series (C-13 vinyl side chain quasi-axial) concerted methyl migration during the cationic cyclization is not possible and indeed all naturally occurring diterpenes containing carbon skeleton **4** which have been isolated so far[7,8] have the stereochemistry predictable from the cationic cyclization of an appropriately substituted (−)- or (+)-pimaradiene derivative. Attempts to effect this transformation under laboratory conditions are now in progress.

(15) The only other structures which can be constructed with Dreiding models and satisfy the chemical evidence presented so far are the mechanistically quite unjustifiable iii and iv. Moreover severe crowding at the α face of iv would be expected to interfere with the facile lactonization actually observed. Thus bromolactonization of the tetracyclic substance (see Experimental) results in the formation of a bromo derivative whose infrared spectrum (band at 1770 cm.$^{-1}$) established it as a γ-lactone, presumably v.



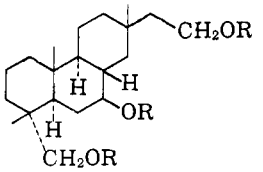
(16) W. Herz and J. Wahlborg, *J. Org. Chem.*, **30**, 1881 (1965).



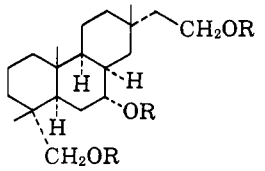
The intermediacy of **9c** required by the proposed cyclization mechanism was established by converting **9b** to **9d** and solvolyzing the latter. This resulted in a quantitative yield of **10a**.

Acetolysis of **8d** had thus led to a substance whose carbon skeleton differed from the desired **4**, although its mode of formation makes it likely that representatives of system **10** will be found among natural products of the future. We therefore undertook the transformation of isopimaric acid into derivatives of **4** by methods which were not intended to simulate possible biogenetic processes, but would nevertheless serve to correlate the two diterpenoid types.

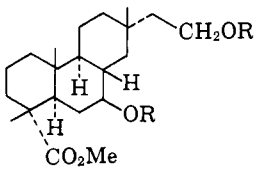
Dihydroboration of methyl isopimarate (1:1 ratio of diene to diborane) for a prolonged period followed by oxidation gave a complex mixture of products from which two triols, m.p. 241–242° (**13a**, 34%) and m.p. 175° (**14a**, 6%), and two diol esters, m.p. 167–169° (**15a**, 3.6%) and m.p. 75° (**16a**, 1.9%), could be obtained.[17] On the assumption that the triols were formed in a slow reduction step from initially generated mono- or dialkylboranes,[18] the contact time was reduced to 3 hr. This resulted in greatly improved yields of the diol esters **15a** and **16a**, the latter being formed in considerable excess (17 and 62% yields). No indication that the triols **13a** and **14a** were present was obtained but a small amount of a diol **17** which had resulted from nonterminal addition[19a] of diborane to the vinyl side chain was isolated.



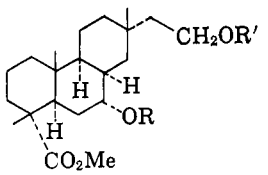
13a, R = H
b, R = Ac



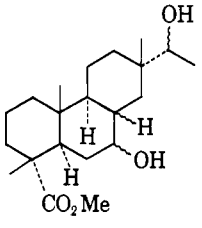
14a, R = H
b, R = Ac



15a, R = H
b, R = Ac



16a, R = H; R′ = H
b, R = Ac; R′ = Ac.
c, R = H; R′ = Ac



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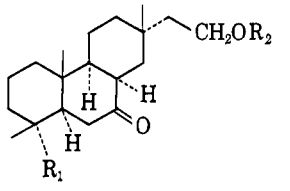
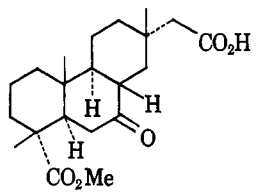


18a, R_1 = CH_2OH; R_2 = H
b, R_1 = CO_2Me; R_2 = H
c, R_1 = CH_2OBs; R_2 = Bs
d, R_1 = CO_2Me; R_2 = Bs
e, R_1 = CO_2Me; R_2 = Ac



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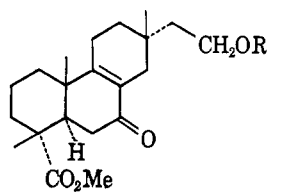
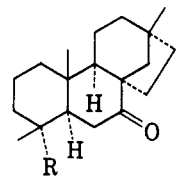
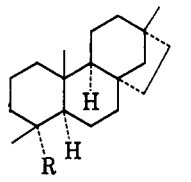


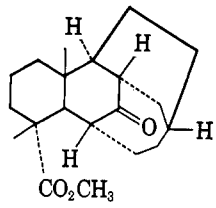
20a, R = H
b, R = Ac



21a, R = CH_2OBs
b, R = CO_2CH_3
c, R = CO_2H
d, R = CO_2-*t*-Bu



22a, R = CO_2CH_3
b, R = CO_2H
c, R = CH_2OH
d, R = CHO
e, R = CN
f, R = CH_3



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Taking into account the known *cis* mode of addition during the hydroboration–oxidation process[19b] and the predisposition of the tricyclic diterpene system toward attack from the less hindered α side, it was expected that the preponderantly formed diol ester, *i.e.*, the substance, m.p. 75°, would have the stereochemistry represented by **16a** and the minor product, m.p. 167–169°, strucure **15a**.

Support for this assignment was found in the n.m.r spectra of the two diacetates **15b** and **16b**. The acetate **15b** prepared from the diol ester, m.p. 167–169°, exhibits the H-7 signal as a broad triplet extending from 4.75 to 4.35 and centered at 4.5 p.p.m., while in the derivative **16b** prepared from the diol ester, m.p. 75°, this signal is a broadened singlet at 4.68 p.p.m. (half-height width of 6 c.p.s.). The greater splitting in the former can be accounted for if H-7 is axial (*i.e.*, α) since it would then experience two large axial–axial and one small axial–equatorial coupling. The second signal is characteristic of H-7 equatorial (*i.e.*, β) which is coupled to two equatorial and one axial protons (all couplings small).[20] The chemical shift difference between the H-7 protons of **15b** and **16b** is smaller than usual (about 0.4 p.p.m.),[21] perhaps because equatorial H-7 (in **16a**) is shielded by the C-8–C-14 bond or, more plausibly, because of the long-range effect of the carbomethoxy group.

(17) Yields are based on isolation of sharply melting crystalline material although infrared and n.m.r. analysis of the various fractions indicated that the hydroboration products were formed in larger quantities. The apparent preponderance of high-melting triol **13a** relative to the other products is perhaps partially due to its solubility characteristics which cause it to separate in crystalline form during the work-up (see Experimental).

(18) H. C. Brown and K. A. Keblys, *J. Am. Chem. Soc.*, **86**, 1795 (1964).

(19) H. C. Brown, "Hydroboration," W. A. Benjamin, Inc., New York, N. Y., 1962: (a) pp. 12, 113–122; (b) pp. 14–16, 123–135.

(20) A similar argument has been employed by A. I. Scott, D. W. Young, S. A. Hutchinson, and N. S. Bhacca [*Tetrahedron Letters*, **No. 15**, 849 (1964)] in assigning the configuration of the 2-hydroxyl group of isorosenolic acid. See also ref. 9 for an analogous diagnosis of the stereochemistry of the two diols prepared by hydroboration–oxidation of isopimaradiene.

(21) L. M. Jackman, "Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," Pergamon Press, Ltd., Oxford, 1959, p. 116.

Since the triol, m.p. 175°, can be prepared also by lithium aluminum hydride reduction of the diol ester, m.p. 75° (**16a**), it belongs to the same stereochemical series as **16a** and can be assigned formula **14a**, the epimeric triol, m.p. 241–242°, being represented by **13a**. This assignment is also supported by n.m.r. evidence. In the spectrum of the triacetate **13b**, the C-7 proton gives rise to a signal (broad triplet from 4.6–4.2 centered at 4.4 p.p.m., axial H) comparable with H-7 of **15b**, while the corresponding signal in the n.m.r. spectrum of **14b** is found at 4.79 p.p.m. (broadened singlet, half-height width 6 c.p.s., equatorial H) which correlates with H-7 of **16b**.[22]

Configurations having been assigned to the diol esters and triols, attention could be turned again toward the synthesis of compounds of type **4**. Since the selective tosylation of the primary hydroxyl group of **15a** and **16a** offered some initial difficulties, selective oxidation of the secondary hydroxyl groups with N-bromoacetamide was investigated. Treatment of **13a** and **15a** with a slight excess of the oxidizing agent in aqueous *t*-butyl alcohol afforded the ketodiol **18a** and the ketol ester **18b**, respectively, in excellent yield. Excess bromoacetamide converted **15a** to a mixture of **18a** (43%) and **19** (34%). Since **18a**, **18b**, and **19** were unchanged either on chromatography over basic alumina or on treatment with base, they must possess the more stable 8β-hydrogen configuration.

