Improved Synthesis of 1, 1, 1-Trimethylolalkanes from Hexanal and Nonanal

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Abstract

Reaction of hexanal or nonanal with formaldehyde under the usual conditions for the Tollens condensation gave the expected 1,1,1-trimethylolalkanes in 65–70% yields. Characterization of the crude product mixtures by silylation and subsequent gas-liquid chromatographic analysis permitted identification of by-products. The major by-products were the 2,2-bis(hydroxymethyl) alkanals resulting from incomplete reaction with formaldehyde; minor by-products were the formate esters of the hydroxymethyl compounds.

These findings permitted modification of the procedure to give 1,1,1-trimethylolalkanes in 85–90% yields. The modifications included a) isolation from alkaline rather than acidic solution to prevent ester formation and b) hydrogenation of the crude reaction products to convert the 2,2-bis(hydroxymethyl)alkanals to the 1,1,1-trimethylolalkanes.

Introduction

REACTION OF ALDEHYDES with formaldehyde in alkaline solution to give trimethylol compounds (the Tollens condensation) is well known (2–11, 12–13, 15–20, 23–28, 30–34). The various catalysts used in aqueous alcohol or aqueous solvent systems are: calcium hydroxide (5,8,13,15,28), potassium hydroxide (13,28,32), sodium hydroxide (4,17,18,23,25, 28,30,31), and sodium methoxide (26). The reported yields of trimethylol compounds decrease as the carbon chain of the aldehyde increases. Some examples for 1,1,1-tris(hydroxymethyl)alkanes, $RC(CH_2OH)_3$, are listed in the order of R, percentage yield, and pertinent reference in parentheses: CH_3, 96, (24); C_2H_5, 90, (8); C_3H_7, 93, (24); iso C_3H_7, 63, (17); C_4H_9, 70, (18); C_5H_{11}, 61, (32); C_8H_{17}, 65, (32); C_9H_{19}, 47, (32); $C_{10}H_{21}$, 32–45, (13,32); and $C_{11}H_{23}$, 51, (32). Reported yields for 2,2-dimethyl propanediol-1,3 vary from 50 to 87% (11,31,33).

Hexanal and nonanal result from reductive ozonolysis of soybean oil or methyl soyate. Conversion of these aldehydes to trimethylol compounds yields products useful in alkyd resins, lubricants, and plasticizers.

Experimental Section

Hexanal and nonanal were obtained by the reductive ozonization of soybean oil or methyl soyate (22) and were purified through their sodium bisulfite addition compounds (21). Other chemicals were commercial grade and were used without further purification. Gas-liquid chromatographic (GLC) analyses were carried out on an F&M Model 810 gas chromatograph, equipped with flame ionization detectors. The reaction products were converted to acetates or trimethylsilyl ethers for GLC analysis. The acetates were chromatographed on 0.64 cm × 61.0 cm column, packed with 20% SE-30 silicone gum rubber on 80/100 Gas-Chrom P. Trimethylsilyl ethers were chromatographed on a 0.64 cm × 122 cm column packed with 0.2% SF-96 methyl silicone fluid on 70/80 mesh glass beads.

1,1,1-Tris(hydroxymethyl)pentane

This compound, designated as Trish 5, was prepared by two procedures that differed only in the manner of isolating reaction products. In the first procedure, similar to those reported in the literature, a solution of sodium hydroxide (12.0 g, 0.3 mole) in 25 ml of water was placed in a three-necked flask, fitted with a nitrogen ebullition tube, thermometer, and reflux column, under a nitrogen atmosphere. Aqueous formaldehyde (68.7 g, 0.84 mole CH_2O) was added slowly, and the temperature was maintained below 10C by means of external cooling. Hexanal (23.0 g, 0.23 mole) was added slowly with rapid stirring; the temperature was controlled below 30C. After exothermic reaction ceased, the temperature of reaction mixture was increased to 60C and maintained for 5 hr. The reaction mixture was then allowed to stand at ambient temperature for an additional 16 hr.

