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Synthesis of 4-Alkyl-2(5*H*)-furanones

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An alternative method for the synthesis of 4-alkyl-2(5*H*)-furanones is described. Intramolecular carbene addition reaction of α-diazo compounds (**4**) in the presence of rhodium acetate or copper acetylacetonate furnished the bicyclic compounds (**5**), which were subjected to cyclopropane ring-opening reaction to give the 4-alkyl-4,5-dihydrofuran-2(3*H*)-ones (**6**) regioselectively. These compounds (**6**) were further converted into 4-alkyl-2(5*H*)-furanones (**14**) in several steps.

Keywords——carbene; intramolecular addition; butenolide; cyclopropanation; ring-opening reaction

2-Butenolides [2(5*H*)-furanones] are present in natural products[1-3] such as cardenolide and marrubiaside, and have also been used widely as synthetic intermediates.[4-7] With regard to the syntheses of butenolide,[2] several methods, including cyclization of γ-hydroxy acid,[8] oxidation of furans,[9] partial reduction of maleic anhydrides,[10] conversion of γ-butyrolactones,[11] and carbonyl insertion[12] using transition metals, have been reported to date. Some of those syntheses, however, required long reaction sequences, the yields were often not satisfactory, and some of the methods have limitations on the nature of the substituent at the C-4 position. We therefore investigated an alternative synthesis of 2-butenolides by utilizing an intramolecular carbene addition reaction[13] of allyl α-diazomalonate derivatives, followed by regioselective cyclopropane ring-opening reaction[14] as key reactions. Here we wish to report our results on butenolide synthesis.

The olefinic esters (**3a**, **b**), prepared from *trans*-crotyl alcohol (**1a**) and cinnamyl alcohol (**1b**) by treatment with the acid chloride of ethyl hydrogen malonate (**2**), were treated with tosyl azide in the presence of triethylamine in acetonitrile to afford the diazo compounds (**4a**, **b**) in 93 and 98% yields, respectively. Cyclization of **4a**, **b** was carried out as follows. A solution of the diazo compounds (**4a**, **b**) in benzene in the presence of rhodium acetate or copper acetylacetonate was refluxed for 1 h to give the bicyclic compounds (**5a**, **b**) in 61 and 67% yields, respectively. Regioselective ring opening of the cyclopropanes (**5a**—**d**)[15] using trimethylsilyl iodide[16] furnished the γ-butyrolactones (**6a**—**d**) as single products in 57—65% yields. In order to convert the cyclopropane derivative into the 2-butenolide derivative directly, thermolysis of **5d** was carried out by heating in *o*-dichlorobenzene at 180 °C for 2 h; however, the olefinic ester (**7**) was obtained in a low yield instead of the desired product.

When **6d** was treated with 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) in ether, the formation of the cyclopropane (**5d**) was observed instead of the expected elimination product. Reduction of the iodides (**6a**—**d**) with tri-*n*-butyltin hydride in the presence of azobisisobutyronitrile gave **8a**—**d**, which were subjected to hydrolysis, and the resulting carboxylic acids (**9a**—**d**), were decarboxylated to afford the β-substituted γ-butyrolactones (**10a**—**d**) in 53—66% yields from **8a**—**d**. Oxidative decarboxylation[17] of **9d** using lead tetraacetate, copper (II) acetate and pyridine in benzene did not afford the expected butenolide (**14d**), but the α-

