Regiocontrolled Formation of 4,5-Dihydro-3(2*H*)-furanones from 2-Butyne-1,4-diol Derivatives. Synthesis of Bullatenone and Geiparvarin

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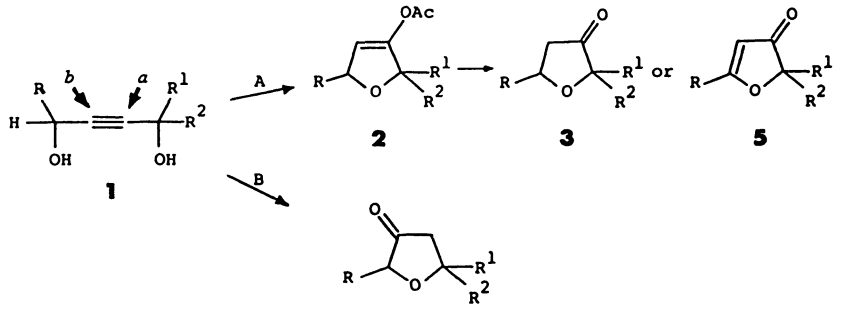
Two new methods for selective hydration of 1,1,4-trisubstituted 2-butyne-1,4-diols (**1**) to give 4,5-dihydro-3(2*H*)-furanone derivatives are reported. The first involves selective monoacetylation of the less hindered hydroxyl group of **1** followed by Ag(I)-catalyzed rearrangement and cyclization to give 3-acetoxy-2,2,5-trisubstituted 2,5-dihydrofurans (**2**). Final hydrolysis yielded 2,2,5-trisubstituted 4,5-dihydro-3(2*H*)-furanones. Oxidation of the enol acetates **2** with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone gave 3(2*H*)-furanones. The new method was applied to the synthesis of naturally occurring 3(2*H*)-furanones such as bullatenone and geiparvarin from the corresponding 2-butyne-1,4-diol derivatives. The second approach is concerned with the synthesis of the opposite regioisomer, 2,5,5-trisubstituted 4,5-dihydro-3(2*H*)-furanones, from diols **1** with a polymer reagent Hg/Nafion-H.

In extension of our efforts in regio- and stereoselective cyclopentannulation starting with 2-butyne-1,4-diol derivatives,[1] we have found that the acetylenic diols provide excellent means of regiocontrolled construction of 3(2*H*)-furanone skeleton.[2] Compounds of this type are important in view of their distribution in nature,[3] cytotoxic and antitumor actions,[4] and versatility as synthetic intermediates[5,6] in the synthesis of muscarine alkaloids,[7] for example. The furanones are valued by perfumers,[8] pharmacologists,[7] and the food and beverage industries.[9] The 3-hydroxyfurans have been investigated with theoretical interest[10] in keto-enol tautomerism. Among the methods for the construction of the 3(2*H*)-furanone ring, the transformation of 2-butyne-1,4-diol derivatives into 4,5-dihydro-3(2*H*)-furanones is most promising in a practical sense because of the simple synthetic pathway.[11] Though well-established for symmetrical 2-butyne-1,4-diols, this process has not been used for the synthesis of furanone derivatives in general, due mainly to the lack of the regiocontrol in the hydration of the carbon-carbon triple bond.[12,13] Many naturally occurring 3-furanones possess the 2,2,5-trisubstituted 3(2*H*)-furanone ring-system,[3] which is not readily accessible by previous methods.[11,12] Selective hydration at the position *a* (or *b*) in the formula **1** is, therefore, important in respect of regiocontrolled construction of the 3(2*H*)-furanone skeleton.

We have found that introduction of an oxygen function at the position *a* of the triple bond of **1** to give **3** is achieved by method A (Scheme 1) with complete regioselectivity. This involves selective monoacetylation of unsymmetrical 2-butyne-1,4-diols **1** followed by Ag(I)-catalyzed cyclization with acetoxyl migration to give enol acetates **2**, whose hydrolysis yields 2,2,5-trisubstituted 4,5-dihydro-3(2*H*)-furanones (**3**). In contrast, the opposite regioisomer **4** of the dihydrofuranones was prepared directly from the diol **1** by treatment with a polymer reagent Hg/Nafion-H[14] (method B). Details are reported herein.[15]

*Transformation of Diols **1** into 4,5-Dihydro-3(2H)-furanones of Type **3** (Method A).* Unsymmetrically substituted 2-butyne-1,4-diols (**1**) were prepared from corresponding carbonyl compounds and propargyl alcohol derivatives. Treatment of **1** with acetic anhydride and pyridine at 25 °C resulted in acetylation of the less hindered hydroxyl group. The intermediates **1** were not necessarily isolated and were subjected directly to the monoacetylation; especially effective for **6f** and **6g**.

The monoacetates **6** were then treated with 5 mol% of silver perchlorate (or silver tetrafluoroborate) in refluxing benzene in the dark to give the enol acetates **2**[16] in good yields. Results are summarized in Table 1. The transformation can be explained by assuming Ag(I)-catalyzed isomerization[17] of the monoacetates **6** to allenyl acetates **7** followed by Ag(I)-assisted cyclization[18] (Scheme 2). The selective introduction of an



Scheme 1.

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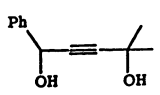
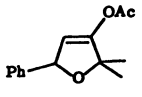
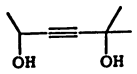
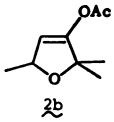
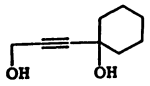
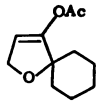
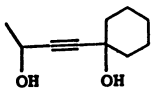
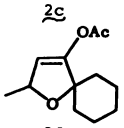
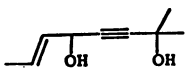
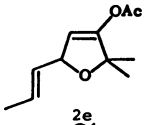
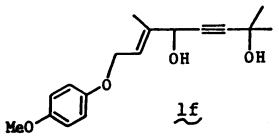
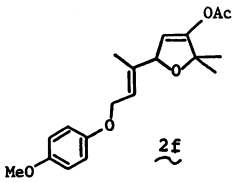
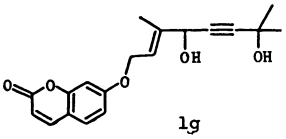
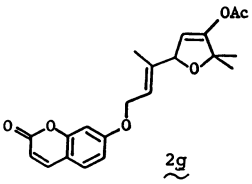
TABLE 1. Ag(I)-CATALYZED SYNTHESIS OF DIHYDRO-3(2*H*)-FURANONE ENOL ACETATES **2**[a)]

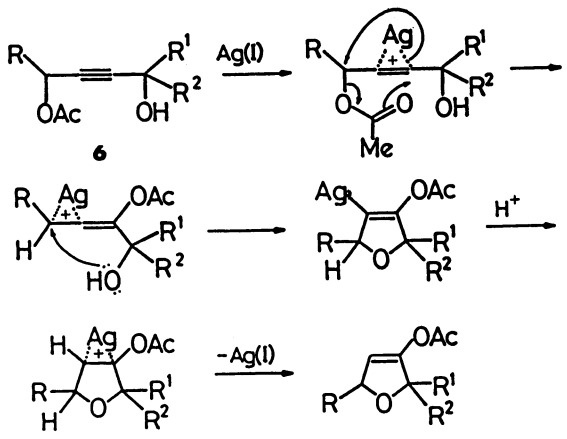
2-Butyne-1,4-diol derivative **1**	Yield[b)]/% of monoacetate **6**	Yield[b)]/% of dihydro-3(2*H*)-furanone enol acetate **2**
 **1a**	99	 **2a** 83
 **1b**	>99	 **2b** 99
 **1c**	>99	 **2c** 63[c)]
 **1d**	>99	 **2d** 80
 **1e**	90	 **2e** 74
 **1f**	81[d)]	 **2f** 63
 **1g**	86[d)]	 **2g** 61[d)]

a) The monoacetates **6** were treated with 5 mol% of silver perchlorate. b) Isolated yields. c) Silver tetrafluoroborate (10 mol%) was used. d) Overall yields from the corresponding aldehyde and 2-methyl-3-butyn-2-ol. e) Silver perchlorate (15 mol%) was employed.

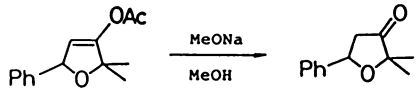
oxygen function at the position *a* is now achieved by this Ag(I)-mediated intramolecular rearrangement. Although this reaction was monitored very carefully, the allenyl acetates **7** were never isolated. It is worthy to note that the carbon-carbon double bond in the substrate **1** was not affected (Table 1, compounds **2e**, **2f**, and **2g**) and the olefinic configuration was completely retained through the reaction.

Finally, the enol acetate **2** was converted into the 4,5-dihydro-3(2*H*)-furanone **3** by treatment with sodium methoxide in methanol at r.t. (Scheme 3).

Oxidation of the Enol Acetates 2 to 3(2H)-Furanones 5. Application to a Practical Synthesis of Bullatenone (5a) and Geiparvarin (5g). The attempted transformation of **2** into the corresponding 3(2*H*)-furanones **5** involves the bromination dehydrobromination process (Scheme 3). Molecular bromine was allowed to react with the enol acetates **2** and the resulting bromodihydrofuranones **8** were treated with Li_2CO_3 (and LiCl) in *N*,*N*-dimethylformamide (DMF) or hexamethylphosphoric triamide (HMPA) to give **5**. Although this transformation was effective for **5a** and **5e**, the yield of **5f** was disappointedly low.



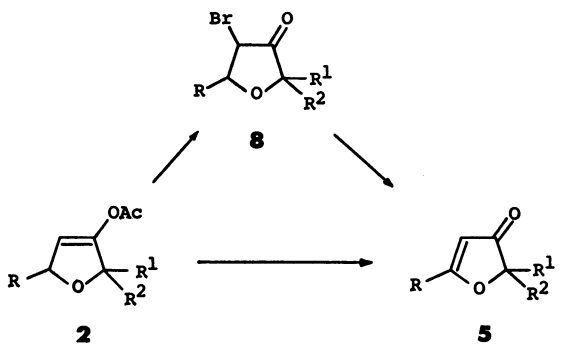
Scheme 2.



Scheme 3.

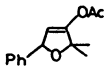
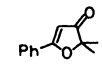
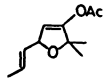
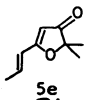
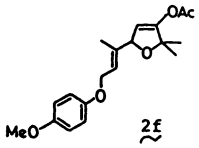
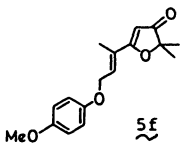
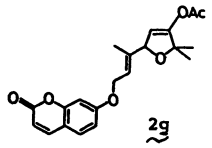
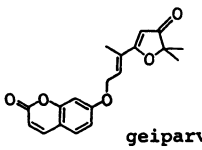
The use of 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) very much improved the oxidation step. Treatment of **2** with DDQ in benzene at 25 °C for several hours afforded **5** quantitatively (Table 2). The present transformation of the diols **1** into 3-furanones of type **3** and **5** should hold considerable promise as a general synthetic method.

Thus, the combined process allowed us to synthesize bullatenone (**5a**),[19)] a naturally occurring 3(2*H*)-



Scheme 4.

Table 2. Isolated yields (%) of 3(2*H*)-furanones **5**

Enol acetate **2**	3(2*H*)-Furanone **5**	Oxidation with DDQ[a]	Bromination and dehydromination[b]
 **2a**	 bullatenone **5a**	99	85
 **2e**	 **5e**	>99	66
 **2f**	 **5f**	>99	46
 **2g**	 geiparvarin **5g**	>99	

a) The enol acetates were treated with DDQ (1.2—1.9 equiv). b) See the experimental part for each transformation.

