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Oxidation of Terpenoid Diols with Chlorine Dioxide: Preparation of Ketols and α-Chlorohydroxyketones of Carane and Pinane Structures

L. L. Frolova[a], A. V. Popov[a], L. V. Bezuglaya[a], I. N. Alekseev[a], P. A. Slepukhin[b], and A. V. Kuchin[a]

[a] *Institute of Chemistry, Komi Scietific Center, Ural Branch, Russian Academy of Sciences, ul. Pervomaiskaya 48, Syktyvkar, 167982 Russia*
e-mail: frolova-ll@chemi.komisc.ru

[b] *I.Ya. Postovskii Institute of Organic Synthesis, Ural Branch, Russian Academy of Sciences, Yekaterinburg, Russia*

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Abstract—Vicinal terpenoid diols of carane- and pinane-type structures have been oxidized with chlorine dioxide in pyridine to form the corresponding ketols in the preparative yield of 52–72%, the selectivity of α-hydroxyketones formation being 80–90%. It has been shown that the diols reactivity towards oxidation with ClO_2 depends mainly on the stereochemistry of hydroxy groups. The catalysts, $VO(acac)_2$, $Mo(CO_6)$, and $MoCl_5$ have practically no effect on the oxidation process. When the reaction has been performed in dimethylformamide, the hydroxyketone chlorination occurred at high conversion.

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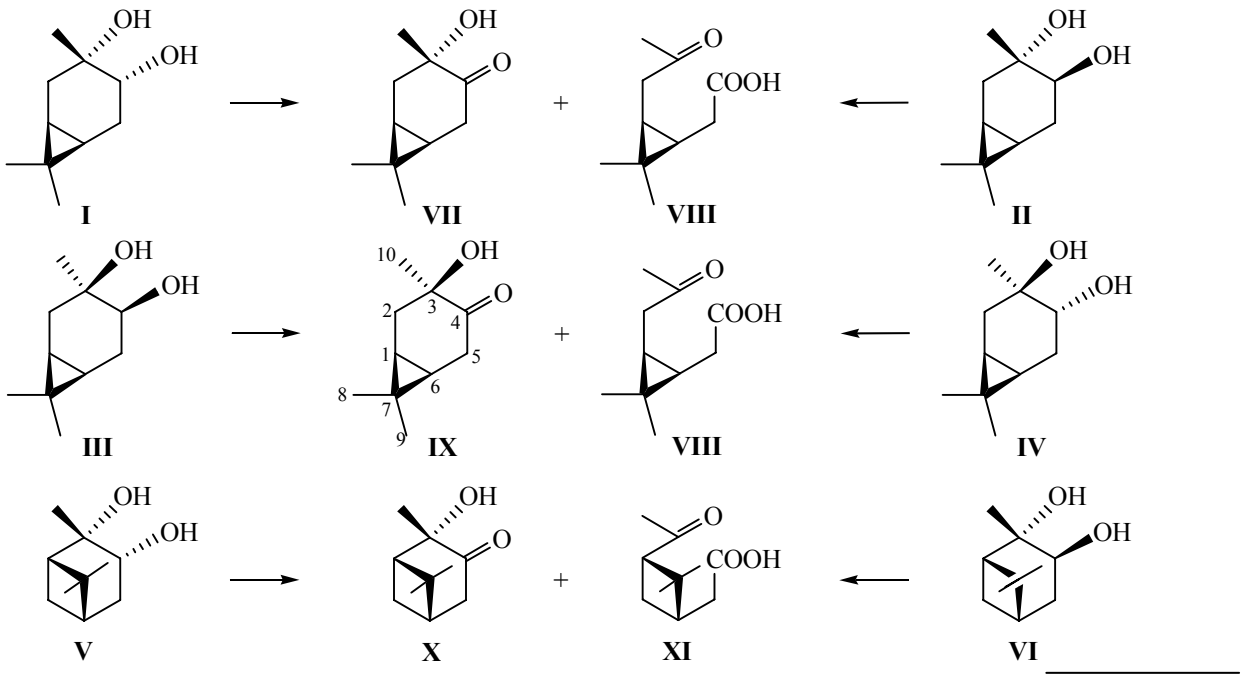
Polyfunctional monoterpenoids (ketols, amino alcohols, diketones, diols, etc.) are successfully used in the organic synthesis as chiral starting materials for preparation of analogs of optically active natural products [1, 2] and ligands giving rise to the asymmetric reactions catalysts [3–6]. Two well known groups of the mentioned substances are derivatives of 2α-hydroxypinan-3-one and camphorquinone, easily obtained (in both enantiomer forms) via oxidation of α-pinene with $KMnO_4$ [7] and of bromocamphor with oxygen in dimethylsulfoxide DMSO [8], respectively. Ketol derivatives of 3-carene are less available due to the absence of preparatory single-stage methods of their synthesis. For example, 3α-hydroxycarane-4-one was formed with very low yield via oxidation of 3-carene with $KMnO_4$ in acetone [9]; under conditions of phase-transfer catalysis its yield was up to 19–24% [10]. Thus, carane-based hydroxyketones preparation via oxidation of the corresponding 3,4-diol precursors seems more promising. Following the study of chlorine dioxide reactivity and its application as oxidizing agent, in this work we considered the results of ClO_2 reactions with terpenoid diols: optical isomers of caranediol-3,4 (**I–IV**) и and pinanediol-2,3 (**V–VI**).