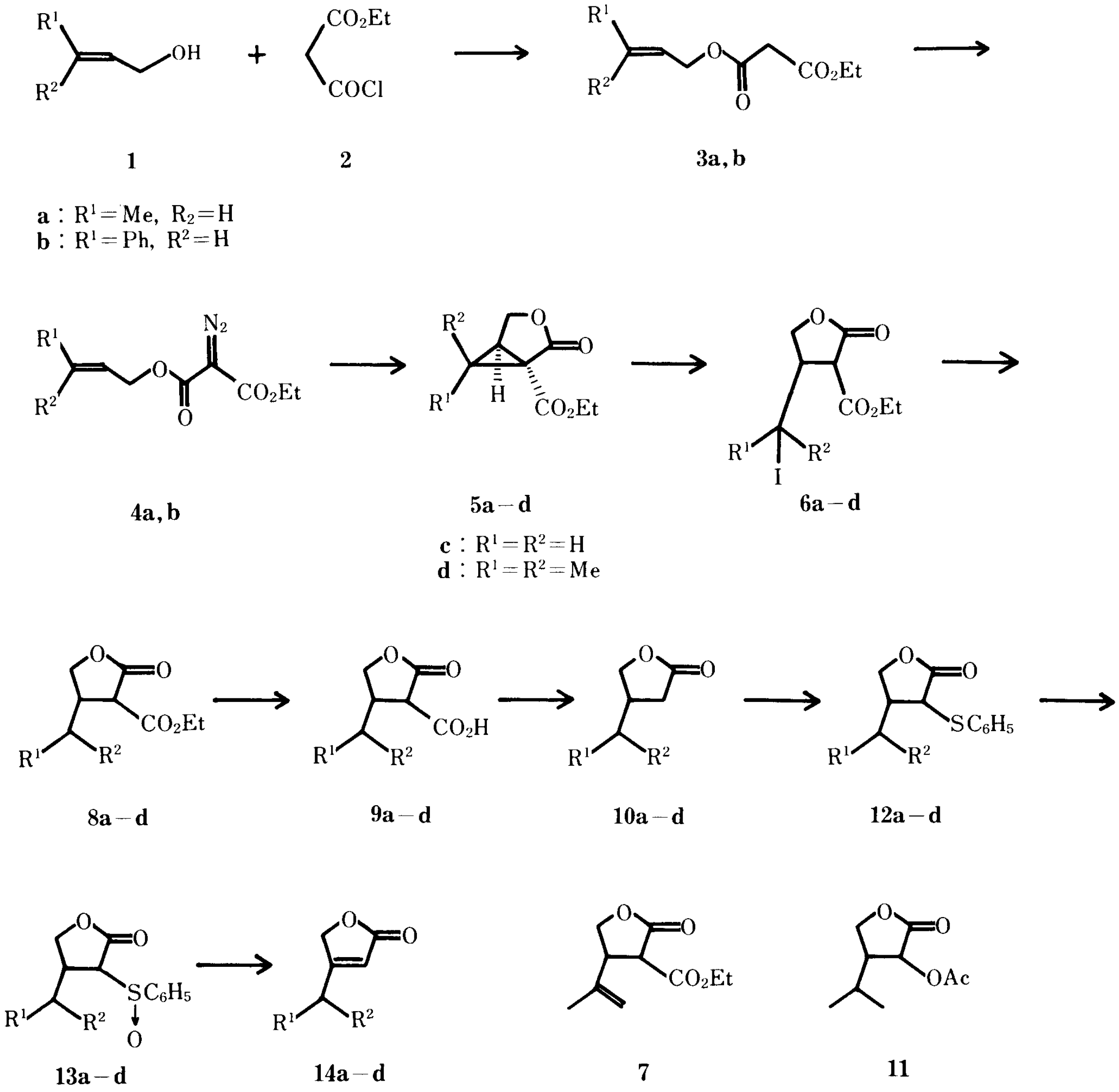

Chart 1

acetoxy-γ-butyrolactone (**11**) and the decarboxylation compound (**10d**) were obtained in 32 and 45% yields, respectively. Finally, conversion of the compounds (**10a**—**d**) into the corresponding 2-butenolides (**14a**—**d**) was achieved by adopting the known procedure[18] which involved the introduction of a phenyl sulfenyl group at the α-position to the carbonyl group, followed by its oxidative elimination by treatment with *m*-chloroperbenzoic acid to give the butenolides (**14a**—**d**) in 40—46% yields from **10a**—**d**.

Thus, the synthesis of 2-butenolides from allyl alcohols could be achieved by employing an intramolecular carbene addition reaction and subsequent cyclopropane ring-opening reaction as key steps. Since the synthesis of 3-alkylfurans from the corresponding 4-alkyl-2(5*H*)-furanones by reduction with diisobutylaluminum hydride followed by acid treatment has been reported,[5] this procedure represents an alternative synthesis of 3-alkylfurans.