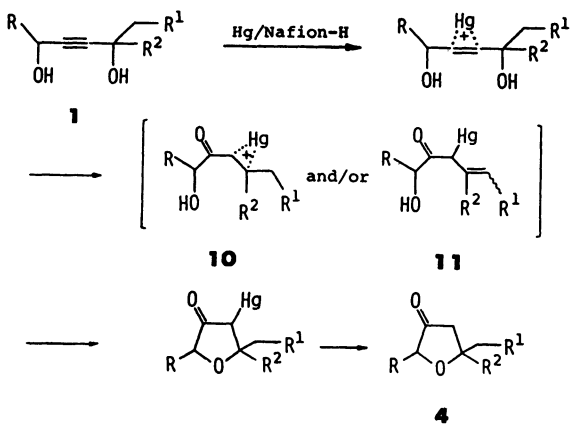
furanone isolated from blistered leaf myrtle (*Myrtus bllata*),[3b] a shrub endemic to New Zealand, in 81% overall yield from benzaldehyde. The dilithium salt of 2-methyl-3-butyn-2-ol was allowed to react with benzaldehyde in THF to give 4-methyl-1-phenyl-2-pentyne-1,4-diol (**1a**) (98% yield). The adduct **1a** was converted into the monoacetate **6a** (99% yield) which was then subjected to Ag(I)-catalyzed rearrangement and cyclization to yield the enol acetate **2a** (84% yield); finally oxidation of **2a** with DDQ afforded bullatenone **5a** in a quantitative yield.

Similarly, an antitumor 3(2*H*)-furanone, geiparvarin (**5g**)[3e-h] isolated from *Geijera parviflora*, was stereospecifically synthesized from (*E*)-4-(2-oxo-2*H*-chromen-7-yloxy)-2-methyl-2-butenal (**9**)[20] in 52% overall yield. Treatment of **9** with 2-methyl-3-butyn-2-ol dianion followed by acetylation gave the corresponding monoacetate **6g** (86% overall yield). The monoacetate **6g** was then treated with 15 mol% of silver perchlorate in refluxing benzene, giving rise to **2g** (61% yield), whose oxidation with DDQ yielded geiparvarin (**5g**) quantitatively. The spectral data (IR, ^{1}H-NMR) and mp were identical with those of the natural product.[3d-f] The absence of the (*Z*) isomer[9a,b] in the reaction product was ascertained by the ^{1}H-NMR spectra.

Hg/Nafion-H Catalyzed Transformation of Acetylenic Diols **1** *into 4,5-Dihydro-3(2H)-furanones of Type* **4** *(Method B).* In order to introduce an oxygen function at the position *b* in the formula **1** to obtain **4**, diols **1** were treated with the polymer reagent Hg/Nafion-H in the presence of 5 equiv of water in ethanol at 25 °C for several hours; results are summarized in Table 3. Apparently, introduction of the oxygen function into **1** takes place at the acetylenic carbon of less steric hindrance.[21] Although the selectivity in **1a**, **1b**, and **1d** (secondary *vs.* tertiary hydroxyl) was moderate (4 : 1 to 1 : 1), the preference of the primary hydroxyl group over the tertiary one was excellent. This is exemplified in the reaction of **1c** and **1i—n**.

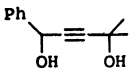
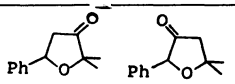
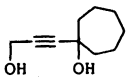
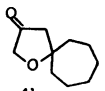
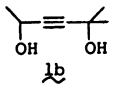
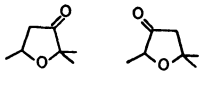
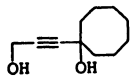
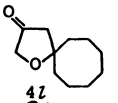
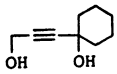
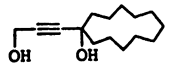
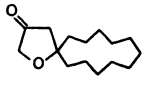
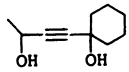
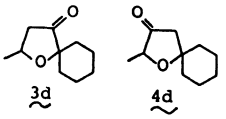
In order to gain an insight into the reaction mechanism, the propargyl alcohol adducts of 2-methylcyclohexanone were prepared. Cyclization of the 3 : 2 mixture of the diastereomers[1] **1j** and **1j'** gave the dihydro-3(2*H*)-furanones **4j** and **4j'** as a 40 : 60 diastereomeric mixture. The separately isolated **1j** or **1j'** also produced a 48 : 52 or 45 : 55 mixture of **4j** and **4j'**; the ratio being very similar irrespective of the stereochemistry of the diol (**1j** or **1j'**). The hypothetical mechanism of Scheme 5 explains the results. The Hg(II)-catalyzed hydration and elimination of the hydroxyl group lead to **10** and/or **11** and final cyclization produces the desired dihydro-3(2*H*)-furanones **4**.

Although the Hg/Nafion-H catalyzed formation of **4** is extremely efficient, a side reaction sometimes competes with the transformation of **1m**[22] into **4m** particularly.



Scheme 5.

TABLE 3. Hg/NAFION-H CATALYZED DIHYDRO-3(2*H*)-FURANONE SYNTHESIS

Entry	Diol	Yield/% of dihydro-3(2*H*)-furanone[a]	3 : 4	Entry	Diol	Yield/% of dih-ydro-3(2*H*)-furanone[a]
1	 1a	 3a 4a	70[b] 1 : 4	10	 1k	 4k 62[d]
2	 1b	 3b 4b	80 1 : 2	11	 1l	 4l 50[e]
3	 1c	 4c 62		12	 1m	 4m 68[f]
4	 1d	 3d 4d	70 1 : 1–2	13	1m	4m 66[g]
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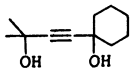
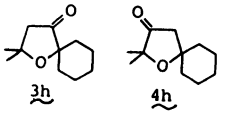
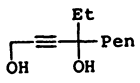
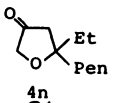
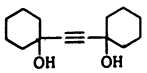
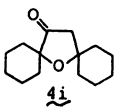
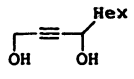
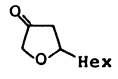
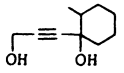
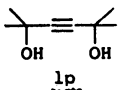
5	 1h	 3h 4h	95 1 : 2	15	 1n	 4n 59[i]
6	 1i	 4i 90		16	 1o	 4o 43[j]
7	 1j + 1j'	 4j + 4j' 78 40 : 60[c]		17	 1p	 4p 90[k]
8	1j	4j + 4j' 63 48 : 52[c]				
9	1j'	4j + 4j' 82 45 : 55[c]				

a) Isolated yields refer to fully characterized compounds produced from the diols **1** on treatment with Hg/Nafion-H. b) (*E*)-4-Hydroxy-4-methyl-1-phenyl-1-penten-3-one (**12a**) was produced (11% yield) as a by-product. c) The diastereomeric ratio of **4j** to **4j'**. d) The transformation was carried out at 60 °C in a 1 : 1 mixture of hexane–ethanol. 3-Cycloheptylidene-1-hydroxy-2-propanone (**12k**) was produced (13% yield) along with **4k**. e) A by-product, 3-cyclooctylidene-1-hydroxy-2-propanone (**12l**) was formed in 23% yield. f) 3-Cyclododecylidene 1-hydroxy-2-propanone (**12m**) was produced (10% yield) along with **4m**. g) The reaction was carried out at 50 °C, **12m** being produced in 3% yield. h) The transformation was carried out at 0—10 °C. The yield of **12m** was 22% i) 4-Ethyl-1-hydroxy-3-nonen-2-one (**12n**) was formed(30% yield) as a by-product. *j*) 1-Ethoxy-4-hydroxy-3-decanone (**12o**) was produced (15% yield) along with **4o**. k) Using the recoverd polymer regent, **1p** was converted into **4p** in 82% yield.

A by-product, 3-cyclododecylidene-1-hydroxy-2-propanone (**12m**), was produced in 10% yield which was slowly converted into **4m** under the reaction conditions. Formation of **12m** was temperature-dependent; at 50 °C only 3%; at 0—10 °C as much as 22% yield, whereas the yield of **4m** remained almost constant. In any event, the procedure is applicable to the synthesis of dihydrofuranones of type **4**.

As is usual with polymer reagent, the experimental procedure for Hg/Nafion-H mediated transformation is very simple. Workup involves only removal of the catalyst by filtration and concentration of the filtrates. The polymer reagent could be recovered easily by washing with dichloromethane and drying, and reused: For example, the diol **1p** was converted into **4p** repeatedly (first run, 90% yield, and second run with the recovered reagent, 82% yield). The present Hg/Nafion-H catalyzed transformation proceeded under milder conditions (25 °C) with higher selectivity than the previous methods.[11,12] Whereas the diol **1b** gives a 1 : 1 mixture of 3-furanones **3b** and **4b** with a conventional catalyst, HgO,[12d] in ether-aqueous sulfuric acid, the transformation with Hg/Nafion-H preferred **4b** formation (**3b** : **4b** 1 : 2).

Experimental

Distillation was carried out by use of Kugelrohr (Büchi) and boiling points were determined by measuring the bath temperature. All mp and bp are not corrected. ^{1}H-NMR spectra (tetramethylsilane as an internal standard) were obtained on a Varian EM 390 spectrometer, chemical shifts being given in ppm units, IR spectra of neat liquid film samples (unless otherwise noted) on a Shimadzu IR-27G spectrometer, MS on a Hitachi RMU-6L spectrometer, and exact mass on a Hitachi M 80 spectrometer. Gas-liquid phase chromatography (GLC) analyses were performed with a Yanagimoto

GCG-550F chromatograph, and preparative GLC with a JEOL-JGC-20K chromatograph. Preparative TLC plates (20 cm × 20 cm) were prepared with Merck Kiesel-gel PF_{254}. Column chromatography was carried out with silica gel (Wakogel C-100) at atmospheric pressure. Propargyl alcohol and 2-methyl-3-butyn-2-ol were distilled before use. 3-Butyn-2-ol (Tokyo Kasei-Kogyo Co. or Nakarai Chemicals Ltd., 55% aqueous solution) was used.

*Preparation of 4-Methyl-1-phenyl-2-pentyne-1,4-diol (**1a**) (A Typical Procedure).* A hexane solution of butyllithium (1.53 M,† 19.6 ml, 30.0 mmol) was added at −78 °C under an argon atmosphere to a THF (150 ml) solution of 2-methyl-3-butyn-2-ol (1.26 g, 15.0 mmol). The reaction mixture was stirred for 2 h at −78 °C. To this solution a THF (4 ml) solution of benzaldehyde (1.06 g, 10.0 mmol) was added at −65 °C. The whole was stirred for 6 h and allowed to warm to 25 °C. The resulting solution was then poured into water (50 ml) and extracted with ethyl acetate. The extracts were dried with anhydrous sodium sulfate and concentrated to yield a crude product. Purification of the residue by column chromatography (hexane–ethyl acetate 1 : 1) gave the diol **1a**[19a] (1.87 g, 98% yield) having ^{1}H-NMR (CCl_4): δ=1.43 (s, 6H), 4.13 (br s, 1H), 5.34 (s, 1H), 7.1—7.6 (m, 5H); IR (CCl_4): 3330, 1162, 942 cm^{-1}; MS: *m/e* 190 (M^+).