As a preliminary step, hydroxyketones **VII** and **IX** were prepared by oxidation process using chromic acid; the reaction was performed at 0–5°C in diethyl ether medium during 2–3 h. Under those conditions, the conversion of starting caranediols **I** and **IV** was 99 and 89%, and the selectivity of ketols formation was 40 and 28%, respectively. The major reaction product was cyclopropane ketoacid **VIII** that was isolated from both reaction mixtures by chromatography on SiO_2, the yield being 42 and 55%, respectively. The spectral and physicochemical properties of both acid samples were identical to those reported in the literature [11].

Vicinal diols oxidation with the formation of carbonyl compounds and a carboxylic acid is a well known process. In [10, 12], the systems $KMnO_4$–AcOH–H_2O–Bu_4NBr and $Co(acac)_2$–2-methylpropanal–O_2 (or air) were used for oxidation of 3-carene and pinanediol-2α,3α (**V**), respectively, for preparation of the acids **VIII** and **XI**. It was demonstrated that in both cases the reaction proceeded through formation of the corresponding ketols (**VII** or **X**), their oxidation giving the acid product.

In our previous study we showed that pyridine was the most suitable solvent for oxidation of the secondary saturated and allylic terpenoid alcohols with chlorine dioxide, acetylacetonate of vanadyl and cobalt, or zirconium oxychloride might be used as catalyst [13].



The conditions of diols **I–VI** oxidation with chlorine dioxide and the respective results are given in Table 1.

As expected, for the major factor affecting the oxidation rate was the oxidizer attack on C–H bond, the compounds **II**, **III**, and **IV**, having less sterically hindered proton at C^4 or C^3, were the fastest to be oxidized. Full conversion was observed within 1–3 h, the selectivity of ketols **VII**, **IX**, **X** formation being 84–90%. The corresponding acids **VIII** and **XI** were obtained in minor amounts (10–16%). The reaction mixtures composition was determined by integration of non-overlapping signals in the ^{1}H NMR spectra (most often, those of CH_3 groups). In the cases of the most sterically hindered carane-based diols **I** and **IV** full conversion could not be reached even in 5–7 h, the selectivity of ketols formation was 80–81%.

We performed the oxidation of caranediol-3α,4α in the presence of catalysts (Table 2). Ni(II), Co(II), Cr(III), and VO acetylacetonates appeared to slow down the oxidation process, instead of accelerating it. As an example, in the presence of the most active of acetylacetonates used, $VO(acac)_2$, the conversion of **I** in 3 h was 40%, being 58% in the absence of any catalyst. The selectivity of ketol **VII** formation was below 80%. In the presence of molybdenum-containing catalysts the oxidation was not accelerated as well, however, the ketol formation selectivity was somewhat increased under such conditions, to 89–91% instead of 84%.