Oxidation of the epimeric diol ester **16a** with N-bromoacetamide proceeded much less smoothly (see Experimental). Yields of the ketol ester **18b**, presumably formed by isomerization of the intermediate *cis* ketone (H-8, α) whose presence was not observed, never exceeded 30%, the remainder consisting of a complex mixture of products. One of these, from a run using excess N-bromoacetamide, was apparently **20b** and identified through its dinitrophenylhydrazone. Such a compound could have arisen through bromination at C-8 of a *trans–anti–cis*-fused tricyclic derivative[23] followed by dehydrobromination. Its formation strengthens the assignment of formula **16a** to the low-melting diol ester.

Because **16a** was the predominantly formed isomer in the hydroboration–oxidation reaction, other means were sought to convert this compound to the required ketol ester and to improve the efficiency of the synthetic scheme. Although selective tosylation had been unsuccessful (*vide supra*), selective acetylation of the primary hydroxyl group in **16a** was achieved by treatment with acetic acid–sulfuric acid at 25°. The monoacetate **16c**, formed in 80% yield, was readily oxidized with Jones or Sarett reagent to the oily ketone **18e** (characterized as its 2,4-dinitrophenylhydrazone) which was easily hydrolyzed (with concomitant epimerization at C-8) to the ketol ester **18b**, the over-all yield from **16a** being not less than 50%.

Cyclization of **18c** and **18d** to **21a** and **21b**, compounds possessing the desired carbon skeleton **4**, was accomplished readily with potassium *t*-butoxide in *t*-butyl alcohol at room temperature. Conversion of **21b** to the thioketal followed by Raney nickel treatment resulted in **22a** which was hydrolyzed to **22b**, the dihydro derivative of a new resin acid.

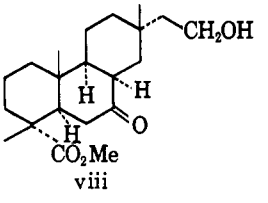
The possibility that preferred enolization of **18c** and **18d** toward C-6 might have led to compounds of type **23** was considered slight since models demonstrate that such compounds experience severe nonbonded interactions which would effectively raise the energy of the transition state leading to attack by the side chain on C-8. Since the cyclized substances gave a weak, though definitely positive Zimmermann test,[26] we conclude that the postulated structures are correct. Moreover, **21** exhibited the same relatively weak negative Cotton effect also found in 7-ketoisohibaene[9] and not the profoundly altered o.r.d. curve to be expected from **23** by inspection of the model.

Lithium aluminum hydride reduction of **22a** followed by oxidation led *via* **22c** to **22d**. The latter was converted to the semicarbazone whose Wolff–Kishner reduction by standard procedures[27] afforded as the only isolable product the nitrile **22e** (22%). Its infrared spectrum contained the characteristic peak at 2230 cm.$^{-1}$, while the n.m.r. spectrum showed signals corresponding to only three methyl groups, one of which appeared downfield from the others at 1.29 p.p.m.

The Wolff–Kishner reduction was therefore repeated on the aldehyde following the method of King and coworkers[28] to give isohibane (**22f**) which proved to be very alcohol volatile. This observation possibly accounts for the absence of **22f** in the semicarbazone reduction and the low yield in the hydrazone reduction because in both cases the reduction mixture is concentrated. When the procedure was modified to eliminate removal

(22) Even though the material balance of crystalline products in the hydroboration of methyl isopimarate involving prolonged contact time with diborane is poor, the great predominance of triol **13**[9] which is generated by addition from the sterically more hindered β side needs to be commented upon (for a partial explanation see footnote 17), particularly in view of the considerably lower yields of diol ester **15a**, the oxidation product of the necessary intermediate, from the hydroborations involving a short contact time. A possible *rationale* for this observation is that the prolonged contact time (prior to oxidation) allows the kinetically favored, but less stable precursor of **16a** (C-7–B bond axial) to equilibrate[19] to the thermodynamically favored precursor of **15a** (C-7–B bond equatorial), which is then oxidized to **13a**. A referee has suggested that the higher melting triol was isolated preferentially, because of its lower solubility[17] and that the resulting triol mixture, rich in the 175° isomer, decomposed on the alumina column used for the separation, thus accounting for the apparent anomaly in isomer distribution. However, the low-melting isomer remained unaffected by prolonged treatment with alumina.

(23) Work done by Corey and Sneen[24] and Jones and Wluka[25] has shown that 7-keto-5-α steroids having *trans*-fused B/C rings do not undergo direct C-8 bromination but instead furnish 6β-bromo derivatives through the Δ^5-enol. It has been suggested[24] that the Δ^7-enol is not formed because the 8β-hydrogen is shielded by the angular methyl groups. This reason for the nonformation of a Δ^7-enol would not apply to the 8α-ring B/C *cis*-fused viii initially formed by oxidation of **16a**. Indeed, enolization of viii toward Δ^7 to relieve nonbonded interactions inherent in the *cis*-B/C fusion (C-10 methyl and 14-methylene diaxial) would be favored. If instead of undergoing bromination the Δ^7-enol reverts to the keto form, the more stable



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ketone **18b** will be produced as actually observed. Side-chain aldehyde produced by excess oxidizing agent might be trapped by intramolecular aldol condensation with the Δ^7-enol as observed by Wenkert, Jeffs, and Mahajan[9] in the isopimarane series and be subject to further oxidation, thus accounting for the poor yield.

(24) E. J. Corey and R. A. Sneen, *J. Am. Chem. Soc.*, **78**, 6269 (1956).

(25) E. R. H. Jones and D. J. Wluka, *J. Chem. Soc.*, 911 (1959).

(26) Models show that the C-6 methylene group of **21** is quite hindered and would not be expected to give a strong test.

(27) R. E. Ireland and P. W. Schiess, *J. Org. Chem.*, **28**, 6 (1963).

(28) F. E. King, D. H. Goodson, and T. J. King, *J. Chem. Soc.*, 1117 (1955).

of solvents, **22f** was obtained in 84% yield and is thus available for comparison with material produced by appropriate transformations of potential natural products.

Experimental[29]

Hydroboration of Methyl Isopimarate with Diisoamylborane.—To a solution of diisoamylborane prepared from 1.51 g. (0.04 mole) of sodium borohydride, 7.3 g. (0.104 mole) of 2-methyl-2-butene, and 7.4 g. (0.052 mole) of boron trifluoride etherate in 35 ml. of diglyme was added in a nitrogen atmosphere at 0° with stirring a solution of 14.82 g. (0.047 mole) of methyl isopimarate[30] in 40 ml. of diglyme over a period of 10 min. The mixture was stirred at room temperature for 60 hr. and cooled to −10°. A few drops of water were added to destroy excess diisoamylborane and then 20 ml. of cold 3 *N* sodium hydroxide solution. This was followed by dropwise addition of 20 ml. of 30% hydrogen peroxide at such a rate that the temperature did not exceed 50°. The mixture was extracted thoroughly with ether, and the ether was washed with several portions of water, dried, and distilled, residual diglyme being removed at 1 mm. The residue, 14.9 g., was recrystallized from methanol to yield 13.9 g. (89%) of methyl 20-hydroxy-Δ^7-dihydroisopimarate (**8c**), m.p. 83–86°. The analytical sample was recrystallized from isooctane: m.p. 90–90.5°; $[\alpha]^{21}D$ −3.26°; infrared bands at 3600 (nonbonded OH) and 1730 cm.$^{-1}$ (ester); n.m.r. signals at 0.79, 0.88, and 1.28 (methyl singlets), 3.66 (methyl ester), 3.72 t (2 protons, J = 7 c.p.s., $-CH_2O$), and 5.3 d p.p.m. (J = 5 c.p.s., broadened, H-7).

