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Constituents of *Torilis scabra* D.C. II

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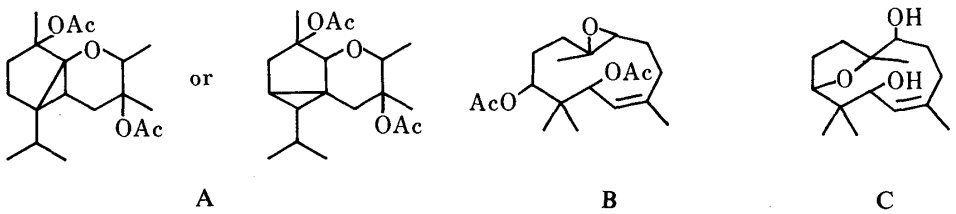
Novel five humulenoids were isolated from *Torilis scabra* D.C. and their structures were determined by chemical reaction and instrumental analysis. The chiroptical method for determining the absolute configuration of allylic alcohols, reported by Harada and Nakanishi, was found to be applicable to eleven-membered-ring humulenoids.

Keywords——*Torilis scabra*; humulenoid; X-ray analysis; absolute configuration; caucalol diacetate; neocaucalol diacetate; circular dichroism

Introduction

Torilis scabra D.C. (Japanese name "O-yabujirami"; Umbelliferae) is a biennial plant found only in Japan and south Korea. The fruits are used in Japan as a substitute for a Chinese crude drug "She chuang zi"[1] and also as a traditional insecticide.[2] The existence of two compounds named caucalol diacetate and apocaucalol diacetate in the fruits were reported by Mitsui,[3a] and the structure of the former was cited as formula A in Fig. 1, but the structure of the latter was not clarified.[3] The structures of caucalol diacetate and isocaucalol, which was obtained by treatment of caucalol diacetate with a strong base, were corrected to B and C, respectively (Fig. 1), by Sasaki and co-workers.[3b]



A B C

Fig. 1

In the course of our study on Japanese native *Torilis* species, we have already reported the isolation of several sesquiterpenoids biogenetically related to epoxygermacrene-D from *T. japonica* (Japanese name "Yabujirami").[4] In this work, a part of which was reported in our preliminary communication,[5] we present the structures of four novel humulenoids from *T. scabra* determined by means of X-ray analysis, chemical reaction, and the chiroptical method of Harada, Nakanishi *et al.*[6] for determining the absolute configuration of allylic alcohols. The absolute configuration of caucalol diacetate which had not been determined previously, was identified.

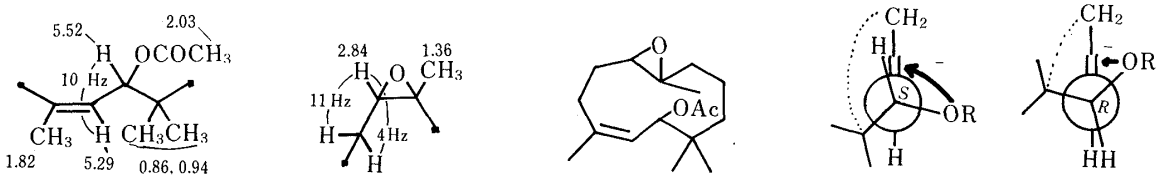
Results and Discussion

The fresh fruits of *T. scabra* collected at Hachioji, Tokyo, were treated in the same manner as described previously,[4a] and compounds I—V were isolated from the *n*-hexane extract by column chromatography, high-performance liquid chromatography (HPLC), and fractional recrystallization.

The molecular formula of compound I was assigned as $C_{17}H_{28}O_3$ and I was shown to be an acetyl ester of a sesquiterpene alcohol from the proton (^{1}H-) and carbon-13 (^{13}C-) nuclear magnetic resonance (NMR) spectra [^{1}H-; δ 2.03 (3H, s): ^{13}C-; 170.44 (s)]. The presence of partial structures D and E (Fig. 2) in I were indicated by spin–spin decoupling experiments in the ^{1}H-NMR and I was suggested to be a monocyclic sesquiterpenoid. These data strongly suggested that the basic skeleton of I was humulene type. The structure of compound I was assigned as F (Fig. 2) based on the above data and biogenetic considerations.

Compound II ($C_{15}H_{26}O_2$) was assigned as a desacetyl derivative of I because the base catalyzed hydrolysis of I gave II. In the usual way, II was converted to the *p*-bromobenzoyl ester (IIb) and IIb showed a strong negative Cotton curve in the circular dichroism (CD) spectrum. Because the coupling constant between the C1 and C2 protons of IIb was 10 Hz in the ^{1}H-NMR spectrum, two conformational isomers IIc and IId were considered at the allylic ester position, as illustrated in Fig. 2. The rotational isomer IIc was suggested to be the preferred conformer in the case of *S* configuration because of the steric hindrance of IId, but application of the benzoate rule to eleven-membered rings such as IIb is difficult because of the flexibility of the molecule.