Additionally, oxidation of diol **I** in the presence of $ZrOCl_2$ was studied, the reaction time being 2, 4, 8, or

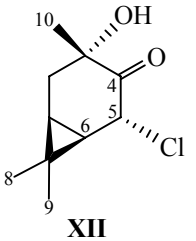
Table 1 . Results of **I–VI** oxidation with chlorine dioxide in pyridine at 20°C

Comp. no.	Reaction time, h	Conversion, %	Ketol formation selectivity, %	Preparative ketol yield, %
I	3.0	58	84	–
	6–7	75–79	80–81	60–64
II	1.5	49	88	–
	3.0	98	81	59
III	1.5	100	90	72
IV	1.5	20	100	–
	5.0	80	80	52
V	1.0	76	92	–
	2.0	100	90	–
VI	1.0	100	84	65

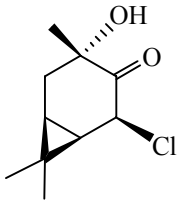
Table 2. Results of diol **I** oxidation with ClO_2 in pyridine (reaction time 3 h, 20°C, 3 wt % of catalyst)

Catalyst	Conversion, %	Selectivity, %
$Ni(acac)_2$	9	78
$Co(acac)_2$	28	71
$Cr(acac)_3$	34	79
$VO(acac)_2$	40	77
$Mo(CO)_6$	47	89
$MoCl_5$	45	91

10 h; the results are collected in Table 3. The highest conversion of **I** was achieved within 10 h, however, the selectivity was down to 74% From the products of caranediol-3α,4α oxidation, besides ketone **VII** (major product) and acid **VIII**, the crystalline fraction was isolated with the yield of about 3%; according to NMR results, this minor fraction contained 5α-chloro–3α-hydroxycaran-4-one (**XII**) and 5β-chloro–3α-hydroxycaran-4-one (**XIII**) in the ratio of 5:4. The structures of those products could be established by means of NMR due to the low number of protons and negligible signals overlap in the ^1H NMR spectrum. In general, NMR spectra of the isomers **XII** and **XIII** were very similar, except for the signals of atoms in the close vicinity of C^5, they were: H^5 (5.57 and 4.17 ppm, respectively), C^5 (63.4 and 58.4 ppm), H^6 (1.76 and 1.04 ppm), C^6 (34.2 and 30.1 ppm), and methyl group C^8H_3 (0.8 and 1.10 ppm). The notable spectral feature was the difference in the multiplicity of the signals of the only methylene group, C^2H_2, (doublet of doublets for both protons of the *cis*-isomer and a combination of H_{endo} doublet with H_{exo} doublet of doublets in the case of *trans*-isomer); this pointed at different conformation of cyclohexane cycle of those molecules.



XII



XIII

Compound **XII** was the only product of the prolonged (15 h) oxidation of diol **I** with chlorine dioxide in dimethylformamide medium. GLC analysis of the products in the course of the reaction revealed

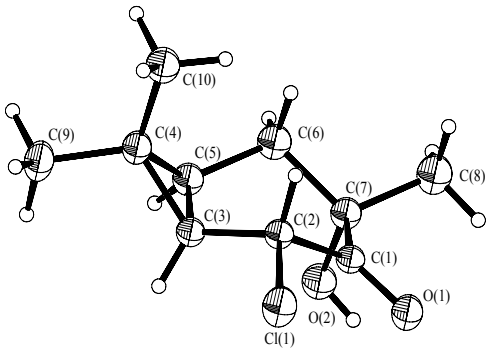
Table 3. Results of diol **I** oxidation with ClO_2 in the presence of $ZrOCl_2$ (5 wt %) in pyridine at 20°C

Time, h	Conversion, %	Selectivity, %
2	46	91
4	60	87
8	92	77
10	94	74

that after 3 h the reaction was completed to 50%; the content of hydroxyketone **VII** was 42%, and that of chlorinated derivative **XII** was 4%. After 7 h of the reaction duration, at 65% overall conversion, the ketol content was down to 37%, and that of the chlorinated derivative was up to 22%. Within 15 h diol **I** conversion was full (99%), the content of **XII** having reached 76%, with less than 0.5% of the ketol. 5α-Chloro-3α-hydroxycaran-4-one, isolated with chromatography on SiO_2 and recrystallized from the hexane–diethyl ether mixture, showed the melting point of 97–98°C and $[\alpha]_D$ –302.5 (c = 0.4 in EtOH). Its structure was unambiguously confirmed by **X**-ray diffraction data (see Figure). Note that in contrast to the case of pyridine solution, upon oxidation in dimethylformamide practically no acid **VIII** was formed.

It is known that the corresponding enols or enolate-ions are subjected to oxidation rather that ketones proper [14]. When introducing the electronegative substituents in the α-position to the carbonyl group, the CH-acidity of the carbonyl compound increases and so does the enol content. The solvent nature also influences the enolization state. Dimethylformamide is a bipolar aprotic solvent and it is used as catalyzing reaction medium in chlorination syntheses. Furthermore, the dimethylformamide–sulfinyl chloride (Vilsmeier reagent) is often used as chlorinating agent [15]. Similar complex formation may be expected in the case of ClO_2 and dimethylformamide.

