Conversion of 2-Alkyl-2-(2-oxopropyl)cyclopentane-1,3-diones into 2,3,5- and 2,3,4-Trisubstituted Cyclopent-2-enones by Intramolecular Aldolizations to 2,3-Diacylcyclopropanolates Followed by Remarkable Skeletal Rearrangements[1]

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2-Alkyl-2-(prop-2-ynyl)cyclopentane-1,3-diones **2**, conveniently prepared from 2-alkylcyclopentane-1,3-diones **1** and prop-2-ynyl bromide, afford the triketones **3** by Hg^{2+}-catalyzed hydration of the acetylenic triple bond. Treatment of these triketones with aqueous sodium hydroxide gives rise to the 2,3,5-trisubstituted cyclopent-2-enones **5**, which are accompanied by the isomeric 2,3,4-trisubstituted cyclopent-2-enones **7** as byproducts. The formation of these isomers can be avoided, when the 2,2-disubstituted cyclopentane-1,3-diones **2** are first converted by ring cleavage into the 5-alkyl-4-oxooct-7-ynoic acids **4** and then by subsequent hydration into the 5-alkyl-4,7-dioxoalkanoic acids **6**. An intramolecular aldolization of the latter forms exclusively the cyclopentenones **5**. A mechanism explaining the simultaneous formation of **5** and **7** from **3** is based on the formation of the 2,3-diacylcyclopropanolates **11** and **16** by intramolecular aldolization and subsequent ring opening to the 2-acetylcyclohexane-1,4-diones **13** and **18**. A further ring opening to the 4,7-dioxoalkanoates **15** and **20** followed by intramolecular aldol condensation then gives rise to the isomeric trisubstituted cyclopent-2-enones **5** and **7**.

2,2-Dialkylated cyclopentane-1,3-diones with a carbonyl group in one of the side chains possess various possibilities for intramolecular aldol reactions. By the reaction of one keto group of the ring with the activated methyl group of the 3-oxobutyl side chain, 2-methyl-2-(3-oxobutyl)cyclopentane-1,3-dione affords a tetrahydroindene-1,5-dione, known as a versatile intermediate for the total synthesis of steroids.[2] Under special conditions the condensation of the keto group in the side chain with a methylene group of the ring leads predominantly to the formation of a bicyclo[3.2.1]octane-7,8-dione system.[3] Recently, we have shown that also 3-(1-methyl-2,5-dioxocyclopentyl)propanal reacts in the last mentioned way, forming a bicyclo[3.2.1]octane-7,8-dione.[4] In this connection it was of interest for us to investigate whether 2-alkyl-2-(2-oxopropyl)cyclopentane-1,3-diones of type **3** are able to cyclize to bicyclic systems, which exhibit independently of the regioselectivity of the aldolization two five-membered rings. Although a direct cyclization of the triketone **3a** to the bis-*nor*-Wieland−Miescher ketone has failed,[5] we now report on our results on the intramolecular aldolization of the triketones **3**.

Results and Discussion

The starting triketones **3** were easily available from the corresponding 2-alkylcyclopentane-1,3-diones **1**[6] by C-alkylation with prop-2-ynyl bromide in water[7] followed by Hg^{2+}-catalyzed hydration.[8] Since 2,2-dialkylated cyclopentane-1,3-diones are smoothly cleaved by aqueous alkali to 5-alkylated 4-oxoalkanoic acids,[9] it was expected that **3** should be cleaved by sodium hydroxide in water to **6** and then cyclized to the cyclopent-2-enone **5**.

In practice, the triketone **3a** gave indeed the cyclopent-2-enone **5a** when treated with 2 equiv of sodium hydroxide in water. However, this compound contained about 10% of a side product, which was identified by ^1H and ^{13}C NMR as the isomeric cyclopent-2-enone **7a**. The homologous triketones **3b**−**e** exhibited an analogous behavior. By treatment with aqueous sodium hydroxide they afforded mixtures of the isomeric cyclopent-2-enones **5b**−**e** and **7b**−**e**. With growing alkyl side chain the

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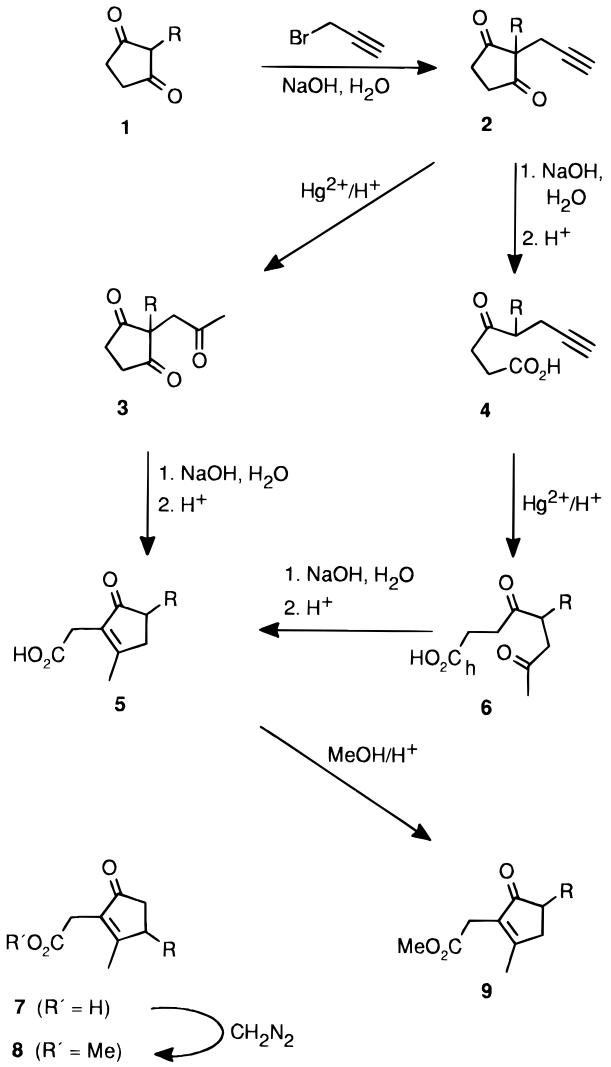
Scheme 1