Anal. Calcd. for $C_{21}H_{34}O_3$: C, 75.40; H, 10.25; O, 14.35. Found: C, 76.07; H, 9.81; O, 14.31.

The methanesulfonate **8d** was prepared from 7.99 g. of **8c** and 7 ml. of methanesulfonyl chloride in 40 ml. of dry pyridine at 0°. After 12 hr. in the refrigerator, the mixture was decomposed with ice–hydrochloric acid, the oil was extracted with ether, and the organic extract was thoroughly washed and dried. Evaporation of the solvent yielded 9.44 g. of an oil which crystallized on trituration with 50 ml. of petroleum ether (b.p. 35–60°), yield 8 g. of solid, m.p. 64°. Recrystallization from hexane furnished 6.1 g. (62%) of mesylate: m.p. 70–70.5°; $[\alpha]^{21}D$ 0.71°; infrared bands at 1730 (ester), 1485 and 1475 cm.$^{-1}$ (methanesulfonate); n.m.r. signals at 0.81, 0.89, and 1.26 (methyl singlets), 2.98 (methyl of methanesulfonate), 3.62 (methyl ester), 4.30 t (2 protons, J = 7.5 c.p.s., $-CH_2OSO_2R$), and 5.30 d p.p.m. (br, J = 5 c.p.s., H-8).

Anal. Calcd. for $C_{22}H_{36}O_5S$: C, 64.04; H, 8.79; O, 19.39. Found: C, 63.87; H, 8.63; O, 19.25.

Acetolysis of the Methanesulfonate 8d. A.—A solution of 1.0 g. of the mesylate in 62.5 ml. of glacial acetic acid was refluxed for 3 hr. and concentrated at reduced pressure; residual acetic acid was removed at 1 mm. The residue was chromatographed over 20 g. of alumina (Alcoa F-20); solvent and eluent were 50-ml. portions of ethyl acetate. The first fraction contained 0.76 g. of a yellow oil which was rechromatographed over alumina. Benzene eluted 0.68 g. of essentially pure **10a** (89%) which was recrystallized with considerable losses from methanol, m.p. 66–67°, yield 0.31 g. (40%). The analytical sample melted at 71.5–72°: $[\alpha]^{21}D$ −20°; infrared band at 1740 cm.$^{-1}$ (ester); n.m.r. signals at 0.97, 0.97, 1.27 (methyl singlets), and 3.62 p.p.m. (methyl ester).

Anal. Calcd. for $C_{21}H_{32}O_2$: C, 79.70; H, 10.19; O, 10.11. Found: C, 79.47; H, 9.96; O, 10.42.

B.—Acetolysis of 10 g. of the mesylate in 365 ml. of glacial acetic acid containing 1.99 g. of anhydrous sodium acetate at the boiling point for 21 hr. was followed by removal of acetic acid *in vacuo*, solution of the residue in water, and extraction with ether. The ether extract was washed, dried, and concentrated, and the residue, 8.55 g., was chromatographed over alumina; solvent and eluent were ethyl acetate. This did not induce crystallization. The recovered material, 8.06 g., was therefore rechromatographed, using 500-ml. eluent fractions which were monitored by infrared analysis. Fractions 1–3 (petroleum ether, b.p. 35–60°) and 5 (1:1 petroleum ether–benzene and benzene) furnished 2.36 g. (30%) of the tetracyclic ester prior to crystallization. Fractions 6–13 (1:1 petroleum ether–benzene) yielded 2.06 g. (23%) of oily **9a**: n.m.r. signals at 0.92, 0.98, and 1.18 (methyl singlets),[31] and 1.99 p.p.m.

Anal. Calcd. for $C_{23}H_{36}O_4$: C, 73.37; H, 9.64; O, 17.00. Found: C, 73.29; H, 9.59; O, 16.93.

Fractions 14–24 (1:1 benzene–ether and ether) yielded 3.28 g. (40%) of gummy **9b**: n.m.r. signals at 0.86, 0.96, and 1.17 (methyl singlets), and 3.60 p.p.m. (methoxyl) superimposed on a triplet (2 protons, J = 8 c.p.s., $-CH_2OH$). Acetylation converted **9b** to **9a**. The *p*-bromobenzenesulfonate **9d** was prepared in the usual fashion from 1.0 g. of **9b**. The gummy product was taken up in benzene and chromatographed over 20 g. of silicic acid. Benzene eluted 1.6 g. of **9d** which partially crystallized on standing and was recrystallized from petroleum ether, m.p. 73–75°.

Anal. Calcd. for $C_{27}H_{37}BrO_5S$: C, 58.56; H, 6.74; Br, 14.44; O, 14.45. Found: C, 58.42; H, 6.68; Br, 14.15; O, 14.47.

Acetolysis of 1.1 g. of **9d** with glacial acetic acid at the reflux temperature followed by the usual work-up and chromatography over alumina furnished, from the benzene eluate, 0.6 g. (100%) of an oil which was identified as **10a** by its infrared and n.m.r. spectrum. Recrystallization from methanol gave material identical with **10a** by melting point and mixture melting point. Oxidation of the tetracyclic methyl ester, 0.63 g., with sodium dichromate–acetic acid at room temperature for 65 hr. followed by 2 hr. at 95° yielded, after the usual work-up, an oil, 0.54 g., which exhibited an additional carbonyl band at 1670 cm.$^{-1}$ (conjugated transoid ketone) and had an ultraviolet maximum at 248 mμ (ϵ 3800), but could not be induced to crystallize even after chromatography. The low extinction coefficient indicated that this was a mixture. This was supported by the n.m.r. spectrum which demonstrated the presence of compounds having different methoxyl chemical shifts. The methyl region was complex, approximately six protons being found near 1.3 p.p.m. (deshielding by carbomethoxy and new carbonyl groups), but there were no vinyl protons.

Hydrolysis of 1 g. of the tetracyclic ester at the reflux temperature with 5% ethanolic sodium hydroxide solution for 66 hr. followed by acidification gave an amorphous colorless acid which was chromatographed over silicic acid but could not be crystallized satisfactorily, n.m.r. signals at 0.99, 0.99, and 1.28 p.p.m. (three methyl singlets). Treatment with diazomethane regenerated **10a**. Conversion to the cyclohexylamine salt gave crystalline material which was recrystallized from chloroform containing a few drops of cyclohexylamine, m.p. 192°. Drying at elevated temperatures caused partial decomposition, but prolonged drying at room temperature furnished material which gave satisfactory analytical values.

Anal. Calcd. for $C_{20}H_{30}O_2 \cdot C_6H_{13}N$: C, 77.75; H, 10.79; N, 3.49; O, 7.97. Found: C, 77.04; H, 11.00; N, 3.65; O, 8.04.

The amorphous tetracyclic acid, 0.22 g., was added in small portions to 3 ml. of concentrated sulfuric acid kept at 0°. After 1 hr., the mixture was poured into ice water and extracted with ether. The organic layer was washed with potassium bicarbonate solution and water and dried. Concentration furnished 0.21 g. of crystalline material which was recrystallized from methanol–water: yield 0.18 g.; m.p. 121–122°; $[\alpha]^{21}D$ −34.6°; infrared bands at 1780 cm.$^{-1}$ (γ-lactone); n.m.r. signals at 0.99, 0.99, and 1.10 p.p.m. (methyl singlets).

Anal. Calcd. for $C_{20}H_{30}O_2$: C, 79.42; H, 10.00; O, 10.58. Found: C, 79.47; H, 9.96; O, 10.75.

Dihydroisopimaric acid, m.p. 174–175°, was prepared by the method of Edwards and Howe.[12] The infrared spectrum differed significantly from that of **10b**; n.m.r. signals were at 0.70, 0.90, 1.26 (3 methyl singlets), and 5.27 p.p.m. (complex, H-7); lacton-

(29) Melting points and boiling points are uncorrected. Analyses are by Dr. F. Pascher, Bonn, Germany. Infrared spectra were run in carbon tetrachloride unless otherwise specified, ultraviolet spectra in 95% ethanol, rotations in chloroform. N.m.r. spectra were run on an A-60 spectrometer in deuteriochloroform with tetramethylsilane serving as internal standard. Signals are reported in p.p.m. Optical rotatory dispersion curves were determined by Dr. L. R. Tether on a Rudolph recording spectropolarimeter. Alumina used for chromatographic separations was Alcoa grade F-20.