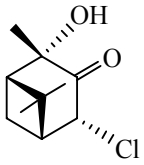
According to **X**-Ray diffraction data, **XII** crystallized in the chiral space group. The cyclohexane fragment was present in the *pseudoboat* conformation. The chlorine atom was located in the equatorial ("bowsprit") position, the cyclopropane ring connection was equatorial, and the hydroxy group took the axial position. The bond lengths and bond angles in the molecule were typical of that class of compounds. The cyclopropane fragment formed almost ideal triangle: C^4–C^5 1.5116(18) Å, C^3–C^5 1.5068(17) Å, C^3–C^4 1.5074(16) Å; $C^3C^5C^4$ 59.92(8)°, $C^5C^3C^4$ 60.20(8)°,



Structure of 5α-chloro-3α-hydroxycaran-4-one **XII** according to X-ray diffraction data.

$C^3C^4C^5$ 59.88(8)°; the bond lengths of hydroxy and the carbonyl groups were customary: C^1–O^1 1.2079(13) Å, O^2–C^7 1.4282(15) Å. Due to steric hindrance, the molecular packing revealed no adequate intermolecular hydrogen bonding [$O^1\cdots O^2$ 3.157(1) Å, $0.5 + x$, $0.5–y$, $–z$].

Similar chlorinated derivative was obtained via 2α-hydroxypinan-3-one (**X**) prolonged treatment with chlorine dioxide in dimethylformamide (4 days, room temperature), the reaction yield was 50%. The chromatography on silica gel of the reaction mixture allowed isolation of the initial ketol and its chlorination product **XIV**, the latter after recrystallization had melting point of 69°C and $[\alpha]_D$ of –4.9 (c = 0.3 in EtOH) (for 2α-hydroxypinan-3-one $[\alpha]_D = +1.5$).



XIV

Probably, the chlorinated products were formed via reactions of the secondary chlorinated derivatives (formed from ClO_2 via its interaction with the diols) rather than via direct interaction with the oxidizer. This could explain relatively fast formation of the chlorinated derivative **XII** during oxidation of the carane-based diol **I**, oppositely to slow chlorination of the pinane-based ketol **X**. In the latter case the oxidation was not observed, and the acids were not obtained.

To conclude, the oxidation of secondary-tertiary terpenoid diols with chlorine dioxide in pyridine was suitable and relatively selective method of the respective ketols preparation, as compared with the method involving chromic acid. Use of the catalysts [$(VO(acac)_2$, $ZrOCl_2$, $Mo(CO)_6$, or $MoCl_5$] was not necessary, unlike the case of the oxidation with ClO_2 of terpenoid secondary saturated alcohols (menthol and borneol) [13]. Using dimethylformamide instead of pyridine led to selective formation of the respective α-chlorinated hydroxyketones. In general, pinane-based diols were oxidized faster and with higher selectivity than carane-based ones. The prepared 3α-hydroxycaran-4-one and 3β-hydroxycaran-4-one were used in the preparation of chiral palladium complexes [16].

EXPERIMENTAL

GLC analysis was performed using Shimadzu GC-2010AF chromatograph, (HP column, flame-ionization detector, helium as carrier gas). IR spectra were recorded from thin film or KBr tablet on a spectrophotometer IR Prestige 21 (Shimadzu). NMR spectra were recorded on a spectrometer Bruker Avance-II-300 at the operating frequency 300 MHz (^{1}H) or 75 MHz (^{13}C) in $CDCl_3$ or DMSO-d_6. The TP instrument was used to determine melting point. Refractive indices were determined with IRF-454BM instrument. The optical rotation angle was determined with P3002RS automated polarimeter (Kruss, Germany).

The column chromatography was performed on silica gel 60 (70–230 mesh) (Lancaster). Thin layer chromatography was performed using Sorbfil plates, hexane and petroleum ether–diethyl ether as eluents, and phosphomolybdic acid in EtOH (10%) or vanillin in EtOH (3%) as developers. Aqueous ClO_2 (8–9 g l^{-1}) was provided by OAO MBP Syktyvkarskii LPK. Freshly distilled solvents were used to perform the reactions. Compounds **I**–**VI** were prepared by the known methods [7, 18–20], however, their spectral characteristics were not described in detail, thus we reported the revised and refined spectral data.

