Cyclisation of Acetylenecarboxylic Acid. Synthesis of γ-Methylenebutyrolactones

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Various γ-*exo*-methylenebutyrolactones have been synthesized in excellent yield by the cyclisation of acetylenecarboxylic acids in the presence of a catalytic amount of mercury(II) oxide. Cyclisation of terminal acetylene compounds [*e.g.* (1a)—(1e)] proceeded regioselectively to give γ-*exo*-methylenebutyrolactones as the sole product. Disubstituted acetylenes [(1f)—(1i)] also gave the (*Z*)-configurational enol lactone, but small amounts of an (*E*)-isomer of a γ-*exo*-enol lactone and a δ-lactone (α-pyrone) were also formed. Spectral properties and stereochemistry of the *exo*-enol lactones are also discussed.

COMPOUNDS which have an unsaturated γ- or δ-lactone ring are reported to have carcinogenic [1] and anti-tumour [2] activity, as well as other biological properties.[3]

Recently many naturally occurring γ-*exo*-enol lactones have been reported; *i.e.* the mould metabolites tetrenolin [4] and the acetylenic sesquiterpene freelingyne [5] from *Eremophila freelingii*, the carotenoid pigment peridinin,[6] multicolic acid [7] from *Penicillium multicolor*, and a marine natural product with antimicrobial activity, fimbrolides.[8]

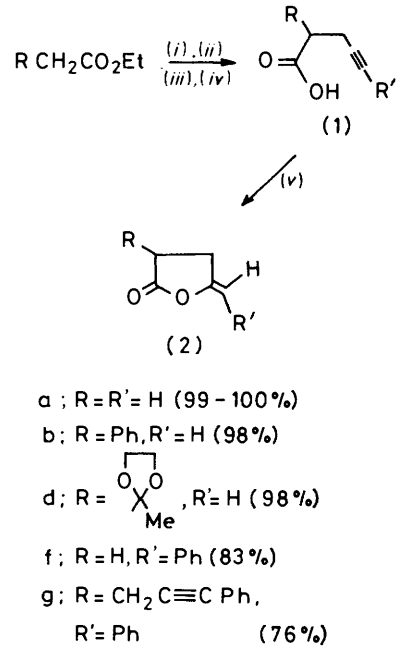
The synthetic approaches to γ-methylenebutyrolactones from furan,[9] azidoquinone,[10] maleic anhydride,[11] and phosphoranylidenebutenolide [12] have been described in the literature. The other known route is the cyclisation of acetylenic precursors, which includes the cyclisation of pent-4-ynoic acid using silver nitrate,[13] base,[14] triethylamine–Ac_2O,[15] and mercury(II) acetate [16] as catalysts.

The author has also reported a high-yield regioselective synthesis of γ-methylenebutyrolactones by the cyclisation of acetylenecarboxylic acids in the presence of a catalytic amount of mercury(II) oxide.[17] The present paper describes the synthesis of various γ-methylenebutyrolactones in detail.

RESULTS AND DISCUSSION

Pent-4-ynoic acid (1a) was prepared from diethyl malonate and prop-2-ynyl bromide followed by hydrolysis and decarboxylation, and by the oxidation [18] of pent-4-ynol with Jones reagent. The acetylenecarboxylic acid (1a) was heated at 60 °C for 30 min in the presence of yellow mercury(II) oxide without solvent, and γ-methylenebutyrolactone (2a) was obtained in quantitative yield. The structure of (2a) was determined by the spectral data; *i.e.* the i.r. spectrum of (2a) showed bands at 1 815, 1 670, and 890 cm^{-1} (five-membered *exo*-enol lactone carbonyl, double bond, and terminal methylene, respectively). The ^1H n.m.r. spectrum of this compound showed signals at δ 2.52—3.04 (m, 4 H), 4.25 (q, 1 H), and 4.66 (q, 1 H), for CH_2CH_2 and two olefinic proton signals.[19] The mass spectrum of (2a) gave the molecular peak at *m/e* 98.[16]