(30) M.p. 62–62.5°, prepared in 96% yield from diazomethane and isopimaric acid. The latter was isolated from WW gum rosin, kindly supplied by Mr. Ray V. Lawrence and Dr. Glen W. Hedrick, Naval Stores Laboratory, Olustee, Fla. by the procedure of D. E. Baldwin, V. M. Loeblich, and R. V. Lawrence [*J. Org. Chem.*, **23**, 25 (1958)].

(31) The conversion of abietic acid to $\Delta^{8,9}$-dihydroabietic acid is also accompanied by a downfield shift of the C-10 methyl signal (from 0.81 to 0.97 p.p.m.).

ization furnished the known γ-lactone, m.p. 107–108.5°, with n.m.r. signals at 0.82, 0.87, and 1.12 p.p.m.

Bromolactonization of 0.03 g. of the tetracyclic acid by the method of Winterstein and Egli[32] gave 0.025 g. of a neutral substance containing bromine which solidified after chromatography and appeared to be homogeneous (thin layer chromatography). The infrared spectrum exhibited a sharp γ-lactone band at 1770 cm.$^{-1}$. Recrystallization from aqueous methanol furnished crystals, m.p. 120–122°, but the material could not be analyzed satisfactorily.

Bromination of $\Delta^{8,9}$ resin acid derivatives under comparable conditions results in acidic compounds exhibiting dienic absorption in the ultraviolet.

Hydroboration of Methyl Isopimarate with Diborane. A.—To a solution of 57 g. (0.18 mole) of methyl isopimarate and 10.6 g. (0.28 mole) of sodium borohydride in 225 ml. of diglyme was added with stirring in a nitrogen atmosphere 51 g. (0.36 mole) of boron trifluoride etherate over 1.5 hr. After 65 hr. at room temperature, the mixture was cooled in an ice bath and excess diborane was destroyed with water. Then 125 ml. of 3 *N* sodium hydroxide solution was added slowly followed by 125 ml. of 30% hydrogen peroxide. After 2 hr. the mixture was poured into water and extracted thoroughly with ether. During this procedure, crystalline **13a** separated and was filtered by suction; 18.6 g., m.p. 232–233°. Recrystallization from ethanol and methanol raised the melting point to 241–242°; infrared spectrum (KBr) devoid of carbonyl absorption; n.m.r. signals in trifluoroacetic acid at 0.95, 0.95, and 1.02 (methyl singlets), 4.19 (2 protons, center of H-18 AB system, J = 10 c.p.s., $\delta_B - \delta_A$ = 16), 4.5 t p.p.m. (J = 8 c.p.s., H-20, superimposed on H-7).

Anal. Calcd. for $C_{20}H_{36}O_3$: C, 74.02; H, 11.18; O, 14.79. Found: C, 73.75; H, 11.32; O, 15.10.

The triacetate **13b** was prepared with acetic anhydride–pyridine and melted at 122° after recrystallization from methanol–water: infrared band ($CHCl_3$) at 1735 cm.$^{-1}$; n.m.r. signals at 0.84, 0.90, 0.92 (methyl singlets), 2.06, 2.06, 2.08 (acetate singlets), 3.74 br (2 protons, H-18), 4.14 t (2 protons, J = 7.5 c.p.s., H-20), and 4.4 c p.p.m. (H-7).

Anal. Calcd. for $C_{26}H_{42}O_6$: C, 69.30; H, 9.39; O, 21.30. Found: C, 69.21; H, 9.28; O, 21.06.

The filtrate from the separation of **13a** was extracted with ether and chloroform; the combined organic layers were washed, dried, and evaporated, yielding a residue of 37 g. A suspension of 33 g. of the residue in benzene–petroleum ether was chromatographed over 725 g. of alumina. Benzene–petroleum ether (1:1), benzene, benzene–ether (1:1), and ether eluted 1.5 g. of noncrystalline material; ether–methanol (1:1) eluted 30.1 g. of noncrystalline material which was rechromatographed over 750 g. of alumina. Fractions 3–7 (750-ml. portions of 9:1 ether–methanol) eluted 19.8 g. of noncrystalline material, fractions 8–12 (750-ml. portions of 9:1 ether–methanol) eluted 1.95 g. of solid which on recrystallization from methanol furnished 1.0 g. of **13a**, and fractions 14–17 (750-ml. portions of 3:1 ether–methanol) gave 4.4 g. of gum which was taken up in hot methanol and concentrated; total yield of crystalline **14a** 3.5 g., m.p. 172–173°. Recrystallization from isopropyl alcohol raised the melting point to 175°; infrared spectrum (KBr) was devoid of carbonyl absorption; n.m.r. signals (trifluoroacetic acid) at 0.98, 0.98, 1.20, (methyl singlets), 4.10 br (2 protons, H-18), 4.50 t (2 protons, H-20), and 5.15 br p.p.m. (H-7, half-height width 7 c.p.s.).

Anal. Calcd. for $C_{20}H_{36}O_3$: C, 74.02; H, 11.18; O, 14.79. Found: C, 73.96; H, 11.18; O, 14.89.

The triacetate **14b**, prepared with pyridine–acetic anhydride, could not be induced to crystallize but was purified by chromatography: infrared band ($CHCl_3$) at 1735 cm.$^{-1}$; n.m.r. signals at 0.85, 0.93, and 1.10 (methyl singlets), 2.06, 2.06, and 2.08 (acetate singlets), 3.73 (2 protons, center of AB band, J = 13 c.p.s., $\delta_B - \delta_A \sim 5$, H-18), 4.11 t (2 protons, J = 7 c.p.s., H-20), and 4.79 br p.p.m. (half-height width 6 c.p.s., H-7).

Anal. Calcd. for $C_{26}H_{42}O_6$: C, 69.30; H, 9.30; O, 21.30. Found: C, 69.01; H, 9.15; O, 21.65.

Fractions 3–7 were rechromatographed over 450 g. of alumina with 750-ml. portions of ether (**1**), 1:1 ether–ethyl acetate (**4**), 1:1 ethyl acetate–acetone (**9**), 99:1 ether–methanol (**2**), 9:1 ether–methanol (**3**), and 3:1 ether–methanol (**3**). Fractions 9–11, 6.9 g., were taken up in acetone, diluted with water until cloudy, and allowed to stand. The precipitate, 4 g., was taken up in 250 ml. of isooctane and 150 ml. of acetone, filtered, concentrated to remove the acetone, and allowed to stand. There precipitated 2.3 g. of crystalline **15a**, m.p. 167–169°. The melting point was not raised by further crystallization from benzene; infrared bands (KBr pellet) at 3550 and 1715 cm.$^{-1}$; n.m.r. signals at 0.90, 0.90, and 1.20 (methyl singlets), 3.20 c (H-7), 3.67 (methoxyl), and 3.8 t (2 protons, J = 8 c.p.s., H-20).

Anal. Calcd. for $C_{21}H_{36}O_4$: C, 71.55; H, 10.30; O, 18.15. Found: C, 71.77; H, 9.97; O, 18.58.

The noncrystalline diacetate **15b**, prepared with acetic anhydride–pyridine, was purified by chromatography: infrared bands ($CHCl_3$) at 1735 cm.$^{-1}$; n.m.r. signals at 0.92, 0.94, and 1.19 (methyl singlets), 3.68 (methoxyl), 4.14 t (2 protons, J = 8 c.p.s., H-20), and 4.56 t br p.p.m. (H-7).

Anal. Calcd. for $C_{25}H_{40}O_5$: C, 68.77; H, 9.24; O, 21.99. Found: C, 68.51; H, 9.46; O, 21.60.

Fractions 18–20, 3.2 g., were taken up in acetone, diluted with isopentane, and chilled. The solid **16a** which separated was recrystallized from a small amount of methanol: yield 1.2 g.; m.p. 73–75°; infrared band ($CHCl_3$) at 3700, 3500, and 1715 cm.$^{-1}$; n.m.r. signals at 0.89, 1.08, 1.19 (methyl singlets), 3.42 (1.5 protons, methanol of crystallization), and 3.67 p.p.m. (methoxyl) superimposed on H-20 and H-7 signals.

Anal. Calcd. for $C_{21}H_{36}O_4 \cdot 0.5CH_3OH$: C, 69.98; H, 10.40; O, 19.50. Found: C, 69.74; H, 9.98; O, 19.48.