Experimental

Infrared (IR) spectra were taken on a Hitachi 260-10 spectrophotometer. Nuclear magnetic resonance (NMR) spectra were recorded on JEOL PMS-60 SI and JEOL JNM-FX 100 spectrometers with tetramethylsilane as an internal standard. Low and high resolution mass spectra (MS) were taken on a JEOL JMS-D-300 spectrometer.

Melting points were determined on a Yanagimoto micro-melting point apparatus and are uncorrected.

***trans*-Crotyl Ethyl Malonate (3a)**——Oxalyl chloride (50.8 g, 0.40 mol) was added slowly to a stirred solution of ethyl hydrogen malonate (26.4 g, 0.20 mol) in dry CH_2Cl_2 (370 ml) at 0 °C, and the reaction mixture was refluxed for 2 h. Removal of the solvent afforded the acid chloride (**2**). The crude chloride was added slowly to a stirred solution of *trans*-crotyl alcohol (14.4 g, 0.20 mol), triethylamine (27.8 ml, 0.20 mol), and 4-dimethylaminopyridine (2.44 g, 0.02 mol) in dry CH_2Cl_2 (300 ml) at room temperature. The mixture was stirred for 2 h, then water was added and the resulting mixture was extracted with benzene. The extract was washed with brine, dried over Na_2SO_4 and concentrated to dryness *in vacuo*. The residue was purified by column chromatography on silica gel (350 g) using benzene as the eluant, to give **3a** (17.5 g, 47%) as a colorless oil. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 1740 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.25 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.75 (3H, d, J=5 Hz, $C\underline{H}_3CH$), 3.30 (2H, s, $COCH_2CO$), 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.60 (2H, d, J=5 Hz, OCH_2), 5.40—5.90 (2H, m, $C\underline{H}=C\underline{H}$). MS *m/e*: 186 ($M^+$). *Anal.* Calcd for $C_9H_{14}O_4$: C, 58.05; H, 7.58. Found: C, 57.79; H, 7.87.

Cinnamyl Ethyl Malonate (3b)——By the same procedure as described above for the preparation of **3a**, compound **3b** was obtained from cinnamyl alcohol (26.8 g, 0.20 mol) and the acid chloride (**2**) in 41% yield (20.4 g) as a colorless oil. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 1740 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.25 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 3.30 (2H, s, $COCH_2CO$), 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.80 (2H, d, J=6 Hz, OCH_2), 6.00—6.75 (2H, m, $C\underline{H}=C\underline{H}$), 7.35 (5H, s, ArH). MS *m/e*: 248 (M^+). *Anal.* Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.50. Found: C, 67.27; H, 6.86.

***trans*-Crotyl Ethyl α-Diazomalonate (4a)**——Tosyl azide (65.1 g, 0.33 mol) was added slowly to a stirred solution of **3a** (55.8 g, 0.30 mol) and triethylamine (46 ml, 0.33 mol) in acetonitrile (500 ml) at room temperature. Stirring was continued for 3 h, then the solvent was removed *in vacuo*, to give a residue which was purified by column chromatography on silica gel (900 g). Elution with benzene afforded the diazo compound (**4a**) (62.3 g, 98%) as a pale yellow oil. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 2150 (N_2), 1750 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.25 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.75 (3H, d, J=5 Hz, $C\underline{H}_3CH$). 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.60 (2H, d, J=5 Hz, OCH_2), 5.20—5.90 (2H, m, $C\underline{H}=C\underline{H}$).

Cinnamyl Ethyl α-Diazomalonate (4b)——By the same procedure as described above for the preparation of **4a**, compound **4b** was obtained from **3b** (74.4 g, 0.30 mol) and tosyl azide (65.1 g, 0.33 mol) in 93% yield (76.4 g) as a pale yellow oil. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 2150 (N_2), 1750 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.25 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.80 (2H, d, J=6 Hz, OCH_2), 6.00—6.75 (2H, m, $C\underline{H}=C\underline{H}$), 7.35 (5H, s, ArH).