The molar ratio of (1a) : HgO = 100 : 4—6. No α- or β-angelica lactone or 3,4-dihydropyrone was formed in this reaction, and the lactone (2a) was the sole product. This cyclisation reaction proceeded equally well in aprotic solvents such as chloroform, acetone, benzene, dioxan, and dimethylformamide (DMF), but in a protic solvent (1a) gave a saturated lactol ether.[17] When (1a) was heated at 100 °C for 3—6 h without mercury(II) oxide, (2a) was not obtained and (1a) was recovered almost quantitatively.† The formation of (2a) was also



a ; R = R' = H (99 - 100%)
b ; R = Ph, R' = H (98%)
d ; R = , R' = H (98%)
f ; R = H, R' = Ph (83%)
g ; R = $CH_2C{\equiv}CPh$, R' = Ph (76%)

SCHEME (*i*) NaH–THF(DME) or LDA–THF; (*ii*) $R'C{\equiv}CCH_2X$ (X = Cl or Br); (*iii*) 5—10% NaOH–H_2O; (*iv*) H^+–H_2O, reflux; (*v*) HgO, heat, solvent

examined by treatment of (1a) with mercury(II) acetate. The results of the solvent effect are summarized in Table 1.

Acetylenecarboxylic acids (1b) and (1c) were prepared by a similar method to (1a). Compound (1d) was synthesized by alkylation of ethyl acetoacetate with prop-2-ynyl bromide followed by acetalisation and alkaline hydrolysis. Compound (1e) was obtained by the decomposition of the selenadiazole,[20] which was pre-

† Phenylpropargylidenemalonic acid (1i) cyclised when heated at 200 °C without a catalyst to give the 4-ylidenebutenolide (2i).[13]

pared from selenium dioxide and the semicarbazone of 2-acetylcyclohexanecarboxylic acid.

The cyclisation of (1b) and (1d) was carried out under similar conditions, and the *exo*-enol lactones (2b) and (2d) were obtained as colourless oils (both in quantitative yield); the ethylenedioxy-protecting group in (1d) did not decompose. Compounds (1c) and (1e) also cyclised to afford the desired *exo*-enol lactones (2c) and (2e) in 91 and 92% yields, respectively. In the cyclisation of (1c) the expected compounds (3) or (4) were not obtained and the spirodilactone (2c) was the sole product. The spectral data of all the *exo*-enol lactones are given in Table 2.

TABLE 1

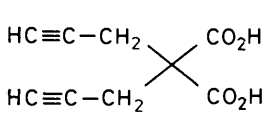
Solvent effect on the formation of (2a)

Catalyst	Solvent	Ratio (%) Lactone (2a)	: (1a)
HgO	None	100	0
	Chloroform	88	12
	Benzene	92	8
	Acetone	87	13
	Dioxan	55	45
	Methanol	*a*	
$Hg(OAc)_2$ [b]	Chloroform	81	19
	Benzene	90	10

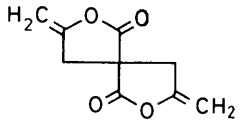
[a] No (2a) was obtained. The product was 5-methoxy-5-methyl-γ-butyrolactone. The details of this reaction will be presented elsewhere. [b] Amos and Katzenellenbogen [16] reported that mercuric acetate catalysed the cyclisation of (1a) in CH_2Cl_2 at room temperature for 24 h to give (2a) in 74% yield.

In contrast to these results, 5-phenylpent-4-ynoic acid (1f) did not cyclise during 5—7 h below 80 °C in the presence of mercury(II) oxide with or without solvent. However, when (1f) was heated at 110 °C in the presence of mercury(II) oxide without solvent for 3 h, compounds (2f) (37%) and [(5) + (6)] (41%) were obtained. Treatment of (1f) in refluxing DMF with mercury(II) oxide for 2 h gave the *exo*-enol lactone (2f) (83%), accompanied by a mixture of (5) and (6) (9%).

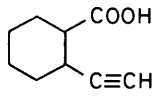
In principle, considering the steric configuration of these acetylenic acids, the cyclisation to γ- or δ-lactone is equally possible. The ease of cyclisation is sensitive not only to the nature of the substituent attached to the triple bond, but also on the reaction conditions.[21] It is also very difficult to assign the configuration of the *exo*-enol double bond, in cases where only one stereoisomer is available, because the chemical shift of the olefinic proton varies considerably depending on the structure of the molecule, especially the substituent attached to the *exo* double bond. However, when both isomers can be detected the chemical shift of the olefinic proton is at lower field in the (*E*)-isomer than in the (*Z*)-isomer.[22] The difference arises from the deshielding effect of the lactone oxygen.