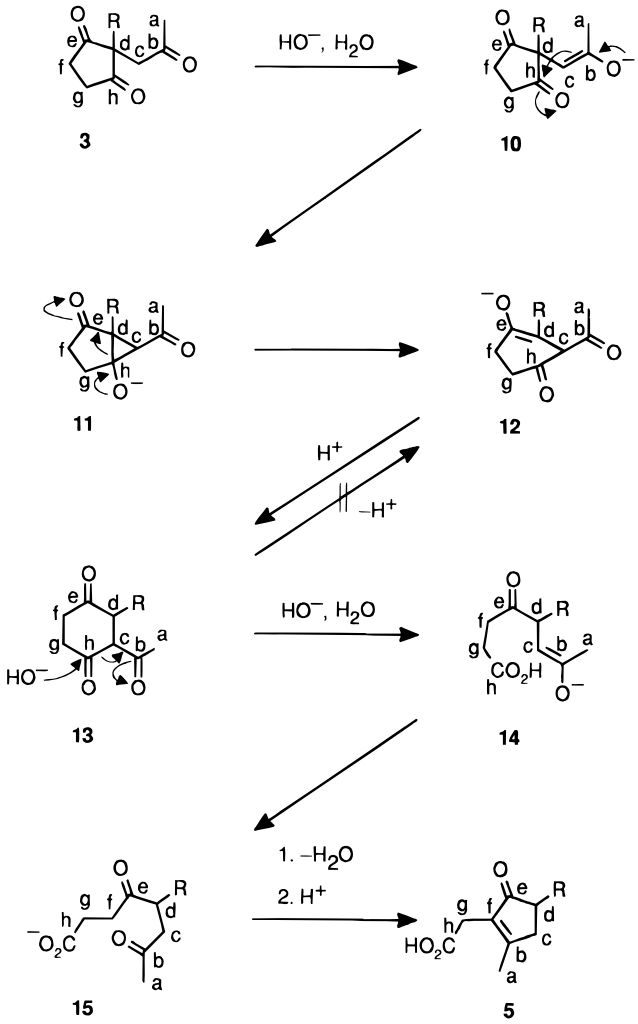


	a	b	c	d	e
R	Me	Et	*n*-Pr	*n*-Bu	*n*-C_5H_{11}

amount of the side product **7** increased from 10 to 27% as determined by GLC analysis after conversion of the mixture of **5** and **7** into a mixture of the methyl esters **9** and **8** (Scheme 1).

The mechanism for the conversion of the triketones **3** into the 2,3,5-trisubstituted cyclopent-2-enones **5**, published recently in preliminary form,[10] is shown in Scheme 2. Deprotonation of **3** with sodium hydroxide at the methylene group of the side chain affords the carbanion **10**. Nucleophilic attack of C_c at one of the carbonyl groups of the ring gives rise to the diacylcyclopropanolate **11**. Cleavage between C_h and C_d and protonation leads to ring enlargement via **12** to the 2-acetylcyclohexan-1,4-dione **13**. As a 2-substituted 1,3-diketone this compound suffers an alkali-promoted ring opening via **14** to the carboxylate **15** which condenses as a 1,4-diketone to the cyclopent-2-enone **5**.[11] This mechanism is based on the fact that the intermediate **13a** can be isolated in a yield of about 70%, when the reaction of **3a** with 1 equiv of aqueous sodium hydroxide is quenched after 2 min by acidification.

Scheme 2



In the case of the alkali-promoted conversion of **3a** into **5a**, the intermediate **13a** could be recognized in the reaction mixture by ^{1}H NMR monitoring. The spectra measured immediately after addition of 0.5 equiv of sodium hydroxide to the solution of **3a** in methanol and 15 min later reveal the growth of the characteristic doublet of **13a** at 1.29 ppm parallel to the decrease of the singlet of **3a** at 1.21 ppm.[12] After addition of a further 0.5 equiv of aqueous sodium hydroxide, the ^{1}H NMR spectrum of the reaction mixture discloses almost exclusively the signals of the sodium enolate of **13a**. The spectra measured after addition of two further 0.5 equiv of alkali showed the appearance and subsequent disappearance of the doublet of the sodium carboxylate **15a** at 1.24 ppm and the final formation of the doublet at 1.22 ppm of the sodium salt of **5a**.

Thus, ^{1}H NMR monitoring and the isolation of **13a** as intermediate ruled out the generally accepted mechanism whereby the 4,7-dioxoalkanoate **15a** is directly formed by an attack of a hydroxide ion on one of the ring carbonyl groups of **3a**.

In order to determine the structure of the 2,3,4-trisubstituted cyclopent-2-enones **7**, obtained as byproducts, the crude mixtures of the isomers **5** and **7** were esterified with diazomethane and then separated by flash chromatography on silica. In this way the methyl esters **8a**, **8b**, and **8e** were obtained in analytically pure form.

