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Transformations of Several Monoterpenoids in the Presence of Aldehydes in Supercritical Solvents

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Abstract—The reactivity of verbenol epoxide and isopulegol in supercritical solvents in the presence of aromatic aldehydes was studied using a flow type reactor and a heterogeneous catalyst (Al_2O_3) or no catalyst. The intramolecular transformations or interactions of reagents with the solvent prevailed in all cases; the yield of the products of intermolecular reactions of terpenoids with aldehydes was up to 1%. The aldehydes did not interact with verbenol epoxide but produced a considerable effect on the distribution of its isomerization products.

Keywords: supercritical solvent, terpenoids, verbenol epoxide, isopulegol, aldehydes, alumina.

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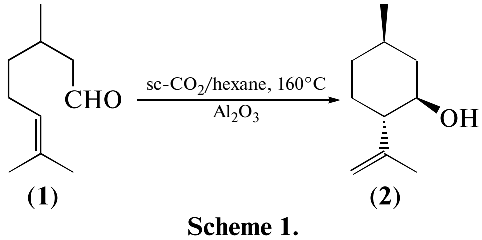
INTRODUCTION

Due to their unique properties, supercritical fluids (SCFs) are attractive solvents for performing many chemical reactions and serve as a basis for new technologies. For example, using a supercritical fluid as a reaction medium leads to a substantial increase in the rate of the thermal isomerization of monoterpenes [1] and produces a considerable effect on the route of the intramolecular transformations of labile monoterpenoids: α-pinene [2], verbenone [3], and verbenol [4] epoxides. Recently, it was shown that using a combination of an SCF and a heterogeneous catalyst allowed various transformations of natural organic compounds: isomerization [5], Meerwein–Ponndorf–Verley reduction [5, 6], oxidation with air oxygen [7], and intramolecular cyclization of citronellal **1** to isopulegol **2** [8]:



Scheme 1.

The possibility of intermolecular reactions of terpenoids with aldehydes in SCFs, however, remained completely uninvestigated; under the normal conditions they lead to various heterocyclic compounds with frameworks of various types [9–14]. The goal of this study, therefore, was to investigate the possibility of reactions of monoterpenoids with aldehydes in SCF in a flow type reactor.

EXPERIMENTAL

The reagents used for this study included benzaldehyde (**11**), *p*-fluorobenzaldehyde (**4**), vaniline (**9**), 3,4,5-trimethoxybenzaldehyde (**14**), (–)-isopulegol (**2**) (Aldrich), Al_2O_3 (Macherey–Nagel, pH 7 ± 0.5, 50–200 μm, free surface according to BET ~130 m^2/g). Verbenol epoxide (**3**) was synthesized from (–)-verbenone (Aldrich) by the procedures of [10, 15]. The experimental studies of reactions in a supercritical solvent were performed on a laboratory unit described in detail in [2, 8] using a tube reactor with a length of 6 m and an inner diameter of 1.75 mm (reactor volume 14.4 cm^3) or a similar tube reactor containing 22.1 cm^3 (20.6 g) of granulated Al_2O_3.

The reaction mixture was fed to the reactor in two flows. The first flow (supercritical CO_2) was introduced with a syringe pump through a heat exchanger, where it was heated to the reaction temperature, to a mixer situated at the inlet of the reactor. The second flow (1% solution of reagents for each component in a corresponding organic solvent) was supplied to the same mixer with a piston pump.

The reaction mixture was cooled at the outlet of the reactor and forwarded to analysis. The composition of the liquid reaction products was analyzed by chromato-mass spectrometry on an Agilent 7890A chromatograph with an Agilent 5975C quadrupole mass analyzer as a detector. For analysis we used an HP-5MS quartz column (5%-diphenyl–95%-dimethylsiloxane copolymer, length 30 m, inner diameter 0.25 mm, and film thickness of the stationary phase 0.25 μm). Scanning at $m/z = 29–500$. The qualitative analysis was performed by comparing the retention times of components and their total mass spectra with the corresponding data for pure substances if they were available or with the data of NIST 2.0 and Wiley 7 databases. The composition of the mixtures was calculated from the peak areas in the chromatograms without using any correcting coefficients.