The diacetate **16b**, prepared from acetic anhydride–pyridine, was recrystallized from a small amount of methanol: m.p. 130–131°; infrared band ($CHCl_3$) at 1735 cm.$^{-1}$; n.m.r. signals at 0.93, 1.10, 1.18 (methyl singlets), 2.03, 2.08 (acetate singlets), 3.63 (methoxyl), 4.10 t (2 protons, J = 7 c.p.s., H-20) and 4.70 br p.p.m. (half-height width 6 c.p.s., H-7).

Anal. Calcd. for $C_{25}H_{40}O_6$: C, 68.77; H, 9.24; O, 21.99. Found: C, 68.85; H, 9.33; O, 22.28.

B.—To a solution of 37.5 g. (0.114 mole) of methyl isopimarate and 7.71 g. of sodium borohydride (0.202 mole) in 25 ml. of diglyme was added with stirring 38.4 g. of boron trifluoride etherate (0.27 mole) over 4 hr. After 3 hr. at room temperature the mixture was oxidized and worked up as described in A. No crystals separated during the ether extraction; yield of crude oily product from the ether extract was 46.8 g. This was dissolved in the minimum amount of benzene and chromatographed over alumina. Benzene–ether (2:1, 750 ml.), benzene–ether (1:1, 1 l.), benzene–ether (1:3, 2.4 l.), and ether (3.75 l.) eluted 4.1 g. of unidentified gums. The last ether fractions, 0.75 g., could be crystallized from aqueous acetone to give 0.4 g. of needles (**17**): m.p. 191–194°; infrared band (film) at 3700 (broad, –OH), 1720 cm.$^{-1}$ (ester); n.m.r. signals at 0.86, 0.92, and 1.22 (methyl singlets), 1.16 d (**7**, methyl doublet), 3.25 c (H-7), 3.47 q (H-19), and 3.73 p.p.m. (methoxyl). Owing to an accident the substance was lost before it could be analyzed, but its structure was apparent from the n.m.r. spectrum.

Ether–acetone (1:1, 2.5 l.) eluted 7.03 g. (17%) of crude diol ester **15a** which crystallized on trituration with water. Ether–methanol (19:1) and methanol eluted 25.5 g. (63%) of crude diol ester **16a** as an oil which partially crystallized on seeding and cooling.

Conversion of Diol Ester 16a to Triol 14a.—A solution of 0.28 g. of **14a** in 75 ml. of dry ether was added to 0.2 g. of lithium aluminum hydride with stirring. The mixture was refluxed for 6 hr. and cooled. Excess hydride was decomposed with 2 ml. of ethyl acetate, and the mixture was hydrolyzed with 15 ml. of water and 25 ml. of 10% hydrochloric acid. The ether layer was separated, the aqueous layer was extracted with ether, and the combined ether layers were washed, dried, and evaporated. The residue, 0.28 g., was recrystallized from isopropyl alcohol and identified as **14a** by melting point, mixture melting point and infrared and n.m.r. spectra.

Oxidation of 15a. A. With Excess N-Bromoacetamide.—To a solution of 3.5 g. (0.01 mole) of **15a** in 90 ml. of *t*-butyl alcohol was added 4.1 g. (0.03 mole) of N-bromoacetamide and 14.8 ml. of water. The solution, which gradually became deep orange-red was allowed to stand at room temperature for 17 hr., diluted with 1 l. of water, and treated with *ca.* 5 ml. of 1 *N* sodium thio-

(32) A. Winterstein and R. Egli, *Z. physiol. Chem.*, **202**, 207 (1931). For recent applications of this procedure to the structure elucidation of β,γ-unsaturated acids, see C. Djerassi, D. B. Thomas, A. L. Livingston, and C. R. Thompson, *J. Am. Chem. Soc.*, **79**, 5292 (1957) (medicagenic acid); and S. W. Pelletier, N. Adityachaudhury, M. Tomasz, J. J. Reynolds, and R. Mechoulam, *Tetrahedron Letters*, 3065 (1964) (senegenic acid).

sulfate solution to discharge the color. The solution was extracted with ethyl acetate, and the organic extract was washed, dried, and concentrated.

The residue, 4.15 g. (positive test with Brady's reagent), was dissolved in benzene and chromatographed over 150 g. of silicic acid. Two major compounds were isolated. The first (**19**, 1.24 g. (34%), was eluted with benzene–ether (1:1) and was soluble in potassium bicarbonate solution. After recrystallization from benzene–hexane, the keto acid **19** melted at 163.5–164.5°: $[\alpha]^{25}D$ + 2.6° (*c* 0.8); infrared bands (Nujol) at 3200–2700 (bonded –OH), 1725 (ester), and 1700 cm.$^{-1}$ (ketone); n.m.r. signals at 0.98, 1.07, and 1.18 (methyl singlets), 3.52 (methoxyl), and 10.55 p.p.m. (acid –OH, disappears on shaking with D_2O).

Anal. Calcd. for $C_{21}H_{32}O_5$: C, 69.20; H, 8.85; O, 21.95. Found: C, 69.08; H, 8.65; O, 22.07.

The second fraction, 1.51 g., m.p. 88–92°, was eluted with benzene–ether (2:3) and was induced to solidify on trituration with petroleum ether. Recrystallization with difficulty from a large volume of *n*-hexane furnished the ketol ester **18b** as colorless plates: m.p. 90–91°; $[\alpha]^{25}D$ +0.6° (*c* 1.6); o.r.d. (*c* 0.125, methanol) $[\alpha]_{600}$ 0.7°, $[\alpha]_{589}$ −0.6°, $[\alpha]_{308}$ −23.4°, $[\alpha]_{275}$ + 47.5° (last reading); infrared bands (Nujol) at 3600, 1730, and 1700 cm.$^{-1}$; n.m.r. signals at 0.88, 1.10, and 1.22 (methyl singlets), 3.64 (methoxyl), and 3.70 t p.p.m. (2 protons, J = 7.5 c.p.s., H-20). Because of the difficulties of crystallizing **18b**, it was subsequently identified most conveniently through the bromobenzenesulfonate which may be prepared quantitatively and used in the next step (*vide infra*).

Anal. Calcd. for $C_{21}H_{34}O_4$: C, 72.00; H, 9.71; O, 18.29. Found: C, 71.91; H, 9.99; O, 17.96.

The dinitrophenylhydrazone was recrystallized from ethanol and melted at 179–180°.

Anal. Calcd. for $C_{27}H_{38}N_4O_7$: C, 61.11; H, 7.17; N, 10.56. Found: C, 60.89; H, 7.27; N, 10.46.

B.—By repeating this experiment using 1.1 moles of N-bromoacetamide/mole of **15a**, **18b** was obtained in virtually quantitative yield. Chromatography of a solution of 0.198 g. of **18b** in benzene over 25 g. of basic alumina (Alcoa F-20) required methanol for elution of the adsorbed material, 0.195 g., shown to be identical with **18b** by thin layer chromatography (one spot), infrared and n.m.r. spectra, and mixture melting point.

A solution of 0.3 g. of **18b** in 10 ml. of dry pyridine was cooled to 0°, mixed with 0.51 g. of *p*-bromobenzenesulfonyl chloride, set aside in the refrigerator for 3 days, poured into ice–hydrochloric acid, and extracted thoroughly with ether. The washed and dried extracts were concentrated and the residual **18d**, 0.533 g., recrystallized from methanol: m.p. 132.5–133.5°; $[\alpha]^{25}D$ −1.7° (*c* 1.2); infrared bands (Nujol) at 1720 (ester), 1705 cm.$^{-1}$ (ketone) and typical phenyl frequencies; n.m.r. signals at 0.83, 1.09, 1.22 (methyl signals), 3.68 (methoxyl), 4.18 t p.p.m. (2 protons, J = 7 c.p.s., H-20).

Anal. Calcd. for $C_{27}H_{37}BrO_6S$: C, 56.94; H, 6.50; Br, 14.07; O, 16.87. Found: C, 57.10; H, 6.13; Br, 14.24; O, 17.18.