The X-ray analysis of IIb was undertaken and the absolute configuration of IIb was identified from the anomalous dispersion of the bromin atom. Figure 3 is a stereoscopic drawing of the molecule and the structures of I and II are illustrated in Fig. 4. Because the dihedral angle between C3–C2 and C1–O1 was calculated as 175.47° and *S* configuration at the C1 position was established, the preferred conformation was concluded to be IIc. The preferred rotamer cited in our preliminary communication[5] was thus erroneous and should



D E F IIc IId

Fig. 2

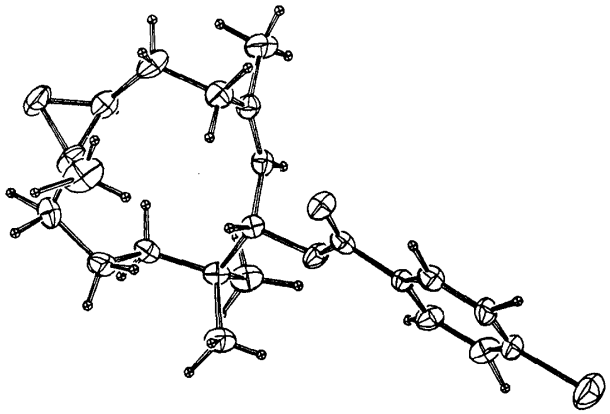
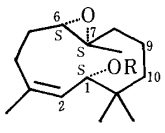


Fig. 3



I: R=Ac
II: R=H
IIb: R=*p*-Br–C_6H_4–CO

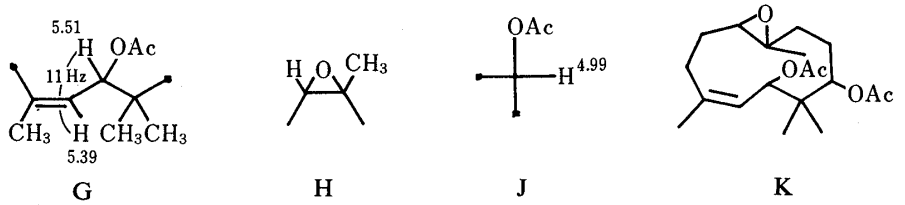
Fig. 4

be corrected to rotamer IIc. The benzoate rule was found to be applicable to these eleven-membered rings, as with open-chain allylic benzoates.[6b]

The molecular formula of compound V was found to be $C_{19}H_{30}O_5$ and V was shown to be a diacetyl ester of a sesquiterpene diol from the NMR spectra [^{1}H-; δ 2.03, 2.08 (each 3H, s), ^{13}C-; δ 170.09 (s), 170.90 (s)]. The spectral data for V led to the partial structures G, H, and J in Fig. 5. The molecular structure K was deduced from these data and biogenetic considerations. The whole structure of V including the configuration was solved by X-ray analysis by the direct method and a stereoscopic view of the molecule is shown in Fig. 6.

The base-catalyzed hydrolysis of V under mild conditions afforded Va and the reaction proceeded only at the allylic acetoxy group. Compound Va was converted to the *p*-bromobenzoyl ester Vb. Compound Vb showed a negative Cotton curve in the CD spectrum and the coupling constant between the C1 and C2 protons of Vb was 10 Hz. Two conformers (IIc and IId) are illustrared in Fig. 2, and IIc was the preferred rotamer because of the steric hindrance of IId. Thus, the *S* configuration was established at the C1 position and the full structure of V including the absolute configuration is illustrated in Fig. 7. We named compound V neocaucalol diacetate. Apocaucalol diacetate was similar to compound V in physical properties [V: mp 169—171 °C, $[\alpha]_D$ −108.3° in $CHCl_3$; apocaucalol diacetate[3a]: mp 165 °C, $[\alpha]_D$ −126.4° in $CHCl_3$], but the structure has not yet been determined.

Compound III was assigned the formula $C_{17}H_{28}O_3$ and the structure of III was concluded to be F from the spectral data. Compound III was converted to the *p*-bromobenzoyl ester IIIb *via* the allylic alcohol IIIa. The Cotton effect of IIIb was negative and the coupling constant between the C1 and C2 protons was 10 Hz. Thus, the *S* configuration at the C1 position was established on the same basis as in the case of compound V.