In general, experiments of no less than 10 mmol scale are preferable in order to secure high yields of the adducts **1**. This procedure applies to the synthesis of **1b**, **1c**, **1e**, **1h**, **1i**, **1k**, **1l**, **1n**, and **1o**. The yields and spectral properties are summarized below.

*2-Methyl-3-hexyne-2,5-diol (**1b**).*[23] Yield 95%. Bp 132—140 °C (bath temp)/3.0 Torr;** ^{1}H-NMR (CCl_4): δ=1.41 (d, J=6.8 Hz, 3H), 1.49 (s, 6H), 4.4—4.7 (m, 3H); IR: 3320, 1165 cm^{-1}; MS: *m/e* 113 (M^+-CH_3).

*1-(3-Hydroxy-1-propynyl)cyclohexanol (**1c**).*[24] Yield 88%. ^{1}H-NMR (CCl_4): δ=1.0—2.2 (m, 10H), 4.33 (s, 2H), 4.56 (br s, 2H); IR: 3330, 1073 cm^{-1}; MS: *m/e* 154 (M^+).

*2-Methyl-6-octen-3-yne-2,5-diol (**1e**).*[25] Yield 90%. ^{1}H-NMR (CCl_4): δ=1.49 (s, 6H), 1.74 (d, J=6.0 Hz, 3H), 4.28 br s, 2H), 4.79 (d, J=5.3 Hz, 1H), 5.57 (dd, J=15.2, 5.3 Hz, 1H), 5.78 (dq, J=15.2, 6.0 Hz, 1H); IR: 3340, 1164, 963, 944 cm^{-1}; MS: *m/e* 139 (M^+-CH_3).

*1-(3-Hydroxy-3-methyl-1-butynyl)cyclohexanol (**1h**).*[5a,26] Yield 84%. Mp 95.0—96.0 °C (methanol); ^{1}H-NMR (CCl_4): δ=1.0—2.1 (m+s (δ=1.53), 16H), 4.10 (br s, 2H); IR (Nujol): 3250, 1460, 1080, 950 cm^{-1}; MS: *m/e* 182 (M^+).

*Bis(1-hydroxycyclohexyl)acetylene (**1i**).*[27] This product was prepared from cyclohexanone and 1-ethynylcyclohexanol (51% yield, 99% yield based on consumed 1-ethynylcyclohexanol). ^{1}H-NMR ($CDCl_3$): δ=0.9—2.2 (m, 20H), 2.27 (br s, 2H); IR (Nujol): 3350, 1070 cm^{-1}; MS: *m/e* 222 (M^+).

*1-(3-Hydroxy-1-propynyl)cycloheptanol (**1k**).* Yield 79%. Bp 131—132 °C (bath temp)/0.15 Torr; ^{1}H-NMR (CCl_4): δ=1.2—2.2 (m, 12H), 4.27 (br s, 2H), 4.37 (s, 2H); IR: 3340, 1461, 1445, 1026 cm^{-1}; MS: *m/e* (rel intensity) 168 (M^+, 4), 150(11), 111(71), 65(75), 55(100), 40(93). Found: C, 71.15; H, 9.80%. Calcd for $C_{10}H_{16}O_2$: C, 71.39; H, 9.59%.

*1-(3-Hydroxy-1-propynyl)cyclooctanol (**1l**).* Yield 54%. Bp 153—154 °C (bath temp)/0.10 Torr; ^{1}H-NMR ($CDCl_3$): δ=1.1—2.1 (m, 14H), 4.26 (s, 2H), 4.46 (br s, 2H); IR: 3340, 1447, 1040, 1014 cm^{-1}; MS: *m/e* (rel intensity) 182 (M^+, trace), 164(7), 111(46), 93(48), 79(50), 65(57), 55(100), 41(99). Found: *m/e* 164.1226. Calcd for $C_{11}H_{16}O$: M^+-H_2O, 164.1201

*4-Ethyl-2-nonyne-1,4-diol (**1n**).* Yield 81%. Bp 109—110 °C (bath temp)/0.13 Torr; ^{1}H-NMR (CCl_4): δ=0.9—2.0 (m+t (δ=0.97, J=6.6 Hz)+t (δ=1.01, J=7.5 Hz), 16H), 3.30 (br s, 1H), 3.55 (br s, 1H), 4.26 (s, 2H); IR: 3350, 1465, 1011 cm^{-1}; MS: *m/e* (rel intensity) 155 ($M^+-C_2H_5$, 37), 113 (100), 67 (89), 43 (82). Found: C, 71.67; H, 11.13%. Calcd for $C_{11}H_{20}O_2$: C, 71.70; H, 10.94%.

*2-Decyne-1,4-diol (**1o**).*[28] Yield 77%. ^{1}H-NMR (CCl_4): δ=0.7—1.9 (m, 13H), 4.1—4.8 (m, 5H); IR: 3310, 1017 cm^{-1}; MS: *m/e* 170 (M^+).

*1-(3-Hydroxy-1-butynyl)cyclohexanol (**1d**).* Potassium hydroxide (3.36 g, 60.0 mmol) was dissolved in a 55% aqueous solution of 3-butyn-2-ol (2.86 g, 22.5 mmol) and the resulting mixture was stirred at 40 °C for 10 min. To this solution cyclohexanone (1.47 g, 15.0 mmol) dissolved in THF (3 ml) was added drop by drop during 2 h at 25 °C. The whole was stirred for 26 h at 40 °C, then diluted with ether (20 ml) and cold water (10 ml). Extractive workup with ether gave an oil (3.05 g). Purification of the crude adduct by column chromatography (hexane–ethyl acetate 2 : 1 to 1 : 1) afforded the diol **1d**[23] (2.27 g, 90% yield). ^{1}H-NMR (CCl_4): δ=1.0—2.1 (m+d (δ=1.43, J=6.9 Hz), 13H), 4.01 (br s, 2H), 4.53 (q, J=6.9 Hz, 1H); IR: 3330, 1072 cm^{-1}; MS: *m/e* 168 (M^+).

*Transformation of the Diols **1** into the Enol Acetates **2**.*

*Preparation of 3-Acetoxy-2,2-dimethyl-5-phenyl-2,5-dihydrofuran (**2a**) (A Typical Procedure):* A dichloromethane (0.25 ml) solution of **1a** (0.21 g, 1.1 mmol) was treated with acetic anhydride (0.5 ml) and pyridine (0.05 ml) at 25 °C. As soon as the starting diol was consumed (1.5 h), all the volatile materials were evaporated. Purification of the residue by column chromatography (hexane–ethyl acetate 10 : 1 to 2 : 1) gave 5-acetoxy-2-methyl-5-phenyl-3-pentyn-2-ol (**6a**) (0.25 g, 99% yield) having ^{1}H-NMR (CCl_4): δ=1.51 (s, 6H), 2.03 (s, 3H), 2.96 (br s, 1H), 6.41 (s, 1H), 7.2—7.6 (m, 5H); IR: 3400, 1740, 1220 cm^{-1}; MS: *m/e* (rel intensity) 232 (M^+, trace), 190 (4), 189(4), 172(33), 129(31), 43(100).

A benzene (1 ml) solution of **6a** (77 mg, 0.33 mmol) was heated at 80 °C in the presence of silver perchlorate (4 mg, *ca.* 5 mol%) for 10 h in the dark under an argon atmosphere. The reaction mixture was then diluted with dichloromethane (10 ml) at 25 °C and washed with 10% aqueous ammonia (3 ml) and sat. aqueous sodium chloride solution (3 ml). Concentration of the organic phase gave the crude product which was purified by column chromatography (hexane–ethyl acetate 10 : 1) to afford **2a** (65 mg, 84% yield). Bp 122—124 °C (bath temp)/ 0.04 Torr; ^{1}H-NMR (CCl_4): δ=1.36 (s, 3H), 1.38 (s, 3H), 2.17 (s, 3H), 5.70 (d, J=1.5 Hz, 1H), 5.81 (d, J=1.5 Hz, 1H), 7.26 (br s, 5H); IR: 1781, 1698, 1658, 1207, 1193, 1050 cm^{-1}; MS: *m/e* (rel intensity) 232 (M^+, 2), 217(2), 190(34), 189(19), 105(41), 102(27), 77(32), 43(100). Found: C, 72.48; H, 6.84%. Calcd for $C_{14}H_{16}O_3$: C, 72.39; H, 6.94%.

This procedure applies to the synthesis of **6b—e**, **2b**, and **2d—g**, whose physical properties are summarized below.

*5-Acetoxy-2-methyl-3-hexyn-2-ol (**6b**) and 3-Acetoxy-2,2,5-trimethyl-2,5-dihydrofuran (**2b**):* The monoacetate **6b** showed ^{1}H-NMR (CCl_4): δ=1.43 (d, J=6.8 Hz, 3H), 1.44 (s, 6H), 2.01 (s, 3H), 2.66 (br s, 1H), 5.33 (q, J=6.8 Hz, 1H); IR: 3425, 1740, 1230 cm^{-1}; MS: *m/e* (rel intensity) 196 (M^+, trace), 144(3), 118(7), 99(20), 84(39), 56 (28), 43(100). The Bp of **2b**: 101—102 °C (bath temp)/18 Torr; ^{1}H-NMR (CCl_4): δ=1.22 (s, 3H), 1.23 (d, J=6.0 Hz, 3H), 1.27 (s, 3H), 2.14 (s, 3H), 4.83 (dq, J=1.7, 6.0 Hz, 1H), 5.66 (d, J=1.7 Hz, 1H); IR: 1782, 1760, 1660, 1204, 1033 cm^{-1}; MS: *m/e* (rel intensity) 170 (M^+, trace), 155(6), 128(9), 126(13), 113(30), 68(23), 43(1000). Found: C, 63.62; H, 8.46%. Calcd for $C_9H_{14}O_3$: C, 63.51; H, 8.29%.

*1-(3-Acetoxy-1-propynyl)cyclohexanol (**6c**) and 4-Acetoxy-1-oxaspiro[4.5]dec-3-ene (**2c**):* ^{1}H-NMR (CCl_4) of **6c**: δ=1.0—2.0 (m, 10H), 2.06 (s, 3H), 2.30 (br s, 1H), 4.64 (s, 2H); IR:

† 1 M=1 mol dm^{-3}.

** 1 Torr=133.322 Pa.

3420, 1747, 1229 cm^{-1}; MS: *m/e* (rel intensity) 196 (M^+, 1), 154(19), 153(22), 139(48), 111(52), 43(100). Silver tetrafluoroborate (10 mol%) was used instead of silver perchlorate for the transformation of **6c** into **2c** having bp 122—125 °C (bath temp)/0.04 Torr; ^{1}H-NMR (CCl_4): δ=1.4—1.9 (m, 10H), 2.13 (s, 3H), 4.54 (d, J=1.7 Hz, 5.73 (t, J=1.7 Hz, 1H); IR: 1780, 1757 (sh), 1658, 1194 cm^{-1}; MS: *m/e* (rel intensity) 196 (M^+, 3), 168(8), 153(12), 111(28). 97(17), 81(12), 69(13), 55(27), 43(100). Found: C, 67.60; H, 8.33%. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22%.