Oxidation of 16a.—Oxidation of **16a** with 1.1 mole equiv. of N-bromoacetamide in the manner described for **15a** resulted in recovery of considerable quantities of starting material, presumably due to further transformation of initial oxidation product under the influence of the oxidizing agent. Oxidation of 3.5 g. (0.01 mole) of **16a** in 90 ml. of *t*-butyl alcohol with 2.8 g. (0.02 mole) of N-bromoacetamide and 10 ml. of water for 19 hr. and work-up in the manner described for **15a** resulted in an oil which was chromatographed over silicic acid. Benzene and benzene–ether (19:1) eluted a small amount of unidentified material. The first 100-ml. portion of benzene–ether (1:1) eluted 1.7 g. of a gummy fraction, which exhibited infrared bands (film) at 1740 (broad), 1665, and 1615 cm.$^{-1}$ (no OH), and had λ_{max} 249 mμ (ε 2000) indicating the presence of some α,β-unsaturated ketone, presumably **20b**. The n.m.r. spectrum had signals at 4.12 t (–CH_2OAc), 3.60 (methoxyl), 2.0 (acetate), and three methyl singlets at 1.2, 1.1, and 0.89 p.p.m. It furnished a dinitrophenylhydrazone, m.p. 134.5–140.5° (singlet spot on t.l.c.), λ_{max} 385 mμ (conjugated ketone).

Anal. Calcd. for $C_{29}H_{38}N_4O_8$: C, 61.04; H, 6.71. Found: C, 60.73; H, 6.84.

Subsequent benzene–ether (1:1) portions eluted 0.74 g. of gum, shown to be a mixture by thin layer chromatography. Benzene–ether (3:2) eluted 0.8 g. of **18b**, identified spectroscopically (n.m.r., infrared), by thin layer chromatography, and by conversion to **18d**. Benzene–ether (4:1) eluted 0.22 g. of a viscous fraction homogeneous on thin layer chromatography whose infrared spectrum bands at 3500, 1730, 1665, and 1610 cm.$^{-1}$ suggested that it might be **20a**. However, the dinitrophenylhydrazone, m.p. 183–185°, exhibited the ultraviolet absorption of a saturated ketone: λ_{max} 368 mμ (ε 9700).

Anal. Calcd. for $C_{27}H_{36}N_4O_7$: C, 61.35; H, 6.86; N, 10.60. Found: C, 61.39; H, 6.75; N, 10.37.

Best results were obtained when the oxidation was carried out in the presence of pyridine. To a solution of 21.0 g. (0.06 mole) of **16a** in 250 ml. of acetone, 25 ml. of water, and 25 ml. of pyridine was added 9.25 g. (0.065 mole) of N-bromoacetamide. The mixture was allowed to stand at room temperature for 7 hr., poured into 1 l. of water, extracted with ethyl acetate, and worked up as described previously. The crude product which did not crystallize was dissolved in benzene and chromatographed over 250 g. of silicic acid. Benzene eluted a small amount of unidentified material. Successive fractions of benzene–ether (3:2) eluted first 2.4 g. of a mixture containing the keto acetate **18e** [n.m.r. and infrared spectra (see below)], which furnished a dinitrophenylhydrazone, and then 3.3 g. of a mixture containing some **18b** isolated as its dinitrophenylhydrazone. Benzene–ether (1:1) eluted 6.1 g. of **18b**; ether and ether–methanol (1%), 5.7 g. of unidentified oils.

Alternative Conversion of 16a to 18b.—A solution of 2.0 g. of **16a** in 20 ml. of acetic acid was allowed to stand with 2 drops of concentrated sulfuric acid for 3.5 hr. at 25°, diluted with water, and extracted with ether. The combined extract was washed thoroughly with aqueous sodium carbonate solution, dried, and evaporated. The gummy residue was chromatographed over 100 g. of silica gel deposited with benzene. Elution with benzene–ether (7:1 and 4:1) gave 0.2 g. of **16b**, m.p. and and m.m.p. 130–131°, while elution with benzene–ether (2:1) yielded **16c** as a colorless oil: 1.56 g.; n.m.r. signals at 0.93, 1.10, 1.22 (methyl singlets), 2.05 (acetate), 3.69 (methoxyl), and 3.95–4.3 m p.p.m. (2 protons, H-20).

A solution of 5.87 g. of **16c** in 60 ml. of pyridine was added to a stirred mixture of 6 g. of chromic oxide in 60 ml. of pyridine. Stirring was continued at 25° for 45 min., dry ether was added, the mixture was filtered through Celite, and the red-brown precipitate was washed thoroughly with dry ether. The filtrate and washings were washed, dried, and evaporated to give **18e** as a pale yellow oil, 4.93 g., infrared bands (film) at 1740–1700 and 1230 cm.$^{-1}$ (no hydroxyl). The dinitrophenylhydrazone crystallized from ethanol as orange needles: m.p. 144–146°; n.m.r. signals at 0.98, 1.10, 1.32 (methyl singlets), 2.08 (acetate), 3.73 (methoxyl), 4.23 t p.p.m. (2 protons, H-20, J_{AB} = 7.5 c.p.s.), and the expected aromatic resonances.

Anal. Calcd. for $C_{29}H_{40}N_4O_8$: C, 60.82; H, 7.04; N, 9.78; O, 22.35. Found: C, 60.80; H, 7.11; N, 9.74; O, 22.24.

A solution of 4.9 g. of **18e** in 100 ml. of methanol was allowed to stand with 5.6 g. of potassium hydroxide in 100 ml. of 10% aqueous methanol for 1.25 hr. at 25°, poured into water, extracted with ether, washed, dried, and evaporated to yield, after chromatography over silica gel and elution with benzene–ether (3:2), 3.49 g. of **18b** (50% over-all from **16a**).

Oxidation of 13a.—A solution of 6.48 g. of **13a** in 700 ml. of *t*-butyl alcohol was oxidized with 3.04 g. of N-bromoacetamide in 70 ml. of water at room temperature for 15 hr. Work-up in the manner described for the oxidation of **15a** furnished 7.8 g. of dihydroxy ketone **18a** which was recrystallized from aqueous acetone, m.p. 165.5–166.5°, infrared bands (Nujol) at 3400 and 1705 cm.$^{-1}$.

Anal. Calcd. for $C_{20}H_{34}O_3$: C, 74.49; H, 10.63; O, 14.89. Found: C, 74.56; H, 10.27; O, 14.93.

The di-*p*-bromobenzenesulfonate **18c** was prepared from 6.4 g. of **18a** and 16.5 g. of *p*-bromobenzenesulfonyl chloride in the usual manner. The resultant gum was dissolved in the minimum quantity of benzene and chromatographed over 130 g. of silicic acid; eluents were benzene, benzene–ether (4:1), and benzene–ether (1:1). The last fractions, 6.00 g., were recrystallized from methanol: m.p. 113–114°; infrared bands ($CHCl_3$) at 1700 cm.$^{-1}$ and characteristic phenyl frequencies; n.m.r. signals at 0.84, 0.84, 1.08 (methyl singlets), 3.67 br (2 protons, H-18), 4.25 t (2 protons, J = 7 c.p.s., H-20), and 7.85 s p.p.m. (8 protons, aromatic).

Anal. Calcd. for $C_{32}H_{40}Br_2O_7S_2$: C, 50.53; H, 5.30; O, 14.73. Found: C, 50.81; H, 5.54; O, 14.23.

Cyclization of 18d.—To a chilled solution of potassium *t*-butoxide, prepared from 3.1 g. of potassium and 280 ml. of dry

t-butyl alcohol, was added a warm solution of 4.5 g. of **18d** in 170 ml. of *t*-butyl alcohol. The mixture was stirred for 1.5 hr. under nitrogen at room temperature (a cloudiness developed 1–2 min. after addition), poured into water, saturated with sodium chloride, and extracted thoroughly with ether. The combined extracts were washed, dried, and evaporated at reduced pressure to give a pale yellow oil which was taken up in benzene and chromatographed over 100 g. of alumina deposited with petroleum ether. Elution with benzene furnished 2.14 g. (81%) of **21b** which was recrystallized from aqueous methanol: m.p. 84.5–85°; infrared bands ($CHCl_3$) at 1720 (ester) and 1700 cm.$^{-1}$ (ketone); n.m.r. signals at 0.99, 1.19, 1.19 (methyl singlets), and 3.65 p.p.m. (methoxyl); o.r.d. (*c* 0.0217, methanol) $[\alpha]_{600}$ 0°, $[\alpha]_{589}$ −18°, $[\alpha]_{310}$ −189°, $[\alpha]_{263}$ +355°, and $[\alpha]_{250}$ +291° (last reading).

