Medium-Ring 1,5-Dienes. Part II.[1] The Radical and Electrophile-induced Cyclisation of Germacra-1(10),4,7(11)-triene †

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The (*E,E*)-cyclodeca-1,5-diene derivative, germacra-1(10),4,7(11)-triene (1), has been cyclised to a variety of *trans*-decalin (selinane) derivatives by using the electrophilic reagents hypobromous acid, mercury(II) acetate, and sulphuric acid and radical-mediated reactions with benzenethiol, diphenyl disulphide, and carbon tetrachloride. A concerted mechanism in combination with a preferred reacting conformation is proposed to account for the high regio- and stereo-specificity of the reactions.

THE early suggestions of Ruzicka [3] and of Barton and de Mayo [4] that the terpenoid cyclodeca-1,5-dienes might be involved in the biosynthesis of some bicyclic sesquiterpenoids have been elaborated by Hendrickson [5] and by Parker, Ramage, and Roberts.[6] At the inception of this work a number of cyclisations of these systems had been discovered [7] but there were no cases in which the stereochemistry of both the medium-ring diene and the cyclisation product(s) had been unambiguously established. We therefore set out to prepare and study the cyclisation of germacra-1(10),4,7(11)-triene ‡ (1) and its derivatives while Rogers and Allen were to establish the stereochemistry of the germacratriene by *X*-ray crystallographic methods.

The constitution of germacra-1(10),4,7(11)-trien-8-one (2) has been firmly established by the extensive work of Sorm and his collaborators,[9] during the course of which the alcohol (3) was prepared. Acetylation of (3) gave the acetate (4) which was smoothly hydrogenolysed to the triene (1) with lithium in ammonia. Germacratriene (1) readily undergoes auto-oxidation but is relatively stable at 0 °C in the absence of air. Material exposed to the air for several weeks showed (mass spectrometry) the incorporation of up to 8 atoms of oxygen. A crystalline silver nitrate complex of germacratriene (1) was prepared, and Rogers and Allen, by *X*-ray methods, established that both endocyclic double bonds were of *E*-stereochemistry and that the ring adopted a crown conformation.[10] Since *N*-bromosuccinimide–acetone–water had been successful for the stereoselective cyclisation of humulene,[11] we first investigated the reaction of this mixture with germacratriene (1). A crystalline bromohydrin ¶ was obtained (31%) in which there were present two quaternary methyl (τ 8.91 and 8.82) and two vinylic methyl groups (τ 8.32); that the latter were contained in an isopropylidene group followed from the shift to high field of the methyl signals (τ 8.64) in the monoepoxide. Reduction of the bromohydrin (5) with lithinium ammonia gave the alcohol (6), and the concurrent disappearance of the low-field signal (τ 6.14, $W_{\frac{1}{2}}$ 16 Hz) of (5) established that the bromine was on a secondary carbon atom. The alcohol (6) is identical with ' juniper camphor ' [12] but since there was disagreement [13] about the stereochemistry of (6) we degraded it to the crystalline ketol (13) (osmium tetraoxide followed by cleavage with periodate), which on dehydration (phosphoryl chloride–pyridine) gave a mixture (85 : 15) of the olefin (14) and the endocyclic double bond isomer (τ 4.65), which were separated by p.l.c. on silver-nitrate-

† Portions of this work have been published in preliminary form. All compounds described are racemates, but only one enantiomer is represented in formulae.

‡ Germacratriene (1) has been isolated from natural sources.[8]

¶ Initially prepared by Dr. M. D. Solomon.

[1] Part I, J. K. Sutherland, *Tetrahedron*, 1974, **30**, 1651.

[2] E. D. Brown, M. D. Solomon, J. K. Sutherland, and A. Torre, *Chem. Comm.*, 1967, 111; T. W. Sam and J. K. Sutherland, *ibid.*, 1971, 970.

[3] L. Ruzicka, *Experientia*, 1953, **9**, 357.

[4] D. H. R. Barton and P. de Mayo, *J. Chem. Soc.*, 1957, 150.

[5] J. B. Hendrickson, *Tetrahedron*, 1959, **7**, 82.

[6] W. Parker, J. S. Roberts, and R. Ramage, *Quart. Rev.*, 1967, **21**, 331.

[7] See *e.g.* refs. 4 and 9 and A. S. Rao, A. Paul, Sadgopal and S. C. Bhattacharyya, *Tetrahedron*, 1961, **13**, 319.

[8] G. Büchi, personal communication, 1967; *ibid.*, K. Nishimura, N. Shinoda, and Y. Hirose, *Tetrahedron Letters*, 1969, 3097.

[9] I. Ognjanov, D. Ivanov, V. Herout, M. Horak, J. Pliva, and F. Sorm, *Coll. Czech. Chem. Comm.*, 1958, **23**, 2033.

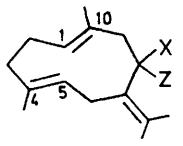
[10] F. H. Allen and D. Rogers, *Chem. Comm.*, 1967, 588.

[11] J. M. Greenwood, M. D. Solomon, J. K. Sutherland, and A. Torre, *J. Chem. Soc.* (*C*), 1968, 3004.

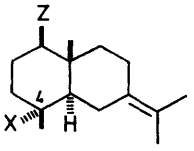
[12] V. Herout, O. Motl, and F. Sorm, *Coll. Czech. Chem. Comm.*, 1958, **23**, 1293.