*1-(3-Acetoxy-1-butynyl)cyclohexanol (**6d**) and 4-Acetoxy-2-methyl-1-oxaspiro[4.5]dec-3-ene (**2d**)*: The monoacetate **6d** showed ^{1}H-NMR (CCl_4): δ=1.1—2.0 (m+d (δ=1.45, J=6.9 Hz), 14H), 2.03 (s, 3H), 5.41 (q, J=6.9 Hz, 1H); IR: 3425, 1740, 1235 cm^{-1}; MS: *m/e* (rel intensity) 168 ($M^+-C_2H_2O$, 15), 107(30), 80(58), 43(100). The bp of **2d**: 92 °C (bath temp)/0.05 Torr; ^{1}H-NMR (CCl_4): δ=1.22 (d, J=6.3 Hz, 3H), 1.2—1.9 (m, 10H), 2.10 (s, 3H), 4.73 (dq, J=1.5, 6.3 Hz, 1H), 5.60 (d, J=1.5 Hz, 1H); IR: 1784, 1758, 1659, 1198 cm^{-1}; MS: *m/e* (rel intensity) 210 (M^+, 4), 168(16), 153(24), 125(42), 111(51), 69(22), 55(25), 43(100). Found: C, 68.37;H, 8.87%. Calcd for $C_{12}H_{18}O_3$: C, 68.54; H, 8.63%.

*5-Acetoxy-2-methyl-6-octen-3-yn-2-ol (**6e**) and 3-Acetoxy-2,2-dimethyl-5-[(E)-1-propenyl]-2,5-dihydrofuran (**2e**)*: ^{1}H-NMR (CCl_4) of **6e**: δ=1.48 (s, 6H), 1.77 (d, J=6.8 Hz, 3H), 2.04 (s, 3H), 2.17 (br s, 1H), 5.66 (dd, J=15.3, 6.5 Hz, 1H), 5.84 (d, J=6.5 Hz, 1H), 6.03 (dq, J=15.3, 6.8 Hz, 1H); IR: 3430, 1738, 1224 cm^{-1}; MS: *m/e* (rel intensity) 196 (M^+, trace), 136(39), 121(47), 77(45), 43(100). The enol acetate **2e** showed bp 117—118 °C (bath temp)/0.04 Torr; ^{1}H-NMR (CCl_4): δ=1.25 (s, 3H), 1.28 (s, 3H), 1.69 (d, J=5.3 Hz, 3H), 2.14 (s, 3H), 5.02 (dd, J=1.5, 5.9 Hz, 1H), 5.52 (dd, J=5.9, 15.0 Hz, 1H), 5.61 (d, J=1.5 Hz, 1H), 5.62 (dq, J=15.0, 5.3 Hz, 1H); IR: 1781, 1761 (sh), 1656, 1200, 1041, 963 cm^{-1}; MS: *m/e* (rel intensity) 154 (M^+, 30), 139(42), 113(12), 111(18) 69(26), 43(100). Found: C, 67.40; H, 8.42%. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22%.

*Preparation of (E)-5-Acetoxy-2,6-dimethyl-8-(4-methoxyphenoxy)-6-octen-3-yn-2-ol (**6f**)*: Under an argon atmosphere a THF (8 ml) solution of 4-methoxyphenol (**13**) (1.30 g, 10.5 mmol) was added to sodium hydride (50% in oil, 0.50 g, 10.5 mmol) in THF (15 ml) at 25 °C in 10 min. After stirring for 30 min ethyl 4-bromotiglate (2.07 g, 10.0 mmol) dissolved in THF (3 ml) was added to the reaction mixture . The whole was stirred for 4.5 h at reflux temperature. Workup followed by column chromatography (hexane–ethyl acetate 5 : 1 to 2 : 1) gave ethyl (*E*)-4-(4-methoxyphenoxy)-2-methyl-2-butenoate (**14**) (1.61 g, 51% yield; 97% yield based on the consumed phenol **13**). ^{1}H-NMR (CCl_4): δ=1.30 (t, J=7.2 Hz, 3H), 1.88 (s, 3H), 3.74 (s, 3H), 4.20 (q, J=7.2 Hz, 2H), 4.62 (d, J=6.2 Hz, 2H), 6.7—7.0 (m, 5H); IR: 1712, 1658, 1593, 1510, 1233, 1134, 1039, 826 cm^{-1}; MS: *m/e* (rel intensity) 250 (M^+, 18), 177(9), 133(9), 124(100), 123(71), 109(26), 99(18), 95(13), 43(24). Found: *m/e* 250.1219. Calcd for $C_{14}H_{18}O_4$: M^+, 250.1205.

An ether (10 ml) solution of **14** (1.28 g, 5.1 mmol) was added at 0 °C to an ether (20 ml) suspension of lithium aluminum hydride (0.18 g, 4.6 mmol). After stirring for 5 min at 0 °C, extractive workup gave (*E*)-4-(4-methoxyphenoxy)-2-methyl-2-buten-1-ol (**15**) (0.90 g, 85% yield) having ^{1}H-NMR ($CDCl_3$): δ=1.73 (s, 3H), 3.67 (br s, 1H), 3.75 (s, 3H), 4.05 (s, 2H), 4.50 (d, J=7.2 Hz, 2H), 5.75 (t, J=7.2 Hz, 1H), 6.80 (s, 4H).

A dichloromethane (10 ml) solution of the crude alcohol **15** (0.86 g, 4.1 mmol) was added to pyridinium chlorochoromate (1.34 g, 6.2 mmol) and sodium acetate (0.10 g, 1.2 mmol) in dichloromethane (10 ml) at 0 °C. The reaction mixture was stirred for 2 h at 0—25 °C, and then diluted with ether (50 ml). The resulting solution was filtered through silica gel and celite. Concentration of the filtrate gave (*E*)-4-(4-methoxyphenoxy)-2-methyl-2-butenal (**16**) (0.58 g, 70% yield), ^{1}H-NMR (CCl_4): δ=1.82 (s, 3H), 3.77 (s, 3H), 4.81 (d, J=3.6 Hz, 2H), 6.65 (t, J=3.6 Hz, 1H), 6.82 (s, 4H), 9.54 (s, 1H). The crude aldehyde **16** was subjected to the next transformation without further purification.

A hexane solution of butyllithium (1.57 M, 5.3 ml, 8.3 mmol) was added at −78 °C to 2-methyl-3-butyn-2-ol (0.35 g, 4.2 mmol) in THF (55 ml). The mixture was stirred for 2 h. To this solution was added a THF (5 ml) solution of **16** (0.57 g, 2.8 mmol) at −50 °C. The resulting solution was stirred for 4 h and allowed to warm to 25 °C. Water (30 ml) and ethyl acetate (30 ml) were then added. Extraction with ethyl acetate and concentration of the extracts gave (*E*)-2,6-dimethyl-8-(4-methoxyphenoxy)-6-octen-3-yne-2,5-diol (**1f**) (0.82 g) having ^{1}H-NMR (CCl_4): δ=1.50 (s, 6H), 1.78 (s, 3H), 3.50 (br s, 2H), 3.70 (s, 3H), 4.46 (d, J=6.0 Hz, 2H), 4.70 (s, 1H), 5.84 (t, J=6.0 Hz, 1H), 6.71 (s, 4H).

The crude adduct **1f** (0.81 g, 2.8 mmol) in dichloromethane (0.5 ml) was treated with acetic anhydride (1.5 ml) and pyridine (0.15 ml) for 1.6 h at 25 °C. Purification of the concentrated residue (0.89 g) by column chromatography (hexane–ethyl acetate 5 : 1 to 2 : 1) gave **6f** (0.74 g, 81% yield from **16**). Bp 168—170 °C (bath temp)/0.05 Torr; ^{1}H-NMR (CCl_4): δ=1.48 (s, 6H), 1.79 (s, 3H), 2.06 (s, 3H), 2.66 (br s, 1H), 3.73 (s, 3H), 4.50 (d, J=6.0 Hz, 2H), 5.78 (s, 1H), 5.93 (t, J=6.0 Hz, 1H), 6.75 (s, 4H); IR: 3450, 1739, 1510, 1224, 1037, 1015 cm^{-1}; MS: *m/e* (rel intensity) 332 (M^+, 1), 314(1), 272(1), 191(6), 149(19), 124(57), 109(26), 43(100). Found: C, 68.93; H, 7.21%. Calcd for $C_{19}H_{24}O_5$: C, 68.65; H, 7.28%.

*3-Acetoxy-2,2-dimethyl-5-[(E)-3-(4-methoxyphenoxy)-1-methyl-1-propenyl]-2,5-dihydrofuran (**2f**)*: Bp 160—162 °C (bath temp)/0.05 Torr; ^{1}H-NMR (CCl_4): δ=1.27 (s, 3H), 1.30 (s, 3H), 1.67 (s, 3H), 2.15 (s, 3H), 3.71 (s, 3H), 4.49 (d, J=6.0 Hz, 2H), 5.11 (br s, 1H), 5.63 (d, J=1.5 Hz, 1H), 5.70 (t, J=6.0 Hz), 6.73 (s, 4H); IR: 1778, 1657, 1592, 1509, 1230, 1205, 1040, 1013 cm^{-1}; MS: *m/e* (rel intensity) 332 (M^+, 1), 209(6), 167(91), 124(100), 113(45), 78(97), 52(25), 43(72). Found: C, 68.80; H, 7.25%. Calcd for $C_{19}H_{24}O_5$: C, 68.65; H, 7.28%. The double bond in the appendage was supposed to have the (*E*) configuration on analogy of the results of **2e**, **2g**, and **5g**.

*(E)-5-Acetoxy-2,6-dimethyl-8-(2-oxo-2H-chromen-7-yloxy)-6-octen-3-yn-2-ol (**6g**)*: A hexane solution of butyllithium (1.67 M, 18.0 ml, 30.0 mmol) was added at −78 °C to 2-methyl-3-butyn-2-ol (1.3 g, 15.0 mmol) in THF (120 ml). After stirring for 3 h (*E*)-4-(2-oxo-2*H*-chromen-7-yloxy)-2-methyl-2-butenal (**9**)[20] (2.4 g, 10.0 mmol) dissolved in THF (5 ml) was added at −78 °C. The reaction mixture was stirred for 3 h, being warmed to −20 °C and treated with methanol (30 ml) and water (20 ml). Extractive workup gave the crude adduct **1g** (3.06 g), whose dichloromethane (3 ml) solution was stirred with acetic anhydride (1.9 ml) and pyridine (4.0 ml) for 3 h at 20 °C and then concentrated. Purification of the residue by column chromatography (hexane–ethyl acetate 1 : 1) gave **6g** (3.2 g, 86% yield from **9**). Bp 205—210 °C (bath temp)/0.02 Torr; ^{1}H-NMR ($CDCl_3$): δ=1.50 (s, 6H), 1.84 (s, 3H), 2.09 (s, 3H), 4.63 (d, J=6.0 Hz, 2H), 5.84 (s, 1H), 5.93 (t, J=6.0 Hz, 1H), 6.25 (d, J=9.3 Hz, 1H), 6.7—6.9 (m, 2H), 7.34 (d, J=5.8 Hz, 1H), 7.61 (d, J=9.3 Hz, 1H); IR: 3435, 1734, 1613, 1225, 1123 cm^{-1}. Found: C, 68.13; H, 6.03%. Calcd for $C_{21}H_{22}O_6$: C, 68.09; H, 5.99%.