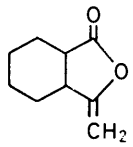
(1c)



(2c) 91%



(1e)



(2e) 92%

The cyclisation of (1f) gave three products (2f), (5), and (6). Compound (2f) has i.r. spectral bands at 1 800 ($\nu_{C=O}$, lactone) and 1 685 cm^{-1} ($\nu_{C=C}$). The n.m.r. spectrum of (2f) showed a quartet at δ 5.38 for the *exo*-enol olefinic proton. Although compounds (5) and (6) could not be separated, from the spectrum of the mixture the structures of (5) and (6) were assigned as follows:

TABLE 2

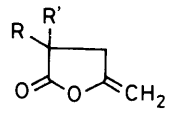
Spectral properties of γ-methylenebutyrolactones

Compound	I.r./cm^{-1} [a] ν(C=O)	ν(C=C)	N.m.r. (δ) [b] *Exo*-olefin proton		(*m/e*) [c] M^+	Base peak
(2a)	1 815	1 670, 885	4.25 (q)	4.66 (q)	98 (100)	
(2b)	1 800	1 670, 895	4.22 (m)	4.64 (q)	174 (41)	104
(2c)	1 790	1 675, 880	4.52 (m)	4.90 (m)	180 (30)	68
(2d)	1 800	1 670, 885	4.20 (q)	4.56 (q)	184 (14)	53
(2e)	1 800	1 670, 885	4.27 (q)	4.60 (q)	152 (21)	67
(2f)	1 800	1 685,	5.38 (q)		174 (100)	
(2g)	1 805	1 690	5.46 (s)		288 (44)	105
(2h)	1 790	1 680, 1 640	6.68 (s)	8.48 (s)	216 (100)	
(2i)	1 750	1 645	6.10 (s)	7.62 (s)	248 (100)	
(9)	1 785, 1 745	1 645	6.13 (d)	6.25 (q)	172 (62)	115

[a] I.r. spectra were measured for liquid films [(2a), (2b), (2d), and (2e)] and KBr discs [(2c), (2f)—(2i), and (9)]. [b] N.m.r. spectra were measured in CCl_4 [(2a), (2b), (2d), (2e), and (2g)], in $CDCl_3$ [(2c), (2f), (2i), and (9)] and in [$^2H_6$]DMSO (2h). [c] Relative intensity of molecular-ion peak in parentheses.

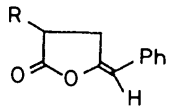
(5) was a γ-methylenebutyrolactone [(*E*)-isomer] and (6) was a six-membered lactone (α-pyrone).* The olefinic proton signal at δ 6.18 in the n.m.r. spectrum of (5) is at lower field than that of (2f), so that (5) is the (*E*)-isomer and (2f) is the (*Z*)-isomer.

Compound (1g) cyclised by similar treatment as for

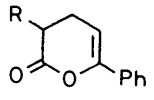


(3) R = CO_2H, R' = $CH_2C{\equiv}CH$

(4) R = H, R' = $CH_2C{\equiv}CH$



(5) R = H



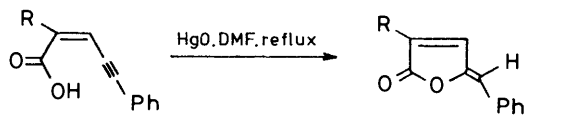
(6) R = H

(7) R = $CH_2C{\equiv}C$—Ph

(8) R = $CH_2C{\equiv}C$—Ph

(1f) and lactone (2g) was obtained in 76% yield. In this reaction also three isomers were obtained and the ratio was 9 : 1 {(2g) : [(7) + (8)]}.*

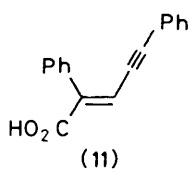
This cyclisation is also applicable to the syntheses of 4-ylidenebutenolides as evidenced by the successful synthesis of (2h) and (2i). Substituted pent-2-en-4-ynoic acids (1h) and (1i) were prepared from the condens-



(1h,i)

(2h) R = CO_2H (88%)

(2i) R = Ph (72%)



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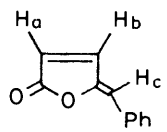