The contact time (τ) of the reaction mixture was calculated as the ratio of the catalyst volume in the reactor V_c (cm^3) (reactor volume without a catalyst) to the total consumption of the mixture at the inlet of the reactor Q (cm^3/s); for a flow of 5 mL/min, $\tau \sim 4.5$ min. The transformations were performed at temperatures $T = 60–245$°C and pressures $P = 145–230$ atm. The temperature and pressure that provide the supercritical conditions of the reaction mixture were chosen on the basis of thermodynamic calculations and phase diagram construction.

The ^{1}H and ^{13}C NMR spectra were recorded on a Bruker DRX-500 spectrometer (operating frequencies 500.13 MHz for ^{1}H and 125.76 MHz for ^{13}C) for $CDCl_3$ solutions of the substances. The chloroform solvent was used as an internal standard ($\delta_H = 7.24$, $\delta_C = 76.90$ ppm). The structure of the obtained compounds was determined by analyzing the ^{1}H NMR spectra using the ^{1}H–^{1}H double resonance spectra and by analyzing the ^{13}C NMR spectra recorded in a J-modulation mode (JMOD) with off-resonance proton suppression and ^{13}C–^{1}H two-dimensional correlation spectra on direct constants (C–H COSY, $^1J_{C,H} = 160$ Hz). The high-resolution mass spectra were recorded on a DFS Thermo Scientific spectrometer in a magnetic scanning mode at $m/z = 15–500$ with electron impact ionization (70 eV) during the direct introduction of the sample.

Interaction of (–)-isopulegol (2) with 3,4,5-trimethoxybenzaldehyde (14) in the presence of clay K-10. 3,4,5-Trimethoxybenzaldehyde (**14**) (0.99 g) and isopulegol (**2**) (1.27 g) were added to a suspension of clay K-10 (4.0 g) preliminarily calcinated at 105°C for 3 h in CH_2Cl_2 (60 mL). The mixture was stirred for 1 h at room temperature. Then EtOAc (15 mL) was added. The catalyst was filtered off, the solvent distilled off, and the residue separated on a silica gel column (9 g) (60–200 μm, Macherey–Nagel) (hexane with a chloroform gradient from 0 to 100% as an eluent). This gave (2*R*,4a*R*,7*R*,8a*R*)-4,7-dimethyl-2-(3,4,5-trimethoxyphenyl)octahydro-2*H*-chromen-4-ol **15a,b** (0.483 g, 22%) (a mixture of 4*S*-(**15a**) and 4*R*-(**15b**)-isomers in a ratio of 3.4 : 1); (2*R*,4a*S*,7*R*,8a*R*)-7-methyl-4-methylene-2-(3,4,5-trimethoxyphenyl)octahydro-2*H*-chromene (**16**) 0.166 g, 8%); and (2*R*,7*R*,8a*R*)-4,7-dimethyl-2-(3,4,5-trimethoxyphenyl)-3,5,6,7,8,8a-hexahydro-2*H*-chromene (**17**) (0.109 g, 5%).