*3-Acetoxy-5-[(E)-3-(2-oxo-2H-chromen-7-yloxy)-1-methyl-1-propenyl]-2,2-dimethyl-2,5-dihydrofuran (**2g**)*: Bp 180—183 °C

(bath temp)/0.05 Torr; ^{1}H-NMR ($CDCl_3$): δ=1.35 (s, 3H), 1.38 (s, 3H), 1.74 (s, 3H), 2.21 (s, 3H), 4.66 (d, J=6.0 Hz, 2H) 5.23 (br s, 1H), 5.69 (d, J=1.5 Hz, 1H), 5.83 (t, J=6.0 Hz, 1H), 6.25 (d, J=9.6 Hz, 1H), 6.8—7.0 (m, 2H), 7.3—7.5 (m, 1H), 7.68 (d, J=9.6 Hz, 1H); IR (CCl_4): 1780, 1745, 1615, 1196, 1121 cm^{-1}; MS: *m/e* (rel intensity) 370 (M^+, trace), 343 (1), 326(1), 167(15), 162(8), 59(23), 55(18), 43(100). Found: C, 68.29; H, 5.75%. Calcd for $C_{21}H_{22}O_6$: C, 68.09; H, 5.99%.

Transformation of **2a** *into 2,2-Dimethyl-5-phenyl-4,5-dihydro-3(2H)-furanone (***3a***).* The enol acetate **2a** (33 mg, 0.14 mmol) was treated with a methanol solution of sodium methoxide (0.01 M, 1 ml, 0.01 mmol) at 25 °C for 40 min. Workup followed by column chromatography (hexane–ethyl acetate 10 : 1) gave **3a**[13q,29] (25 mg, 90% yield). ^{1}H-NMR (CCl_4): δ=1.27 (s, 3H), 1.34 (s, 3H), 2.39 (dd, J=10.4, 18.0 Hz, 1H), 2.79 (dd, J=6.3, 18.0 Hz, 1H), 5.15 (dd, J=6.3, 10.4 Hz, 1H), 7.2—7.5 (m, 5H); IR: 1752, 1171, 1010, 693 cm^{-1}; MS: *m/e* 190 (M^+).

Oxidation of the Enol Acetates **2** *to 3(2H)-Furanones* **5**.

(1) Bromination-dehydrobromination of **2a** *(A Typical Procedure)*: A chloroform solution of bromine (0.5 M, 1.4 ml, 0.69 mmol) was added at −20 °C in 10 min to **2a** (0.16 g, 0.69 mmol) dissolved in chloroform (0.5 ml). The reaction mixture was stirred for 30 min and allowed to warm up to 25 °C. Concentration of the resulting solution afforded crude 4-bromo-2,2-dimethyl-5-phenyl-4,5-dihydro-3(2*H*)-furanone (**8a**) (*ca.* 0.19 g) having ^{1}H-NMR (CCl_4): δ=1.35 (s, 3H), 1.64 (s, 3H), 4.38 (d, J=3.6 Hz, 1H), 5.25 (d, J=3.6 Hz, 1H), 7.43 (s, 5H); IR: 1725, 1172, 1110 cm^{-1}.

The bromide **8a** (*ca.* 0.19 g) dissolved in DMF (1 ml) was treated with lithium carbonate (0.23 g, 3.5 mmol) at 120 °C for 40 min. Workup followed by column chromatography (hexane–ethyl acetate 10 : 1) gave bullatenone (**5a**) (0.11 g, 85% yield from **2a**). Mp 67.5—68.0 °C (hexane); ^{1}H-NMR (CCl_4): δ=1.43 (s, 6H), 5.89 (s, 1H), 7.3—7.6 (m, 3H), 7.7—7.9 (m, 2H); IR (CCl_4): 1702, 1608, 1594, 1568, 1162 cm^{-1}; MS: *m/e* (rel intensity) 188 (M^+, 22), 102 (100). The spectral data (IR, ^{1}H-NMR) and mp were identical with the recorded ones.[10f,10g,19]

*2,2-Dimethyl-5-[(E)-1-propenyl]-3(2H)-furanone (***5e***).* According to the method described above **2e** (0.31 g, 1.6 mmol) was transformed into the corresponding bromide which was treated with lithium chloride (0.20 g, 4.8 mmol) and lithium carbonate (0.35 g, 4.8 mmol) in HMPA (2 ml) at 80 °C for 11 h. Workup and purification by column chromatography (hexane–ethyl acetate 5 : 1) gave **5e** (0.16 g, 66% overall yield). Bp 120—122 °C (bath temp)/0.04 Torr; ^{1}H-NMR (CCl_4): δ=1.33 (s, 6H), 1.96 (d, J=6.8 Hz, 3H), 5.29 (s, 1H), 6.23 (d, J=15.8 Hz, 1H), 6.74 (dq, J=15.8, 6.8 Hz, 1H); IR: 1700, 1651, 1565, 1382, 1177, 984, 964 cm^{-1}; MS: *m/e* (rel intensity) 152 (M^+, 23), 137(8), 94(11), 66(100). Found: C, 71.32; H, 8.09%. Calcd for $C_9H_{12}O_2$: C, 71.02; H, 7.95%.

*2,2-Dimethyl-5-[(E)-3-(4-methoxyphenoxy)-1-methyl-1-propenyl]-3(2H)-furanone (***5f***).* According to the method for the transformation of **2e** into **5e**, the enol acetate **2f** was converted into **5f** (46% overall yield) having mp 77.5—78.0 °C (methanol); bp 165—168 °C (bath temp)/0.05 Torr; ^{1}H-NMR (CCl_4): δ 1.35 (s, 6H), 1.96 (s, 3H), 3.70 (s, 3H), 4.62 (d, J=6.0 Hz, 2H), 5.43 (s, 1H), 6.66 (t, J=6.0 Hz, 1H), 6.70 (s, 4H); IR (CCl_4): 1702, 1564, 1509, 1226, 1181, 1041 cm^{-1}; MS: *m/e* (rel intensity) 288 (M^+, 5), 200(9), 151(11), 124(18), 109(18), 79(45), 40(100). Found: C, 70.70; H, 7.09%. Calcd for $C_{17}H_{20}O_4$: C, 70.81; H, 6.99%. The double bond in the appendage was supposed to have the (*E*) configuration by comparison with the results of **5e** and **5g**.

(2) Oxidation of the Enol Acetate **2a** *with DDQ (A Typical Procedure)*: The enol acetate **2a** (0.11 g, 0.49 mmol) was treated with DDQ (0.16 g, 0.71 mmol) in benzene (1 ml) at 25 °C for 1.8 h. The reaction mixture was washed with sat. aqueous sodium sulfite solution. The aqueous layer was extracted with dichloromethane. Concentration of the combined organic layer followed by column chromatography of the residue (dichloromethane–ethyl acetate 20 : 1) gave **5a** (92 mg, 99% yield). This procedure applies to the synthesis of **2e—g**.

*5-[(E)-3-(2-oxo-2H-chromen-7-yloxy)-1-methyl-1-propenyl]-2,2-dimethyl-3(2H)-furanone, Geiparvarin (***5g***).* Mp 159.5—160.5 °C (colorless prisms from methanol); ^{1}H-NMR ($CDCl_3$): δ=1.39 (s, 6H), 2.01 (s, 3H), 4.82 (d, J=6.0 Hz, 2H), 5.57 (s, 1H), 6.22 (d, J=9.3 Hz, 1H), 6.6—7.0 (m+t (δ 6.73, J=6.0 Hz), 3H), 7.37 (d, J=8.7 Hz, 1H), 7.61 (d, J=9.3 Hz, 1H); IR ($CHCl_3$): 1727, 1696, 1615, 1561, 1278, 1171, 1158, 1123, 1017, 838 cm^{-1}; MS: *m/e* (rel intensity) 326 (M^+, trace), 249(11), 247(11), 149(19), 99(48), 83(63), 55(85), 43(100). The synthetic material showed more than 97% purity of the (*E*) isomer as evidenced by the ^{1}H-NMR spectrum consistent with the literature values.[3e-g,9b]

Hg/Nafion-H Catalyzed Transformation of Acetylenic Diols **1** *into 4,5-Dihydro-3(2H)-furanones of Type* **4** *(Method B, a Typical Procedure).* The polymer reagent Hg/Nafion-H[14] was prepared as follows. Nafion® 511 (20.4 g) was treated with 12% hydrochloric acid (25 ml) for 6 h and the resin was filtered and superficially washed with water. This procedure was repeated 5 times. Finally the resin was washed more thoroughly with water and dried at 85 °C for 10 h under *ca.* 1 Torr to give Nafion®-H, perfluorinated resin-sulfonic acid, which contained 0.94 mmol of $-SO_3H$ group per 1 g. The resin-sulfonic acid (20.4 g) was stirred in sat. aqueous mercury(II) acetate solution (25 ml) at 25 °C for 7 h. The resin was collected by filtration, washed with water, and dried at 25°C under 1 Torr for 1 d. Hg/Nafion-H thus prepared contained 0.38 mmol of Hg(II) per 1 g.

The diols **1** (1 mmol) in ethanol (1 ml) were treated with Hg/Nafion-H (*ca.* 0.5 g) in the presence of water (5 mmol) at 25 °C for several hours. The reaction mixture was filtered, and the catalyst was washed with dichloromethane. Concentration of the combined filtrates followed by purification gave the desired products.

*5,5-Dimethyl-2-phenyl-4,5-dihydro-3(2H)-furanone (***4a***).* The reaction of **1a** with Hg/Nafion-H afforded a 1 : 4 mixture of **3a** and **4a** (14% and 56% isolated yield respectively) along with a by-product, (*E*)-4-hydroxy-4-methyl-1-phenyl-1-penten-3-one (**12a**) (11% yield). Physical properties of **4a** are given. Bp 108—109 °C (bath temp)/0.05 Torr; ^{1}H-NMR (CCl_4): δ=1.40 (s, 3H), 1.55 (s, 3H), 2.35 (s, 2H), 4.82 (s, 1H), 7.2—7.5 (m, 5H); IR: 1758, 1182, 1056, 699 cm^{-1}; MS: *m/e* (rel intensity) 190 (M^+, 4), 162(11), 107(100), 105(35), 56(98). Found: C, 75.90; H, 7.59%. Calcd for $C_{12}H_{14}O_2$: C, 75.76; H, 7.42%. The enone **12a** showed bp 131—132 °C (bath temp)/0.14 Torr; ^{1}H-NMR (CCl_4): δ=1.40 (s, 6H), 3.64 (br s, 1H), 7.04 (d, J=15.6 Hz, 1H), 7.3—7.7 (m, 5H), 7.81 (d, J=15.6 Hz, 1H); IR: 3450, 1681, 1610, 1600, 1071, 973, 764 cm^{-1}; MS: *m/e* (rel intensity) 172 (M^+-H_2O, 2), 147(25), 132(32), 131(47), 104(34), 59(100). Found: C, 75.50; H, 7.51%. Calcd for $C_{12}H_{14}O_2$: C, 75.76; H, 7.42%.

*2,2,5-Trimethyl-4,5-dihydro-3(2H)-furanone (***3b***) and 2,5,5-Trimethyl-4,5-dihydro-3(2H)-furanone (***4b***).* A mixture of **3b**[12b] and **4b**[12b] (**3b** : **4b** being 1 : 2 based on ^{1}H-NMR) were produced in 80% yield. The mixture showed bp 135—140 °C (bath temp)/20 Torr; IR: 1759, 1371, 1195, 1098 cm^{-1}; MS: *m/e* 128 (M^+); ^{1}H-NMR (CCl_4) of **3b**: δ 1.13 (s, $C\underline{H}_3$–C–CH_3), 1.18 (s, CH_3–C–$C\underline{H}_3$), 1.29 (d, J=5.2 Hz, CH–$C\underline{H}_3$), 2.03 (dd, J=9.9, 17.4 Hz, $\underline{H}$–C–H), 2.49 (dd, J=6.0, 17.4 Hz,

H–C–H), 4.0—4.4 (m, CH–CH_3, 0.33H); ^{1}H-NMR (CCl_4) of **4b**: δ=1.25 (d, J=6.9 Hz, CH–CH_3), 1.31 (s, CH_3–C–CH_3), 1.40 (s, CH_3–C–CH_3), 2.25 (s, H–C–H), 3.91 (q, J=6.9 Hz, CH–CH_3, 0.67H).