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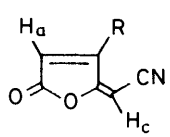

(10)

ation of 3-phenylprop-2-ynal with the corresponding acid or its ester. Diacid (1h) was cyclised in the presence of mercury(II) oxide in DMF to afford the 4-ylidenebutenolide (2h) in 88% yield as the sole product. Butenolide (2h) was heated at 240—250 °C for 20 min to give the decarboxylated product (9), m.p. 86—87 °C.[13]

Bothner-By and Harris [23] have shown that 1,4-vinyl protons in a *trans,trans*-configuration show coupling constants ranging from 1.3 to 1.9 Hz. All other long-range coupling constants were found to be appreciably smaller; *e.g.* the coupling constants for 1,4-vinyl protons in the *cis,trans*-configuration were found to range between 0 and 0.9 Hz. This can be applied to the determination of the stereochemistry of 4-ylidenebutenolides; thus, Moore [24] reported that the n.m.r. spectra of the butenolide (10) show an AB pattern for the H_aH_c vinyl protons with coupling constants of 1.4—1.6 Hz. These results agree with the proposed (*Z*)-configuration. The n.m.r. spectrum of the 4-ylidenebutenolide (9) (see Table 2) had J_{ac} 0.8 Hz; thus (9) has the (*Z*)-configuration.† This result indicates that (2h) also has the (*Z*)-configuration.

Compound (1i) was synthesised by the method of Wiley,[25] but the acetylenecarboxylic acid obtained was a mixture of (*E*)- and (*Z*)-isomers. This mixture was cyclised to give the desired 4-ylidenebutenolide (2i); (*E*)-2,5-diphenylpent-2-en-4-ynoic acid (11) was recovered. Compound (2i) has the (*Z*)-configuration, by comparison of the spectral data and melting point with those of the authentic sample.[26]

As described above, the cyclisation of the disubstituted acetylenes (1f)—(1i) is a little slow and needs a high temperature, compared with (1a)—(1e). Although three stereoisomeric enol lactones may be formed, where applicable the (*Z*)-isomer is usually formed in over 80% yield, and can be purified easily.

The present cyclisation method is very simple, and gives high yield and is regioselective. This method is applicable to many γ-*exo*-methylenebutyrolactone syntheses.

EXPERIMENTAL

N.m.r. spectra were recorded with a JEOL JNM MH-100 spectrometer using tetramethylsilane as internal standard. I.r. spectra were obtained on a Hitachi 260-10 spectrometer. Mass spectra were measured with a JEOL JMS-D300 spectrometer. T.l.c. and column chromatography used Merck Kieselgel G (type 60) and 70—230 mesh silica gel, respectively. THF and DME were distilled from $LiAlH_4$. DMF was distilled, and then all solvents were dried over molecular sieves (4A $^1/_{16}$).

Acetylenecarboxylic acids (1a), (1b), (1c), and (1f) were synthesised by the usual method, *i.e.* the alkylation of the corresponding ester with equimolar amount of prop-2-ynyl bromide followed by hydrolysis (5% sodium hydroxide solution) and appropriate decarboxylation.

Pent-4-ynoic acid (1a) was also synthesised by the reverse oxidation of pent-4-ynol [27] by the method of Holland,[18] m.p. of (1a) 52—55 °C (lit.,[18] 54.5—56.5 °C).

2-(1,1-*Ethylenedioxyethyl*)*pent-4-ynoic Acid* (1d).—Ethyl

* Compound (7) was isolated as a solid (>95% pure). From i.r. and n.m.r. spectra (7) is the (*E*)-isomer of the γ-*exo*-enol lactone. By comparison of these spectral results, the structures of (5) was also postulated to be the (*E*)-isomer (see Experimental section).

† Castañer and Pascual [13] synthesised the compounds (2h) and (9), but they did not describe their stereochemistry. The author re-examined their cyclisation method, and found that the product contained an (*E*) : (*Z*) mixture in the ratio 11 : 89 (see Experimental section).