[13] K. R. Varma, T. C. Jain, and S. C. Bhattacharyya, *Tetrahedron*, 1962, **18**, 979.

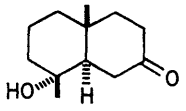
impregnated silica gel. The methylene ketone (14) was identical with an authentic sample,[14] establishing the



(1) X = Z = H
(2) XZ = : O
(3) X = OH, Z = H
(4) X = OAc, Z = H



(5) X = OH, Z = Br
(6) X = OH, Z = H
(7) X = OH, Z = HgOAc
(8) X = Cl, Z = CCl_3
(9) X = Z = PhS
(10) X = H, Z = PhS
(11) X = Z = H
(12) X = H, Z = Me



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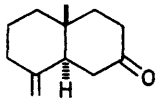
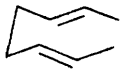


(14)



C
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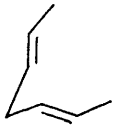
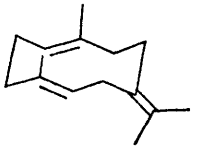
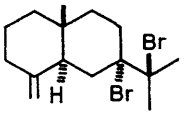


T
(16)



(17)

constitution and stereochemistry of the ring system. The equatorial disposition of the bromine and hydroxy-functions was assigned on the basis of the $W_{\frac{1}{2}}$ value of the CHBr n.m.r. signal[15] and the predominant formation of exocyclic methylene compounds[16] on dehydration of (13) and related compounds, respectively. Reaction of germacratriene (1) with bromine in carbon tetrachloride took an apparently different course in that the dibromide (18), τ 5.29 (1 H, s), 5.61 (1 H, s), 7.93 (3 H, s), and 7.94 (3 H, s), was isolated in low yield. Reduction of (18) with zinc in acetic acid gave the diene (19), identical with the major component obtained on dehydration (phosphoryl chloride–pyridine) of the alcohol (6). Clearly the dibromide (18) must have arisen from bromination of material cyclised *in situ*; indeed (16) could be obtained by bromination of the diene mixture [(19) and (20)] and we have shown that germacratriene (1) is cyclised with great facility (chromatography on grade I alumina or dissolution in commercial methylene chloride) to the diene mixture. It is notable that a 1 : 1 mixture of (19) and (20) is obtained on direct cyclisation whereas dehydration of (6) gave a 4 : 1 ratio. Cyclisation of (1) with aqueous mercury(II) acetate followed by reduction with sodium borohydride[17] also gave some of the diene mixture, accompanied by the alcohol (6), which, however, could be prepared in quantitative yield by cyclisation of germacratriene (1) with acetone–sulphuric acid. Acetone as co-solvent was unique amongst the solvents tested in that its use gave solely the alcohol, unaccompanied by any elimination products; possibly germacratriene (1) is solvated predominantly with acetone molecules, one of which interacts with the carbocation centre after cyclisation, to give $RO{\cdot}C^{+}Me_2$ rather than hydration or elimination product. The oxonium ion could then be converted into the alcohol *via* the hemiacetal. The latter was the only reaction in which quantitative yields of selinanes were obtained, and in order to determine if cyclisation to a guaiane system was a competing process authentic mixtures of selinane hydrocarbons were prepared by reduction of (19) and (20) and mixtures of guaianes by dehydration and reduction of (21).[18] The mother



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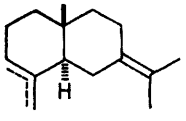
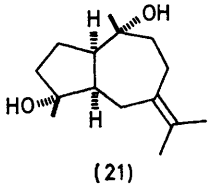
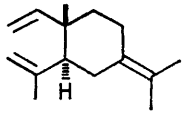


(19) $\Delta^{4(14)}$
(20) Δ^{3}



(21)



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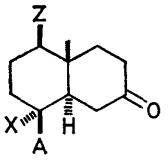
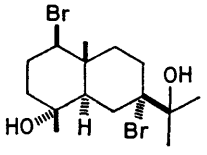


(22) X = Z = H, A = Me
(23) Z = A = H, X = Me
(24) X = Z = Me, A = H
(25) Z = CCl_3, X = Cl, A = Me



(27)

liquors from the cyclisation with hypobromous acid were then treated successively with lithium–ammonia, phosphoryl chloride–pyridine, and hydrogen–Adams

[14] J. A. Marshall, M. T. Pike, and R. D. Carroll, *J. Org. Chem.*, 1966, **31**, 2933.
[15] K. L. Williamson and W. S. Johnson, *J. Amer. Chem. Soc.*, 1961, **83**, 4623.
[16] D. H. R. Barton, A. da S. Campos-Neves, and R. C. Cookson, *J. Chem. Soc.*, 1956, 3500.
[17] F. G. Bordwell and M. L. Douglass, *J. Amer. Chem. Soc.*, 1966, **88**, 993.
[18] E. D. Brown, J. K. Sutherland, and T. W. Sam, following paper.

catalyst. Comparison (g.l.c.) of the mixture obtained with the standards indicated *ca.* 10% of guaiane present and, if it is accepted that the loss during handling *etc.* is the same for each series, this should reflect the true figure for cyclisation to guaiane derivatives.