*1-Oxaspiro[4.5]decan-3-one (**4c**).*[12a] ^{1}H-NMR (CCl_4): δ=1.1—2.0 (m, 10H), 2.24 (s, 2H), 3.94 (s, 2H), IR: 1760, 1184, 1064 cm^{-1}; MS: *m/e* 154 (M^+).

*2-Methyl-1-oxaspiro[4.5]decan-4-one (**3d**) and 2-Methyl-1-oxaspiro[4.5]decan-3-one (**4d**).* The ratio of **3d**[12g] to **4d**[12d] (1 : 1 to 1 : 2) was estimated by the examination of the ^{1}H-NMR spectrum of the mixture having IR: 1755, 1450, 1190, 1105, 1065 cm^{-1}; MS: *m/e* 168 (M^+); ^{1}H-NMR (CCl_4, *refers to **4d**): δ=1.0—2.0 (m+d (δ=1.22*, J=6.8 Hz)+d (δ=1.38, J=6.3 Hz), 13H), 2.05 (dd, J=10.2, 17.9 Hz), 2.20* (d, J=17.6 Hz), 2.32* (d, J=17.6 Hz), 2.50 (dd, J=6.0, 17.9 Hz), 3.88* (q, J=6.8 Hz, CH–CH_3, 0.69—0.50H), 4.23 (ddq, J=6.0, 10.2, 6.8 Hz, CH–CH_3, 0.31—0.50H).

*2,2-Dimethyl-1-oxaspiro[4.5]decan-4-one (**3h**) and 2,2-Dimethyl-1-oxaspiro[4.5]decan-3-one (**4h**).* The ratio of **3h**[5e] to **4h**[5e] was estimated by GLC (PEG 20 M, 10% on Celit 545, 2 m, 123 °C, N_2 carrier gas 0.5 kg/cm^2, FID detector) to be *ca.* 1 : 2, R_t being 5.7 min and 6.4 min respectively; each isomer could be isolated by preparative GLC (PEG 20 M, 30% on Celite 545, 3 m, 150 °C, He carrier gas 0.8 kg/cm^2, TCD detector; **3h** R_t 7.0 min; **4h**, R_t 8.5 min). The structure of regioisomers was established by the examination of the ^{1}H-NMR spectra in the presence of Eu(fod)$_3$. ^{1}H-NMR (CCl_4) of **3h**: δ=1.1—1.8 (m+s (δ=1.36), 16H), 2.39 (s, 2H); **4h**: δ=1.22 (s, 6H), 1.2—1.9 (m, 10H), 2.36 (s, 2H). The mixture showed IR: 1754, 1159, 990 cm^{-1}; MS: *m/e* 182 (M^+).

*7-Oxadispiro[5.1.5.2]pentadecan-14-one (**4i**).*[30] Bp 150—151 °C (bath temp)/8 Torr; ^{1}H-NMR (CCl_4): δ=1.0—2.2 (m, 20H), 2.38 (s, 2H); IR: 1750, 1451, 1064, 990 cm^{-1}; MS: *m/e* 222 (M^+).

*6-Methyl-1-oxaspiro[4.5]decan-3-one (**4j**) and (**4j'**).* A 3 : 2 diastereomeric mixture of **1j** and **1j'** (TLC, hexane–ethyl acetate 1 : 2, R_f 0.14 and 0.22 respectively)[1] was transformed into **4j** and **4j'**, which were separated by preparative TLC (hexane–ethyl acetate 5 : 1, double development) to give **4j** (R_f 0.35—0.45) and **4j'** (R_f 0.45—0.55). Physical properties of **4j** are given. Bp 111—112 °C (bath temp)/0.12 Torr; ^{1}H-NMR (CCl_4): δ=0.94 (d, J=6.9 Hz, 3H), 1.0—2.0 (m, 9H), 2.06 d, J=18.3 Hz, 1H), 2.35 (d, J=18.3 Hz, 1H), 3.92 (s, 2H); IR: 1761, 1184, 1067 cm^{-1}; MS: *m/e* (rel intensity) 168 (M^+, 41), 125(43), 111(100), 98(45), 67(42). Found: C, 71.41; H, 9.84%. Calcd for $C_{10}H_{16}O_2$: C, 71.39; H, 9.59%. The isomer **4j'** showed bp 92—93 °C (bath temp)/0.05 Torr; ^{1}H-NMR (CCl_4): δ=0.97 (d, J=5.9 Hz, 3H), 1.0—2.0 (m, 9H), 2.06 (d, J=18.0 Hz, 1H), 2.51 (d, J=18.0 Hz, 1H), 3.90 (s, 2H); IR: 1760, 1188, 1066 cm^{-1}; MS: *m/e* (rel intensity) 168 (M^+, 38), 125(48), 111(100), 98(46), 67(46). Found: C, 71.25; H, 9.86%. Calcd for $C_{10}H_{16}O_2$: C, 71.39, H, 9.59%.

*1-Oxaspiro[4.6]undecan-3-one (**4k**).* Isolated by preparative TLC (hexane–ethyl acetate 2 : 1, R_f 0.60—0.75) along with 3-cycloheptylidene-1-hydroxy-2-propanone (**12k**) (R_f 0.40—0.50). The furanone **4k** showed bp 109 °C (bath temp)/0.15 Torr; ^{1}H-NMR (CCl_4): δ=1.2—2.1 (m, 12H), 2.24 (s, 2H), 3.88 (s, 2H); IR: 1760, 1462, 1447, 1066 cm^{-1}; MS: *m/e* (rel intensity) 168 (M^+, 16), 111(100), 98(44), 83(44), 67(47). Found: C, 71.26; H, 9.76%. Calcd for $C_{10}H_{16}O_2$: C, 71.39; H, 9.59%. Bp of **12k**: 120—125 °C (bath temp)/0.20 Torr; ^{1}H-NMR (CCl_4): δ=1.3—2.0 (m, 8H), 2.42 (t, J=5.0 Hz, 2H), 2.95 (t, J=5.0 Hz, 2H), 3.05 (br s, 1H), 4.13 (s, 2H), 5.99 (s, 1H); IR: 3455, 1704, 1678, 1605, 1444, 1066 cm^{-1}; MS: *m/e* (rel intensity) 168 (M^+, 4), 137(76), 113(100), 95(67), 67(65), 55(80). Found *m/e* 168.1145. Calcd for $C_{10}H_{16}O_2$: M^+, 168.1149.

*1-Oxaspiro[4.7]dodecan-3-one (**4l**).* Isolated by preparative TLC (hexane–ethyl acetate 3 : 1, R_f 0.61—0.72) together with 3-cyclooctylidene-1-hydroxy-2-propanone (**12l**) (R_f 0.50—0.60). Physical properties of **4l** are given. Bp 110—112 °C (bath temp)/0.15 Torr; ^{1}H-NMR (CCl_4): δ=1.0—2.4 (m+s (δ=2.22), 16H), 3.89 s, 2H); IR: 1760, 1180, 1064 cm^{-1}; MS: *m/e* (rel intensity) 182 (M^+, 12), 111 (100), 98(63), 83(35), 55(40). Found: C, 72.42; H, 10.20%. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95%. The enone **12l** showed bp 102—103 °C (bath temp)/0.18 Torr; ^{1}H-NMR (CCl_4): δ=1.1—2.1 (m, 10H), 2.34 (t, J=6.0 Hz, 2H), 2.79 (t, J=6.0 Hz, 2H), 2.99 (br s, 1H), 4.10 (s, 2H), 6.02 (s, 1H); IR: 3450, 1682, 1607, 1449, 1050 cm^{-1}; MS: *m/e* (rel intensity) 182 (M^+, 4), 151(69), 81(100), 67(71), 55(83). Found: C, 72.26; H, 10.20%. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95%.

*1-Oxaspiro[4.11]hexadecan-3-one (**4m**).* Mp 81.5—82.0 °C (colorless needles from hexane); ^{1}H-NMR (CCl_4): δ=1.2—2.0 (m, 22H), 2.19 (s, 2H), 3.87 (s, 2H), IR ($CHCl_3$): 1763, 1471, 1448, 1180, 1062 cm^{-1}; MS: *m/e* (rel intensity) 238 (M^+, 8), 111 (100), 98(56), 55(48). Found: C, 75.64; H, 10.98%. Calcd for $C_{15}H_{26}O_2$: C, 75.58; H, 11.00%. The by-product was proved to be 3-cyclododecylidene-1-hydroxy-2-propanone (**12m**) having mp 43.0—44.0 °C (hexane); bp 136—138 °C (bath temp)/0.04 Torr; ^{1}H-NMR (CCl_4): δ=1.1—1.9 (m, 18H), 2.27 (t, J=6.8 Hz, 2H), 2.80 (t, J=6.8 Hz, 2H), 3.09 (br s, 1H), 4.61 (s, 2H), 6.07 (s, 1H); IR (CCl_4): 3455, 1687, 1614, 1063 cm^{-1}; MS: *m/e* (rel intensity) 238 (M^+, 3), 207(33), 83(56), 55(100). Found: C, 75.41; 11.13%. Calcd for $C_{15}H_{26}O_2$: C, 75.58; H, 11.00%.

*5-Ethyl-5-pentyl-4,5-dihydro-3(2H)-furanone (**4n**).* Bp 89 °C (bath temp)/0.13 Torr; ^{1}H-NMR (CCl_4): δ=0.6—1.9 (m, 16H), 2.24 (s, 2H), 3.89 (s, 2H); IR: 1761, 1465, 1185, 1067 cm^{-1}; MS: *m/e* (rel intensity) 155 ($M^+-C_2H_5$, 38), 113(100), 85(55), 57(72), 55(84). Found: *m/e* 155.1057. Calcd for $C_9H_{15}O_2$: $M^+-C_2H_5$, 155.1071. The by-product, (*E*)- and (*Z*)-4-ethyl-1-hydroxy-3-nonen-2-one (**12n**) showed bp 110 °C (bath temp)/0.08 Torr; ^{1}H-NMR (CCl_4): δ=0.7—2.0 (m, 12H), 2.22 (m, 2H), 2.63 (m, 2H), 3.07 (br s, 1H), 4.12 (s, 2H), 5.87 (s, 0.5H), 5.97 (s, 0.5H); IR: 3450, 1688, 1618, 1462, 1071, 1053 cm^{-1}; MS: *m/e* (rel intensity) 184 (M^+, trace), 153(73), 83(59), 69(59), 57(64), 55(50), 41(100). Found: C, 71.45; H, 11.19%. Calcd for $C_{11}H_{20}O_2$: C, 71.70; H, 10.94%.