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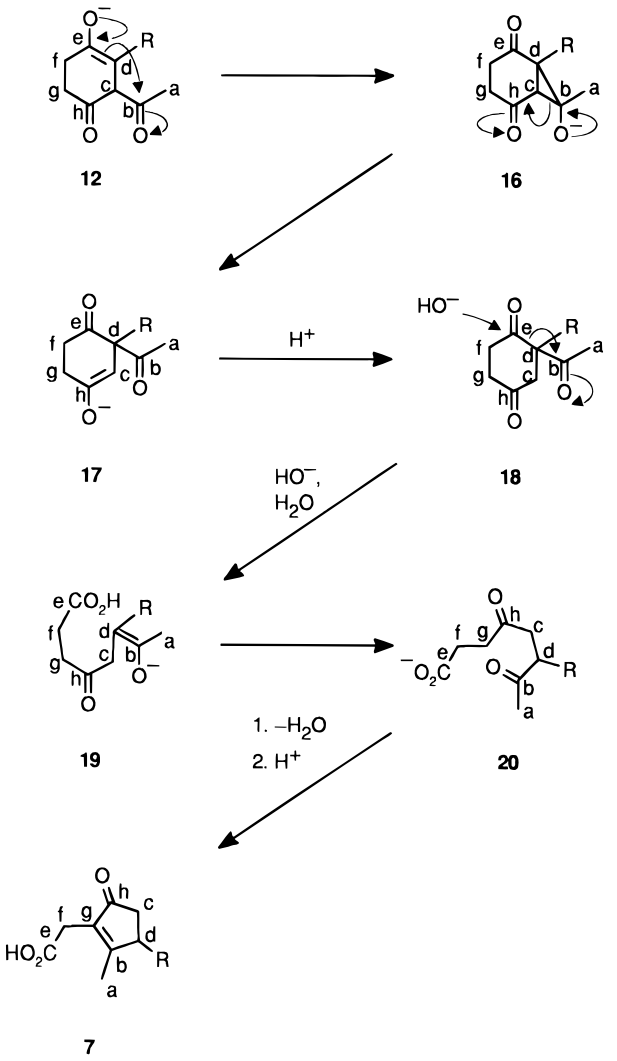
(11) For a rewiew, see: Ellison, R. A. *Synthesis* **1973**, 397.

(12) The chemical shifts are related to methanol as internal standard. δ CH_3 of MeOH = 3.47 ppm.

Scheme 3



The coupling patterns in the ^{1}H NMR spectra of **8a** and **8e** as well as the signal multiplicity of the ^{13}C NMR spectra, ascertained by attached proton tests (APT) and coupled spectra, are in agreement with the given structures (see Experimental Section). HETCOR measurements supported the carbon−hydrogen assignments. Final evidence for the structure of **8a** and **8e** came from nuclear Overhauser difference spectrometry. An independent proof was achieved by an X-ray crystal structure analysis of the dicyclohexylammonium salts prepared from **5b** and **7b**.[13]

The formation of the 2,3,4-trisubstituted cyclopent-2-enones **7** by treatment of the triketones **3** with sodium hydroxide in water was an unexpected competitive side reaction, which reached starting from **3e** an amount of 27% of the isolated cyclopentenone fraction. In order to explain this surprising reaction course, it can be assumed that the carbonyl group in the side chain of the anionic intermediate **12** is intramolecularly attacked by the nucleophilic C_d of the enolate moiety forming a 2,3-diacylcyclopropanolate **16** (Scheme 3). Opening of the cyclopropane ring between C_b and C_c and regeneration of the carbonyl group at C_b gives rise to the enolate **17**. This reaction sequence from **12** to **17** *via* **16** represents a 1,2-acyl transposition, inasmuch as the acetyl group containing C_a and C_b has migrated from C_c in **12** to C_d in **17**. In the next step the 2-acetylcyclohexane-1,4-dione **18** obtained by protonation of the enolate **17** suffers ring opening by attack of a hydroxide ion on the carbonyl group at C_e, which is part of a 2,2-disubstituted 1,3-diketone system, known to be especially prone to deacylation. The open-chain enolate **19** rearranges to the 4,7-dioxoalkanoate **20**, which cyclizes as a 1,4-diketone to the 2,3,4-trisubstituted cyclopentenone **7**.[11] As a consequence of this reaction sequence, the carbon skeleton is significantly reorganized on the route from **3** to **7**. Obviously, starting with a sequence of the carbon atoms in **3** of the type abcdefgh, the reaction ends in **7** with a sequence of the type ab−dc−hgfe (Scheme 3).

The proposed mechanism for the competitive formation of the cyclopentenones **5** and **7** is in agreement with the fact that **5** can be prepared uncontaminated by **7**, if the triketone **13** or the acid **6** are treated with aqueous sodium hydroxide. The reason for this observation may consist in the fact that the protonation of **12** to **13** is an irreversible process. A deprotonation of **13** is expected to occur at C_c, but not at C_d. The last common intermediate of the formation of **5** and **7** from **3**, the enolate **12**, can therefore be reached neither from **13** nor from **6**.