1-Ethoxycarbonyl-6-methyl-3-oxa-2-oxobicyclo[3.1.0]hexane (5a)——A solution of **4a** (12.7 g, 0.06 mol) and $Cu(acac)_2$ (0.10 g) in dry benzene (300 ml) was refluxed for 1 h. Evaporation of the solvent gave the residue, which was chromatographed on silica gel using benzene–ethyl acetate (95 : 5, v/v) as the eluant, to give **5a** (6.7 g, 61%) as a pale yellow oil. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 1780 and 1720 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.25 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.28 (3H, d, J=5 Hz, $CHC\underline{H}_3$), 1.50—1.90 (1H, m, C_6-H), 2.35—2.70 (1H, m, C_5-H), 4.20 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.12—4.32 (2H, m, OCH_2). MS *m/e*: 184 (M^+). *Anal.* Calcd for $C_9H_{12}O_4 \cdot 0.1H_2O$: C, 58.12; H, 6.61. Found: C, 57.71; H, 6.72.

1-Ethoxycarbonyl-3-oxa-2-oxo-6-phenylbicyclo[3.1.0]hexane (5b)——By the same procedure as decribed above for the preparation of **5a**, compound **5b** was obtained from **4b** (16.4 g, 0.06 mol) and $Rh_2(OAc)_4$ (0.10 g) in 67% yield (9.9 g) as colorless plates, mp 91—92 °C (from benzene–hexane). IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 1780 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.90 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 2.90 (1H, d, J=6 Hz, $C\underline{H}Ph$), 3.15—3.45 (1H, m, C_5-H), 4.00 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.35—4.45 (2H, m, OCH_2), 7.30 (5H, s, ArH). MS *m/e*: 246 (M^+). *Anal.* Calcd for $C_{14}H_{14}O_4$: C, 68.28; H, 5.73. Found: C, 68.10; H, 5.78.

Thermolysis of 5d——A solution of **5d** (0.10 g, 0.5 mmol) in *o*-dichlorobenzene (5 ml) was stirred at 180 °C for 2 h. Evaporation of the solvent gave the crude product, which was chromatographed on silica gel using benzene as the eluant to give 0.03 g (30%) of 3-ethoxycarbonyl-4-isopropenyl-4,5-dihydrofuran-2(3*H*)-one (**7**) as a colorless oil. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 1780 and 1720 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.30 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.75 (3H, s, $C=C\text{–}CH_3$), 3.40—3.75 (2H, m, C_3-H and C_4-H), 4.05 and 4.50 (each 1H, each dd, J=8, 8 Hz, C_5-H_2), 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.85 and 4.93 (each 1H, each s, $C=CH_2$). MS *m/e*: 198 (M^+).

3-Ethoxycarbonyl-4-(1-iodoalkyl)-4,5-dihydrofuran-2(3*H*)-one (6a—d): Typical Procedure——Trimethylsilyl chloride (13.0 g, 0.12 mol) was added slowly to a stirred solution of the cyclopropane derivative (**5c**)[15] (10.2 g, 0.06 mol) in dry acetonitrile (300 ml) in the presence of sodium iodide (18.0 g, 0.12 mol) at room temperature, and the reaction mixture was stirred for 15 h. The mixture was poured into 5% Na_2SO_3 saturated with KF and extracted with ether. The extract was washed with brine, dried over Na_2SO_4 and concentrated to dryness *in vacuo*. The residue was chromatographed on silica gel using benzene–ethyl acetate (95 : 5, v/v) as the eluant.

3-Ethoxycarbonyl-4-(1-iodoethyl)-4,5-dihydrofuran-2(3*H*)-one (**6a**): Reddish oil.[19] Yield: 57%. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 1780 and 1740 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.30 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.90 (3H, d, J=7 Hz, $CHC\underline{H}_3$), 2.75—3.25 (1H, m, C_4H), 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.00—4.70 (3H, m, C_5-H_2 and CHI). MS *m/e*: 312 (M^+).

3-Ethoxycarbonyl-4-(1-iodobenzyl)-4,5-dihydrofuran-2(3*H*)-one (**6b**): Reddish oil.[19] Yield: 60%. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}: 1780 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.10 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 3.10 (1H, d, J=8 Hz, C_3-H), 3.80 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.00—5.00 (4H, m, C_5-H_2, C_4-H and $C\underline{H}Ph$), 7.30 (5H, s, ArH). MS *m/e*: 374 (M^+).