*5-Hexyl-4,5-dihydro-3(2H)-furanone (**4o**).* Bp 120 °C (bath temp)/0.15 Torr; ^{1}H-NMR (CCl_4): δ=0.7—1.9 (m, 13H), 2.04 (dd, J=9.5, 17.7 Hz, 1H), 2.46 (dd, J=6.3, 17.7 Hz, 1H), 3.70 (d, J=17.3 Hz, 1H), 3.99 (d, J=17.3 Hz, 1H), 4.18 (m, 1H); IR: 1765, 1170, 1064 cm^{-1}; MS: *m/e* (rel intensity) 170 (M^+, 6), 140(34), 85(97), 57(100), 55(83), 43(77) Found: C, 70.30; H, 10.75%. Calcd for $C_{10}H_{18}O_2$: C, 70.55; H, 10.66%. The by-product was proved to be 1-ethoxy-4-hydroxy-3-decanone (**12o**) having bp 113—114 °C (bath temp)/0.09 Torr; ^{1}H-NMR (CCl_4): δ=0.7—2.0 (m+t (δ=1.15, J=7.1 Hz), 16H), 2.63 (t, J=6.3 Hz, 2H), 3.30 (br s, 1H), 3.45 (q, J=7.1 Hz, 2H), 3.65 (t, J=6.3 Hz, 2H), 4.04 (m, 1H); IR: 3480, 1712, 1115 cm^{-1}. Found: C, 66.88; H, 11.42%. Calcd for $C_{12}H_{24}O_3$: C, 66.63; H, 11.18%.

*2,2,5,5-Tetramethyl-4,5-dihydro-3(2H)-furanone (**4p**).* Using the recovered polymer reagent Hg/Nafion-H (200 mg), **1p** (91 mg, 0.64 mmol) was converted into **4p**[11] (74 mg, 82% yield) having ^{1}H-NMR (CCl_4): δ=1.20 (s, 6H), 1.33 (s, 6H), 2.37 (s, 2H); IR: 1757, 1369, 1153, 990 cm^{-1}; MS: *m/e* 142 (M^+).

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References

1) T. Hiyama, M. Shinoda, H. Saimoto, and H. Nozaki, *Bull. Chem. Soc. Jpn.*, **54**, 2747 (1981).

2) For a preliminary communication on this work, see H. Saimoto, T. Hiyama, and H. Nozaki, *J. Am. Chem. Soc.*, **103**, 4975 (1981).

3) For example, a) Budlein-A and B: A. Romo de Vivar, C. Guerrero, E. Diag, E. A. Bratoeff, and L. Jimenetz, *Phytochemistry*, **15**, 525 (1976); b) Bullatenone: C. W. Brandt, W. I. Taylor, and B. R. Thomas, *J. Chem. Soc.*, **1954**, 3245; c) Eremantholides: R. F. Raffauf, R.-K. C. Huang, P. W. Le Queane, S. B. Levery, and T. E. Brennan, *J. Am. Chem. Soc.*, **97**, 6884, (1975); d) P. W. Le Quesne, S. B. Levery, M. D. Menachery, T. F. Brennan, and R. F. Raffauf, *J. Chem. Soc., Perkin Trans. 1*, **1978**, 1572; e) Geiparvarin: F. N. Lahey and J. K. MacLeod, *Aust. J. Chem.*, **20**, 1943 (1967); f) R. M. Carman, F. N. Lahey, and J. K. MacLeod, *ibid.*, **20**, 1957 (1967); g) D. L. Dreyer and A. Lee, *Phytochemistry*, **11**, 763 (1972); h) K. Padmawinata, *Acta Pharm.*, **4**, 1 (1973); *Chem. Abstr.*, **79**, 75897n (1973); i) Goyazensolide: W. Vichnewski, S. J. Sarti, B. Gilbert, and W. Herz, *Phytochemistry*, **15**, 191 (1976); j) Jatrophone: S. M. Kupchan, C. W. Sigel, M. J. Matz, J. A. Saenz Renauld, R. C. Haltiwanger, and H. F. Bryan, *J. Am. Chem. Soc.*, **92**, 4476 (1970); k) S. M. Kupchan, C. W. Sigel, M. J. Matz, C. J. Gilmore, and R. F. Bryan, *ibid.*, **98**, 2295 (1976); l) Sirodesmins: P. J. Curtis, D. Greatbanks, B. Hesp, A. F. Cameron, and A. A. Freer, *J. Chem. Soc., Perkin Trans. 1*, **1977**, 180; m) J. P. Férézou, C. Riche, A. Quesneau-Thierry, C. Pascard-Billy, M. Barbier, J. F. Bousquet, and G. Boudart, *Nouv. J. Chem.*, **1**, 327 (1977); *Chem. Abstr.*, **87**, 179449z (1977); n) A flavor component of pineapple and strawberry: J. O. Rodin, C. M. Himel, R. M. Silverstein, R. W. Leeper, and W. A. Gortner, *J. Food Sci.*, **30**, 280 (1965); o) B. Willharm, M. Stoll, and A. F. Thomas, *Chem. Ind. (London)*, **1965**, 1629.

4) Biological activity[a-d,h,j-l] was discussed in connection with the addition reaction of model biological nucleophiles to many antitumor agents: S. M. Kupchan, D. C. Fessler, M. A. Eakin, and T. J. Giacobbe, *Science*, **168**, 376 (1970); E. Fujita and Y. Nagao, *Bioorg. Chem.*, **6**, 287 (1977) and Ref. 13q.

5) For example, preparation of tetrahydrofuran-3,4-diones and their monooximes connected with the synthesis of 4-hydroxy-3-furanones: a) G. B. Bennett, W. J. Houlian, R. B. Mason, and R. G. Engstrom, *J. Med. Chem.*, **19**, 709 (1976); b) I. K. Korobitsyna, Yu. K. Yur'ev, Yu. A. Cheburkov, and E. M. Lukia, *Zh. Obshch. Khim.*, **25**, 734 (1955); *Chem. Abstr.*, **50**, 2536f (1956); c) I. K. Korobitsyna, Yu. K. Yur'ev, and K. V. Kuznetsova, *ibid.*, **27**, 1792 (1957); *Chem. Abstr.*, **52**, 4659i (1958); d) I. K. Korobitsyna, I. G. Zhukova, and Yu. K. Yur'ev, *ibid.*, **29**, 2190 (1959); *Chem. Abstr.*, **54**, 10989a (1960); e) I. K. Korobitsyna, K. K. Pivnitskii, and Yu. K. Yur'ev, *ibid.*, **29**, 3880 (1959); *Chem. Abstr.*, **54**, 21032i (1960); f) I. K. Korobitsyna, I. G. Zhukova, V. V. Voronkova, and Yu. K. Yur'ev, *Dokl. Akad. Nauk SSSR*, **117**, 237 (1957); *Chem. Abstr.*, **52**, 9062i (1958). Photochemical ring expansion: g) P. Yates, A. K. Verma, and J. C. L. Tam, *J. Chem. Soc., Chem. Commun.*, **1976**, 933; h) P. Yates and R. O. Loutfy, *Acc. Chem. Res.*, **8**, 209 (1975). Preparation of tetronic acid derivatives: i) S. Gelin and D. Hartmann, *J. Heterocycl. Chem.*, **13**, 521 (1976); j) T. Reffstrup and P. M. Boll, *Acta Chem. Scand., Ser. B*, **31**, 727 (1977). Synthesis of 2-, 4-, and 5-oxopyrrol derivatives: k) S. Gelin and R. Gelin, *J. Org. Chem.*, **44**, 808 (1979); l) S. Gelin, *Synthesis*, **1978**, 291; m) B. Chantegrel and S. Gelin, *J. Heterocycl. Chem.*, **15**, 1215 (1978).

6) a) A. B. Smith, III and P. J. Jerris, *Tetrahedron Lett.*, **21**, 711 (1980); b) P. J. Jerris and A. B. Smith, III, *J. Org. Chem.*, **46**, 577 (1981); c) A. B. Smith, III, M. A. Guaciaro, S. R. Schow, P. M. Wovkulich, B. H. Toder, and T. W. Hall, *J. Am. Chem. Soc.*, **103**, 219 (1981); d) W. H. Rastetter and J. Adams, *Tetrahedron Lett.*, **23**, 1319 (1982); J. D. White, T. Nishiguchi, and R. W. Skeean, *J. Am. Chem. Soc.*, **104**, 3923 (1982).

7) Reviews: C. H. Eugster, *Adv. Org. Chem.*, **2**, 427 (1960); S. Wilkinson, *Q. Rev. Chem. Soc.*, **15**, 153 (1961). Recent methods for the synthesis of muscarine alkaloids, see: Z. Lysenko, F. Ricciardi, J. E. Semple, P. C. Wang, and M. M. Joullié, *Tetrahedron Lett.*, **1978**, 2679; A. M. Mubarak and D. M. Bromn, *ibid.*, **21**, 2453 (1980); R. Amouroux, B. Gerin, and M. Chastrette, *ibid.*, **23**, 4341 (1982); H. Meister, *Justus Liebigs Ann. Chem.*, **701**, 174 (1967); **752**, 163 (1971); W. C. Still and J. A. Schneider, *J. Org. Chem.*, **45**, 3375 (1980); Y. Hayakawa, H. Takaya, S. Makino, N. Hayakawa, and R. Noyori, *Bull. Chem. Soc. Jpn.*, **50**, 1990 (1977) and references cited therein.

8) R. Teranishi, "Gustation and Olfaction," ed by G. Ohloff and A. F. Thomas, Academic Press, New York (1971), p. 165.

9) M. A. Gianturco, P. Friedel, and A. S. Gimmarino, *Tetrahedron*, **20**, 1763 (1964); G. Büchi, E. Demole, and A. F. Thomas, *J. Org. Chem.*, **38**, 123 (1973); L. Re and G. Ohloff, Swiss Patent 540 650 (1974); *Chem. Abstr.*, **80**, 69406f (1974); L. Re, B. Maurer, and G. Ohloff, *Helv. Chim. Acta*, **56**, 1882 (1973).

10) a) Elguero, C. Marzin, A. R. Katritzky, and P. Linda, "Advances in Heterocyclic Chemistry, Supplement 1, The Tautomerism of Heterocycles," ed by A. R. Katritzky and A. J. Boulton, Academic Press, New York (1976), pp. 222—228; b) A. R. Katritzky and J. M. Lagowski, "Advances in Heterocyclic Chemistry," ed by A. R. Katritzky, Academic Press, New York (1963), Vol. 2, pp. 5—8; c) P. Bosshard and C. H. Eugster, "Advances in Heterocyclic Chemistry," ed by A. R. Katritzky and A. J. Boulton, Academic Press, New York (1966), Vol. 7, pp. 462—468; d) M. Anteunis and M. Vandewalle, *Spectrochim. Acta, Part A*, **27**, 2119 (1971); e) I. K. Korobitsyna, I. G. Zhukova, and Yu. K. Yur'ev, *Zh. Obshch. Khim.*, **29**, 2196 (1959); *Chem. Abstr.*, **54**, 10989f (1960); f) R. E. Rosenkranz, K. Allner, R. Good, W. V. Philipsborn, and C. H. Eugster, *Helv. Chim. Acta*, **46**, 1259 (1963); g) A. Hofmann, W. V. Philipsborn, and C. H. Eugster, *ibid.*, **48**, 1322 (1965); h) A. Hofmann and C. H. Eugster, *ibid.*, **49**, 53 (1966); i) P. M. Burke, W. F. Reynold, J. C. L. Tam, and P. Yates, *Can. J. Chem.*, **54**, 1449 (1976); j) D. W. Henry and R. M. Silverstein *J. Org. Chem.*, **31**, 2391 (1966); k) E. C. Kendall and Z. Hajos, *J. Am. Chem. Soc.*, **82**, 3219, 3220 (1960). Conformational equilibrium constants for a number of 1-oxaspiro[*n*. 5]-alkanes, see: l) P. Picard and J. Moulines, *Tetrahedron*, **34**, 671 (1978).