Conclusion

In conclusion, the conversion of the 2-acetonyl-2-alkyl-1,3-diketones **3** into the isomeric cyclopentenones **5** and **7** has been recognized as a process involving one or two rearrangements of intermediately formed 2,3-diacylcyclopropanolates into 2-acetyl-3-alkyl- and 2-acetyl-2-alkyl-1,4-diketones, respectively. When compared with the intramolecular aldolization of the structurally related 2-methyl-2-(2-oxobutyl)cyclopentane-1,3-dione[2,3] and 3-(1-methyl-2,5-dioxocyclopentyl)propanal,[4] the mechanism described here seems to be unique. In future experiments it has to be elucidated whether the skeletal rearrangements via 2,3-diacylcyclopropanolates observed here are restricted to 2-acetonyl-2-alkylcyclopentane-1,3-diones or whether they can be performed generally with cyclic or even acyclic 2-substituted 2-acetonyl-1,3-diketones.

Experimental Section

General. ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ at 300 and 75 MHz, respectively, with HMDS as internal standard. Flash chromatography was performed on silica gel 60 (0.04−0.063 mm, E. Merck). 2-Methyl- and 2-ethylcyclopentane-1,3-dione were supplied by Jenapharm GmbH, Jena, Germany.

General Procedure for the Preparation of the 2-Alkyl-2-(prop-2-ynyl)cyclopentane-1,3-diones 2. Prop-2-ynyl bromide (35.7 g, 0.3 mol) was added to a solution of NaOH (12.0 g, 0.3 mol) and a 2-alkylcyclopentane-1,3-dione **1**[6b] (0.3 mol) in H_2O (240 mL). This mixture was stirred at 60 °C for 8−11 h and then extracted with CH_2Cl_2 (5 × 30 mL). The combined extracts were concentrated under reduced pressure. The residue was dissolved in MeOH (30 mL) and stirred with H_2O (15 mL) and concentrated H_2SO_4 (2.5 mL) at reflux temperature for 3 h in order to cleave the undesired O-alkylation product. Then MeOH was removed under reduced pressure, and the remaining mixture was extracted with CH_2Cl_2 (5 × 30 mL). The combined extracts were washed with saturated aqueous $NaHCO_3$ (3 × 20 mL), dried over Na_2SO_4, and concentrated under reduced pressure. Distillation of the residue afforded the prop-2-ynyl compounds **2**. According to this procedure, the compounds **2c**−**e** were prepared. **2a** and **2b** were prepared according to the procedure of ref 7b.

2-Propyl-2-(prop-2-ynyl)cyclopentane-1,3-dione (2c): yield 27.3 g (51%), colorless oil, bp 91−92 °C/80 Pa; ^{1}H NMR

(13) The authors have deposited the atomic coordinates for these structures with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, upon request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, U.K.

δ 0.76 (t, J = 7 Hz, 3H), 0.90−1.35 (m, 2H), 1.40−1.70 (m, 2H), 2.01 (t, J = 2.4 Hz, 1H), 2.36 (d, J = 2.4 Hz, 2H), 2.72 (s, 4H); ^{13}C NMR δ 14.29, 17.99, 23.63, 36.65, 37.25, 59.69, 70.86, 78.96, 215.6. Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.13; H, 7.92. Found: C, 73.85; H, 8.09.

2-Butyl-2-(prop-2-ynyl)cyclopentane-1,3-dione (2d): yield 31.7 g (55%), colorless oil, bp 107−108 °C/133 Pa; ^{1}H NMR δ 0.76 (t, J = 6.6 Hz, 3H), 0.90−1.40 (m, 4H), 1.40−1.80 (m, 2H), 1.98 (t, J = 2.4 Hz, 1H), 2.35 (d, J = 2.4 Hz, 2H), 2.71 (s, 4H); ^{13}C NMR δ 13.57, 22.92, 23.68, 26.65, 34.94, 36.69, 59.60, 70.77, 78.94, 215.8. Anal. Calcd for $C_{12}H_{16}O_2$: C, 74.97; H, 8.39. Found: C, 74.92; H, 8.74.

2-Pentyl-2-(prop-2-ynyl)cyclopentane-1,3-dione (2e): yield 37.8 g (61%), colorless oil, bp 121−122 °C/133 Pa; ^{1}H NMR δ 0.82 (t, J = 6.6 Hz, 3H), 0.97−1.42 (m, 6H), 1.42−1.81 (m, 2H), 1.94 (t, J = 2.4 Hz, 1H), 2.44 (d, J = 2.4 Hz, 2H), 2.75 (s, 4H); ^{13}C NMR δ 13.82, 22.12, 23.64, 24.19, 31.95, 35.12, 36.69, 59.59, 70.82, 79.00, 215.5. Anal. Calcd for $C_{13}H_{18}O_2$: C, 75.69; H, 8.80. Found: C, 75.43; H, 8.99.

General Procedure for the Preparation of the 2-Alkyl-2-(2-oxopropyl)cyclopentane-1,3-diones 3. Prop-2-ynyl compound **2** (0.2 mol) was dissolved in MeOH (80 mL) and H_2O (27 mL). The solution was added to a mixture of $HgSO_4$ (400 mg), H_2O (18 mL), MeOH (53 mL), and concentrated H_2SO_4 (0.2 mL) and refluxed for 8−11 h. H_2O (200 mL) was added, MeOH was removed under reduced pressure, and the remaining mixture was extracted with EtOAc (5 × 30 mL). The combined extracts were washed with saturated aqueous $NaHCO_3$ (3 × 10 mL), dried over Na_2SO_4, and concentrated under reduced pressure. The residue was purified by distillation or recrystallization. According to this general procedure the following triketones **3** were prepared.