Anal. Calcd. for $C_{21}H_{32}O_3$: C, 75.86; H, 9.70; O, 14.44. Found: C, 75.60; H, 9.55; O, 14.43.

The yellow dinitrophenylhydrazone melted at 201–202° after recrystallization from methanol.

Anal. Calcd. for $C_{27}H_{36}N_4O_6$: C, 63.26; H, 7.08; O, 18.73; N, 10.93. Found: C, 63.82; H, 6.86; N, 11.21; O, 18.07.

Prolonged stirring of the reaction mixture (*e.g.*, 18 hr.) gave, after similar working up, a yellow oil which crystallized from petroleum ether as colorless needles of the acid **21c** (16% yield): m.p. 198–199°; infrared bands (Nujol) at 3300–3000 and 2650–2600 cm.$^{-1}$ (acid); n.m.r. signals at 1.00, 1.18, 1.18 (methyl singlets), and 10.25 p.p.m. br (1 proton, COO*H*) (removed on shaking with deuterium oxide).

Anal. Calcd. for $C_{20}H_{30}O_3$: C, 75.43; H, 9.50; O, 15.07. Found: C, 75.50; H, 9.42; O, 15.39.

This acid **21c** was presumably formed by transesterification to give the *t*-butyl ester **21d** which was subsequently hydrolyzed by acid treatment during working up. Treatment of **21c** with ethereal diazomethane gave **21b**, m.p. and m.m.p. 83–85°.

Preparation of 22a.—A solution of 2.14 g. of **21b** in 6 ml. of ethanedithiol was treated with 3 ml. of boron trifluoride etherate for 5 min.; the mixture was cooled during the addition. Methanol (30 ml.) was added, and the white precipitate of the thioketal was collected and washed with cold methanol: yield 2.60 g. (99%); m.p. 249–254°; n.m.r. signals at 0.98, 1.08, 1.16 (methyl singlets), 3.20 s (4 protons, thioketal ring methylenes), and 3.67 p.p.m. (methoxyl).

A suspension of 2.60 g. of the thioketal in 600 ml. of absolute ethanol was heated with Raney nickel (9 teaspoons) for 24 hr. and filtered while hot, and the filtrate was evaporated. The residual solid, 2.07 g., was chromatographed over a column of 180 g. of silica gel prepared in petroleum ether. Elution with petroleum ether–benzene (4:1, 2:1) and benzene gave 1.97 g. of ester **22a** (95%), which crystallized from methanol as colorless prisms: m.p. 102–103°; $[\alpha]^{25}D$ +47° (*c* 0.254); infrared band ($CHCl_3$) at 1725 cm.$^{-1}$ (ester); n.m.r. signals at 0.98, 1.02, 1.15 (methyl singlets), and 3.65 p.p.m. (methoxyl).

Anal. Calcd. for $C_{21}H_{34}O_2$: C, 79.19; H, 10.72; O, 10.05. Found: C, 78.84; H, 10.68; O, 10.14.

Dihydroisohibaic Acid (22b).—A solution of 0.5 g. of **22a** in 25 ml. of dry collidine was refluxed with 1 g. of lithium iodide in a nitrogen atmosphere for 13.5 hr., cooled, acidified, and extracted with ether. The ether extracts were treated with 100 ml. of 3 *N* sodium hydroxide solution; this caused the separation of a flocculent precipitate which was filtered, washed with water, suspended in 50 ml. of 10% hydrochloric acid, and thoroughly extracted with ether. The combined ether extracts were washed with water, dried, and evaporated, yield of crude **22b** 0.49 g., which crystallized on trituration with methanol. Recrystallization from aqueous acetone raised the melting point to 197–198°; $[\alpha]^{27}D$ +55.5° (*c* 1.2); n.m.r. signals at 0.99, 1.02, and 1.18 p.p.m. (methyl singlets).

Anal. Calcd. for $C_{20}H_{32}O_2$: C, 78.90; H, 10.59; O, 10.51. Found: C, 78.40; H, 10.72; O, 10.74.

Cyclization of 18c.—To a solution of potassium *t*-butoxide, prepared from 3 g. of potassium and 250 ml. of *t*-butyl alcohol was added, in a nitrogen atmosphere, 4.56 g. of the di-*p*-bromobenzene sulfonate **18c**. After 11 hr. at room temperature, the mixture was worked up as described in the preparation of **21b**, yield of crude **21a** 3.42 g. It was purified by chromatography over silicic acid (75 g.); solvent was benzene. Benzene–ether (5:1) eluted the product (**21a**), 3.03 g., which could not be induced to crystallize: n.m.r. signals at 0.83, 1.01, 1.14 (methyl singlets), 3.66 s (2 protons, H-18), and 7.85 s p.p.m. (4 protons, aromatic).

The orange dinitrophenylhydrazone was chromatographed over silicic acid and recrystallized from methanol: m.p. 185–186°; n.m.r. signals at 0.92, 1.09, 1.09 (methyl singlets), 3.82 (center of AB quartet, J = 10 c.p.s., $\delta_B - \delta_A$ = 26, H-18), 7.85 p.p.m. (4 aromatic protons of bromobenzenesulfonate), and 3 aromatic protons of dinitrophenylhydrazine nucleus.

Anal. Calcd. for $C_{32}H_{37}BrN_4O_7S$: C, 54.62; H, 5.69; Br, 11.38; O, 15.92. Found: C, 54.37; H, 5.93; Br, 11.51; O, 15.98.

The thioketal of **21a** melted at 160–162°: n.m.r. signals at 0.80, 0.97, 1.06 (methyl singlets), 3.20 br (4 protons, thioketal methylenes), 3.74 (center of AB band, J = 9.5 c.p.s., $\delta_B - \delta_A$ = 11.5, H-18), and 7.85 p.p.m. (4 protons, aromatic).

Preparation of 22d.—A solution of 1.97 g. of **22a** (6.2 mmoles) in 50 ml. of dry ether was added to a suspension of 0.8 g. (21 mmoles) of lithium aluminum hydride in 100 ml. of dry ether and the mixture was heated under reflux for 2 hr., then treated cautiously with wet ether, water, and finally 2 *N* hydrochloric acid. The ether layer was separated, washed with water, dried, and evaporated to give the alcohol **22c** as a white solid, 1.75 g. (97%), which crystallized from ethanol as colorless needles: m.p. 100–101°; infrared bands at 3680, 1055, 1040 cm.$^{-1}$ (hydroxyl); n.m.r. signals at 0.75, 0.98, 1.02 (methyl singlets), 3.08, and 3.43 p.p.m. (AB quartet, 2 protons, CH_2OH, J_{AB} = 11 c.p.s.).

Anal. Calcd. for $C_{20}H_{34}O$: C, 82.69; H, 11.80. Found: C, 82.25; H, 11.59.

Jones reagent (deaerated with nitrogen) was added dropwise to a stirred solution of 0.70 g. of alcohol **22c** (0.70 g.) in 50 ml. of acetone at 0° while nitrogen was bubbled through the reaction mixture. When a brown color persisted for 5 min., the mixture was slowly diluted with water, and the crystalline precipitate which separated was filtered, washed with water, and crystallized from methanol to give colorless plates of aldehyde **22d** (0.64 g., 92%): m.p. 94–95°; infrared bands (Nujol) at 2700 and 1730 cm.$^{-1}$ (aldehyde); n.m.r. signals at 0.98, 1.05, 1.05 (methyl singlets), and 9.23 p.p.m. (1-proton singlets, CHO). This material was very hygroscopic and could not be analyzed satisfactorily. Hence it was characterized and analyzed as the semicarbazone.

The semicarbazone of **22d**, prepared by the method of Fieser,[33] crystallized from methanol as colorless needles: m.p. 230–231°; infrared bands at 3550, 3250 (NH stretching), 1695, 1575 (amide), and 1630 cm.$^{-1}$ (C=N stretching).

Anal. Calcd. for $C_{21}H_{35}N_3O$: C, 73.00; H, 10.21; N, 12.16. Found: C, 73.32; H, 10.04; N, 12.12.