11) H. Richet, *Ann. Chim.*, **3**, 317 (1948); F. Leonard, A. Wajngurt, and H. Horn, *J. Org. Chem.*, **21**, 1402 (1956); M. S. Newman and W. R. Reichle, *Org. Synth.*, Coll. Vol. V, 1024 (1973).

12) a) J. Colonge, R. Falcotet, and R. Gaumont, *Bull. Soc. Chim. Fr.*, **1958**, 211; b) S. A. Vartanyan, G. A. Chukhadzhyan R. A. Melikyan, and Sh. A. Babanya, *Izv. Akad. Nauk Arm. SSR, Khim. Nauki*, **15**, 45 (1962); *Chem. Abstr.*, **58**, 6756b (1963); c) A. S. Medvedeva, M. F. Shostakoviskii, G. G. Chichkareva, T. A. Favorskaya, and V. K. Voronov, *Zh. Org. Khim.*, **7**, 641 (1971); *J. Org. Chem. USSR*, **7**, 649 (1971); d) A. S. Medvedeva, L. P. Safronova, I. D. Kalikhuman, and V. M. Vlasov, *Izv. Akad. Nauk SSSR, Ser. Khim.*, **1975**, 1175; *Bull. Acad. Sci. USSR, Chem. Sci.*, **1975**, 1082; Ref. 5b, 5c, and 5e.

13) Other methods for the synthesis of 3-furanones, see: a) J. E. Semple and M. M. Joullié, *Heterocycles*, **14**, 1825 (1980);

b) I. N. Nazarov and S. G. Matsoyan, *Zh. Obshch. Khim.*, **27**, 2951 (1957); *Chem. Abstr.*, **52**, 8080f (1958); c) G. Casnati and A. Ricca, *Tetrahedron Lett.*, **1967**, 327, d) M.-A. Barrow, A. C. Richards, R. H. Simithers, and H. M. R. Hoffmann, *ibid.*, **1972**, 3101; e) M. Bertrand, J. P. Dulcere, G. Gil, J. Grimaldi, and P. Sylvestre-Panthet, *ibid.*, **1976**, 1507; f) D. Caine and W. D. Samuels, *ibid.*, **21**, 4057 (1980); g) J. E. Semple, A. E. Guthrie, and M. M. Joullie, *ibid.*, **21**, 4561 (1980); h) T. H. Chan and B. S. Ong, *Tetrahedron*, **36**, 2269 (1980); i) P. Picard and J. Moulines, *Bull. Soc. Chim. Fr.*, **1974**, 2889; j) R. Gerin, A. Galliand, B. Chantegrel, and S. Gelin, *ibid.*, **1974**, 1043; k) M. Yamamoto, *J. Chem. Soc., Perkin Trans. 1*, **1976**, 1688; l) J. Yoshimura, S. Kondo, M. Ihara, and H. Hashimoto, *Chem. Lett.*, **1979**, 819; m) Ch. Meister and H.-D. Scharf, *Synthesis*, **1981**, 733, 737; n) M. Matsui, T. Ogawa, T. Kitahara, and K. Takagi, Japan Kokai Patent 79, 115, 369 (1978); *Chem. Abstr.*, **92**, 110828h (1980); o) D. Gange and P. Magnus, *J. Am. Chem. Soc.*, **100**, 7746 (1978); p) K. C. Nicolaou, R. L. Magolda, W. J. Sipio, W. E. Barnette, Z. Lysenko, and M. M. Joullié, *ibid.*, **102**, 3784 (1980); q) A. B. Smith, III, P. A. Levenberg, P. J. Jerris, R. M. Scarborough, Jr., and P. M. Wovkulich, *ibid.*, **103**, 1501 (1981) and references cited therein.

14) Nafion® is a perfluorinated resin-sulfonic acid commercially available from E. I. du Pont de Nemours and Co. The author is indebted to E. I. du Pont de Nemours and Co. and Mitsui Fluorochemical Co. for a generous gift of the potassium salt of Nafion® 511. *Cf.* G. A. Olah and D. Meider, *Synthesis*, **1978**, 671; G. A. Olah, J. Kaspi, and J. Bukala, *J. Org. Chem.*, **26**, 4187 (1977).

15) Other approaches to 3(2*H*)-furanone derivatives, see: T. Hiyama, M. Shinoda, H. Saimoto, and H. Nozaki, *Heterocycles*, **15**, 263 (1981) and references cited therein. Preparation of 3-furanones from acetylene derivatives, see: F. Bohlmann, *Chem. Ber.*, **94**, 1104 (1961); c) H. Meister, German Patent 1147593 (1963); *Chem. Abstr.*, **59**, 11427b (1963); d) German Patent 1150658 (1964); *Chem. Abstr.*, **60**, 2895e (1964); e) S. A. Vartanyan, L. V. Oganova, and Sh. O. Badanyan, *Izu. Akad. Nauk Arm. SSR, Khim. Nauki*, **17**, 709 (1964); *Chem. Abstr.*, **63**, 4232e (1965); f) B. P. Gusev, I. I. Nazarova, and V. F. Kucherov, *Izv. Akad. Nauk SSSR, Ser. Khim.*, **1965**, 688; g) I. I. Nazarova, B. P. Gusev, and V. F. Kucherov, *ibid.*, **1967**, 1580; h) V. M. Al'bitskaya and E. D. Venus-Danilova, *Zh. Obshch. Khim.*, **30**, 349 (1960); *Chem. Abstr.*, **54**, 22558g (1960); i) A. N. Volkov, A. V. Bogdanova, and G. P. Kugatova-Shemyakina, *Zh. Org. Khim.*, **3**, 316 (1967); *Chem. Abstr.*, **66**, 115346x (1967); j) L. I. Vereshchagin, S. R. Gainulina, L. P. Kirillova, and T. V. Lipovich, *ibid.*, **5**, 1557 (1969); *Chem. Abstr.*, **72**, 12456c (1970); k) B. P. Gusev, I. I. Nazarova, and V. F. Kucherov, *Khim. Atsetilena*, **1968**, 88; *Chem. Abstr.*, **71**, 61082r (1969); l) D. R. Williams, A. Abbaspour, and R. M. Jacobson, *Tetrahedron Lett.*, **22**, 3564 (1981). For preparation of 4-hydroxy-3-furanones, see: m) M. Baumann and W. H. Hoffmann, *Synthesis*, **1981**, 709; Ref. 9, 10j, and 10k. For preparation of 2-alkylidene-3(2*H*)-furanones, see: n) I. da Rocha Pitta, M. do Socorro Lacerda, and C. Luu Duc, *J. Heterocycl. Chem.*, **16**, 821 (1979); o) B. Chantegrel and S. Gelin, *Synthesis*, **1981**, 45.

16) Similar enol acetates were prepared from the corresponding dihydro-3(2*H*)-furanones and transformed into 4-chloro-4,5-dihydro-3(2*H*)-furanones, see: I. K. Korobitsyna, I. G. Zhukova, V. A. Kuvshinova, N. N. Gaidamovich, and Yu. K. Yur'ev, *Dokl. Akad. Nauk SSSR*, **114**, 327 (1957); *Chem. Abstr.*, **52**, 349f (1958). See also Ref. 10l.

17) D. G. Oelberg and M. D. Schiavelli, *J. Org. Chem.*, **42**, 1804 (1977); W. R. Been, *ibid.*, **33**, 3113 (1968); P. D. Landor and S. R. Landor, *J. Chem. Soc.*, **1956**, 1015; G. Saucy, R. Marbet, H. Lindlar, and O. Isler, *Helv. Chim. Acta*, **42**, 1945 (1959); H. Schlossarczyk, W. Sieber, M. Hesse, H.-J. Hansen, and H. Schmid, *ibid.*, **56**, 875 (1973); F. Hoffmann-La-Roche and Co., A.-G. Belgian Patent 617174 (1962); *Chem. Abstr.*, **59**, 1540f (1963); A. C. Day and M. C. Whiting ,*J. Chem. Soc., C*, **1966**, 464.

18) G. Leandri, H. Monti, and M. Bertrand, *Tetrahedron*, **30**, 289 (1974); L.-I. Olsson and A. Claesson, *Synthesis*, **1979**, 743; P. Audin, A. Doutheau, and J. Gore, *Tetrahedron Lett.*, **23**, 4337, (1982); J.-J. Chilot, A. Doutheau, and J. Gore, *ibid.*, **23**, 4693 (1982).

19) a) W. Parker, R. A. Raphael, and D. I. Wilkinson, *J. Chem. Soc.*, **1958**, 3871; b) A. Takeda, S. Tsuboi, and T. Sakai, *Chem. Lett.*, **1973**, 425; c) L. D. Gavrilov, M. I. Klopotova, and L. I. Vereshchagin, *Zh. Org. Khim.*, **10**, 2064 (1974); d) J. E. Baldwin, R. C. Thomas, L. I. Kruse, and L. Silberman, *J. Org. Chem.*, **42**, 3846 (1977); e) A. B. Smith, III and P. J. Jerris, *Synth. Commun.*, **8**, 421 (1978); f) M. Ito, M. Ohno, E. Takeo, Y. Oda, and K. Tsukida, *Heterocycles*, **12**, 505 (1979); g) Y. Takahashi, H. Hagiwara, H. Uda, and H. Kosugi, *ibid.*, **15**, 225 (1981).

20) The aldehyde **9** was prepared by selenium dioxide oxidation of 7-(3-methyl-2-butenyloxy)coumarin, see: E. V. Lassak and I. A. Southwell, *Aust. J. Chem.*, **25**, 2451 (1972).

21) *Cf.* Ref. 12d.

22) M. Karpf and A. S. Dreiding, *Helv. Chim. Acta*, **59**, 1226 (1976).

23) M. F. Shostakovskii, V. M. Vlasov, and A. A. Vasileva, *Izv. Akad. Nauk SSSR, Ser. Khim.*, **1964**, 696.

24) K. Zeil and H. Meyer, *Ber. Deuch. Chem. Ges.*, **75**, 356 (1942).

25) A. I. Nogaideli, K. Ya. Dzagnidze, and R. PaPava, *Zh. Obshch. Khim.*, **28**, 116 (1958); *Chem. Abstr.*, **52**, 12758a (1958).

26) S. A. Vartanyan, G. A. Chukhadzhyan, and V. N. Zhamagortsyan, *Izv. Akad. Nauk Arm. SSR, Khim. Nauki*, **12**, 107 (1959); *Chem. Abstr.*, **55**, 5370c (1961).

27) A. Babayan, B. Akopyan, and R. G. Kevhyan, *J. Gen. Chem.*, **9**, 1631 (1939); *Chem. Abstr.*, **34**, 2788 (1940).

28) M. Gouge, *Ann. Chim.*, **6**, 648 (1951).

29) I. N. Nazarov and A. N. Elizarova, *Bull. Akad. Sci. U. R. S. S., Classe Sci. Chim.*, **1948**, 107; *Chem. Abstr.*, **42**, 7738a (1948).

30) I. K. Korobitsyna, L. A. Kazitsyna, and Yu. K. Yur'ev, *Zh. Obshch. Khim.*, **25**, 1349 (1955); *Chem. Abstr.*, **49**, 15481h (1955).

31) For Nafion®-H catalyzed ether formation, see: G. A. Olah, A. P. Fung, and P. Malhotra, *Synthesis*, **1981**, 474.