2-Methyl-2-(2-oxopropyl)cyclopentane-1,3-dione (3a): yield 23.5 g (70%), colorless crystals, mp 67 °C (hexane); ^{1}H NMR δ 0.99 (s, 3H), 2.01 (s, 3H), 2.83 (s, 4H), 3.11 (s, 2H);^{13}C NMR δ 19.32, 28.11, 34.69, 51.66, 52.33, 206.1, 216.1. Anal. Calcd for $C_9H_{12}O_3$: C, 64.27; H, 7.19. Found: C, 64.44; H, 7.04.

2-Ethyl-2-(2-oxopropyl)cyclopentane-1,3-dione (3b): yield 24.0 g (66%), colorless crystals, mp 40−42 °C (hexane); ^{1}H NMR δ 0.79 (t, J = 7.6 Hz, 3H), 1.46 (q, J = 7.6 Hz, 2H), 1.99 (s, 3H), 2.76 (m, 4H), 3.06 (s, 2H); ^{13}C NMR δ 8.35, 27.50, 28.23, 35.62, 50.38, 56.70, 206.2, 216.3. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.91; H, 7.74. Found: C, 65.79; H, 7.89.

2-Propyl-2-(2-oxopropyl)cyclopentane-1,3-dione (3c): yield 29.8 g (76%), colorless crystals, mp 68−70 °C (heptane); ^{1}H NMR δ 0.76 (t, J = 6.8 Hz, 3H), 0.92−1.58 (m, 4H), 1.98 (s, 3H), 2.50−3.00 (m, 4H), 3.08 (s, 2H); ^{13}C NMR δ 14.26, 17.40, 28.22, 35.73, 36.77, 51.11, 56.67, 206.2, 216.5. Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.29; H, 8.18.

2-Butyl-2-(2-oxopropyl)cyclopentane-1,3-dione (3d): yield 30.7 g (73%), colorless crystals, mp 54−56 °C (hexane); ^{1}H NMR δ 0.78 (t, J = 6.6 Hz, 3H), 0.94−1.86 (m, 6H), 1.99 (s, 3H), 2.40−3.02 (m, 4H), 3.08 (s, 2H); ^{13}C NMR δ 13.57, 22.93, 26.00, 28.23, 34.41, 35.72, 51.10, 56.48, 206.2, 216.6. Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.54; H, 8.63. Found: C, 68.50; H, 8.43.

2-Pentyl-2-(2-oxopropyl)cyclopentane-1,3-dione (3e): yield 36.3 g (81%), light-yellow oil, bp 131−135 °C/133 Pa; ^{1}H NMR δ 0.77 (t, J = 6.4 Hz, 3H), 0.97−1.86 (m, 8H), 1.98 (s, 3H), 2.40−3.05 (m, 4H), 3.09 (s, 2H); ^{13}C NMR δ 13.83, 22.18, 23.46, 28.15, 31.95, 34.44, 35.61, 50.76, 56.42, 206.2, 216.2. Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.99. Found: C, 69.80; H, 8.94.

General Procedure for the Preparation of the (±)-5-Alkyl-4-oxooct-7-ynoic Acids 4. Prop-2-ynyl dione **2** (100 mmol) was added to a solution of NaOH (8.00 g, 200 mmol) in H_2O (100 mL) and stirred at 20 °C for 8 h. Then the mixture was washed with Et_2O (3 × 20 mL), acidified with 5 M H_2SO_4, and extracted again with Et_2O (5 × 30 mL). The combined extracts of the acidified reaction mixture were dried over Na_2SO_4 and concentrated under reduced pressure. The remaining octynoic acid **4** was purified by distillation or recrystallization. According to this procedure the following compounds were prepared.

(±)-5-Methyl-4-oxooct-7-ynoic acid (4a): yield 13.3 g (79%), colorless solid, mp 25−30 °C, bp 120 °C/0.8 Pa; ^{1}H NMR δ 1.14 (d, J = 6.8 Hz, 3H), 1.96 (t, J = 2.4 Hz, 1H), 2.02−3.00 (m, 7H), 9.31 (s, 1H); ^{13}C NMR δ 16.01, 21.72, 27.79, 35.57, 45.25, 70.00, 81.81, 178.6, 210.3. Anal. Calcd for $C_9H_{12}O_3$: C, 64.27; H, 7.19. Found: C, 63.99; H, 7.24.

(±)-5-Ethyl-4-oxooct-7-ynoic acid (4b): yield 11.8 g (65%), colorless crystals, mp 46−47 °C (hexane); ^{1}H NMR δ 0.81 (t, J = 7 Hz, 3H), 1.30−1.82 (m, 2H), 1.89 (t, J = 2.4 Hz, 1H), 2.20−2.90 (m, 7H), 10.50 (s, 1H); ^{13}C NMR δ 11.04, 19.75, 23.97, 27.63, 37.02, 51.98, 69.86, 81.76, 178.9, 210.3. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.91; H, 7.74. Found: C, 65.73; H, 7.69.

(±)-4-Oxo-5-propyloct-7-ynoic acid (4c): yield 12.2 g (62%), colorless crystals, mp 40−41 °C (heptane); ^{1}H NMR δ 0.83 (t, J = 6.8 Hz, 3H), 0.96−1.80 (m, 4H), 1.90 (t, J = 2.4 Hz, 1H), 2.20−2.90 (m, 7H), 10.52 (s, 1H); ^{13}C NMR δ 14.00, 20.09, 20.33, 27.65, 33.21, 37.05, 50.55, 69.89, 81.78, 178.3, 210.3. Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.03; H, 8.13.