3-Ethoxycarbonyl-4-iodomethyl-4,5-dihydrofuran-2(3*H*)-one (**6c**): Reddish oil.[19] Yield: 59%. IR $\nu_{\text{max}}^{\text{CHCl}_3}$ cm^{-1}:

1780 and 1740 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.30 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 3.10—3.45 (1H, m, C_4-H), 3.28 (2H, d, J=7 Hz, CH_2I), 3.30 (1H, d, J=7 Hz, C_3-H), 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.00—4.60 (2H, m, C_5-H_2). MS *m/e*: 298 (M^+).

3-Ethoxycarbonyl-4-(1-iodoisopropyl)-4,5-dihydrofuran-2(3*H*)-one (**6d**): Reddish oil.[19] Yield: 65%. IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.30 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.95 (6H, s, $C(CH_3)_2$), 2.25—2.55 (1H, m, C_4-H), 3.60 (1H, d, J=9 Hz, C_3-H), 4.30 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 4.10—4.65 (2H, m, C_5-H_2). MS *m/e*: 327 (M^++1).

Reaction of 6d with DBU——A solution of **6d** (0.26 g, 0.8 mmol) in ether (8 ml) containing DBU (0.36 ml, 2.4 mmol) was stirred at room temperature for 10 h. Evaporation of the solvent gave the crude product, which was chromatographed on silica gel using benzene as the eluant to give 0.15 g (95%) of **5d**.

3-Ethoxycarbonyl-4-alkyl-4,5-dihydrofuran-2(3*H*)-one (8a—d): General Procedure——A solution of the iodide (**6a**—**d**) (0.02 mol) and tri-*n*-butyltin hydride (0.02 mol) in dry tetrahydrofuran (THF) (140 ml) was heated at 50 °C, and then a catalytic amount of α,α'-azobisisobutyronitrile was added. The mixture was refluxed for 1 h, then diluted with benzene, washed with water and brine, and dried over Na_2SO_4. Removal of the solvent gave the residue, which was chromatographed on silica gel using benzene–hexane (9 : 1, v/v) as the eluant.

3-Ethoxycarbonyl-4-ethyl-4,5-dihydrofuran-2(3*H*)-one (**8a**): Colorless oil.[19] Yield: 61%. IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1740 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.95 (3H, t, J=7 Hz, $CHCH_2C\underline{H}_3$), 1.30 (3H, t, J=7 Hz, -$OCH_2C\underline{H}_3$), 1.50—1.90 (2H, m, $CHC\underline{H}_2$-), 2.60—3.10 (1H, m, C_4-H), 3.30 (1H, d, J=7 Hz, C_3-H), 3.90 and 4.55 (each 1H, each dd, J=8, 8 Hz, C_5-H_2). MS *m/e*: 186 (M^+). *Anal.* Calcd for $C_9H_{14}O_4$: C, 57.50; H, 7.56. Found: C, 57.35; H, 7.77.

3-Ethoxycarbonyl-4-benzyl-4,5-dihydrofuran-2(3*H*)-one (**8b**): Pale yellow oil.[19] Yield: 78%. IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1740 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.20 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 2.75 (2H, d, J=6 Hz, $C\underline{H}_2Ph$), 3.05—3.45 (2H, m, C_3-H and C_4-H), 4.00 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 3.70—4.45 (2H, m, C_5-H_2), 7.10 (4H, s, ArH). MS *m/e*: 248 (M^+). *Anal.* Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.50. Found: C, 67.62; H, 6.66.

3-Ethoxycarbonyl-4-methyl-4,5-dihydrofuran-2(3*H*)-one (**8c**): Colorless oil.[19] Yield: 75%. IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1740 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.25 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.30 (3H, d, J=7 Hz, $CHC\underline{H}_3$), 2.80—3.20 (1H, m, C_4-H), 3.15 (1H, d, J=7 Hz, C_3-H), 3.85 and 4.50 (each 1H, each dd, J=8, 8 Hz, C_5-H_2), 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$). MS *m/e*: 172 (M^+). *Anal.* Calcd for $C_8H_{12}O_4$: C, 55.80; H, 7.03. Found: C, 55.86; H, 7.22.