G H J K

Fig. 5

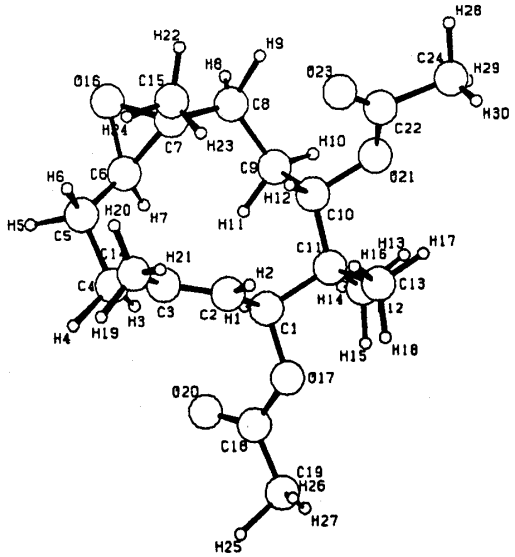
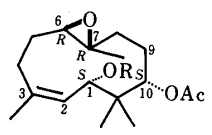


Fig. 6

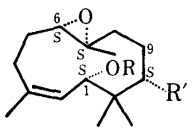


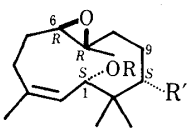
V: R=Ac
Va: R=H
Vb: R=*p*-Br–C_6H_4–CO

Fig. 7

TABLE I. ^{13}C-NMR Signals of the Epoxy Moiety

Compounds	I	II	III	IIIa	IV	IVa	V	Va
Doublet	60.60	60.54	62.13	62.16	60.02	60.08	62.33	62.21
Singlet	60.60	60.54	62.62	62.79	60.02	60.08	62.62	62.85





I: R=Ac, R′=H
II: R=H, R′=H
IIb: R=*p*-Br-C_6H_4-CO, R′=H
IV: R=Ac, R′=OAc
IVa: R=H, R′=OAc
IVb: R=*p*-Br-C_6H_4-CO, R′=OAc

III: R=Ac, R′=H
IIIa: R=H, R′=H
IIIb: R=*p*-Br-C_6H_4-CO, R′=H
V: R=Ac, R′=OAc
Va: R=H, R′=OAc
Vb: R=*p*-Br-C_6H_4-CO, R′=OAc

Fig. 8

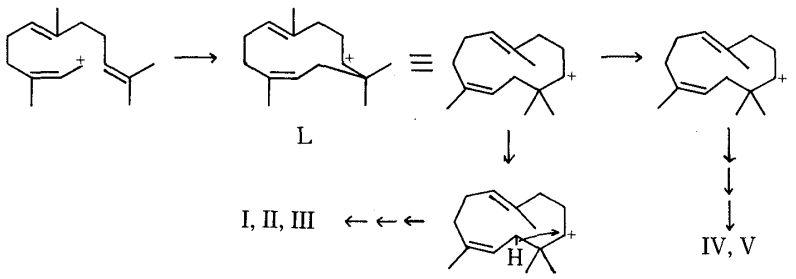


Fig. 9

Compound IV was identical with caucalol diacetate as regards physical properties [IV: mp 124.5—125 °C, $[\alpha]_D$ +27.7° in $CHCl_3$; lit.[3a] mp 121—122 °C. $[\alpha]_D$ +32.4° in $CHCl_3$] and the structure of IV was indicated as K (Fig. 5). Caucalol monoacetate[3a] (IVa) was obtained by partial hydrolysis of IV; the reaction was proceeded only at the allylic acetoxy group. The *S* configuration at the C1 position was deduced from the negative Cotton curve in the CD spectrum and the coupling constant of the allylic ester proton of IVb, the *p*-bromobenzoate of IVa.

From the ^{13}C-NMR signals of the partial structure B, all the compounds isolated and hydrolyzed could be classified into two groups, S (I, II, IV, IVa) and R (III, IIIa, V, Va). The ^{13}C-signals of the epoxy carbons in the S group appeared at essentially the same position whereas those in the R group were at a different position (Table I). The configuration of part B of group S was 6*S*, 7*S* (related to compound IIb) and that of group R was 6*R*, 7*R* (correlated to compound V).

The structures of all the compounds were cited at Fig. 8. Compounds I—III are humulenoids of a unique type because of the lack of functional groups at the C9 and/or C10 positions. From the viewpoint of biosynthesis, I—III seemed to be synthesized from *trans*, *cis*-farnesyl pyrophosphate *via* a hydride shift of the presumed carbonium ion (L) intermediate, as shown in Fig. 9.

Experimental

Spectral data were obtained on the following instruments: optical rotation, on a JASCO DIP-4 in $CHCl_3$ solution; infrared (IR), on a JASCO A-302 in CCl_4 solution; ultraviolet (UV), on a Hitachi 557 in EtOH solution; CD, on a JASCO J-500C in EtOH solution; ^{1}H-NMR, on a Varian EM 390 and a JEOL FX-200 in $CDCl_3$ solution with tetramethylsilane as an internal standard; ^{13}C-NMR, on a JEOL FX-100 in $CDCl_3$ solution; mass spectrum (MS), on a Hitachi M-80. HPLC was carried out on a CIG column system (Kusano Scientific Co., Tokyo) with WAKO GEL (50 μ silica gel) as the stationary phase.