2-acetylpent-4-ynoate [28] (3.36 g, 20 mmol) was treated with ethylene glycol (4.96 g, 80 mmol, excess) and toluene-*p*-sulphonic acid (142 mg) by the usual procedure. The acetalised product (2.12 g, 10 mmol) was hydrolysed with 5% sodium hydroxide solution (50 ml) and the reaction mixture was carefully neutralised at 5 °C on an ice–water bath with 1.4 mol equiv. of oxalic acid, and then extracted with chloroform (3 × 20 ml). The chloroform layer was worked up as usual to give a white solid, which was recrystallised from benzene to give (1d) (1.29 g, 76.7%) as colourless plates, m.p. 92—92.5 °C (Found: C, 58.8; H, 6.56. $C_9H_{12}O_4$ requires C, 58.7; H, 6.57%); $\nu_{max.}$ (KBr) 3 230 (≡CH), 2 100 (C≡C), 1 735, and 1 715 cm^{-1} (C=O); δ ($CDCl_3$) 1.40 (s, 3 H), 2.00 (t, 1 H, *J* 2.0 Hz), 2.60 (m, 2 H), 2.96 (q, 1 H), and 4.00 (m, 4 H).

2-*Ethynylcyclohexanecarboxylic Acid* (1e).—2-Acetylcyclohexanecarboxylic acid semicarbazone, m.p. 205—206 °C (Found: C, 52.7; H, 7.45; N, 18.4. $C_{10}H_{17}N_3O_3$ requires, C, 52.9; H, 7.54; N, 18.5%), was treated by a known method [20] and (1e) was obtained as colourless needles, m.p. 90—91 °C (from n-hexane) (Found: C, 70.9; H, 7.98. $C_9H_{12}O_2$ requires C, 71.0; H, 7.95%); $\nu_{max.}$ (KBr) 3 310 (≡CH), 2 120 (C≡C), and 1 695 cm^{-1} (C=O); δ (CCl_4) 1.04—2.18 (m, 8 H), 1.98 (d, 1 H, *J* 2.3 Hz), 2.40 (m, 1 H,) and 3.22 (m, 1 H) (Found: M^+, 152, $C_9H_{12}O_2$ requires *M*, 152).

2-(3-*Phenylprop*-2-*ynyl*)-5-*phenylpent*-4-*ynoic Acid* (1g).—By the usual procedure, diethyl malonate (4.8 g, 30 mmol) was alkylated with 3-phenylprop-2-ynyl chloride [29] (9.1 g, 60 mmol) to afford diethyl bis(3-phenylprop-2-ynyl)malonate (10.7 g, 92%) as colourless needles, m.p. 79—80 °C [from n-hexane–benzene (5 : 1)] (Found: C, 77.2; H, 6.4. $C_{25}H_{24}O_4$ requires C, 77.3; H, 6.23%); $\nu_{max.}$ (KBr) 1 735 (C=O), 1 600, 1 495, and 695 cm^{-1} (phenyl); δ (CCl_4) 1.24 (t, 6 H), 3.12 (s, 4 H), 4.15 (q, 4 H), and 7.00—7.32 (m, 10 H). This ester (5.82 g, 15 mmol) was hydrolysed by the usual method to give a white solid. This solid contained two components on t.l.c. with R_F value of 0.53 (component A) and 0.1—0.4 (component B) [eluant benzene–ethyl acetate (4 : 1)]. Component A dissolved in hot benzene easily, so the benzene solution was decanted from component B, concentrated, and the solid residue was recrystallized twice from n-hexane–benzene (3 : 1) to give colourless needles, m.p. 113.5—114.5 °C (337 mg) (Found: C, 83.2; H, 5.7. $C_{20}H_{16}O_2$ requires, C, 83.3; H, 5.59%); $\nu_{max.}$ (KBr) 1 700 (C=O), 1 495, and 695 cm^{-1} (phenyl); δ (CCl_4) 2.98 (s, 5 H) and 7.20—7.60 (m, 10 H) (Found: M^+, 288, $C_{20}H_{16}O_2$ requires *M*, 288). These data suggest that component A is 2-(3-phenylprop-2-ynyl)-5-phenylpent-4-ynoic acid (1g). The residue was recrystallised from benzene–ethyl acetate (2 : 1) to give 2,2-bis-(3-phenylprop-2-ynyl)malonic acid as colourless crystals, m.p. 164—167 °C; $\nu_{max.}$ (KBr) 1 710 (C=O), 1 495, and 695 cm^{-1} (phenyl); δ ([$^2H_6$]DMSO) 3.14 (s, 4 H) and 7.36 (s, 10 H). The mass spectrum of component B showed the same pattern as that of component A, so all the residue (4.70 g) was decarboxylated by heating with dioxan–H_2O (60 ml, 1 : 1) for 10 h. The resulting aqueous solution was concentrated to dryness and the residue was extracted with chloroform and worked up as usual. The residue obtained was mostly component A. The residue was treated as described above to give pure (1g), yield 3.46 g (80.1%).