3-Ethoxycarbonyl-4-isopropyl-4,5-dihydrofuran-2(3*H*)-one (**8d**): Colorless oil.[19] Yield: 64%. IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.95 (6H, d, J=6 Hz, $C(CH_3)_2$), 1.30 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.45—2.00 (1H, m, -$C\underline{H}(CH_3)_2$), 2.45—3.05 (1H, m, C_4-H), 3.30 (1H, d, J=9 Hz, C_3-H), 4.25 (2H, q, J=7 Hz, $C\underline{H}_2CH_3$), 3.85—4.75 (2H, m, C_5-H_2). MS *m/e*: 200 (M^+). *Anal.* Calcd for $C_{10}H_{16}O_4$: C, 59.98; H, 8.05. Found: C, 60.07; H, 8.25.

3-Carboxyl-4-alkyl-4,5-dihydrofuran-2(3*H*)-one (9a—d): General Procedure——A 0.25 N NaOH solution (70 ml) was added to a stirred solution of the ester (**8a**—**d**) (17.5 mmol) in EtOH (130 ml) at 0 °C and the mixture was stirred at room temperature for 1 h. After removal of the solvent, the residue was diluted with water (100 ml), washed with benzene, and acidified with 5% HCl at 0 °C. The acidic solution was extracted with chloroform. The extract was washed with water, dried over Na_2SO_4 and evaporated to give the acid (**9a**—**d**),[19] which was used for the next reaction without further purification.

3-Carboxyl-4-ethyl-4,5-dihydrofuran-2(3*H*)-one (**9a**): Pale yellow oil. Yield: 90%. IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1730 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.00 (3H, t, J=7 Hz, $CH_2C\underline{H}_3$), 1.30—1.80 (2H, m, $CHC\underline{H}_2CH_3$), 2.70—3.10 (1H, m, C_4-H), 3.30 (1H, d, J=9 Hz, C_3-H), 3.95 and 4.50 (each 1H, each dd, J=8, 8 Hz, C_3-H_2), 9.70 (1H, s, CO_2H). MS *m/e*: 158 (M^+). High resolution MS *m/e*: Calcd for $C_7H_{10}O_4$: 158.0577. Found: 158.0564.

3-Carboxyl-4-benzyl-4,5-dihydrofuran-2(3*H*)-one (**9b**): Pale yellow oil. Yield: 90%. IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1740 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 2.85 (2H, d, J=4 Hz, $C\underline{H}_2Ph$), 3.00—3.45 (1H, m, C_4-H), 3.30 (1H, d, J=8 Hz, C_3-H), 3.80—4.60 (2H, m, C_5-H_2), 7.20 (5H, s, ArH), 8.10 (1H, s, CO_2H). MS *m/e*: 220 (M^+). High resolution MS *m/e*: Calcd for $C_{12}H_{12}O_4$: 220.0734. Found: 220.0702.

3-Carboxyl-4-methyl-4,5-dihydrofuran-2(3*H*)-one (**9c**): Pale yellow oil. Yield: 88%. IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1740 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.25 (3H, d, J=6 Hz, CH_3), 2.85—3.25 (1H, m, C_4-H), 3.25 (1H, d, J=9 Hz, C_3-H), 3.90 and 4.50 (each 1H, each dd, J=8, 8 Hz, C_5-H_2), 8.30 (1H, s, CO_2H). MS *m/e*: 145 (M^++1). High resolution MS *m/e*: Calcd for $C_6H_9O_4$: 145.0497. Found: 145.0462.