Compound **15a**. ^{1}H NMR spectrum, δ, ppm: 0.93 d ($C^{18}H_3$, $J_{18,9} = 6.6$ Hz); 0.93 dddd (H^{8a}, $^2J = J_{8a,7a} = J_{8a,9a} = 12.8$, $J_{8a,7e} = 3.0$ Hz); 1.04 dddd (H^{7a}, $^2J = J_{7a,6a} = J_{7a,8a} = 12.8$, $J_{7a,8e} = 3.2$ Hz); 1.13 ddd (H^{10a}, $^2J = 12.5$, $J_{10a,9a} = 12.5$, $J_{10a,1a} = 11.0$ Hz); 1.29 s ($C^{17}H_3$); 1.31 ddd (H^{6a}, $J_{6a,7a} = 12.8$, $J_{6a,1a} = 10.0$, $J_{6a,7e} = 3.0$ Hz); 1.40–1.51 m (H^{9a}); 1.73 dm (H^{8e}, $^2J = 12.8$ Hz); 1.76 dd (H^{4a}, $^2J = 12.8$, $J_{4a,3a} = 11.7$ Hz); 1.89 dd (H^{4e}, $^2J = 12.8$, $J_{4e,3a} = 2.0$ Hz); 1.94 dddd (H^{7e}, $^2J = 12.8$, $J_{7e,6a} = J_{7e,8a} = J_{7e,8e} = 3.0$ Hz); 2.01 dddd (H^{10e}, $^2J = 12.5$, $J_{10e,1a} = J_{10e,9a} = 4.2$, $J_{10e,8e} = 1.5$ Hz); 3.25 ddd (H^{1a}, $J_{1a,10a} = 11.0$, $J_{1a,6a} = 10.0$, $J_{1a,10e} = 4.2$ Hz); 3.79 s ($C^{20}H_3$); 3.84 s ($C^{19}H_3$); 4.35 dd (H^{3a}, $J_{3a,4a} = 11.7$, $J_{3a,4e} = 2.0$ Hz); 6.56 s (H^{12}, H^{16}). ^{13}C NMR spectrum, δ, ppm: 77.45 d (C^1); 76.65 d (C^3); 49.86 t (C^4); 70.82 s (C^5); 51.94 d (C^6), 22.96 t (C^7); 34.29 t (C^8), 31.38 d (C^9); 41.41 t (C^{10}); 137.73 s (C^{11}); 103.17 d (C^{12}, C^{16}); 153.10 s (C^{13}, C^{15}); 137.31 s (C^{14}); 21.28 q (C^{17}); 22.08 q (C^{18}); 55.98 q (C^{19}, C^{21}); 60.64 q (C^{20}). Found $[M]^+$ 350.2084. $C_{20}H_{30}O_5$. Calcd. M 350.2088.

Compound **15b**. The NMR spectral data for isomer **15b** were obtained from the spectra recorded for the 1.0 : 0.25 mixture of **15a** and **15b**. The signals of several protons that overlap the signals of the main isomer, therefore, were not isolated in the ^{1}H NMR spectrum of **15b**. ^{1}H NMR spectrum, δ, ppm: 0.92 d ($C^{18}H_3$, $J_{18,9} = 6.6$ Hz); 0.88–0.98 m (H^{8a}); 1.03–1.23 m (H^{7a}, H^{10a}, H^{6a}); 1.21 s ($C^{17}H_3$); 1.39–1.51 m (H^{9a}); 1.66 dd (H^{4a}, $^2J = 13.7$, $J_{4a,3a} = 11.7$ Hz); 1.69–1.73 m (H^{8e}); 1.78–1.83 m (H^{7e}); 1.80 dd (H^{4e}, $^2J = 13.7$, $J_{4e,3a} = 2.3$ Hz); 1.96–2.02 m (H^{10e}); 3.54 ddd (H^{1a}, $J_{1a,10a} = 11.0$, $J_{1a,6a} = 9.5$, $J_{1a,10e} = 4.2$ Hz); 3.77 s ($C^{20}H_3$); 3.82 s ($C^{19}H_3$, $C^{21}H_3$); 4.69 dd (H^{3a}, $J_{3a,4a} = 11.7$, $J_{3a,4e} = 2.3$ Hz); 6.57 s (H^{12}, H^{16}). ^{13}C NMR spectrum, δ, ppm: 75.53 d (C^1); 74.79 d (C^3); 48.02 t (C^4); 69.38 s (C^5); 49.31 d (C^6); 22.40 t (C^7); 34.32 t (C^8); 31.16 d (C^9); 41.19 t (C^{10}); 138.48 s (C^{11}); 102.97 d (C^{12}, C^{16}); 153.01 s (C^{13}, C^{15}); 137.00 s (C^{14}); 28.11 q (C^{17}), 22.11 к (C^{18}), 60.58 q (C^{20}); 55.91 q (C^{19}, C^{21}).