Isolation of Compounds I—V——The fresh fruits (1.55 kg) of *T. scabra* collected at Ongata-cho, Hachioji, Tokyo in June 1982 were treated in the same manner as described previously.[4a] The *n*-hexane-soluble fraction was chromatographed on silica gel with *n*-hexane and ethyl acetate and the eluates were divided into 11 fractions. The eighth fraction was subjected to HPLC (eluate, *n*-hexane : ethyl acetate = 17 : 3 and *n*-hexane : ethyl acetate : acetonitrile = 25 : 2 : 1) to afford I (1.150 g) and III (0.315 g). Repeated chromatography of the tenth fraction (eluate, *n*-hexane : ethyl acetate : acetonitrile = 15 : 2 : 1) and fractional recrystallization of the products from petroleum ether (bp range: 40—60 °C) gave compounds IV (4.112 g) and V (0.914 g). The final fraction provided compound II (0.083 g) after HPLC (eluate, *n*-hexane : ethyl acetate = 6 : 4).

Compound I (1*S*,6*S*,7*S*)-1-Acetoxy-6,7-epoxyhumul-2(*Z*)-ene: Colorless needles, mp 125—130 °C. $[\alpha]_D$ +21.4° (c = 0.36). MS *m/z* (%): 280 (M^+, 0.4), 265 (0.3), 283 (3), 220 (3), 177 (5), 126 (25), 109 (25), 95 (25), 84 (80), 43 (100). IR cm^{-1}: 3000, 2970, 2930, 2870, 1730, 1655, 1465, 1450, 1385, 1370, 1245, 1130, 1065, 1010, 965. ^{1}H-NMR δ: 0.86 (3H, s). 0.94 (3H, s), 1.36 (3H, s), 1.82 (3H, s), 2.03 (3H, s), 2.84 (1H, dd, J = 4, 11 Hz), 5.29 (1H, d, J = 10 Hz), 5.52 (1H, d, J = 10 Hz). ^{13}C-NMR δ: 16.66 (q), 19.72 (t), 21.16 (q), 22.72 (q), 23.01 (q), 24.04 (q), 25.02 (t), 29.12 (t), 37.02 (s), 37.59 (t), 38.69 (t), 60.60 (s), 60.60 (d), 73.40 (d), 122.58 (d), 140.86 (s), 170.44 (s). *Anal.* Calcd for $C_{17}H_{28}O_3$: C, 72.82; H, 10.06. Found: C, 72.90; H, 10.06.

Compound II (1*S*,6*S*,7*S*)-6,7-Epoxyhumul-2(*Z*)-en-1-ol: Colorless needles, mp 125—130 °C. $[\alpha]_D$ +30.9° (c = 0.22). MS *m/z* (%): 238 (M^+, 1), 223 (2), 220 (1), 205 (1), 177 (2), 137 (21), 109 (42), 97 (34), 84 (100), 83 (81), 82 (49), 81 (92), 69 (72). IR cm^{-1}: 3630, 2940, 2920, 2870, 1660, 1470, 1445, 1385, 1245, 1130, 1060, 1000, 980, 880. ^{1}H-NMR δ: 0.88 (3H, s), 0.98 (3H, s), 1.32 (3H, s), 1.84 (3H, s), 2.87 (1H, dd, J = 4, 11 Hz), 4.30 (1H, d, J = 11 Hz), 5.41 (1H, d, J = 11 Hz). ^{13}C-NMR δ: 16.55 (q), 19.66 (t), 22.89 (q), 22.89 (q), 25.02 (q), 25.02 (t), 28.71 (t), 37.42 (s), 37.54 (t), 39.03 (t), 60.54 (s), 60.54 (d), 70.86 (d), 126.90 (d), 138.03 (s). *Anal.* Calcd for $C_{15}H_{26}O_2$: C, 75.58; H, 10.99. Found C, 75.56; H, 10.96.