3-Carboxyl-4-isopropyl-4,5-dihydrofuran-2(3*H*)-one (**9d**): Colorless needles, mp 54—55 °C (from benzene–hexane). Yield: 89% IR $\nu_{\max}^{\mathrm{CHCl_3}}$ cm^{-1}: 1780 and 1740 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.95 and 1.00 (each 3H, each d, J=7 Hz, $CH(C\underline{H}_3)_2$), 1.50—2.00 (1H, m, -$C\underline{H}(CH_3)_2$), 2.70—3.00 (1H, m, C_4-H), 3.40 (1H, d, J=9 Hz, C_3-H), 4.05 and 4.60 (each 1H, each dd, J=8, 8 Hz, C_5-H_2), 6.35 (1H, s, CO_2H). MS *m/e*: 173 (M^++1). High resolution MS *m/e*: Calcd for $C_8H_{13}O_4$: 173.0814. Found: 173.0822.

4-Alkyl-4,5-dihydrofuran-2(3*H*)-one (10a—d): General Procedure——A solution of the carboxylic acid (**9a**—**d**) (10 mmol) in *N*, *N*-dimethylacetamide (50 ml) was refluxed for 1 h. The mixture was extracted with benzene, and the extract was washed with brine, dried over Na_2SO_4 and evaporated to dryness *in vacuo*. The residue was chromatographed on silica gel using benzene as the eluant.

4-Ethyl-4,5-dihydrofuran-2(3*H*)-one (**10a**): Colorless oil. Yield: 64%. Its spectroscopic data were identical with those reported.[20)]

4-Benzyl-4,5-dihydrofuran-2(3*H*)-one (**10b**): Colorless oil. Yield: 62%. Its spectroscopic data were identical with those reported.[21)]

4-Methyl-4,5-dihydrofuran-2(3*H*)-one (**10c**): Colorless oil. Yield: 61%. Its spectroscopic data were identical with those reported.[22)]

4-Isopropyl-4,5-dihydrofuran-2(3*H*)-one (**10d**): Pale yellow oil. Yield: 74%. Its spectroscopic data were identical with those reported.[23)]

Oxidative Decarboxylation of 9d with Lead Tetraacetate——A solution of **9d** (0.37 g, 2.1 mmol), copper (II) acetate (0.11 g, 0.5 mmol) and pyridine (0.65 ml) in benzene (15 ml) was stirred for 0.5 h and then lead tetraacetate (1.90 g, 4.2 mmol) was added. The reaction mixture was refluxed for 1 h under shielding from light. After cooling, the reaction mixture was diluted with benzene and the organic layer was washed with water and brine, dried over Na_2SO_4 and evaporated to dryness *in vacuo*. The residue was chromatographed on silica gel to give 0.12 g (45%) of **10d** and 3-acetoxy-4-isopropyl-4,5-dihydrofuran-2(3*H*)-one (**11**) (0.15 g, 38%). Compound **11** was obtained as a colorless oil. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1780 and 1750 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.95 and 0.98 (each 3H, each d, $J=7$ Hz, $C(CH_3)_2$), 1.70—2.00 (1H, m, $CHC\underline{H}(CH_3)_2$), 2.20 (3H, s, $COCH_3$), 2.35—2.70 (1H, m, C_4-H), 3.95—4.60 (2H, m, C_5-H_2), 5.40 and 5.55 (each 0.5H, each d, $J=10$, 7 Hz, C_3-H). MS *m/e*: 186 (M^+).

4-Alkyl-3-phenylthio-4,5-dihydrofuran-2(3*H*)-one (12a—d): General Procedure——A solution of lithium diisopropylamide (24 mmol) in dry THF was added to a stirred solution of γ-butyrolactone (**10a**—**d**) (20 mmol) in dry THF (20 ml) at −78 °C. The mixture was stirred for 0.5 h, then a solution of benzenesulfenyl chloride (22 mmol) in dry THF (20 ml) was added and the whole was further stirred at −78 °C for 1 h. After quenching with aqueous ammonium chloride solution, the mixture was extracted with $CHCl_3$ and the extract was washed with aqueous ammonium chloride and brine, and dried over Na_2SO_4. Evaporation of the solvent gave the residue, which was chromatographed on silica gel using benzene–hexane (9 : 1, v/v) as the eluant.