Compound **16**. The NMR spectra of compounds **16** and **17** were recorded for their mixture in a ratio of 1.0 : 0.8. ^{1}H NMR spectrum, δ, ppm: 0.94 d ($C^{18}H_3$, $J_{18,9} = 6.6$ Hz); 1.00 dddd (H^{8a}, $^2J = J_{8a,7a} = 13.5$, $J_{8a,9a} = 12.0$, $J_{8a,7e} = 3.5$ Hz); 1.21 ddd (H^{10a}, $^2J = J_{10a,9a} = 12.5$, $J_{10a,1a} = 11.0$ Hz); 1.26 dddd (H^{7a}, $^2J = J_{7a,8a} = 13.5$, $J_{7a,6a} = 12.0$, $J_{7a,8e} = 3.5$ Hz); 1.43–1.53 m (H^{9a}); 1.74 dm (H^{8e}, $^2J = 13.0$ Hz); 1.79–1.86 m (H^{6a}); 1.88 dddd (H^{7e}, $^2J = 13.0$, $J_{7e,6a} = J_{7e,8a} = J_{7e,8e} = 3.2$ Hz); 1.97–2.03 m (H^{10e}); 2.34 dd (H^{4a}, $^2J = 13.2$, $J_{4a,3a} = 11.4$ Hz); 2.45 dd (H^{4e}, $^2J = 13.2$, $J_{4e,3a} = 2.4$ Hz); 3.09 ddd (H^{1a}, $J_{1a,10a} = 11.0$, $J_{1a,6a} = 10.0$, $J_{1a,10e} = 4.0$ Hz); 3.79 s ($C^{20}H_3$); 3.85 s ($C^{19}H_3$, $C^{21}H_3$); 4.30 dd (H^{3a}, $J_{4a,3a} = 11.4$, $J_{3a,4e} = 2.4$ Hz); 4.66 m and 4.78 m ($2H^{17}$, all $J < 1.5$ Hz); 6.58 s (H^{12}, H^{16}). ^{13}C NMR spectrum, δ, ppm: 81.89 d

Table 1. Transformations of verbenol epoxide **3** in the presence of aldehydes **4** and **9**

No.	Aldehyde	T, °C	P, atm	Conversion of **3**	Content of mixture components, %				
					5	**6**	**7**	**8**, **10**	other products
1 [4]	–	197	170	100	30.5	23.3	2.8	–	43.4
2	**4**	220		70.5	26.4 (37.4)	11.6 (16.5)	3.8 (5.4)	0	28.7 (40.7)
3		260		99.0	37.3	14.8	4.3	0	42.6
4	**9**	175		55.0	11.0 (20.0)	12.6 (22.9)	1.4 (2.5)	0	30.0 (54.5)
5		220		92.8	17.4 (18.7)	22.7 (24.5)	3.0 (3.2)	0.9 (1.0)	48.9 (52.7)
6		220	180	100	26.0	22.3	4.5	0.9	46.3
7		220	200	100	28.4	21.3	5.0	0.4	44.9
8		220	230	100	31.6	22.5	5.6	0	40.3

Note: The contents of the mixture components (GLC–MS data) are given without regard for the contents of aldehydes **4** or **9**. The ratio of the mixture/CO_2 flows = 1/4. According to [4], the reaction was performed in the absence of an aldehyde. The selectivity is indicated in parentheses.

(C^{1}); 44.30 t (C^{4}); 148.02 s ($C^{5}5$); 46.30 d (C^{6}); 25.95 t (C^{7}); 34.01 t (C^{8}); 31.33 d (C^{9}); 41.33 t (C^{10}); 138.01 s (C^{11}); 103.01 d (C^{12}, C^{16}); 153.05 s (C^{13}, C^{15}); 137.08 s (C^{14}); 105.57 t (C^{17}); 22.10 q (C^{18}); 55.93 q (C^{19}, C^{21}); 60.58 q (C^{20}). Found $[M]^+$ 332.1983. $C_{20}H_{28}O_4$. Calcd. M 332.1982.