Compound III (1*S*,6*R*,7*R*)-1-Acetoxy-6,7-epoxyhumul-2(*Z*)-ene: Colorless oil. $[\alpha]_D$ −175.5° (c = 0.33). MS *m/z* (%): 280 (M^+, 0.3), 238 (4), 220 (5), 205 (8), 126 (32), 109 (48), 94 (34), 84 (100), 81 (58), 79 (58), 55 (49). IR cm^{-1}: 2970, 2950, 2860, 1730, 1665, 1460, 1365, 1245, 1120, 1070, 1015, 655, 905, 860. ^{1}H-NMR δ: 0.87 (3H, s), 0.98 (3H, s), 1.28 (3H, s), 1.76 (3H, s), 2.02 (3H, s), 2.70 (1H, m), 5.30 (1H, d, J = 10 Hz), 5.51 (1H, d, J = 10 Hz). ^{13}C-NMR δ: 21.20 (q), 21.59 (q), 21.98 (t), 22.66 (q), 23.78 (q), 23.98 (q), 24.85 (t), 28.41 (t), 36.69 (s), 37.04 (t), 37.04 (t), 62.13 (d), 62.62 (s), 74.46 (d), 122.56 (d), 141.22 (s), 170.31 (s). *Anal.* Calcd for $C_{17}H_{28}O_3$: C, 72.82; H, 10.06. Found C, 72.92; H, 10.04.

Compound IV (Caucalol Diacetate) (1*S*,6*S*,7*S*,10*S*)-1,10-Diacetoxy-6,7-epoxyhumul-2(*Z*)-ene: Colorless plates, mp 124.5—125 °C. $[\alpha]_D$ +27.7° (c = 1.54). MS *m/z* (%): 278 (5), 237 (11), 235 (8), 218 (14), 203 (12), 175 (24), 151 (18), 135 (22), 125 (22), 121 (22), 109 (100), 81 (60). IR cm^{-1}: 2990, 2890, 1740, 1730, 1665, 1450, 1370, 1240, 1135, 1015, 960, 905, 875. ^{1}H-NMR δ: 0.86 (3H, s), 0.89 (3H, s), 1.36 (3H, s), 1.84 (3H, s), 2.01 (6H, s), 2.99 (1H, dd, J = 4, 11 Hz), 4.90 (1H, m), 5.29 (1H, d, J = 11 Hz), 5.46 (1H, d, J = 11 Hz). ^{13}C-NMR δ: 16.43 (q), 18. 51 (q), 18. 51 (q), 20.81 (q), 21.05 (q), 23.12 (q), 25.20 (t), 27.68 (t), 29.29 (t), 34.48 (t), 41.80 (s), 60.02 (s), 60.02 (d), 72.53 (d), 76.05 (d), 121.66 (d), 141.78 (s), 170.14 (s), 170.78 (s). *Anal.* Calcd for $C_{19}H_{30}O_5$: C, 67.43; H, 8.93. Found C, 67.32; H, 8.95.

Compound V (Neocaucalol Diacetate) (1*S*,6*R*,7*R*,10*S*)-1,10-Diacetoxy-6,7-epoxyhumul-2(*Z*)-ene: Colorless needles, mp 169—171 °C. $[\alpha]_D$ −108.3° (c = 0.29). MS *m/z* (%): 338 (M^+, 3), 323 (1), 278 (4), 236 (9), 218 (15), 203 (20), 175 (38), 135 (30), 109 (100). IR cm^{-1}: 2980, 2930, 2890, 1745, 1660, 1460, 1390, 1370, 1235, 1015, 960, 900. ^{1}H-

Table II. Hydrolysis of I, III, IV, and V

Sample (mg)	Solvent (ml)	Base (ml)	Product (mg)	Yield (%)	Mobile phase of HPLC
I (42)	40	8	II (22)	62	7 : 3[a]
III (34)	40	5	IIIa (22)	76	65 : 35[a]
IV (134)	50	10	IVa (78)	66	19 : 1[b]
V (108)	40	10	Va (55)	58	19 : 1[b]

a) *n*-Hexane : ethyl acetate. *b*) Benzene : 2-propanol.

TABLE III. Derivatization of Allylic Alcohols to *p*-Bromobenzoyl Esters

Compound	Starting material (mg)	*p*-BBC[a] (mg)	Product (mg)	Yield (%)	CD $\Delta\varepsilon$ (nm)	UV nm (log ε)	*J*H1–H2 (Hz)
IIb	II (42)	84	48	65	−13.6 (246)	246 (4.35)	10
IIIb	III (7)	40	2	16	−7.2 (244)	245 (4.08)	10
IVb	IV (74)	110	81	68	−25.1 (246)	243 (4.66)	10
Vb	V (17)	70	9	33	−11.6 (247)	246 (4.17)	10

a) *p*-Bromobenzoyl chloride.