X-ray diffraction analysis was performed using four-circle automated diffractometer Xcalibur S following the standard procedure [MoK radiation, graphite monochromator, scanning step 1°, 295(2) K]. A fragment of colorless prism (0.25×0.20×0.15 mm) was used for analysis. The extinction was accounted for by multi-scanning method. According to X-ray diffraction data, the crystal was rhombic, of $P2_12_12_1$ space group, with a = 6.1558(3), b = 8.3038(3), c = 20.3636(6) Å, V = 1040.92(7) Å^3, Z = 4, d_{calc} = 1.293 g cm^{-3}, μ = 0.333 mm^{-1}. 5125 reflections were recorded at the scattering angle of $3.17 < \theta < 30.51°$, 3123 of them being independent (R_{int} = 0.0130), including 2205 with $I > 2\sigma(I)$. The

completeness for θ < 30.51° was of 98.8%. The structure was solved by the direct method and refined using full-matrix PLS along F^2 using SHELXTL software package [17]. Nonhydrogen atoms were refined under anisotropic approximation; hydrogen atoms, besides those of OH group, were localized according to the space electron density peaks and were included into refinement under isotropic approximation in the *rider* model. The OH hydrogen position was refined independently under isotropic approximation. Final parameters of the structure refinement were as follows: $R_1 = 0.0278$, $wR_2 = 0.0650$ for reflections with $I > 2\sigma(I)$; $R_1 = 0.0419$, $wR_2 = 0.0666$ for all reflections, *GOOF* = 1.002, absolute structural parameter of 0.00(6), maximal and minimal peaks of space electron density were 0.185/–0.171 *e* Å^{-3}.

The **X**-ray diffraction data were deposited in the Cambridge Crystallographic Data Centre.

Caranediol-3α,4α (I). $[\alpha]_D$ +14° (acetone), mp 69–70°C. IR spectrum, ν, cm^{-1}: 3323, 2990, 2959, 2930, 1441, 1375, 1140, 1061, 930, 868. ^{1}H NMR spectrum (DMSO-d_6), δ, ppm (*J*, Hz): 0.51 d.d.d (1H, H^1, *J* 4.3, 9.5, 13.8), 0.70 d.d.d (1H, H^6, *J* 2.5, 6.3, 9.5), 0.87 s (3H, C^{10}H$_3$), 0.96 s (3H, C^{8}H$_3$), 1.04 s (3H, C^{9}H$_3$), 1.06 d.d (1H, H^2, *J* 4.3, 15), 1.62–1.75 m (2H, H^5), 1.92 d.d (1H, H^2, *J* 9.5, 15), 2.95 d.d.d (1H, H^4, *J* 7.1, 9.3, 13.8), 3.66 s (1H, OH^3), 4.10 d (1H, OH^4, *J* 7.1). ^{13}C NMR spectrum (DMSO-d_6), δ_C, ppm: 72.51 (C^4), 69.09 (C^3), 33.96 (C^2), 29.29 (C^8), 27.18 (C^5), 27.02 (C^9), 22.53 (C^6), 17.63 (C^1), 17.03 (C^7), 15.84 (C^{10}).

Caranediol-3α,4β (II). Pale-yellow oily substance, n_D 1.4750, $[\alpha]_D$ +62.9 (*c* 0.8, $CHCl_3$). IR spectrum, ν, cm^{-1}: 3421, 2932, 2868, 1454, 1377, 1140, 1045, 926. ^{1}H NMR spectrum, ($CDCl_3$), δ, ppm (*J*, Hz): 0.57–0.71 m (2H, H^1, H^6), 1.02 s (3H, C^{8}H$_3$), 1.05 s (3H, C^{9}H$_3$), 1.18 s (3H, C^{10}H$_3$), 1.39 m (1H, H^2), 1.42 m (1H, H^5), 1.77 d.d (1H, H^2, *J* 8.8, 15), 1.84 br.s (1H, OH), 2.12 br.s (1H, OH), 2.31 m (1H, H^5), 3.53 d.d (1H, H^4, *J* 3.3, 7.0). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 71.75 (C^4), 71.13 (C^3), 28.72 (C^8), 28.36 (C^2), 25.60 (C^5), 25.00 (C^{10}), 18.00 (C^7), 17.80 and 17.48 (C^1, C^6), 15.07 (C^9).