Radical-induced cyclisations of germacratriene (1) were also studied. Irradiation of a solution of benzenethiol and germacratriene (1) in cyclohexane yielded the sulphide (10) (34%), τ 7.34 (1 H, $W_{\frac{1}{2}}$ 15 Hz), 8.40 (6 H, s), 8.97 (3 H, s), and 9.08 (3 H, d, J 7 Hz). Reduction with lithium in ethylamine gave the hydrocarbon (11), which on ozonolysis yielded the ketone (22), identical with the known compound (22) of established stereochemistry.[14] Stereochemistry at C-1 was assigned on the basis of the $W_{\frac{1}{2}}$ value of the C-1 proton n.m.r. signal.[15] The adduct (9) (51%), τ 6.68 (1 H, $W_{\frac{1}{2}}$ 14 Hz),* 8.20 (3 H, s), 8.34 (3 H, s), 8.78 (3 H, s), and 8.87 (3 H, s), was formed on irradiation of germacratriene (1) in the presence of diphenyl disulphide. Hydrogenolysis of (9) with lithium in ethylamine gave the diene mixture [(19) and (20)] (18%), and the isomeric olefins (11) (14%) and its C-4 epimer (54%). Ozonolysis of the total mixture gave the ketones (22) and (23). The major isomer (23) was identical with the minor isomer produced on catalytic hydrogenation of (14). The stereochemistry assigned to the methyl group at C-4 is supported by J values [7 Hz for (11) and (22) and 6 and 5 Hz for the equatorial isomers, *epi*-(11) and (23) [19]]. These results establish the stereochemistry of (9) except for that at C-4; that the methyl group is axial is supported by the value of 0.8 Hz for $\Delta[W_{\frac{1}{2}}(\mathrm{Me}) - W_{\frac{1}{2}}(\mathrm{Me_4Si})]$, within the expected range for long-range coupling with two axial protons.[20] As an internal check, Δ for the C-10 methyl signal was 1.3 Hz (coupling with three axial protons). Irradiation of germacratriene (1) in carbon tetrachloride formed the adduct (8) (31%), τ 6.94 (1 H, $W_{\frac{1}{2}}$ 14 Hz), 8.32 (3 H, s), 8.38 (3 H, s), 8.48 (3 H, s), and 8.73 (3 H, s). The structure and stereochemistry of (8) are assigned by analogy. However a number of spectroscopic and chemical data support the assignment. Reduction of (8) with lithium in ammonia gave a hydrocarbon mixture which contained the C-4 epimer of (12). Ozonolysis of this mixture gave the ketone (24), τ ($\mathrm{Me_2CO}$) 9.22 (3 H, d, J 6 Hz), 9.15 (3 H, d, J 6 Hz), 9.05 (3 H, s), in accord with the environments assigned to the chloro- and trichloromethyl groups. Ozonolysis of the adduct (8) itself yielded the ketone (25), τ 8.43 (3 H, s) and 8.57 (3 H, s). The chemical shift difference between the C-10 methyl signals (0.16 p.p.m.) is similar in this series to that noted for the other *trans*-decalins in going from isopropylidene derivative to ketone. The benzene- and pyridine-induced upfield shifts of the angular methyl signal (0.37 and 0.15 p.p.m. relative to carbon tetrachloride) are in agreement with a *trans*-decalone structure,[21] and $\Delta[W_{\frac{1}{2}}(\mathrm{Me}) - W_{\frac{1}{2}}(\mathrm{Me_4Si})]$ for the C-4 methyl (0.63 Hz) supports its axial disposition. The ketone (25) formed a dimethyl acetal with remarkable facility; refluxing in commercial methanol brought about complete conversion within 1 h and high conversions were possible by using methanol distilled from sodium ethoxide or in the presence of suspended sodium hydrogen carbonate. The readiness of this reaction may be due to adverse dipole–dipole interactions involving the CCl and $\mathrm{CCl_3}$ groups; the higher $\nu_{max.}$ value of 1 717 $\mathrm{cm^{-1}}$, as opposed to those of related ketones, supports this interpretation.

Like germacratrienone (2), the triene (1) readily undergoes Cope rearrangement above 120 °C to give the elemene (26), τ 4.22 (1 H, dd, J 10 and 17 Hz), 4.90—5.50 (4 H, m), 8.31 (3 H, t, J 1 Hz), 8.36 (6 H, s), and 8.96 (3 H, s), the stereochemistry of which was established by reaction with *N*-bromosuccinimide–acetone–water to give the dibromo-diol (27) in low yield. Reduction of (27) with zinc dust in acetic acid yielded the bromohydrin (5), from which (27) could be reformed by hypobromination. The bisbromohydrin (27) is formulated as a dimethylcarbinol since the chemical shift of the side-chain methyl groups is τ 8.52, and the stereochemistry is postulated on the basis of attack from the least hindered side. Reaction of germacratriene (1) with bis(benzonitrile)palladium chloride generated the palladium chloride complex of γ-elemene (26), τ 3.45 (1 H, dd, $W_{\frac{1}{2}}$ 24 Hz), 4.1—5.4 (4 H, m), 7.89 (3 H, s), 8.02 (3 H, s), and 8.36 (6 H, s). The large downfield shift of the angular methyl signal is presumably a contact shift. Dissolution of the complex in dimethyl sulphoxide destroyed it and generated γ-elemene. A similar rearrangement has been noted with (*Z*,*E*)-cyclodeca-1,5-diene.[22]

From the foregoing work it is clear that the preferred mode of cyclisation of germacratriene gives selinane derivatives, and this is also true of other derivatives where an unperturbed 1,5-diene system is present.[21] There are a number of factors which bring this about. In general the cyclisation of medium-ring dienes or trienes with endocyclic double bonds shows high stereoselectivity due to reaction taking place in a single conformation and the π-electron system being in the plane of the ring. This leads to one π-lobe being exposed to the attacking reagent while the other is intra-annular and protected from intermolecular attack, but ideally placed to interact with a similar lobe on the other side of the ring. Within the constraints of a medium-ring there are two distinctive conformations possible for an (*E*,*E*)-1,5-diene unit: C(15) (which on cyclisation would give a chair cyclohexane) and T(16) (which would give a twist-boat or boat cyclohexane). Clearly these different conformations would give different ring-junction stereochemistry. The conformation found for

* The downfield shift of this proton in comparison with the corresponding proton of (10) is presumably due to deshielding induced by the C-4 aromatic ring.