(±)-5-Butyl-4-oxooct-7-ynoic acid (4d): yield 12.8 g (61%), colorless crystals, mp 45−47 °C (hexane); ^{1}H NMR δ 0.80 (t, J = 7 Hz, 3H), 0.95−1.80 (m, 6H), 1.88 (t, J = 2.4 Hz, 1H), 2.20−2.90 (m, 7H), 10.35 (s, 1H); ^{13}C NMR δ 13.77, 20.35, 22.68, 27.69, 28.99, 30.75, 37.03, 50,75, 69.91, 81.79, 178.5, 210.2. Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.54; H, 8.63. Found: C, 68.24; H, 8.73.

(±)-4-Oxo-5-pentyloct-7-ynoic acid (4e): yield 16.4 g (73%), colorless crystals, mp 44−46 °C (heptane); ^{1}H NMR δ 0.80 (t, J = 6 Hz, 3H), 1.00−1.80 (m, 8H), 1.90 (t, J = 2.4 Hz, 1H), 2.20−2.90 (m, 7H), 9.60 (s, 1H); ^{13}C NMR δ 13.92, 20.33, 22.40, 26.49, 27.67, 31.02, 31.80, 37.05, 50.74, 69.90, 81.79, 178.4, 210.3. Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.99. Found: C, 69.54; H, 9.17.

(±)-2-(4-Alkyl-2-methyl-5-oxocyclopentenyl)acetic Acids 5. (a) Obtained together with (±)-2-(3-Alkyl-2-methyl-5-oxocyclopentenyl)acetic Acids 7 by Reaction of the Triketones 3 with Sodium Hydroxide (General Procedure). Triketone **3** (70 mmol) was added to a solution of NaOH (5.60 g, 140 mmol) in H_2O (70 mL) and stirred at ambient temperature for 8 h. The mixture was washed with Et_2O (3 × 20 mL) in order to remove neutral components, acidified with 5 M H_2SO_4, and extracted again with Et_2O (5 × 30 mL). The combined extracts of the acidified aqueous phase were dried over Na_2SO_4 and concentrated under reduced pressure. The remaining mixture of the oily acids **5** and **7** (yield 85−95%) was immediately converted into a mixture of the methyl esters **9** and **8** (see below).

(b) By Intramolecular Cyclization of the 4,7-Dioxoacids 6 (General Procedure). 4,7-Dioxo acid **6** (15 mmol), NaOH (1.20 g, 30 mmol), and H_2O (15 mL) were stirred at 20 °C for 8 h. The mixture was acidified with 5 M H_2SO_4 and extracted with EtOAc (3 × 20 mL). The combined extracts were dried over Na_2SO_4 and concentrated under reduced pressure, thus affording the acid **5** as an oil. For purification and characterization **5** was converted into the corresponding methyl ester **9** (see below).

(c) By Reaction of the 2-Acyl-3-alkylcyclohexane-1,4-diones 13 (Typical Procedure). 13c[10] (392 mg, 2 mmol) was dissolved in 2 N aqueous NaOH (2 mL, 2 mmol) and allowed to stand at ambient temperature for 6 h. Then the reaction mixture was acidified with 2 N H_2SO_4 (2.5 mL) and extracted with Et_2O (2 × 20 mL) and EtOAc (2 × 20 mL). The extracts were dried over Na_2SO_4 and concentrated under reduced pressure. The obtained acid **5c** was esterified with diazomethane to the methyl ester **9c** (240 mg, 57%), identical in all respect with **9c** prepared from **6c**.

Dicyclohexylammonium Salt of Acid 5b. First, 2 N aqueous NaOH (1 mL, 2 mmol) was added to a solution of the methyl ester **9b** (196 mg, 1 mmol) in MeOH (1 mL). After standing at ambient temperature for 24 h, the mixture was acidified with 2 N H_2SO_4 (1.1 mL), and extracted with Et_2O (4 × 20 mL). Evaporation of the solvent afforded the acid **5b** (136 mg, 75%), to which dicyclohexylamine (165 mg, 0.9 mmol) dissolved in pentane (5 mL) was added. To this mixture was added Et_2O until the acid was completely dissolved. The crystals of the dicyclohexylammonium salt of **5b** obtained after 24 h were recrystallized from hexane. Colorless crystals of dimension 0.41 × 0.19 × 0.19 mm^3 were chosen for an X-ray crystal structure determination.[13]

General Procedure for the Preparation of the (±)-5-Alkyl-4,7-dioxooctanoic Acids 6. Octynoic acid **4** (43 mmol) was dissolved in acetone (15 mL) and added dropwise at −20 °C to a solution prepared from $HgSO_4$ (90 mg), concentrated H_2SO_4 (90 mg), H_2O (4.3 mL), and acetone (5 mL). The mixture was stirred at −10 to −20 °C for 5−7 h, diluted with ice-cold H_2O (50 mL), and extracted with EtOAc (3 × 20 mL). The combined extracts were dried over Na_2SO_4 and concentrated under reduced pressure. Analytical samples of the acids **6** were obtained by recrystallization from diethyl ether. **6b** and **6e** were solid only at −20 °C. According to this procedure the following compounds were prepared.

(±)-5-Methyl-4,7-dioxooctanoic acid (6a): yield 7.53 g (94%), colorless crystals, mp 48−49 °C: ^{1}H NMR δ 1.03 (d, J = 6.8 Hz, 3H), 2.04 (s, 3H), 2.13−3.20 (m, 7H), 9.16 (s, 1H); ^{13}C NMR δ 16.52, 27.80, 29.81, 32.69, 35.67, 40.93, 178.2, 207.3, 211.5. Anal. Calcd for $C_9H_{14}O_4$: C, 58.05; H, 7.58. Found: C, 57.90; H, 7.64.