Caranediol-3β,4β (III). $[\alpha]_D$ +42.7° (*c* 1.0, $CHCl_3$), mp 43–44°C. IR spectrum, ν, cm^{-1}: 3451, 2994, 2934, 2864, 1373, 1125, 1051, 984, 908. ^{1}H NMR spectrum (DMSO-d_6), δ, ppm (*J*, Hz): 0.47 d.d.d (1H, H^6, *J* 3.2, 9.2, 12.3), 0.57 d.d.d (1H, H^1, *J* 4.9, 9.2, 14.2), 0.96 s (3H, C^{8}H$_3$), 1.10 and 1.11 s (3H each, C^{10}H$_3$, C^{9}H$_3$), 1.40 d.d (1H, H$_2$, *J* 4.9, 14.3), 1.46 d.d.d.d (1H, H^5, *J* 3.2, 4.7, 8.0, 15.3), 1.57 d.d (1H, H^2, *J* 9.3, 14.3), 2.00 d.d.d (1H, H^5, *J* 6.3, 9.0, 15.3), 3.22 d.d.d (1H, H^4, *J* 4.0, 8.0, 9.0), 3.88 s (1H, OH^3), 4.15 d (1H, OH^4, *J* 4.0). ^{13}C NMR spectrum (DMSO-d_6), δ_C, ppm: 15.82 (C^{10}), 17.83 (C^7), 17.83 (C^6), 18.73 (C^1), 25.98 (C^5), 26.75 (C^9), 29.25 (C^8), 29.84 (C^2), 70.12 (C^3), 71.24 (C^4).

Caranediol-3β,4α (IV). $[\alpha]_D$ –1.7° (*c* 1.6, acetone), mp 81–82°C. IR spectrum, ν, cm^{-1}: 3374, 2984, 2926, 2864, 1449, 1121, 1067, 949. ^{1}H NMR spectrum (DMSO-d_6), δ, ppm (*J*, Hz): 0.60–0.67 m (2H, H^1, H^6), 0.93 s (3H, C^{10}H$_3$), 0.95 s (2H, C^{8}H$_3$), 1.03 s (3H, C^{9}H$_3$), 1.08 d.d (1H, H^2, *J* 4.0, 15.0), 1.52 d.d.d (1H, H^5, *J* 7.8, 9.9, 13.0), 1.80 m (1H, H^2, *J* 15.0), 1.86 d.d (1H, H^5, *J* 7.2, 13.0), 3.11 d.d.d (1H, H^4, *J* 3.9, 7.2, 9.9), 4.03 s (1H, OH^3), 4.24 d (1H, OH^4, *J* 3.9). ^{13}C NMR spectrum (DMSO-d_6), δ_C, ppm: 16.14 (C^7), 19.92 (C^6), 20.02 (C^9), 20.91 (C^1), 28.42 (C^5), 28.99 (C^8), 34.10 (C^2), 71.67 (C^3), 73.44 (C^4).

Pinanediol-2α,3α (V). Mp 56–57°C, $[\alpha]_D$ +3.1° (*c* 8.3, $CHCl_3$). IR spectrum, ν, cm^{-1}: 3468 (OH), 3292, 2920, 1480, 1376, 1266, 1164, 1122, 1086, 1052, 1014, 956, 949, 906. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm (*J*, Hz): 0.92 s (3H, C^{8}H$_3$), 1.26 s (3H, C^{9}H$_3$), 1.29 s (3H, C^{10}H$_3$), 1.37 d (1H, H^7, *J* 10.5), 1.63 d.d.d.d (1H, H^4, *J* 2.5, 5.1, 7.4, 13.9), 1.90 m (1H, H^5), 1.99 d.d (1H, H^1, *J* 5.7, 5.9), 2.17 m (1H, H^7), 2.42 m (1H, H^4), 3.24 s (1H, OH), 3.63 d (1H, OH, *J* 5.9), 3.97 d.d (1H, H^3, *J* 5.4, 9.3). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 73.7 (C^2), 68.9 (C^3), 53.8 (C^1), 40.4 (C^5), 38.8 (C^6), 37.9 (C^4), 29.5 (C^{10}), 27.9 (C^7), 27.7 (C^9), 24.0 (C^8).