After the reaction period the caustic catalyst was neutralized with 90% formic acid. Approximately two-thirds of the water was removed under reduced pressure, and 50 ml of methyl isobutyl ketone (MIBK) were added. The rest of the water was removed azeotropically and the MIBK solution was filtered to remove sodium formate. The sodium formate was washed with 100 ml of hot MIBK; after the combined filtrates were evaporated, 39.3 g of residue were left. GLC analysis of silylated product indicated the presence of four major peaks. Distillation under reduced pressure gave 20.8 g (56%) of 1,1,1-tris(hydroxymethyl) pentane boiling at 100–125C/0.08 mm Hg.

In the second procedure the same amounts of materials were allowed to react under the same conditions. After the reaction period the mixture was transferred to a separatory funnel, and the organic layer was removed. The aqueous layer was saturated with sodium chloride and extracted with four 100-ml portions of diethyl ether. The ether extracts were combined with the organic layer, and Drierite was added to remove traces of water. After the solution was dried for 4 hr, the desiccant was removed by filtration, and the solvent was removed in a rotary evaporator under reduced pressure. The crude product (39.6 g) gave two major peaks.

Hydrogenation of Reaction Products

A sample (4.2 g) of crude product from the first Trish 5 procedure was dissolved in 100 ml of methanol, and 0.2 g of platinum oxide catalyst was added. Hydrogenation was carried out on a Parr shaker at ambient temperature and 40 psi hydrogen for 4 hr. After the catalyst was removed by filtration, the methanol was removed under reduced pressure. Although the GLC peak pattern of the reduction

products was different from that of the starting material, there were still three major peaks. One of these peaks was identified as arising from Trish 5.

A sample (39.6 g) from the second procedure was dissolved in 100 ml of anhydrous methanol. The methanol solution was placed in a 250-ml stainless steel hydrogenation bomb, Raney nickel (0.5 g) was added, and the bomb was flushed with hydrogen before sealing. Hydrogenation was carried out at 100C and 1000 psi for 4 hr. After the bomb cooled to room temperature, catalyst was removed by filtration. Evaporation of methanol gave a product with one major peak upon GLC analysis. Recrystallization from diethyl ether gave 30 g (89%) of Trish 5 (mp 60–61C). Anal. Calc.: C, 59.22; H, 11.18. Found: C, 59.40; H, 11.10.

1,1,1-Tris(hydroxymethyl)octane

Sodium hydroxide (4.80 g, 0.12 mole), dissolved in water (10 ml), and aqueous formaldehyde (32.4 g, 0.4 mole CH_2O) were mixed at 10C in the reaction flask under nitrogen atmosphere. Nonanal (14.2 g, 0.10 mole) was added with rapid stirring and external cooling to maintain a reaction temperature below 30C. After the exothermic reaction had subsided, the reaction mixture was warmed to 60C and held for 5 hr. After the mixture was kept an additional 16 hr at ambient temperature, the product was isolated without neutralization of the caustic catalyst. The crude reaction product (18.5 g) contained two major compounds: 1,1,1-tris(hydroxymethyl)octane, designated as Trish 8, and 2,2-bis(hydroxymethyl)nonanal. The crude product was hydrogenated and recrystallized twice from diethyl ether to give 17.6 g (86%) of Trish 8 (mp 68–69C). Anal. Calc.: C, 64.66; H, 11.84. Found: C, 64.68; H, 11.71.

Trish 5 Triacetate

Trish 5 (6.89 g), acetic anhydride (25 g), and freshly fused sodium acetate (0.2 g) were refluxed under a nitrogen atmosphere in a 100-ml, round-bottomed flask for 4 hr. After the reaction mixture was cooled to room temperature, 100 ml of diethyl ether were added, and excess acetic anhydride was neutralized with saturated sodium bicarbonate solution. The ethereal solution of acetates was dried over

Drierite. The GLC analysis was run on the ethereal solution, and the acetates were distilled. Trish 5 triacetate was isolated by preparative GLC for physical measurements. Infrared analysis indicated a trace of free OH, but carbon and hydrogen analyses checked. Calc.: C, 58.38; H, 8.39. Found: C, 58.37; H, 8.45.