TABLE IV. Atomic Parameters of IIb ($\times 10^4$)

Atom	*X*	*Y*	*Z*	Atom	*X*	*Y*	*Z*
Br	−2093 (18)	7529 (3)	9160 (27)	C13	5285 (14)	6571 (2)	934 (18)
C1	4558 (10)	6237 (2)	4255 (15)	C14	6275 (13)	6743 (2)	4525 (18)
C2	3847 (11)	5969 (2)	2854 (15)	C15	7894 (19)	5584 (3)	8139 (18)
C3	3691 (11)	5649 (2)	3344 (17)	O16	8459 (9)	5209 (2)	5075 (12)
C4	4170 (12)	5487 (2)	5427 (18)	O17	3299 (8)	6477 (1)	4837 (10)
C5	5485 (14)	5223 (2)	5202 (17)	C18	2486 (10)	6413 (2)	6607 (15)
C6	6969 (13)	5360 (2)	4427 (16)	O19	2628 (8)	6164 (1)	7679 (10)
C7	8125 (14)	5547 (2)	5755 (17)	C20	1405 (10)	6694 (2)	7167 (15)
C8	9155 (12)	5808 (3)	4667 (23)	C21	631 (11)	6680 (2)	9138 (17)
C9	8377 (13)	6153 (2)	4737 (20)	C22	−391 (11)	6931 (2)	9740 (18)
C10	7301 (11)	6214 (2)	2797 (16)	C23	1149 (12)	6962 (2)	9740 (18)
C11	5857 (11)	6439 (2)	3136 (16)	C24	107 (14)	7211 (2)	6390 (18)
C12	2954 (15)	5414 (2)	1731 (19)	C25	−651 (11)	7194 (2)	8310 (19)

TABLE V. Bond Lengths of IIb (Å)

Br–C25	1.893 (10)	C8–C9	1.535 (14)
C1–C2	1.513 (12)	C9–C10	1.533 (15)
C1–C11	1.531 (13)	C10–C11	1.531 (13)
C1–O17	1.480 (10)	C11–C13	1.550 (15)
C2–C3	1.329 (12)	C11–C14	1.540 (13)
C3–C4	1.509 (15)	O17–C18	1.325 (11)
C3–C12	1.514 (15)	C18–O19	1.210 (11)
C4–C5	1.542 (15)	C18–C20	1.496 (12)
C5–C6	1.452 (15)	C20–C21	1.393 (14)
C6–C7	1.485 (14)	C20–C23	1.390 (13)
C6–O16	1.454 (13)	C21–C22	1.381 (13)
C7–C8	1.521 (15)	C22–C25	1.400 (15)
C7–C15	1.507 (15)	C23–C24	1.380 (14)
C7–O16	1.452 (11)	C24–C25	1.359 (16)

NMR δ: 0.87 (3H, s), 0.98 (3H, s), 1.37 (3H, s), 1.79 (3H, s), 2.03 (3H, s), 2.08 (3H, s), 2.84 (2H, m), 4.99 (1H, d, J= 8 Hz), 5.39 (1H, d, J=11 Hz), 5.51 (1H, d, J=11 Hz). ^{13}C-NMR δ: 17.99 (q), 18.10 (q), 20.93 (q), 21.10 (q), 24.10 (q), 25.02 (t), 28.37 (t), 30.21 (t), 34.02 (t), 41.69 (s), 62.33 (d), 62.62 (s), 73.17 (d), 74.96 (d), 121.37 (d), 142.82 (s), 170.09 (s), 170.90 (s). *Anal.* Calcd for $C_{19}H_{30}O_5$: C, 67.43; H, 8.93. Found C, 67.40; H, 8.92.

Hydrolysis of Compounds I, III, IV, and V——A methanol solution of the sample was treated with 10% NaOH solution was and the mixture was allowed to stand overnight. The reaction mixture was diluted with water and then extracted with ether, and the organic layer was washed with brine and dried over $MgSO_4$. The product was purified by HPLC.

Table VI. Bond Angles of IIb (°)

C2–C1–C11	113.4 (7)	C13–C11–C1	111.3 (8)
C2–C1–O17	108.8 (7)	C13–C11–C10	109.1 (8)
C11–C1–O17	106.3 (7)	C13–C11–C14	107.3 (8)
C3–C2–C1	126.7 (8)	C1–C11–C10	108.6 (7)
C4–C3–C2	126.2 (9)	C1–C11–C14	109.2 (8)
C4–C3–C12	114.4 (8)	C10–C11–C14	111.3 (8)
C2–C3–C12	119.5 (9)	C18–O17–C1	116.6 (7)
C5–C4–C3	114.3 (8)	O19–C18–O17	124.8 (8)
C6–C5–C4	112.8 (9)	O19–C18–C20	123.9 (8)
C7–C6–C5	125.0 (9)	O17–C18–C20	111.3 (7)
C7–C6–O16	59.2 (6)	C21–C20–C18	117.4 (8)
C5–C6–O16	119.6 (8)	C21–C20–C23	119.9 (8)
C8–C7–C6	118.3 (9)	C18–C20–C23	122.7 (8)
C8–C7–C15	116.6 (9)	C22–C21–C20	120.1 (9)
C8–C7–O16	113.8 (8)	C25–C22–C21	118.5 (9)
C6–C7–C15	121.0 (9)	C24–C23–C20	120.0 (9)
C6–C7–O16	59.3 (6)	C25–C24–C23	119.6 (10)
C15–C7–O16	113.9 (9)	Br–C25–C22	117.4 (8)
C9–C8–C7	111.5 (9)	Br–C25–C24	120.8 (8)
C10–C9–C8	112.1 (9)	C22–C25–C24	121.8 (10)
C11–C10–C9	117.3 (8)	C6–O16–C7	61.4 (6)