Pinanediol-2α,3β (VI). Mp 165–168°C, $[\alpha]_D$ +49.0° (*c* 13, $CHCl_3$). IR spectrum, ν, cm^{-1}: 3332 (OH), 2920, 1456, 1390, 1372, 1356, 1166, 1124, 1088, 1058, 1024, 1000, 920, 898, 852. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm (*J*, Hz): 0.94 s (3H, C^{10}H$_3$), 1.25 s (3H, C^{8}H$_3$), 1.35 s (3H, C^{9}H$_3$), 1.46 d (1H, H^7, *J* 10.2), 1.64 d.d (1H, H^4, *J* 6.6, 14.3), 1.88–1.97 m (3H, H^1, H^5), 2.13 m (1H, H^7, *J* 10.5), 2.46 d.d.d (1H, H^4, *J* 4.5, 10.2, 14.3), 4.17 d.d (1H, H^3, *J* 6.6, 10.2). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 78.5 (C^2), 73.9 (C^3), 54.9 (C^1), 40.2 (C^5), 39.1 (C^6), 34.8 (C^4), 27.5 (C^8), 25.4 (C^7), 24.7 (C^9), 22.8 (C^{10}).

Metal acetylacetonates were prepared according to [21].

General procedure of terpenoid diols oxidation with chromic acid. The oxidizer solution (1 g of $Na_2Cr_2O_7 \cdot 2H_2O$, 1.27 ml of conc. H_2SO_4, and 12 ml of H_2O) was added during 30 min to the solution of 1 g

(0.0059 mol) of **I** or **IV** in 10 ml of diethyl ether; temperature was maintained at 0–4°C. The course of the the reaction was monitored with thin layer chromatography. After the reaction was completed, the mixture was extracted with diethyl ether, washed with saturated aqueous $NaHCO_3$ and NaCl, and dried over anhydrous $MgSO_4$. Reaction products were separated by column chromatography on SiO_2

3α-Hydroxycaran-4-one (VII). Yield 32%, $[\alpha]_D$ +34.6° (*c* 0.6, EtOH) and $[\alpha]_D$ –117° (*c* 0.9, $CHCl_3$), n_D 1.4810. Spectral data correspond to those in [10].

[2,2-Dimethyl-3-(2-oxopropyl)cyclopropyl]acetic acid (VIII) from I. Yield 42%, viscous oily substance, $[\alpha]_D$ –22.6° (*c* 0.5, $CHCl_3$). Spectral data correspond to those in [11].

3β-Hydroxycaran-4-one (IX). Yield 17%, $[\alpha]_D$ +36.9° (*c* 0.7, $CHCl_3$), $[\alpha]_D$ +24.9° (*c* 0.4, EtOH), n_D 1.4750. IR spectrum, ν, cm^{-1}: 3483 (OH), 2935, 2736, 1710 (C=O), 1458, 1411, 1371, 1234, 1186, 1114, 1064, 991, 960, 939, 810, 765, 669. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm (*J*, Hz): 0.82 s (3H, C^9H_3), 0.96 d.d.d (1H, H^1, *J* 5.1, 9.0, 9.6), 1.05 s (3H, C^8H_3), 1.15 d.d.d (1H, H^6, *J* 1.3, 9.0, 10.0), 1.49 s (3H, $C^{10}H_3$), 1.56 d.d (1H, H^2, *J* 5.1, 14.6), 2.35 d.d (1H, H^2, *J* 9.6, 14.6), 2.51 d (1H, H^5, *J* 18.7), 2.77 d.d (1H, H^5, *J* 10.0, 18.7), 3.82 (OH). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 217.3 (C^4), 74.3 (C^3), 35.8 (C^2), 33.8 (C^5), 27.7 (C^8), 24.5 (C^{10}), 22.6 (C^6), 19.8 (C^7), 18.8 (C^1), 14.8 (C^9).

[2,2-Dimethyl-3-(2-oxopropyl)cyclopropyl]acetic acid (VIII) from IV. Yield 55%, $[\alpha]_D$ –23.3° (*c* 0.5, $CHCl_3$). Spectral data correspond to those in [11].

General procedure for terpenoid diols oxidation with ClO_2. 0.5 g of the starting compound **I–VI** was dissolved in 15 ml of pyridine or dimethylformamide with or without the catalyst, and the flow of aerated ClO_2 was passed through the solution. The course of reaction was monitored with thin layer chromatography. After the reaction was completed, the reaction mixture was diluted with diethyl ether, washed with aqueous H_2SO_4 (5%), water, saturated NaCl and then dried over $MgSO_4$. After removal of the ether, the mixture was analyzed by gas-liquid chromatography and NMR spectroscopy, the reaction products were isolated by column chromatography on SiO_2.