[19] L. M. Jackman and S. Sternhell, 'Applications of Nuclear Magnetic Resonance in Organic Chemistry,' 2nd edn., Pergamon, Oxford, 1969, p. 298.

[20] Ref. 19, p. 337 and references there cited.

[21] D. H. Williams and N. S. Bhacca, *Tetrahedron*, 1965, **21**, 2021.

[22] J. C. Trebellas, J. R. Olechowski, and H. B. Jonassen, *J. Organometallic Chem.*, 1966, **6**, 412.

germacratriene as its silver nitrate complex is the crown (17) with a C 1,5-diene conformation, and in a number of subsequent determinations on related compounds a C diene conformation has always been found.[23] However, there are a number of cases where spectroscopic evidence has been presented for the presence of T conformations,[24] usually as minor contributors. The consensus of evidence at present is that C conformations are preferred and it might also be expected that they would be preferred as reacting conformations since they would give the lower energy chair-like transition states; indeed Johnson's work on polyene cyclisation demonstrates this.[25] Thus the stereochemistry of the germacratriene cyclisations can be understood on the basis of *trans*-addition to the double bonds and reaction in a crown conformation. Less clear is why there should be preference for attack at the 1,10-bond. The simplest explanation is that in the rate-determining step a 'cyclisation product-like' transition state is found; then preference for the bicyclo[3.3.0]decane over the [4.3.0] or [5.2.0] system is understandable. There appear to be only two ways in which this situation can be reached, of which the first requires that these are truly concerted reactions with carbon–electrophile and carbon–carbon bond formation occurring synchronously. We feel this explanation is preferable to one involving initial reaction at both double bonds but with the 4,5-intermediate reverting quantitatively and stereospecifically to starting material and thus the reaction being channelled *via* the 1,10-intermediate. That attack of an electrophile would be expected at both double bonds follows from epoxidation results [18] which show a preference for 4,5-epoxidation. If the acid-catalysed cyclisation results are then considered it is apparent that any C-5 cation formed would have to revert quantitatively and stereospecifically to (1) to account for the quantitative yield of (6) and the incorporation of only one deuterium atom when the reaction is carried out in D_2O. Extensive cyclisation studies [26] on (*Z*,*E*)-cyclodeca-1,5-diene have demonstrated the formation of *cis*-decalins, the diene system again reacting in a C conformation.

It appears then that electrophile- or radical-induced cyclisation of cyclodeca-1,5-dienes could provide synthetically useful stereospecific routes to decalins should general synthetic methods for the preparation of these medium-ring dienes become available.

EXPERIMENTAL

N.m.r. spectra were recorded at 60 MHz for solutions in $CDCl_3$ and i.r. spectra for solutions in $CHCl_3$ unless otherwise stated. 'Work-up in the usual way' implies dilution with water, extraction with ether, and washing (aqueous $NaHCO_3$ or 2N-NaOH), drying ($MgSO_4$), and concentration of the extract.

Germacra-1(10),4,7(11)-*triene* (1).—Germacra-1(10),-4,7(11)-trien-8-yl acetate (4) (4.50 g) in dry dioxan (60 ml) was added to a solution of lithium (0.5 g) in liquid ammonia (650 ml). After stirring for 4 h, solid ammonium chloride was added to discharge the blue colour and the ammonia allowed to evaporate overnight. Work-up in the usual way gave an oil which was filtered through type H alumina (150 g) in petroleum (b.p. 40—60 °C). Concentration of the filtrate yielded *germacratriene* (1) (2.70 g), b.p. 105 °C at 0.1 mmHg, τ 5.38 (2 H, m), 8.31 (6 H, s), and 8.52 (6 H, s) (Found: C, 88.3; H, 11.8. $C_{15}H_{24}$ requires C, 88.2; H, 11.8%), which was stored at 0 °C under nitrogen.

Germacratriene–Silver Nitrate Adduct.—Germacratriene (1.5 g) was dissolved in ethanol (33 ml) containing silver nitrate (1.1 g). After 48 h crystals were filtered off and recrystallised from ethanol to give the *adduct* (600 mg), m.p. 144° (Found: C, 47.9; H, 6.4. $C_{15}H_{24}AgNO_3$ requires C, 48.2; H, 6.5%). Dissolution of the complex in aqueous ammonia and usual work-up gave germacratriene.