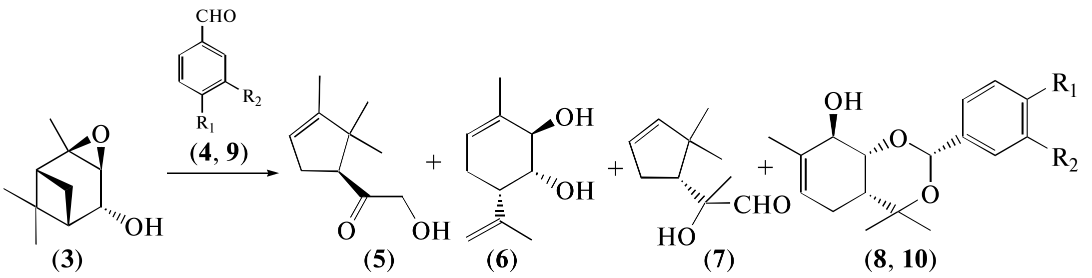
Compound **17**. ^{1}H NMR spectrum, δ, ppm: 0.85–0.94 m (H^{8a}); 0.93 d ($C^{18}H_3$, $J_{18,9} = 6.6$ Hz); 1.06 ddd (H^{10a}, $^2J = J_{10a,\,9a} = J_{10a,\,1a} = 12.0$ Hz); 1.55–1.65 m (H^{9a}); 1.63–1.72 m (H^{7a}, H^{8e}); 1.67 br.s. ($C^{17}H_3$); 1.97–2.04 m (H^{4e}), 2.11 dm (H^{10e}, $^2J = 12.0$ Hz); 2.29–2.35 m (H^{4a}), 2.68–2.74 m (H^{7e}); 3.79 s ($C^{20}H_3$); 3.84 s ($C^{19}H_3$, $C^{21}H_3$); 4.11 br.d. (H^{1a}, $J_{1a,\,10a} = 12.0$ Hz); 4.44 dd (H^{3a}, $J_{3a,\,4a} = 10.8$, $J_{3a,\,4e} = 3.0$ Hz); 6.59 s (H^{12}, H^{16}). ^{13}C NMR spectrum, δ, ppm: 76.29 d (C^{1}); 75.23 d (C^{3}); 39.23 t (C^{4}); 121.76 s (C^{5}); 131.29 s (C^{6}); 26.34 t (C^{7}); 34.90 t (C^{8}); 30.82 d (C^{9}); 42.61 t (C^{10}); 138.50 s (C^{11}); 102.98 d (C^{12}, C^{16}); 153.03 s (C^{13}, C^{15}); 137.22 s (C^{14}); 18.02 q (C^{17}); 21.88 q (C^{18}); 55.91 q (C^{19}, C^{21}); 60.58 q (C^{20}).

The axial orientation of H^{1}, H^{3}, and H^{9} in all compounds under study and of H^{6} in **15a**, **15b**, and **16** follows from the vicinal constants of their spin-spin coupling with the neighboring hydrogen atoms (all $J \geq 10$ Hz).

RESULTS AND DISCUSSION

For the first stage of transformations, as a solvent we used a CO_2–isopropanol mixture, which was successfully used for isomerization of monoterpenoid epoxides [2–4]. Using supercritical CO_2 as a component of a complex solvent allows one to considerably lower the critical temperature of the mixture, thus avoiding undesirable secondary thermal transformations of the reaction products.

As a test reaction, we chose the interaction of verbenol epoxide **3** with p-fluorobenzaldehyde **4** (Scheme 2) in the absence of a catalyst, leading to isomerization products **5–7** and compound **8** (the product of the addition of aldehyde **4** to epoxide **3** [11]) in the presence of montmorillonite clay K-10:



4, **8**: $R_1 = F$, $R_2 = H$
9, **10**: $R_1 = OH$, $R_2 = OMe$

Scheme 2.