4-*Phenylbut*-1-*en*-3-*yne*-1,1-*dicarboxylic Acid* (1h).—Compound (1h) was prepared by known method, m.p. 208—218 °C (lit.,[13] 214—218 °C).

2,5-*Diphenylpent*-2-*en*-4-*ynoic Acid* (1i).—An attempt was made to synthesise acid (1i) from phenylacetic acid (1.86 g, 13.7 mmol) and 3-phenylprop-2-ynal [30] (1.86 g, 14.3 mmol) by the method of Wiley.[25] But the yellow crystals obtained which were crystallized several times from ligroin, gave a different melting point (167—168 °C) from that reported (159 °C [25]). These yellow crystals did not cyclise under the condition described for general procedure B (see later). From these results the compound is believed to be (*E*)-2,5-diphenylpent-2-en-4-ynoic acid (11) (Found: C, 82.3; H, 4.8. $C_{17}H_{12}O_2$ requires, C, 82.2; H, 4.87%); $\nu_{max.}$ (KBr) 2 160 (C≡C), 1 680 (C=O), 1 560 (C=C), and 1 600 cm^{-1} (phenyl); δ ($CDCl_3$) 7.18 (s, 1 H), and 7.22—7.60 (m, 10 H) (Found: M^+, 248. $C_{17}H_{12}O_2$ requires *M*, 248). The mother-liquor gave a red solid which was recrystallized from ligroin to give yellowish orange crystals, m.p. 147—155 °C; $\nu_{max.}$ (KBr) 2 160 (C=C), 1 685—1 670 (broad, C=O), 1 580, 1 560 (C=C), 1 600, and 1 495 cm^{-1} (phenyl). This was considered to be a mixture of (1i) and (11), and so was used in the cyclisation step without further purification.

4,5-*Dihydro*-5-*methylenefuran*-2(3H)-*one* (2a).—*General procedure A*. In a 50-ml round-bottomed flask (1a) (980 mg, 10 mmol) and yellow mercury(II) oxide (58 mg) were heated at 60 °C for 30 min under a nitrogen atmosphere. The product was filtered and the solid was washed with ether. The filtrate was concentrated to give pure (2a) (970 mg, 99%), as a colourless liquid, b.p. 80—86 °C at 20 mmHg (lit.,[19] *ca.* 80 °C at 17 mmHg). The spectral data are listed in Table 2.

Solvent Effect on the Formation of Lactone (2a).—Acetylenecarboxylic acid (1a) (200 mg), yellow mercury(II) oxide (20 mg) or mercury(II) acetate (30 mg) and the appropriate solvent (2 ml) were mixed and the mixture was refluxed for 45 min under a nitrogen atmosphere. The catalyst was removed by filtration and the filtrate was concentrated, weighed, and the n.m.r. spectra recorded using carbon tetrachloride as solvent. Decomposition could not be detected from the n.m.r. spectra. The results are in Table 1.

4,5-*Dihydro*-5-*methylene*-3-*phenylfuran*-2(3H)-*one* (2b).—Compound (2b) was synthesised from (1b) (2.26 g, 13 mmol), m.p. 97.5—98.5 °C (lit.,[31] 98.5 °C), by treatment in refluxing chloroform for 4 h by general procedure A, yield 2.22 g (98.3%) of a colourless liquid, b.p. 109 °C at 0.5—0.8 mmHg (Found: C, 75.8; H, 5.73. $C_{11}H_{10}O_2$ requires C, 75.8; H, 5.73%).

3,8-*Dimethylene*-2,7-*dioxaspiro*[4.4]*nonane*-1,6-*dione* (2c).—According to general procedure A, (1c) (540 mg, 3 mmol), m.p. 140—142 °C (lit.,[32] 139—140 °C), was treated in refluxing acetone for 2 h; to give (2c) as colourless plates, m.p. 111—112 °C * [recrystallised from diethyl ether–carbon tetrachloride (5 : 1)], yield 492 mg (91.2%) (Found: C, 60.1; H, 4.60. $C_9H_8O_4$ requires C, 60.0; H, 4.48%).