The Bromohydrin (5).—Germacratriene (1) (975 mg) was dissolved in acetone (5 ml) and water (1.5 ml). *N*-Bromosuccinimide (858 mg) was added to the cooled (0 °C), stirred solution and the stirring was continued until the mixture gave no colouration with starch–iodide paper (*ca.* 5 min). The bromohydrin (5), which crystallised from the mixture, was filtered off and washed with cold acetone (3 ml). The combined washings and filtrate were worked up in the usual way to give an oil. Treatment of this oil with petroleum (b.p. 60—80°) yielded a further crop. The two crops were combined to give 1β-*bromoselin*-7(11)-*en*-4-*ol* (5) (439 mg, 31%), m.p. 175—178 °C, $\nu_{max.}$ 3 450 cm^{-1} (Found: C, 59.6; H, 8.2; Br, 26.5. $C_{15}H_{25}BrO$ requires C, 59.8; H, 8.3; Br, 26.5%).

The Bromohydrin Epoxide.—The bromohydrin (5) (50 mg) was dissolved in chloroform (4 ml), a solution of perphthalic acid (3 mol equiv.) in ether (5 ml) was added, and the resulting solution was kept at 5 °C for 4 days. It was then worked up in the usual way to give a white solid which was crystallised from petroleum (b.p. 60—80°) to give 1β-*bromo*-7,11-*epoxyselinan*-4-*ol* (43 mg, 81%), m.p. 149—151 °C (Found: C, 56.9; H, 8.0. $C_{15}H_{25}BrO_2$ requires C, 56.8; H, 7.9%).

The Alcohol (6).—(*a*) The bromohydrin (5) (1.9 g) dissolved in dry ether (50 ml) was added to dry liquid ammonia (500 ml). Lithium (0.5 g) was added in small pieces and the resulting blue solution was stirred for 4 h. The reaction was worked up as in the reduction of germacrol acetate, and the product was crystallised from ethanol to give *selin*-7(11)-*en*-4-*ol* (6) (1.03 g, 73%), m.p. 164—166 °C (Found: C, 81.1; H, 11.8. $C_{15}H_{26}O$ requires C, 81.0; H, 11.8%), $\nu_{max.}$ (Nujol) 3 450 cm^{-1}.

(*b*) Germacratriene (1) (106 mg) was dissolved in acetone (3 ml), 2N-sulphuric acid (1 ml) was added, and the solution was left at room temperature overnight. The solution, which contained long, needle-like white crystals, was neutralised with saturated aqueous sodium hydrogen carbonate (1 ml) and then worked up in the usual way. Crystallisation of the product from ethanol gave the alcohol (6) (109 mg, 95%), m.p. 157—159 °C, identical with a sample prepared from the bromohydrin (5).

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The Ketol (13).—The alcohol (6) (807 mg) was dissolved in dry ether (80 ml) containing pyridine (3 ml). Osmium tetraoxide (957 mg) was added and the solution was stirred overnight at room temperature. The resulting brown precipitate was filtered off, washed with ether (5 ml), and dried *in vacuo* to give the crude osmate ester which was dissolved in ethanol (10 ml) and refluxed for 30 min with sodium sulphite (10 g) in water (20 ml). The solution was cooled and filtered (Celite 545) and evaporated to dryness *in vacuo*. The residue was dissolved in water (15 ml) and the solution was extracted with chloroform (3 × 20 ml). The combined extracts were worked up in the usual way to give a glass (330 mg), $\nu_{max.}$ (film) 3 450 cm^{-1}, which was dissolved in methanol (3 ml); sodium periodate (292 mg) in water (3 ml) was added and the resulting solution was set aside overnight, then extracted with chloroform (3 × 5 ml). The combined extracts were washed with water (5 ml), dried, and evaporated to give the ketol (13) (139 mg). The aqueous extracts were continuously extracted overnight with dichloromethane. The organic phase was evaporated to give a further crop (76 mg). The two crops were combined to give 4-*hydroxy*-11,12,13-*trinorselinan*-7-*one* (13) (215 mg, 85%), m.p. 57—58.5 °C (Found: C, 73.1; H, 10.3. $C_{12}H_{20}O_2$ requires C, 73.4; H, 10.3%), $\nu_{max.}$ (Nujol) 3 450 and 1 705 cm^{-1}.

The Ketone (14).—The ketol (13) (111 mg) was dehydrated with phosphoryl chloride (0.5 ml) and pyridine (3 ml). Work-up in the usual way gave an oil (72 mg) which was chromatographed over alumina (10 g; grade III). Elution with 3 : 1 benzene–petroleum (b.p. 40—60 °C) gave a mixture of ketones (26 mg), which was subjected to preparative t.l.c. on silver nitrate–silica, the compounds being detected by spraying with water. The slower moving band was eluted and the material sublimed (45 °C and 0.05 mmHg) to give the pure, crystalline 4a-methyl-8-methylene-*trans*-2-decalone (14) (9 mg, 9%), m.p. and mixed m.p. 51—53 °C, n.m.r. and i.r. spectra identical with those of an authentic sample.[14]

The Dienes (19) *and* (20).—(*a*) Germacratriene (1) (3.4 g) was percolated through alumina (80 g; grade I) with petroleum (b.p. 60—80 °C) as eluant. The solvent was evaporated off and the elution repeated with a fresh batch of alumina (80 g; grade I). Evaporation left a 1 : 1 mixture of the dienes (19) and (20) (2.4 g, 71%), τ 4.7 (½ H, m), 5.30 (½ H, s), 5.55 (½ H, s), 9.13 (1½ H, s), 9.20 (1½ H, s). The dienes (46.5 mg) were separated by preparative t.l.c. on silver nitrate–silica to give *selina*-4(14),7(11)-*diene* (19) (29 mg) as a liquid (Found: C, 88.1; H, 11.7. $C_{15}H_{24}$ requires C, 88.2; H, 11.8%), $\nu_{max.}$ (film) 1 640 and 895 cm^{-1}, τ 5.30 (1 H, s), 5.55 (1 H, s), and 9.20 (3 H, s).