Earlier [4], we showed that in a complex supercritical solvent containing CO_2 and isopropanol, verbenol epoxide **3** was transformed into a complex mixture of isomerization products in which compounds **5–7** were identified; at 197°C the conversion of **3** was quantitative (Table 1). The addition of aldehyde **4** to the reaction mixture did not lead to the formation of intermolecular product **8**, but affected the distribution of products and the conversion of **3**, which was only 70% at 220°C. The presence of aldehyde **4** led to increased selectivity in respect of the products with a cyclopentane framework **5** and **7** and to a decreased content of diol **6** in the reaction mixture. When the reaction temperature was raised to 260°C, the conversion of **3** increased to nearly quantitative, but did not affect the selectivity of transformations. Although the unidentified products amounted to more than 40%, each of these products was up to 5%, and there were no compounds corresponding to the products of interaction of **3** and **4** in the molecular mass and retention time. Unchanged aldehyde **4** was present in all reaction mixtures; its content was independent of the conditions of transformation.

The introduction of two electron donor substituents in the aromatic ring on passing to vanilin **9** should increase the reactivity of aldehyde in the nucleophilic addition, thus increasing the probability of intermolecular transformations. Earlier, the interaction of **3** and **9** in the presence of clay K-10 was reported in [14]. Product **10** formed in this reaction was recently found to have high analgesic activity [16]. The conversion of verbenol epoxide **3** at 175°C was only 55%, and no compound **10** was found in the reaction mixture (Table 1). At the same time, when the reaction temperature was raised to 220°C, we recorded, for the first time, the intermolecular product **10** (1%). Interestingly, the replacement of aldehyde **4** by vanilin **9** led to a change in the ratio of the products of isomerization of epoxide **3** in favor of diol **6**.

Unexpected results were obtained when we studied the effect of pressure on the product ratio: at elevated pressures, the content of **10** decreased, or this product was absent altogether (nos. **5–8**, Table 1). The percent of unidentified products decreased, and that of compounds with a cyclopentane framework **5** and **7** increased.

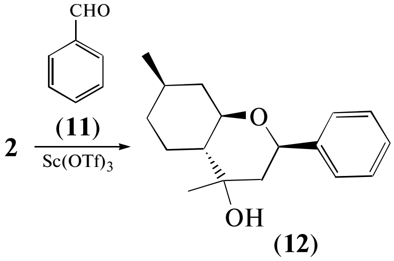
Although we managed to find the conditions that led to the product of the reaction of terpenoid **3** with aldehyde **9** under the supercritical conditions without any catalyst, the intramolecular transformations still prevailed.

Recently, we found [8] that citronellal **1** underwent an effective cyclization to isopulegol **2** in a complex supercritical solvent including CO_2 and hexane in the presence of Al_2O_3. Therefore, it became promising to study the possibility of intermolecular reactions under these conditions. Because epoxides are quickly transformed into isomerization products under these conditions in the presence of Al_2O_3 [5], the substrates should be the compounds that are more stable under the reaction conditions in order to reduce the contribution from the competitive intramolecular processes. As is known [12], the interaction of isopulegol **2** with benzaldehyde **11** in the presence of $Sc(OTf)_3$ leads to the formation of intermolecular product **12**:

Table 2. The content of mixture components (%) according to GLC–MS data recorded during the transformation of a mixture of isopulegol **2** and aldehyde **14**

No.	*T*, °C	**2**	**14**	**16**	**18**	**19**	**20**	**21**
1	200	43.5	20.2	<0.5	6.8	26.6	0	0
2	245	40.3	0	<0.5	2.6	0	46.3	8.1