Table VII. Atomic Parameters of Compound V ($\times 10^4$)

Atom	X	Y	Z	Atom	X	Y	Z
C1	3863 (8)	4092 (0)	1262 (9)	C13	3802 (10)	5777 (5)	−21 (11)
C2	2227 (9)	4103 (5)	1664 (9)	C14	−315 (10)	3560 (7)	2559 (13)
C3	1315 (9)	3387 (6)	2125 (10)	C15	−608 (10)	2876 (6)	−1837 (12)
C4	1839 (10)	2279 (6)	2281 (11)	O16	645 (8)	1215 (4)	−1836 (9)
C5	930 (10)	1604 (6)	1015 (11)	O17	4880 (6)	4551 (4)	2536 (6)
C6	1555 (10)	1666 (6)	−467 (10)	C18	5686 (10)	4026 (7)	3650 (10)
C7	931 (10)	2302 (5)	−1865 (11)	C19	6625 (10)	4622 (9)	4848 (11)
C8	2082 (11)	2625 (6)	−2990 (10)	O20	5632 (10)	3122 (5)	3630 (11)
C9	3524 (10)	3187 (5)	−2181 (10)	O21	3230 (6)	4906 (4)	−2975 (6)
C10	3077 (9)	4622 (5)	−1606 (9)	C22	1856 (10)	5247 (6)	−3746 (9)
C11	4193 (8)	4645 (5)	−252 (9)	O23	570 (7)	5044 (5)	−3459 (8)
C12	5940 (9)	4545 (6)	−512 (11)	C24	2270 (13)	5976 (7)	−5030 (11)

Compound IIIa (1*S*,6*R*,7*R*)-6,7-Epoxyhumul-2(*Z*)-en-1-ol: Colorless oil. $[\alpha]_D$ −250.9° (c=0.22). MS m/z (%): 238 (M^+, 1), 223 (2), 220 (1), 205 (2), 195 (1), 177 (2), 167 (6), 149 (4), 137 (16), 123 (17), 121 (18), 109 (44), 97 (31), 95 (29), 84 (100), 83 (89), 81 (71), 69 (67). IR cm^{-1}: 3630, 2970, 2880, 1665, 1460, 1385, 1240, 1215, 1070, 1045, 985, 870. ^{1}H-NMR δ: 0.90 (3H, s), 0.98 (3H, s), 1.27 (3H, s), 1.77 (3H, s), 2.87 (1H, dd, J=3, 11 Hz), 4.22 (1H, d, J=10 Hz), 5.44 (1H, d, J=10 Hz). ^{13}C-NMR δ: 21.33 (q), 21.68 (q), 22.66 (t), 24.04 (q), 24.33 (q), 24.97 (t), 28.08 (t), 31.59 (t), 37.03 (s), 37.71 (t), 62.16 (d), 62.79 (s), 72.19 (d), 126.78 (d), 138.38 (s). *Anal.* Calcd for $C_{15}H_{26}O_2$: C, 75.58; H, 10.99. Found: C, 75.84; H, 10.97.

Compound IVa (Caucalol Monoacetate) (1*S*,6*S*,7*S*,10*S*)-10-Acetoxy-6,7-epoxyhumul-2(*Z*)-en-1-ol: Colorless cubes, mp 189—191 °C. $[\alpha]_D$ +50.0° (c=1.24). MS m/z (%): 175 (5), 154 (12), 136 (19), 127 (42), 109 (80), 95 (45), 82 (100), 80 (98). IR cm^{-1}: 3640, 2970, 1740, 1660, 1445, 1370, 1235, 1120, 1010, 965, 870. ^{1}H-NMR δ: 0.82 (3H, s), 0.99 (3H, s), 1.31 (3H, s), 1.87 (3H, s), 2.00 (3H, s), 3.02 (1H, dd, J=3, 10 Hz), 4.17 (1H, dd, J=3, 11 Hz), 4.87 (1H, m), 5.40 (1H, d, J=11 Hz). ^{13}C-NMR δ: 16.37 (q), 17.24 (q), 18.74 (q), 20.87 (q), 23.24 (q), 25.20 (t), 27.68 (t), 29.00 (t), 34.42 (t), 42.49 (t), 60.08 (s), 60.08 (d), 70.57 (d), 76.92 (d), 125.92 (d), 139.07 (s), 170.95 (s). *Anal.* Calcd for $C_{17}H_{28}O_4$: C, 68.89; H, 9.52. Found: C, 68.73; H, 9.47.