(*b*) The alcohol (6) (81 mg) was treated with phosphoryl chloride (0.5 ml) in pyridine (2 ml) to give the dienes (19) and (20) (77 mg, 94%) as an oil. The n.m.r. spectrum of this mixture showed that it contained <20% of the diene (20).

Reduction of the Dibromide (18) *with Zinc*.—The dibromide (18) (95 mg) was dissolved in acetic acid (1.5 ml), zinc dust (200 mg) was added, and the suspension was stirred overnight at room temperature. The mixture was filtered, and work-up in the usual way gave an oil which was chromatographed over alumina (10 g; grade I). Petroleum (b.p. 60—80 °C) eluted the diene (19) (40 mg, 77%), identical (n.m.r. and i.r. spectra and g.l.c. retention time) with a sample prepared from germacratriene (1).

The Dibromide (18).—(*a*) Germacratriene (1) (2.0 g) was treated with bromine (1 mol. equiv.) in carbon tetrachloride. Work-up in the usual way and crystallisation of the product from ethanol yielded 7,11-*dibromoselin*-4(14)-*ene* (18) (720 mg, 20%), m.p. 85—87.5 °C (Found: C, 49.8; H, 6.7. $C_{15}H_{24}Br_2$ requires C, 49.5; H, 6.9%).

(*b*) The mixture of dienes (19) and (20) was brominated in carbon tetrachloride as in the bromination of germacratriene (1). Crystallisation of the oily product from ethanol gave the dibromide (18) (83 mg, 31%), m.p. 85—89 °C, identical with a sample prepared from germacratriene (1).

γ-Elemene (26).—Germacratriene (1) (2.2 g) was refluxed under 15 mmHg pressure for 3 h. Chromatography of the product over alumina (100 g; grade I) with petroleum (b.p. 60—80 °C) as eluant gave *γ-elemene* (26) (2.0 g, 91%), $\nu_{max.}$ (film) 1 640, 915, and 895 cm^{-1} (Found: C, 88.1; H, 12.0. $C_{15}H_{24}$ requires C, 88.2; H, 11.8%).

The Bisbromohydrin (27).—(*a*) γ-Elemene (26) (298 mg) was dissolved in acetone (7 ml) and water (1 ml) and *N*-bromosuccinimide was added (520 mg). The solution was stirred for 30 min, at 0 °C. Work-up in the usual way gave an oil which afforded crystals on treatment with petroleum (b.p. 60—80 °C). Recrystallisation from ethyl acetate gave 1,7-*dibromoselinane*-4,11-*diol* (27) (50 mg, 9%), m.p. 134—136 °C (Found: C, 45.5; H, 6.5. $C_{15}H_{26}Br_2O_2$ requires C, 45.2; H, 6.6%).

(*b*) The bromohydrin (5) (292 mg) was dissolved in acetone (8 ml) and water (1 ml), *N*-bromosuccinimide (178 mg) was added, and the solution was stirred for 30 min at room temperature. Work-up in the usual way gave the bisbromohydrin (27) (159 mg, 46%), m.p. 131—134 °C, identical with a sample prepared from γ-elemene (26).

Reduction of the Bisbromohydrin with Zinc.—The bisbromohydrin (27) (111 mg) was dissolved in acetic acid (3 ml) and zinc dust (200 mg) was added. After stirring for 12 h at room temperature the mixture was worked up, giving the bromohydrin (5) (70 mg, 83%), m.p. 174—178 °C, identical with a sample prepared from germacratriene (1).

Hydroxymercuration of Germacratriene (1).—Germacratriene (1) (414 mg) was suspended in water (4 ml) at room temperature and mercury(II) acetate (168 mg) in water (5 ml) was added with stirring. After 15 min a white gum was deposited. Sodium hydroxide solution (4N; 3 ml) and sodium borohydride (300 mg) were added and the black suspension was stirred for 2 h and extracted with chloroform (3 × 10 ml). The extracts were worked up in the usual way to give an oil (308 mg) which was chromatographed over alumina (30 g; grade III). Elution with 1 : 1 benzene–petroleum (b.p. 40—60 °C) gave a 1 : 1 mixture of the dienes (19) and (20) (77 mg, 19%). Elution with benzene gave the alcohol (6) (74 mg, 16%).

Palladium(II) *Chloride Complex of γ-Elemene* (26).—(*a*) Germacratriene (215 mg) was dissolved in dry benzene (8 ml). Bis(benzonitrile)palladium chloride (270 mg) was added and the resulting red solution stirred at room temperature. Within 10 min a yellow precipitate developed. After a further 20 min the suspension was transferred to a centrifuge tube and the precipitate recovered after centrifuging. Dilution of the mother liquor with petroleum gave a further crop which was similarly centrifuged off. The combined solid material (174 mg, 53%) was washed copiously with petroleum and dried *in vacuo* to give the *complex*, m.p. 143—145 °C (Found: C, 47.3; H, 6.2. $C_{15}H_{24}PdCl_2$ requires C, 47.2; H, 6.3%).

(*b*) γ-Elemene (193 mg) dissolved in dry benzene (5 ml)

was treated with bis(benzonitrile)palladium chloride (245 mg) as before. Within 5 min the yellow complex formed, which was filtered off, washed with benzene, then dried (227 mg, 65%), m.p. 143—145 °C.