(±)-5-Ethyl-4,7-dioxooctanoic acid (6b): yield 7.49 g (87%), light-yellow oil; ^{1}H NMR δ 0.80 (t, J = 7 Hz, 3H), 1.00−1.90 (m, 2H), 2.03 (s, 3H), 2.20−3.10 (m, 7H), 9.40 (s, 1H); ^{13}C NMR δ 10.81, 23.88, 27.24, 29.21, 36.46, 44.04, 47.02, 177.1, 207.5, 211.0. Anal. Calcd for $C_{10}H_{16}O_4$: C, 59.98; H, 8.05. Found: C, 59.72; H, 7.77.

(±)-4,7-Dioxo-5-propyloctanoic acid (6c): yield 8.57 g (93%), colorless crystals, mp 37−39 °C (Et_2O): ^{1}H NMR δ 0.84 (t, J = 6.4 Hz, 3H), 1.00−1.80 (m, 4H), 2.06 (s, 3H), 2.20−3.20 (m, 7H), 9.96 (s, 1H); ^{13}C NMR δ 14.00, 20.29, 27.78, 29.79, 33.54, 36.96, 45.07, 45.96, 178.2, 207.5, 211.4. Anal. Calcd for $C_{11}H_{18}O_4$: C, 61.66; H, 8.47. Found: C, 61.42; H, 8.66.

(±)-5-Butyl-4,7-dioxooctanoic acid (6d): yield 9.42 g (96%), colorless crystals, mp 34−36 °C (Et_2O/heptane); ^{1}H NMR δ 0.80 (t, J = 6.4 Hz, 3H), 1.00−1.80 (m, 6H), 2.03 (s, 3H), 2.20−3.20 (m, 7H), 10.65 (s, 1H); ^{13}C NMR δ 13.78, 22.69, 27.81, 29.21, 29.77, 31.07, 36.95, 45.09, 46.13, 178.3, 207.6, 211.4. Anal. Calcd for $C_{12}H_{20}O_4$: C, 63.13; H, 8.83. Found: C, 62.91; H, 8.99.

(±)-4,7-Dioxo-5-pentyloctanoic acid (6e): yield 9.90 g (95%), light-yellow oil; ^{1}H NMR δ 0.80 (t, J = 6.4 Hz, 3H), 1.00−1.80 (m, 8H), 2.04 (s, 3H), 2.20−3.20 (m, 7H), 10.49 (s, 1H). Anal. Calcd for $C_{13}H_{22}O_4$: C, 64.44; H, 9.15. Found: C, 64.33; H, 9.01.

Dicyclohexylammonium Salt of Acid 7b. This salt was obtained in full analogy to the preparation of the dicyclohexylammonium salt of the acid **5b** from the methyl ester **8b** (70 mg, 0.36 mmol). Colorless crystals of dimension of 0.25 × 0.18 × 0.15 mm^3 were chosen for an X-ray crystal structure determination.[13]

General Procedure for the Preparation of the Methyl (±)-2-(3-Alkyl-2-methyl-5-oxocyclopentenyl)acetates 8. A mixture of the crude acids **5** and **7** prepared by treatment of the triketone **3** (10 mmol) with 2 N NaOH (10 mL, see above) was dissolved in diethyl ether (20 mL) and treated with an excess of diazomethane in Et_2O. After usual workup the crude mixture of the methyl esters **8** (minor product) and **9** (major product) was separated by flash chromatography on silica gel. By this procedure the following esters **8** were prepared.

Methyl (±)-2-(2,3-Dimethyl-5-oxocyclopentenyl)acetate (8a). Yield of **8a** and **9a**, 1.27 g (70%); ratio of **8a** to **9a**, 10:90. Separation by twice-repeated flash chromatography with hexane/EtOAc (7:3) and toluene/nitromethane (1:1) as eluent afforded pure **8a** (100 mg, 5.5% from **3a**) as a colorless oil: ^{1}H NMR δ 1.15 (d, J = 7.1 Hz, 3H), 1.98 (dd, J = 18.7, 2.5 Hz, 1H), 1.99 (s, 3H), 2.60 (dd, J = 18.7, 6.6 Hz, 1 H), 2.75 (m, 1H), 3.16 (s, 2H), 3.61 (s, 3H); ^{13}C NMR δ 15.2 (q), 18.9 (q), 28.4 (t), 37.7 (d), 42.8 (t), 52.1 (q), 133.5 (s), 171.1 (s), 177.5 (s), 207.4 (s). Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.91; H, 7.74. Found: C, 65.90; H, 7.81.

Methyl (±)-2-(3-Ethyl-2-methyl-5-oxocyclopentenyl)-acetate (8b). Yield of **8b** and **9b**, 1.66 g (85%); ratio of **8b** to **9b**, 15:85. Separation by flash chromatography with hexane/EtOAc (7:3) as eluent afforded **8b** (220 mg, 11.2% from **3b**) as a colorless oil: ^{1}H NMR δ 0.83 (t, J = 7 Hz, 3H), 1.10−1.35 (m, 2H), 1.95 (s, 3H), 2.00−2.10 (dd, J = 18.5, 2.0 Hz, 1H), 2.45−2.55 (dd, J = 18.5, 6.5 Hz, 1H), 2.64−2.73 (m, 1H), 3.16 (s, 2H,), 3.60 (s, 3H); ^{13}C NMR δ 10.6, 15.4, 25.2, 28.3, 39.7, 44.2, 52.0, 134.1, 170.8, 176.1. Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 66.92; H, 8.27.