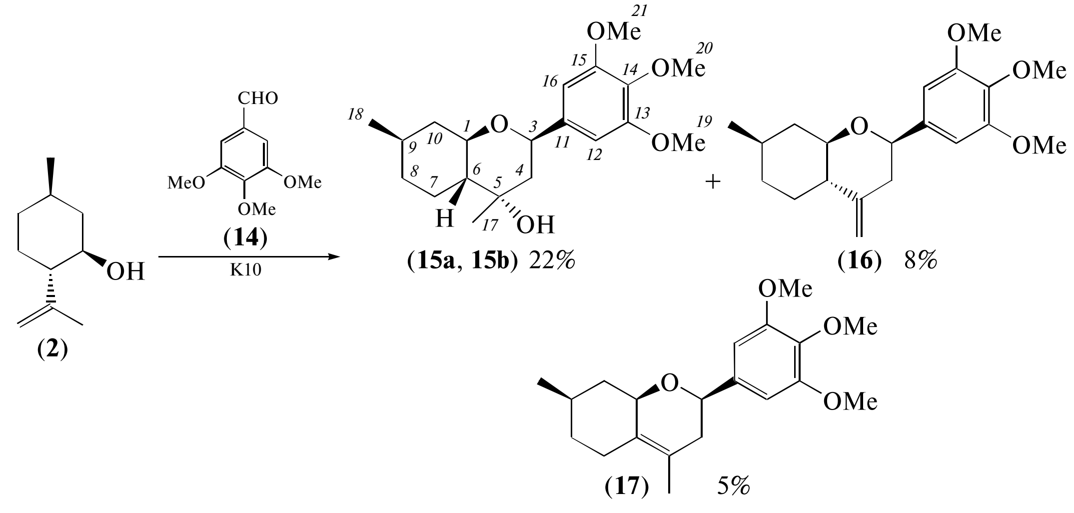
Note: The ratio of mixture/CO_2 flows (mL/min) was 3/5; the pressure $p = 145$ atm.



Scheme 3.

Since isopulegol **2** remains stable at least at 160°C under the reaction conditions [8], we decided to study the reaction of compounds **2** and **11** in the presence of Al_2O_3 in a complex supercritical solvent. It appeared, however, that benzaldehyde **11** was unstable under these conditions and was converted into benzyl alcohol **13**, probably by the Cannizzaro reaction (disproportionation of aldehyde into alcohol and acid). Significant amounts of benzyl alcohol **13** were recorded already at 60°C; at 150°C the percent of **13** in the reaction mixture exceeded that of aldehyde **11**. The products of the reaction of **2** and **11** in the reaction mixture were not found.

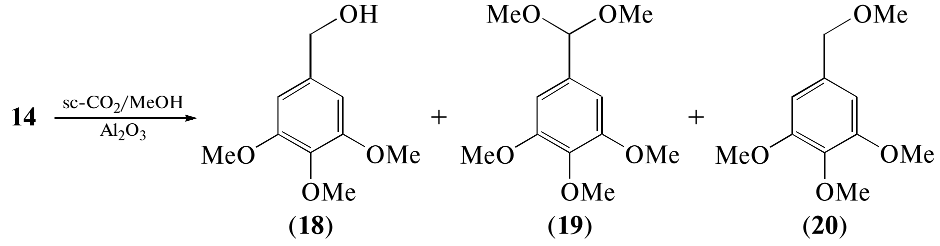
The introduction of donor substituents in the aromatic aldehydes drastically decreases their activity in Cannizzaro reactions. Our next step, therefore, was the replacement of benzaldehyde **11** by 3,4,5-trimethoxybenzaldehyde **14**. Since the reaction of isopulegol **2** with aldehyde **14** was not studied previously, we performed a reaction of **2** with **14** in the presence of montmorillonite clay K-10 and isolated products **15–17**:



Scheme 4.

Compounds **15**–**17** were not described in the literature; their structure was determined by NMR and high-resolution mass spectrometry.

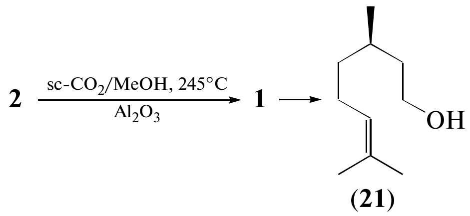
Because of the low solubility of 3,4,5-trimethoxybenzaldehyde **14** in hexane and other nonpolar and low-polar solvents, we used methanol as a solvent. Using an alcohol solvent certainly makes the reduction of **14** to **18** possible under these conditions (the Meerwein–Ponndorf–Verley reaction [5, 6]). However, the content of **18** in the reaction mixture was below 7% even at 200°C because of the low reactivity of **14** in this reaction (Table 2):



Scheme 5.