Addition of Benzenethiol to Germacratriene (1).—(a) *Photoinitiation.* Germacratriene (1) (431 mg) in cyclohexane (spectroscopic grade; 10 ml) containing benzenethiol (0.5 ml) was irradiated (365 nm; A.E.I. Mazda medium-pressure lamp with outer cover intact) for 2 h. The excess of benzenethiol was extracted with sodium hydroxide (10%; 10 ml) and the organic layer washed with water (2 × 20 ml). The residue in the cyclohexane solvent was passed through neutral alumina (grade III; 80 g). Petroleum (b.p. 40—60 °C; 100 ml) eluted hydrocarbons; benzene (100 ml) eluted 1β-*phenylthioselin*-7(11)-*ene* (10), which was obtained as crystals (233 mg, 34%) after evaporation of solvent; m.p. 59—61 °C (Found: C, 80.0; H, 9.4; S, 10.3. $C_{21}H_{30}S$ requires C, 80.2; H, 9.6; S, 10.2%); $\lambda_{max.}$ (EtOH) 216 (ε 10 900) and 257 nm (8 700); τ (CCl_4; 100 MHz) 9.08 (3 H, d, J 7 Hz), 8.97 (3 H, s), 8.40 (6 H, s), 7.34 (1 H, dd, $J + J' = 15$ Hz), and 2.85 (5 H, m).

(b) *Thermal initiation.* Germacratriene (416 mg) in cyclohexane (20 ml) containing 2,2′-azobis(isobutyronitrile) (50 mg) and benzenethiol (0.5 ml) was refluxed under nitrogen for 2 h. Work-up as before gave a product which was purified (p.l.c. on silica gel; chloroform as solvent) to give the 1 : 1 adduct (10) in 25% yield.

Reduction of the Sulphide (10) *by Lithium–Ethylamine.*—The adduct (10) (187 mg) and lithium (100 mg) were mixed with a little dry ether and cooled to −5 °C. Anhydrous ethylamine (40 ml) was condensed into the mixture, which was then stirred for 4 h. Ethanol was then added to destroy the excess of lithium, and ethylamine was removed by warming to room temperature. Work-up in the usual way followed by filtration through an alumina column in petroleum (b.p. 60—80 °C) gave the hydrocarbon (11) as (after complete removal of solvents) a clear oil (124 mg), shown by g.l.c. on DE 301 at 120 °C (N_2 at 15 lb in^{-2}) to be 90% pure; τ (CCl_4) 9.10 (3 H, d, J 7 Hz), 9.03 (3 H, s), and 8.37 (6 H, s).

Ozonolysis of the Olefin (11).—The hydrocarbon mixture (46 mg) was dissolved in dichloromethane (25 ml) containing a few drops of pyridine. The mixture was cooled to −70 °C and an ozone–oxygen stream was passed through for 40 min. The excess of ozone was purged with nitrogen. Zinc (25 mg) was added to the cold mixture, followed by glacial acetic acid (0.5 ml). The mixture was then allowed to warm to room temperature. Filtration through neutral alumina grade III (5 g) and elution with chloroform gave, after removal of solvents, the ketone (22) (34 mg, 85%), analytically pure by g.l.c. on DE 118 at 150 °C and DE 301 at 160 °C; $\nu_{max.}$ (film) 1 707s cm^{-1}, τ (CCl_4; 100 MHz) 9.08 (3 H, d, J 7 Hz) and 8.89 (3 H, s). The semicarbazone, purified by one sublimation at 126 °C and 10^{-5} mmHg, m.p. of 198—199° (sealed tube), was identical with that of the major epimer obtained on hydrogenation of (14).

Addition of Diphenyl Disulphide to Germacratriene.—Germacratriene (1.02 g) was dissolved in cyclohexane (15 ml) containing diphenyl disulphide (1.14 g) and irradiated under nitrogen as before for $3\frac{3}{4}$ h. The solvent was removed under reduced pressure and the residue was diluted with ethanol. The 1 : 1 adduct (9) separated on cooling the solution to −5 °C and was filtered off and washed several times with cold ethanol. The combined filtrate was concentrated; p.l.c. [10% benzene–petroleum (b.p. 40—60 °C)] gave more 1β,4-*bisphenylthioselin*-7(11)-*ene* (9) (1.16 g combined yield, 51%), m.p. 128—130 °C (Found: C, 76.6; H, 8.1; S, 14.9. $C_{27}H_{34}S_2$ requires C, 76.7; H, 8.1; S, 15.2%); $\lambda_{max.}$ (EtOH) 259 (ε 9 500) and 219 nm (ε 19 700), τ ($CDCl_3$; 100 MHz) 8.87 (3 H, s), 8.78 (3 H, s), 8.35 (3 H, s), 8.20 (3 H, s), 6.68 (1 H, dt, $W_{\frac{1}{2}}$ 14 Hz), and 2.8 (10 H, m).

Cleavage of the Bisthioether (9) *with Lithium–Ethylamine.*—The adduct (317 mg) dissolved in anhydrous ethylamine (*ca.* 25 ml) was stirred at room temperature while lithium (300 mg) was added. The mixture was stirred for 6 h, then ethanol was added and the solution was left overnight for the ethylamine to evaporate off. Work-up in the usual way gave a yellow oil which was decolourised by filtration through alumina (grade III; 2 g). The product (137 mg) was a mixture of the dienes (19) and (20) (8% of each), the olefin (11) (14%), its C-4 epimer (54%), and an unidentified hydrocarbon (14%). Fractionation on a methylsilicone gum column at 170 °C (g.l.c.) gave pure endesm-7(11)-ene, τ ($CDCl_3$; 100 MHz) 9.18 (3 H, d, J 6 Hz), 9.13 (3 H, s), and 8.40 (6 H, s).