Methyl (±)-2-(2-Methyl-3-pentyl-5-oxocyclopentenyl)-acetate (8e). Yield of **8e** and **9e**, 1.98 g (83%); ratio of **8e** to **9e**, 27:73. Separation by twice-repeated flash chromatography with hexane/EtOAc (7:3) as eluent afforded **8e** (480 mg, 20.2% from **3e**) as a colorless oil: ^{1}H NMR δ 0.83 (m, 3H), 1.15−1.40 and 1.65−1.80 (2m, 8H), 1.97 (s, 3H), 2.05 (dd, J = 18.6, 2.0 Hz, 1H), 2.49 (dd, J = 18.6, 6.5 Hz, 1H), 2.64−2.74 (m, 1H), 3.16 (s, 2H), 3.60 (s, 3H); ^{13}C NMR δ 14.0 (q), 15.2 (q), 22.5 (t), 26.6 (t), 28.4 (d), 31.9 (t), 32.8 (t), 40.2 (t), 43.2 (d), 52.0 (q), 134.1 (s), 171.0 (s) 176.5 (s), 207.4 (s). Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.56; H, 9.30. Found: C, 70.77; H, 9.55.

General Procedure for the Preparation of the Methyl (±)-2-(4-Alkyl-2-methyl-5-oxocyclopentenyl)acetates 9. Crude acid **5** (10 mmol, obtained from the corresponding acid **6**), *p*-toluenesulfonic acid (400 mg), MeOH (17 mL), and CH_2Cl_2 (34 mL) were set aside at ambient temperature for 5 d. Then the solvents were removed to a large extent under reduced pressure. The residue was dissolved in EtOAc (40 mL) and washed with saturated aqueous $NaHCO_3$ (2 × 5 mL). Drying of the organic phase over Na_2SO_4 and evaporation of the solvent under reduced pressure afforded the ester **9**, which was purified by distillation. According to this procedure the following compounds were prepared.

Methyl (±)-2-(2,4-dimethyl-5-oxocyclopentenyl)acetate (9a): yield 1.27 g (70%), colorless oil, bp 93−94 °C/80 Pa; ^{1}H NMR δ 1.09 (d, J = 7 Hz, 3H), 2.00 (s, 3H), 2.10−3.00 (m, 3H), 3.14 (s, 2H), 3.57 (s, 3H); ^{13}C NMR δ 16.27, 17.18, 28.29, 39.46, 40.92, 51.72, 132.5, 170.6, 171.4, 209.9. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.91; H, 7.74. Found: C, 65.63; H, 7.79.

Methyl (±)-2-(4-ethyl-2-methyl-5-oxocyclopentenyl)acetate (9b): yield 1.67 g (85%), colorless oil, bp 122−124 °C/80 Pa; ^{1}H NMR δ 0.84 (t, J = 7 Hz, 3H), 1.00−1.90 (m, 2H), 2.00 (s, 3H), 2.10−2.90 (m, 3H), 3.14 (s, 2H), 3.57 (s, 3H); ^{13}C NMR δ 11.18, 17.30, 24.40, 28.37, 38.44, 46.37, 51.86, 133.3, 170.8, 171.4, 209.6. Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.32; H, 8.23.

Methyl (±)-2-(2-methyl-5-oxo-4-propylcyclopentenyl)-acetate (9c): yield 1.79 g (85%), colorless oil, bp 98−100 °C/40 Pa; ^{1}H NMR δ 0.84 (t, J = 7 Hz, 3H), 1.00−1.90 (m, 4H), 2.00 (s, 3H), 2.15−3.05 (m, 3H), 3.14 (s, 2H), 3.58 (s, 3H); ^{13}C NMR δ 14.01, 17.30, 20.42, 28.37, 33.63, 39.00, 44.91, 51.86, 133.1, 170.8, 171.4, 209.8. Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.54; H, 8.63. Found: C, 68.92; H, 8.57.

Methyl (±)-(4-butyl-2-methyl-5-oxocyclopentenyl)acetate (9d): yield 1.82 g (81%), light-yellow oil, bp 149−151 °C/93 Pa; ^{1}H NMR δ 0.84 (m, 3H), 0.97−1.91 (m, 6H), 2.01 (s, 3H), 2.18−3.00 (m, 3H), 3.16 (s, 2H), 3.59 (s, 3H); ^{13}C NMR δ 13.93, 17.34, 22.72, 28.40, 29.43, 31.19, 39.02, 45.12, 51.89, 133.1, 170.8, 171.4, 209.9. Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.99. Found: C, 69.28; H, 8.59.

Methyl (±)-2-(2-methyl-5-oxo-4-pentylcyclopentenyl)-acetate (9e): yield 1.98 g (83%), light-yellow oil, bp 127−129 °C/53 Pa; ^{1}H NMR δ 0.81 (m, 3H), 1.00−1.92 (m, 8H), 2.00 (s, 3H), 2.15−2.95 (m, 3H), 3.14 (s, 2H), 3.57 (s, 3H); ^{13}C NMR δ 13.97, 17.30, 22.52, 26.89, 28.41, 31.46, 31.94, 39.07, 45.14, 51.86, 133.2, 170.8, 171.3, 209.8. Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.56; H, 9.30. Found: C, 70.59; H, 9.20.

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Supporting Information Available: ORTEP diagrams for the dicyclohexylammonium salts of **5b** and **7b** (3 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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