Other Procedures

Trimethylsilyl ethers for GLC analysis were prepared by the method of Sweeley et al. (29).

Infrared (IR) analyses were carried out on a Perkin-Elmer Model 337 grating infrared spectrophotometer. The samples were run as smears or carbon tetrachloride solutions in KBr cells of appropriate thickness. The scan rate was 8 min with a slit-width setting of N.

Melting points were determined on a DuPont Model 900 differential thermal analyzer. The sample was packed to a depth of 2 mm in a micro sample holder. Packing was accomplished by dropping the sample tube five times through a 61-cm glass tube. The sample was programmed at 2C/min, and the melting range was determined from extrapolated onset and peak.

Results and Discussion

Two different procedures were used to prepare 1,1,1-tris(hydroxymethyl)pentane (Trish 5). The first followed the procedure most frequently reported in the literature. The caustic catalyst is neutralized with an acid, usually formic acid, before isolation of the reaction product. Water is then removed by heating under reduced pressure. The yields by this procedure were only 65–70%. However a second procedure was devised which gave 85–90% yields. The more successful procedure consisted in modification of the first by a) isolation of the product from an alkaline rather than an acidic solution and b) the addition of a hydrogenation step.

In characterizing the reaction products, it was found by the GLC analysis that they could be satisfactorily determined as silylated derivatives. Free alcohols are eluted only partially and tail considerably on the columns used. Surprisingly, application of this GLC method to the silylated reaction mixture, obtained by the most commonly used condensation procedure, revealed four major products (Fig. 1). Two of these (peaks B and D of Fig. 1) could be eluted from the column without previous conversion to acetates or silyl ethers. The other two peaks (A and C) are owing to silylated derivatives of polyhydric compounds.

IR analysis of the reaction mixture (unsilylated) indicated a considerable amount of ester carbonyl. The ester could result only from the reaction of polyhydric compounds with formic acid, which was used to neutralize the alkali catalyst. Formate esters were still formed but in lesser amounts, when sulfuric acid replaced formic acid for neutralization. Formic acid was formed as the result of the crossed Cannizzaro reaction in the final stage of the Tollens condensation.

The product mixture from the commonly used condensation procedure gave a positive aldehyde test with dinitrophenylhydrazine (DNPH) although no bands in the IR spectrum could be assigned to the aldehydic function. The product mixture was treated with hydrogen over platinum catalyst to hydrogenate the aldehyde obviously present. IR analysis of the hydrogenated product indicated only a slight in-

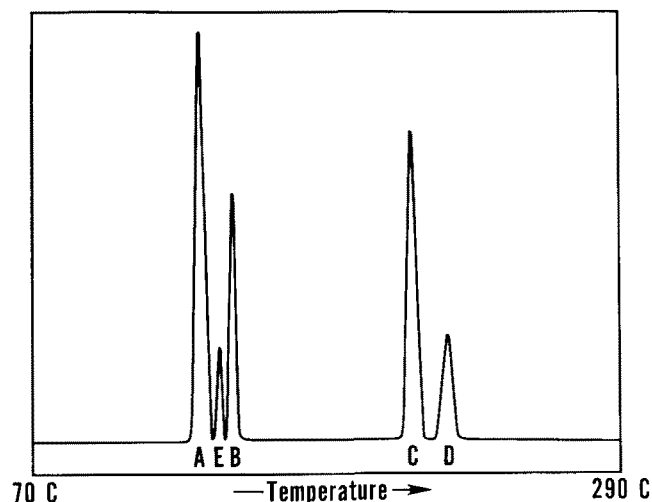70 C   —Temperature→   290 C

FIG. 1. Gas-liquid analysis of reaction products. (A) Trish 5 trisilyl ether, (B) Trish 5 triformate, (C) 2,2-bis(hydroxymethyl) hexanal disilyl ether, (D) 2,2-bis(hydroxymethyl)-hexanal diformate, and (E) Trish 5 silyl ether diformate.

crease in hydroxyl groups, but DNPH gave a negative aldehyde test. GLC analyses of the silylated, hydrogenated product gave a higher peak for A and a new peak, E, but peaks C and D were absent. Evidently the compounds corresponding to peaks C and D were removed during hydrogenation. GLC analysis of the hydrogenated but unsilylated product gave peaks B and E; peak E was displaced to a higher temperature and tailed considerably.