Ozonolysis of the Hydrocarbon Mixture.—The hydrocarbon mixture from the hydrogenolysis of the adduct (9) [70 mg containing 44 mg of a 9 : 1 mixture of (12) and (11)] was dissolved in dichloromethane (15 ml) containing a few drops of pyridine and cooled to −70 °C. Ozone–oxygen was passed through for 40 min. Work-up as before with zinc (50 mg) and glacial acetic acid (0.5 ml) followed by filtration through a silica gel column (5 g) gave, after evaporation of solvents, the ketones (23) and (22) in an 8 : 2 ratio (g.l.c. on DE 301 column at 160 °C) in 78% yield (30 mg); $\nu_{max.}$ (CCl_4) 1 705s cm^{-1}; τ (CCl_4) 9.16 (3 H, d, J 5 Hz) and 8.98 (3 H, s). The *semicarbazone* of 11,12,13-*trinoreudesman*-7-*one* (23) was repeatedly recrystallised from ethanol and sublimed under high vacuum (10^{-5} mmHg) at 130 °C to give a sample, m.p. 209—210 °C (Found: C, 65.8; H, 9.7; N, 17.5. $C_{13}H_{23}N_3O$ requires C, 65.8; H, 9.8; N, 17.7%), identical with the minor product of hydrogenation of (14).

Addition of Carbon Tetrachloride to Germacratriene.—(a) *Photoinitiation.* A solution of germacratriene (631 mg) in AnalaR carbon tetrachloride redistilled from potassium carbonate (16 ml) was irradiated (365 nm) for 3 h under the same conditions as for the benzenethiol addition reaction. The solvent was removed from the brown solution formed. The glassy residue was diluted with a few drops of chloroform and then a larger portion of ethanol (5 ml). On cooling to −5 °C, 4-*chloro*-1β-*trichloromethylselin*-7(11)-*ene* (8) (355 mg, 32%) crystallised out; m.p. 80—84 °C (Found: C, 53.8; H, 6.8; Cl, 39.8. $C_{16}H_{24}Cl_4$ requires C, 53.7; H, 6.8; Cl, 39.6%), τ ($CDCl_3$; 100 MHz) 8.48 (3 H, s), 8.73 (3 H, s), 8.33 (3 H, s), 8.38 (3 H, s), 6.94 (1 H, dd, $W_{\frac{1}{2}}$ 14 Hz).

(b) *Thermal initiation.* Germacratriene (149 mg) and dibenzoyl peroxide (9 mg) dissolved in purified carbon tetrachloride (4 ml) was refluxed under nitrogen for 24 h. Work-up as above gave the adduct (8) (88 mg, 30%).

Ozonolysis of the Adduct (8).—The adduct (410 mg) in dichloromethane (50 ml) containing pyridine (1 ml) was ozonised at −70 °C for 60 min. After 30 min the solution was chromatographed directly on silica gel (200 g) with dichloromethane (250 ml) as solvent. The fraction was evaporated to give 4-*chloro*-1β-*trichloromethyl*-11,12,13-*trinorselinan*-7-*one* (25) as crystals, m.p. 117—123 °C (302 mg, 78%). A sample recrystallised from ethanol (Found: C, 47.0; H, 5.6; Cl, 42.8. $C_{13}H_{18}Cl_4O$ requires C, 47.0; H,

5.5; Cl, 42.7%) showed $\nu_{max.}$ (CCl_4) 1 717s cm^{-1}, τ (CCl_4; 100 MHz) 8.57 (3 H, s) and 8.43 (3 H, s).

The ketone (26 mg) was refluxed in bench methanol (5 ml). On evaporation a waxy solid (24.2 mg) was obtained which was mainly the dimethyl acetal, M^+ 376, τ ($CDCl_3$) 8.77 (3 H, s), 8.47 (3 H, s), and 6.80 (6 H, d).

The Ketone (24).—The adduct (8) (1.45 g) in anhydrous ether (20 ml) was added dropwise to a solution of lithium (300 mg) in liquid ammonia (75 ml) over 20 min. Stirring was continued for 2½ h. Ammonium chloride was added in excess and the mixture left overnight at room temperature. Work-up in the usual way, followed by filtration through grade III alumina (5 g) and elution with ether (10 ml), gave a fraction (after evaporation of solvents) which was distilled (82—92 °C and 1 mmHg) and collected as a clear liquid (345 mg). Analytical g.l.c. (DE 118 at 160 °C) indicated the presence of 67% of the C-4 epimer of (12). The distilled hydrocarbons (345 mg) were ozonised by the usual method in dichloromethane (50 ml) containing pyridine (0.1 ml) at −70 °C for 2 h. After removal of solvent, the residue was chromatographed directly on silica gel (80 g) with chloroform as eluting solvent to give 1β-methyl-11,12,13-trinoreudesman-7-one (24) (156 mg, 70%). The ketone (30 mg) was converted into its *semicarbazide*, m.p. 192 °C (decomp.) (Found: C, 66.8; H, 10.0; N, 17.0. $C_{14}H_{25}N_3O$ requires C, 66.9; H, 10.0; N, 16.7%).

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