Wolff–Kishner Experiments. A.—A mixture of 0.59 g. of the semicarbazone of **22d** and 25 ml. of ethylene glycol was heated in an atmosphere of nitrogen to 150° when it became homogeneous. Solid potassium hydroxide (5.0 g.) was cautiously added (the addition of each pellet caused vigorous boiling), and the mixture gradually was concentrated to b.p. 212° (liquid temperature). At about 180–190° the cloudy mixture became clear and evolution of gas was noted. The solution was then refluxed for 3 hr., cooled, poured into water, and extracted with petroleum ether. Evaporation of the washed and dried combined extracts yielded 0.3 g. of a yellow oil (0.3 g.) which was chromatographed over 15 g. of alumina prepared in petroleum ether. Elution with petroleum ether gave the nitrile **22e**, 0.135 g. (28%), which crystallized from methanol as colorless needles, m.p. 175°, infrared band at 2230 cm.$^{-1}$ (nitrile). The mother liquors on dilution with water gradually deposited the product as colorless rods, m.p. 103–104°. The n.m.r. spectra of the two samples were superimposable, the signals appearing at 0.98, 0.98, and 1.29 p.p.m. (methyl singlets). There were no resonances downfield from 2.3 p.p.m.

Anal. Calcd. for $C_{20}H_{31}N$: C, 84.14; H, 10.95; N, 4.91. Found: C, 83.86; H, 11.01; N, 4.93.

B.—A mixture of 0.204 g. of aldehyde **22d**, 12.5 ml. of ethylene glycol, 0.4 ml. of 95% hydrazine, and 1.25 g. of potassium hydroxide was heated under reflux for 1.75 hr., then concentrated to b.p. 190° (about 0.25 hr.), treated with more hydrazine (0.2 ml.), and refluxed for a further 1.5 hr. The cooled solution was diluted with water and extracted with ether. The washed and dried combined extracts furnished a colorless solid (70 mg., 36%) which was vacuum sublimed at 100° (bath temperature) and 10 mm. to give colorless rods of isohibane **22f**: m.p. 65–67°; $[\alpha]^{27}D$ +56 (*c* 0.572); infrared bands at 1370 and 1390 cm.$^{-1}$ (*gem*-

(33) L. Fieser, "Experiments in Organic Chemistry," D. C. Heath and Co., Boston, Mass., 1957, p. 85.

dimethyl); n.m.r. signals at 0.82, 0.87, 1.00, and 1.01 p.p.m. (methyl singlets).

Anal. Calcd. for $C_{20}H_{34}$: C, 87.51; H, 12.49. Found: C, 87.54; H, 12.25.

C.—The previous procedure was modified because of the observed volatility of the hydrocarbon. A mixture of 0.175 g. of **22d**, 10 ml. of ethylene glycol, and 0.35 ml. of 95% hydrazine was refluxed for 20 min., concentrated to b.p. 193° (about 10 min.), then allowed to cool for 30 min. Colorless needles (probably hydrazone) separated. Potassium hydroxide (1.15 g.), 0.15 ml. of hydrazine, and 3 ml. of ethylene glycol (3 ml.) were added, and the mixture was refluxed for 3 hr. Working up as for B gave isohibane **22f** as a colorless solid (0.14 g., 84%), identical with the hydrocarbon described above.

Resin Acids. III. 9-Hydroxyabietic Acid and Its Transformation Products*[1,2]

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The structure of the substance produced by selenium dioxide oxidation of abietic acid is revised to 9-hydroxyabietic acid. The assignment is based on spectroscopic evidence and on conversion to $\Delta^{7,9\,(11)}$-abietadienoic acid which was in turn synthesized from $\Delta^{8(9)}$-abietenoic acid. In the course of this work, an entry into the pseudoabietic acid series has been effected and the stereochemistry of the various lactones belonging to this series has been elucidated.

Oxidation of abietic acid (**1**) with selenium dioxide furnishes dehydroabietic acid and a hydroxyabietic acid which has been assigned formula **2**, 12-hydroxyabietic acid, by Fieser and Campbell[4] because of its oxidation with potassium permanganate to isobutyric acid, its ultraviolet spectrum which reportedly was superimposable on that of abietic acid, and because of its failure to yield a lactone. The allylic nature of the hydroxyl group demanded by **2** was demonstrated by an attempt at hydrogenation with platinum oxide in acetic acid which resulted in hydrogenolysis and formation of a dihydroabietic acid.[5]

A puzzling feature of the chemistry of hydroxyabietic acid is that on heating at 175–200° in an atmosphere of nitrogen it was reported to undergo dehydration to "anhydrohydroxyabietic acid," m.p. 167.5–169.5°, $[\alpha]^{25}D$ +21°. This substance had an ultraviolet spectrum very similar to that of abietic acid, was oxidized to isobutyric acid with potassium permanganate, was unsaturated toward bromine, gave on nitration the same 12,14-dinitrodehydroabietic acid produced more directly by nitration of dehydroabietic acid, was slowly reduced to a tetrahydroabietic acid under the influence of platinum in acetic acid solution, and was therefore assigned[4] formula **4**. On the other hand, Sandermann[6] claimed to have obtained an acid, m.p. 172°, $[\alpha]D$ +21, identical with "anhydrohydroxyabietic acid," by pyrolysis of maleopimaric acid (**5**),[7] but assigned to it a different structure.

Sandermann named this material "isoabietic acid" and suggested that it was a C-9 stereoisomer of abietic acid, but doubts[5] have been expressed about the homogeneity of "isoabietic acid" and its identity with "anhydrohydroxyabietic acid."

For a number of reasons we had occasion to repeat the selenium dioxide oxidation of abietic acid. Our study of the product whose properties tally with those given in the literature[4] shows that its structure must be revised to 9-hydroxyabietadienoic acid (**6a**). The results are described in this paper, together with relevant material that has led to an entry into the pseudoabietic acid (**7**) series of compounds. Work describing the preparation and proof of structure of authentic 12-hydroxyabietadienoic acid (**2**) will be described in a future publication.

While the infrared and ultraviolet spectrum of the minor selenium dioxide oxidation product[8] indicated the presence of the heteroannular diene chromophore already postulated earlier,[4] the n.m.r. spectrum[9] which had sharp methyl singlets at 0.92 (C-10 methyl) and 1.30 (C-4 methyl), two superimposed methyl doublets centered at 0.94 p.p.m. (J = 7 c.p.s., isopropyl group), and two vinyl resonances very similar to those appearing in the n.m.r. spectrum of abietic acid (broadened signal of H—half-height width 7 c.p.s.—at 5.44, sharp signal of H-14 at 5.73 p.p.m.) immediately showed that revision of the older formula was required. The lack of signals typical of a proton geminal to hydroxyl clearly eliminated C-12 (as originally postulated) and C-6 as the site of the hydroxyl group which must be tertiary. While the signals of the isopropyl methyl groups could be interpreted as arising from two methyl singlets in different magnetic environments, the absence of deshielding suggested that the hydroxyl group was not located at C-18 and that the

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(1) Previous paper: W. Herz, D. Melchior, R. N. Mirrington, and P. J. S. Pauwels, *J. Org. Chem.*, **30**, 1873 (1965).

(2) Supported in part by a grant from the National Science Foundation (GP-1492).

(3) Abstracted from a dissertation submitted by H. J. Wahlborg in partial fulfillment of the requirements for the Ph.D. degree, April 1965.

(4) L. Fieser and W. P. Campbell, *J. Am. Chem. Soc.*, **60**, 159 (1938).

(5) For a review of the literature on these and related matters up to 1953, see J. Simonsen and D. H. R. Barton, "The Terpenes," Vol. III, 2nd Ed., Cambridge University Press, London, 1952, pp. 374–480; Vol. V, 1957, pp. 604–610.

(6) W. Sandermann, *Ber.*, **76**, 1261 (1943).

(7) The stereochemistry of maleopimaric acid shown in formula **5** is as deduced recently by W. D. Lloyd and G. W. Hedrick, *J. Org. Chem.*, **26**, 2029 (1961); L. H. Zalkow, R. A. Ford, and J. P. Kutney, *ibid.*, **27**, 3535 (1962); W. A. Ayer, C. E. McDonald, and J. B. Stothers, *Can. J. Chem.*, **41**, 1113 (1963).

(8) Respectable yields (15%) were realized only when particular attention was paid to washing the crude salt thoroughly to remove residual sulfuric acid.

(9) N.m.r. spectra were run in deuteriochloroform, unless otherwise specified, on a Varian A-60 spectrometer purchased within the aid of a grant from the National Science Foundation. Frequencies are given in parts per million with tetramethylsilane serving as the internal standard.