After alkaline hydrolysis, the hydrogenated product gave only peak A as the silylated derivative. The hydrolyzed, hydrogenated product could not be chromatographed without derivative formation. Recrystallization of the hydrolyzed, hydrogenated product from diethyl ether gave pure Trish 5. Trish 5, then, is responsible for peak A, an ester for peak E, and another ester for peak B.

Alkaline hydrolysis of the unhydrogenated reaction mixture resulted in a product that gave a positive DNPH test and gave only peaks A and C when chromatographed as silyl ethers. If the product was not silylated, no peaks were obtained upon GLC analysis. Since peak C disappeared upon hydrogenation, assignment of this peak to the silylated derivative of 2,2-bis(hydroxymethyl)hexanal seems reasonable. Treatment of the hydrolyzed, unhydrogenated reaction product with excess formaldehyde and caustic did not change the relative amounts of the two compounds responsible for peaks A and C.

IR analyses of the various reaction mixtures were apparently anomalous. For example, no absorption occurred in the region of aldehydic C–H stretching frequency for samples that gave positive DNPH tests. Further, absorption owing to hydroxyl was absent or not so great as expected. The anomalous behavior is explained by hemiacetal formation between the aldehyde and hydroxyl groups (1,23).

Increased yields of polyhydric alcohols from this reaction have been previously reported when one step of the reaction involved hydrogenation (31). Hydrogenation of a mixture of compounds, containing peaks A and C upon GLC analysis, gave the desired Trish product. This result supports the assumption that the by-product giving peak C is the 2-2-bis(hydroxymethyl)alkanal. Preparation of 2,2-bis(hydroxymethyl)alkanal under mild caustic conditions has been previously reported (23,24,31).

There are reports in the literature (8,13) where the final isolation was carried out from a basic medium; however a neutralization step was performed before complete isolation. In the second procedure for the preparation of Trish compounds, the reaction product was extracted from the basic reaction medium. GLC analysis of this material indicated the presence of only peaks A and C in an approximate weight ratio of 3:2. No ester carbonyl appeared in the IR spectrum. Treatment of this mixture with hydrogen in the presence of Raney nickel gave Trish 5 in an over-all yield of 90%.

It is now apparent that the peaks in Fig. 1 are:
(A) Trish 5 trisilyl ether, (B) Trish 5 triformate, (C) 2,2-bis(hydroxymethyl)pentanal disilyl ether, (D) 2,2-bis(hydroxymethyl)pentanal diformate, and (E) Trish 5 silyl ether diformate. Previous reports have described the isolation of various other by-products from this reaction (7,14). The two main

by-products were the formal I and the ether II. Identification of all the major components in the reaction mixture indicates that neither of these by-products was present in measurable amounts.
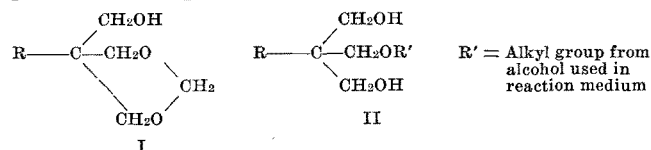
Results are similar when nonanal is substituted for hexanal. Therefore, to obtain the highest yields of long-chain Trish compounds, two steps are necessary: a) reaction products must be isolated directly from basic reaction medium to suppress ester formation, and b) the isolated products must be hydrogenated to convert the 2,2-bis(hydroxymethyl) alkanals to the desired 1,1,1-tris(hydroxymethyl) alkanes.

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