Compound Va (1*S*,6*R*,7*R*,10*S*)-10-Acetoxy-6,7-epoxyhumul-2(*Z*)-en-1-ol: Colorless needles, mp 159—161 °C. $[\alpha]_D$ −125.3° (c=0.43). MS m/z (%): 237 (1), 236 (2), 221 (2), 218 (2), 203 (3), 193 (3), 175 (7), 135 (18), 127 (32), 109

Table VIII. Bond Lengths of Compound V (Å)

C1–C2	1.466 (11)	C8–C9	1.537 (12)
C1–C11	1.544 (10)	C9–C10	1.597 (10)
C1–O17	1.451 (8)	C10–C11	1.500 (10)
C2–C3	1.325 (11)	C10–O21	1.470 (9)
C3–C4	1.563 (11)	C11–C12	1.529 (10)
C3–C14	1.488 (12)	C11–C13	1.581 (10)
C4–C5	1.551 (12)	O17–C18	1.315 (10)
C5–C6	1.426 (13)	C18–C19	1.465 (13)
C6–C7	1.517 (11)	C18–O20	1.223 (12)
C6–O16	1.460 (10)	O21–C22	1.355 (9)
C7–C8	1.507 (13)	C22–O23	1.177 (10)
C7–C15	1.520 (12)	C22–C24	1.542 (12)
C7–O16	1.489 (9)		

Table IX. Bond Angles of V (°)

C2–C1–C11	117.0 (5)	C10–C9–C8	112.6 (6)
C2–C1–O17	108.7 (5)	C11–C10–C9	113.4 (6)
C11–C1–O17	105.8 (5)	C11–C10–O21	107.9 (6)
C3–C2–C1	131.4 (7)	C9–C10–O21	104.3 (6)
C4–C3–C2	123.7 (7)	C12–C11–C1	110.3 (6)
C4–C3–C14	113.1 (7)	C12–C11–C10	113.4 (6)
C2–C3–C14	123.2 (8)	C12–C11–C13	108.9 (6)
C5–C4–C3	112.9 (7)	C1–C11–C10	108.8 (6)
C6–C5–C4	112.2 (7)	C1–C11–C13	107.7 (6)
C7–C6–C5	126.8 (7)	C10–C11–C13	107.6 (6)
C7–C6–O16	60.0 (5)	C18–O17–C1	121.9 (6)
C5–C6–O16	118.0 (7)	C19–C18–O17	114.0 (8)
C8–C7–C6	118.0 (7)	C19–C18–O20	125.1 (9)
C8–C7–C15	118.7 (7)	O17–C18–O20	120.9 (8)
C8–C7–O16	114.4 (7)	C22–O21–C10	116.1 (6)
C6–C7–C15	120.1 (7)	O23–C22–O21	126.0 (7)
C6–C7–O16	58.1 (5)	O23–C22–C24	125.9 (8)
C15–C7–O16	111.1 (7)	O21–C22–C24	108.1 (7)
C9–C8–C7	113.4 (7)	C6–O16–C7	61.9 (5)

(86), 95 (44), 82 (100). IR cm^{-1}: 3630, 2970, 2940, 1740, 1660, 1460, 1385, 1370, 1240, 1060, 1015, 970, 945, 900. ^{1}H-NMR δ: 0.88 (3H, s), 0.97 (3H, s), 1.34 (3H, s), 1.80 (3H, s), 2.07 (3H, s), 2.79 (1H, dd, J=3, 10 Hz), 4.18 (1H, d, J=11 Hz), 4.92 (1H, m), 5.49 (1H, d, J=11 Hz). ^{13}C-NMR δ: 16.84 (q), 18.28 (q), 20.93 (q), 20.93 (q), 24.04 (q), 25.20 (t), 27.96 (t), 30.10 (t), 34.08 (t), 42.09 (s), 62.21 (d), 62.85 (s), 71.03 (d), 75.82 (d), 125.40 (d), 139.93 (s), 171.01 (s). *Anal.* Calcd for $C_{17}H_{28}O_4$: C, 68.89; H, 9.52. Found: C, 69.14; H, 9.57.

Formation of *p*-Bromobenzoyl Ester of II, IIIa, IVa, and Va——A pyridine solution of a sample and *p*-bromobenzoyl chloride was heated at 100 °C for 1 h, then poured into water and extracted with ether. The organic layer was dried over $MgSO_4$ and the product was purified by HPLC.

Crystal Data for V——$C_{19}H_{30}O_5$, M_r=338.4, $P2_1$, Z=2, a=8.4820, b=13.5069, c=8.5300, monoclinic, β=96.350°. Number of reflections=1665. Final R value=0.076.

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