3-(1,1-*Ethylenedioxyethyl*)-4,5-*dihydro*-5-*methylenefuran*-2(3H)-*one* (2d).—According to the general procedure A, (1d) (1.84 g, 10 mmol) was cyclised at 95 °C without solvent for 1 h to give pure (2d) (1.81 g, 98.2%) as a colourless oil, b.p. 112—113 °C at 1 mmHg (Found: C, 58.5; H, 6.55. $C_9H_{12}O_4$ requires, C, 58.7; H, 6.57%).

3-*Methylenehexahydrophthalide* (2e).—Compound (2e) was synthesised from (1e) (1.52 g, 10 mmol) by treatment in refluxing toluene for 2 h by general procedure A, yield 1.39 g (91.7%) of a colourless liquid, b.p. 76—78 °C at 3 mmHg

* Jäger reported [19] the m.p. of the bis-lactone (2c) as 92 °C. The spectral data and combustion analysis of the compound synthesised here also indicated the bis-lactone structure (2c).

(Found: C, 71.0; H, 7.90. $C_9H_{12}O_2$ requires C, 71.0; H, 7.95%).

5-Benzylidene-4,5-dihydrofuran-2(3H)-one (2f).—*General procedure B.* In a 50-ml round-bottomed flask, (1f) (696 mg, 4 mmol), m.p. 99—100 °C (lit.,[20] 99—100 °C), mercury(II) oxide (49 mg), and DMF (4 ml) were mixed and the mixture was heated at 160 °C for 2 h under nitrogen. DMF was removed under reduced pressure and the resulting residue was purified by silica gel column chromatography with benzene to give 640 mg (92%) of product which contained three components, (2f) (83%) and [(5) + (6)] (9%). The yellow paste was crystallised several times from carbon tetrachloride to give pure (2f) as colourless plates, m.p. 90—91 °C * (Found: C, 75.8; H, 5.9. $C_{11}H_{10}O_2$ requires C, 75.8; H, 5.79%). An attempt was made to cyclise compound (1f) (174 mg, 1 mmol) in refluxing chloroform (7 h) or benzene (5 h) in the presence of mercury(II) oxide (10 mg) under nitrogen. None of the desired product was obtained in chloroform solution; in benzene solution only a trace amount of product was detected (by t.l.c.) and almost all the starting material was recovered. Cyclisation of (1f) (348 mg, 2 mmol) at 110 °C was also attempted in the presence of mercury(II) oxide (27 mg) without solvent for 3 h. The reaction mixture was worked up as in general procedure A and the yellow paste obtained (271 mg, 78%) had its i.r. and n.m.r. spectra recorded; $\nu_{max.}$ (film) 1 800, 1 760 (C=O), 1 685—1 665 (C=C), 1 495, and 690 cm^{-1} (phenyl); δ ($CDCl_3$) 2.36—3.10 (m), 5.38 (q, signal A), 5.70 (t, signal B), 6.18 (t, signal C) and 7.00—7.60 (m, aromatic protons). The ratio of the three components (2f), (5), and (6) was calculated as follows; from the n.m.r. spectra the relative intensity of signals A, B, C, and the aromatic protons were 7.5, 6.1, 2.4, and 82.0. When this mixture was passed through a silica gel column as described above, the initial fractions contained much more (2f) than [(5) + (6)], and the later ones contained most of the [(5) + (6)], especially (6). The i.r. and n.m.r. spectra of the initial fractions are superimposable on those of (2f), and the spectra of the later fractions are as follows; $\nu_{max.}$ (film) 1 800 (C=O, shoulder), 1 760 (C=O), 1 675 (C=C, shoulder), 1 665 (C=C), and 1 495 cm^{-1} (phenyl); δ ($CDCl_3$) 2.36—2.80 (m, 3.6 H), 2.80—3.18 (m, 0.4 H), 5.70 (t, 0.9 H), 6.18 (t, 0.1 H), and 7.12—7.60 (m, 5 H). From these results it was concluded that the olefinic proton signals A, B, and C were those of (2f), (6), and (5), respectively. The ratio of (2f) : (5) : (6) in the yellow paste was calculated to be 47 : 38 : 15, and the yields of (2f) and [(5) + (6)] are thus 37 and 41%, respectively. Compounds (5) and (6) could not be separated, but from the above and the following results the structures of (5) and (6) were assigned as (*E*)-5-benzylidene-γ-butyrolactone and an α-pyrone, respectively.