At the same time, a new route of the transformation of aldehyde **14**, leading to the formation of acylal **19**, was revealed. Although the reaction mixture contained substantial amounts of both isopulegol **2** and aldehyde **14**, percent of the intermolecular products of their interaction was insignificant, the main identified intermolecular product being **16**.

At 245°C aldehyde **14** and acylal **19** completely vanished from the reaction mixture; the main product formed from aldehyde was 1,2,3-trimethoxy-5-(methoxymethyl)benzene **20**. Isopulegol **2** also proved unstable at this temperature and was converted into citronellol **21**, evidently through the opening to citronellal **1** followed by its reduction by the Meerwein–Ponndorf–Verley reaction:



Scheme 6.

The content of **16** formed by the interaction of **2** with **14** was insignificant (up to 0.5%).

Thus we have studied the reactivity of isopulegol **2** and verbenol epoxide **3** in supercritical fluids in the presence of aldehydes (benzaldehyde, *p*-fluorobenzaldehyde, vanilin, and 3,4,5-trimethoxybenzaldehyde) using a catalyst (Al$_2$O$_3$) or not. The intramolecular transformations or solvent–reagent reactions were predominant in all instances; the content of the products of the intermolecular reactions of terpenoids with aldehydes was up to 1%. Though aldehydes did not interact with verbenol epoxide **3**, they produced a substantial effect on the distribution of the products of its isomerization.

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REFERENCES

1. V. I. Anikeev, Flavour Fragr. J **25**, 443 (2010).
2. V. I. Anikeev, I. V. Il'ina, K. P. Volcho, et al., J. Supercrit. Fluids **52**, 71 (2010).
3. V. I. Anikeev, I. V. Il'ina, K. P. Volcho, et al., Russ. J. Phys. Chem. A **84**, 1112 (2010).
4. K. P. Volcho, I. V. Il'ina, N. F. Salakhutdinov, and V. I. Anikeev, Arkivoc **8**, 134 (2011).
5. I. V. Il'ina, S. Yu. Kurbakova, K. P. Volcho, et al., J. Saudi Chem. Soc. **15**, 313 (2011).
6. I. V. Il'ina, V. P. Sivcev, K. P. Volcho, et al., J. Supercrit. Fluids **61**, 115 (2012).
7. V. I. Anikeev, I. V. Il'ina, K. P. Volcho, and N. F. Salakhutdinov, Russ. J. Phys. Chem. A **86**, 190 (2012).
8. V. I. Anikeev, I. V. Il'ina, K. P. Volcho, and N. F. Salakhutdinov, Russ. J. Phys. Chem. A **86**, 1917 (2012).
9. N. F. Salakhutdinov, K. P. Volcho, I. V. Il'ina, et al., Tetrahedron **54**, 15619 (1998).
10. I. V. Il'ina and K. P. Volcho, et al., Helv. Chim. Acta **90**, 353 (2007).
11. I. V. Il'ina, D. V. Korchagina, K. P. Volcho, and N. F. Salakhutdinov, Russ. J. Org. Chem. **46**, 998 (2010).
12. J. S. Yadav, S. B. V. Reddy, A. V. Ganesh, and G. G. K. S. Narayana Kumar, Tetrahedron Lett. **51**, 2963 (2010).
13. U. C. Pipas Saha, S. B. Reddy, and K. S. Anil, Org. Lett. **12**, 1824 (2010).
14. I. V. Il'ina, K. P. Volcho, O. S. Mikhalchenko, et al., Helv. Chim. Acta **94**, 502 (2011).
15. I. V. Il'ina, K. P. Volcho, D. V. Korchagina, et al., Helv. Chim. Acta **89**, 507 (2006).
16. T. G. Tolstikova, A. V. Pavlova, E. A. Morozova, et al., RF Patent No. 2430100, Byull. No. 27 (2011).