3α-Hydroxycaran-4-one (VII) was prepared by oxidation of 3α,4α-diol **I** with the yield of 60–64% and by oxidation of 3α,4β-diol **II** with the yield of 59%.

3β-Hydroxycaran-4-one (IX) was prepared by oxidation of 3β,4β-diol **IV** with the yield of 52% and by oxidation of 3β,4α-diol **III** with yield of 72%.

Acid **VIII** was isolated from the products of caranediol-3α,4α **I** oxidation with the yield of 10.5%. Spectral data correspond to those in [11].

2α-Hydroxypinane-3-one (**X**) was prepared by oxidation of pinanediol-2α,3β (**VI**) with the yield of 65%. Spectral data correspond to those in [3].

2-(3'-Acetyl-2',2'-dimethylcyclobutyl)acetic acid (*cis*-pinoic acid) (XI). Yield 11.6%. Spectral data correspond to those in [12].

The total yield of compounds **XII** and **XIII** during **I** oxidation in pyridine was 3%, in the case of dimethylformamide only **XII** was isolated, with the preparative yield of 40%.

5α-Chloro-3α-hydroxycaran-4-one (XII). Mp 97–°98C, $[\alpha]_D$ –302.5 (*c* 0.4 EtOH), R_f 0.62 (diethyl ether–hexane, 2:1). IR spectrum, ν, cm^{-1}: 3516 (OH), 3022, 2962, 2933, 2742, 1730 (C=O), 1454, 1367, 1234, 1139 (C–O), 1062, 1041, 1001, 948, 927, 871, 827, 769 (C–Cl), 707. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm (*J*, Hz): 0.80 s (3H, C^8H_3), 1.00 s (3H, $C^{10}H_3$), 1.05 m (H, H^1, *J* 8.6), 1.22 s (3H, C^9H_3), 1.69 d.d (1H, H^2, *J* 3.5, 15.7), 1.76 d.d (1H, H^6, *J* 8.4, 8.6) 2.35 d.d (1H, H^2, *J* 9.5, 15.7), 5.57 d (1H, H^5, *J* 8.4). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 207.0 (C^4), 76.1 (C^3), 63.4 (C^5), 37.1 (C^2), 34.2 (C^6), 28.4 (C^{10}), 23.2 (C^9), 22.4 (C^7), 21.5 (C^1), 15.0 (C^8).

5β-Chloro-3α-hydroxycaran-4-one (XIII). ^{1}H NMR spectrum ($CDCl_3$), δ, ppm (*J*, Hz): 1.04 m (1H, H^6), 1.07 s (3H, $C^{10}H_3$), 1.10 s (3H, C^8H_3), 1.13 m (3H, H^1), 1.17 s (3H, C^9H_3), 1.45 m (1H, H^2, *J* 15.7), 2.20 d (1H, H^2, *J* 15.7), 4.17 d (1H, H^5, *J* 7.4). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 207.1 (C^4), 75.4 (C^3), 58.4 (C^5), 32.8 (C^2), 30.1 (C^6), 27.3 (C^{10}), 25.7 (C^9), 21.5 (C^7), 20.9 (C^1), 13.7 (C^8).

4α-Chloro-2α-hydroxypinan-3-one (XIV). Yield 45%, mp 69°C, $[\alpha]_D$ –4.9 (*c* 0.3 EtOH), R_f 0.52 (diethyl ether–hexane, 1:1). IR spectrum, ν, cm^{-1}: 3475 (OH), 2974, 2933, 1722 (C=O), 1471, 1375, 1259, 1234, 1155, 1099, 1080, 1051, 947, 912, 846, 719, 680, 623. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm (*J*, Hz): 0.84 s (3H, C^8H_3), 1.29 s (3H, $C^{10}H_3$), 1.37 s (3H, C^9H_3), 2.02 m (1H, H^7), 2.03 m (1H, H^1), 2.30 m (1H, H^5), 2.31 m (1H, H^7), 4.69 d.d (1H, H^4, *J* 2.9, 2.9). ^{13}C NMR

spectrum ($CDCl_3$), δ_C, ppm: 207.7 (C^3), 76.4 (C^2), 50.4 (C^1), 46.4 (C^5), 43.3 (C^4), 39.2 (C^6), 27.8 (C^9), 25.4 (C^{10}), 24.6 (C^7), 22.3 (C^8).

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