5-Benzylidene-4,5-dihydro-3-(3-phenylprop-2-ynyl)furan-2(3H)-one (2g).—By the general procedure B, from (1g) (720 mg, 2.5 mmol), a yellow paste (600 mg, 83.3%) was obtained. The yellow paste was passed through a silica gel column with benzene as eluant and the initial fractions were collected and concentrated to give a white solid, which was recrystallised several times from n-hexane to give an amorphous white solid, m.p. 70—71 °C (Found: C, 83.5; H, 5.4. $C_{20}H_{16}O_2$ requires C, 83.3; H, 5.59%). The later fractions were also collected and concentrated to give a yellow solid; $\nu_{max.}$ (KBr) 1 790 (C=O), 1 675 (C=C), 1 490, and 695 cm^{-1} (phenyl); δ (CCl_4) 2.64—3.36 (m, 5 H), 5.46 (s, 0.2 H), 6.26 (m, 0.8 H), and 7.08—7.52 (m, 10 H). From these results the later fractions contained mainly the (*E*)-isomer of the γ-*exo*-enol lactone (7). As for the cyclisation products of (1f), the ratio of the reaction products (2g) : (7) : (8) were calculated as 91 : 6 : 3, and the yields of (2g) and [(7) + (8)] were 76 and 7%, respectively.

5-Benzylidene-2,5-dihydro-2-oxofuran-3-carboxylic Acid (2h).—According to general procedure B, (1h) (432 mg) was cyclised to (2h) (380 mg, 88%), a yellow amorphous solid, m.p. 220—222 °C (decomp.) [lit.,[13] 218 °C (decomp.)].

5-Benzylidenefuran-2(5H)-one (9).—Compound (1h) (200 mg) was treated by the method of Castañer [13] and the 4-ylidenebutenolide (9) was obtained as colourless needles, m.p. 86—87 °C (lit.,[13] 86—87 °C); δ ($CDCl_3$) 6.13 (d, 1 H, J_{ac} 0.8 Hz), 6.25 (q, 1 H, J_{ab} 5.5, J_{ac} 0.8 Hz), 7.62 (d, 1 H, J_{ab} 5.5 Hz), and 7.44—7.56 and 7.86—8.02 (m, 5 H). From these results, comparing the coupling constant J_{ac} of (9) with those of known (*Z*)-4-ylidenebutenolides [22,33] the stereochemistry of (9) was shown to be (*Z*). This was also supported by the following results; compound (9) was synthesised from (1h) by the method of Castañer,[13] and the yellow solid obtained, after purification by silica gel column chromatography, gave an (*E*),(*Z*)-mixture. The ratio of (*E*) : (*Z*) is *ca.* 11 : 89 (by n.m.r. spectrascopy). The chemical shift and coupling constant of the *exo*-olefin proton of the (*E*)-isomer of (9) are δ 6.42 and *J* 1.8 Hz. The yellow solid was also recrystallised twice from diethyl ether to give the pure (*Z*)-isomer of (9), m.p. 86—87 °C.

5-Benzylidene-3-phenylfuran-2(5H)-one (2i).—The mixture of (1i) and (11) (700 mg) was cyclised by general procedure B for 24 h. The reaction residue showed two spots on t.l.c. with R_F values 0.58 (2i) and 0.17 [recovered (11)] [eluant benzene]. The two components were then preparatively separated. Compound (11) was identified by melting point and the spectral data comparison with those of an authentic sample [recovered (11) 520 mg]. The other component (yellow solid) was recrystallised from ethanol to give 129 mg (71.7%) of (2i) † as yellow crystals, m.p. 141—142 °C (lit.,[26] 141—142 °C).

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* The melting point of (2f) was sharper than that previously reported.[17]

† Compound (1i) in the mixture was calculated as <180 mg, so that the yield of (2i) is >71.7%.

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