4-Ethyl-3-phenylthio-4,5-dihydrofuran-2(3*H*)-one (**12a**): Pale yellow oil. Yield: 60%. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1780 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.90 (3H, t, $J=7$ Hz, $CH_2C\underline{H}_3$), 1.30—1.80 (2H, m, $C\underline{H}_2CH_3$), 2.05—2.60 (1H, m, C_4-H), 3.40 (1H, d, $J=8$ Hz, C_3-H), 3.90 and 4.25 (each 1H, each dd, $J=9$ Hz, 6 Hz, C_5-H_2), 7.20—7.60 (5H, m, ArH). MS *m/e*: 222 (M^+). High resolution MS *m/e*: Calcd for $C_{12}H_{14}O_2S$: 222.0713. Found: 222.0712.

4-Benzyl-3-phenylthio-4,5-dihydrofuran-2(3*H*)-one (**12b**): Pale yellow oil. Yield: 62%. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1780 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 2.50—3.15 (3H, m, C_4-H and $C\underline{H}_2Ph$), 3.45 (1H, d, $J=6$ Hz, C_3-H), 3.65—4.30 (2H, m, C_5-H_2), 7.15 (5H, s, CH_2-$C_6\underline{H}_5$), 7.30 (5H, m, SC_6H_5). MS *m/e*: 284 (M^+). High resolution MS *m/e*: Calcd for $C_{17}H_{16}O_2S$: 284.0869. Found: 284.0849.

4-Methyl-3-phenylthio-4,5-dihydrofuran-2(3*H*)-one (**12c**): Pale yellow oil. Yield: 58%. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1780 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 1.25 (3H, d, $J=7$ Hz, CH_3), 2.50 (1H, m, C_4-H), 3.35 (1H, d, $J=8$ Hz, C_3-H), 3.90 and 4.30 (each 1H, each dd, $J=9$, 6 Hz, C_5-H_2). 7.40 (5H, m, ArH). MS *m/e*: 208 (M^+). High resolution MS *m/e*: Calcd for $C_{11}H_{12}O_2S$: 208.0557. Found: 208.0532.

4-Isopropyl-3-phenylthio-4,5-dihydrofuran-2(3*H*)-one (**12d**): Pale yellow oil. Yield: 60%. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1770 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.95 and 1.00 (each 3H, each d, $J=6$ Hz, $C(CH_3)_2$), 1.60—1.90 (1H, m, $-C\underline{H}(CH)_3)_2)$, 2.10—2.40 (1H, m, C_4-H), 3.50 (1H, d, $J=6$ Hz, C_3-H), 3.80—4.40 (2H, m, C_5-H_2), 7.40 (5H, m, ArH). MS *m/e*: 236 (M^+). High resolution MS *m/e*: Calcd for $C_{13}H_{16}O_2S$: 236.0869. Found: 236.0659.

4-Alkyl-3-phenylsulfinyl-4,5-dihydrofuran-2(3*H*)-one (13a—d): General Procedure——A solution of *m*-chloroperbenzoic acid (22 mmol) in CH_2Cl_2 (50 ml) was added in portions to a stirred solution of the sulfide (**12a**—**d**) (20 mmol) in CH_2Cl_2 (300 ml) at 0 °C and the mixture was further stirred at 0 °C for 0.5 h. The organic layer was washed with aqueous sodium bicarbonate, water and brine, and dried over Na_2SO_4. Removal of the solvent gave the residue, which was chromatographed on silica gel using CH_2Cl_2 as the eluant. The products (**13a**—**d**) obtained are mixtures of diastereomers of the sulfoxide group and the stereochemistry at the C_3- and C_4-positions has not been determined.

4-Ethyl-3-phenylsulfinyl-4,5-dihydrofuran-2(3*H*)-one (**13a**): Colorless oil. Yield: 93%. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1760 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.55 and 0.95 (3H, each t, $J=7$ Hz, $CH_2C\underline{H}_3$), 1.40—1.80 (2H, m, $C\underline{H}_2CH_3$), 2.60—3.00 (1H, m, C_4-H), 3.70 (1H, d, $J=4$ Hz, C_3-H), 3.30—4.60 (2H, m, C_5-H_2), 7.45 (5H, s, ArH). MS *m/e*: 238 (M^+).

4-Benzyl-3-phenylsulfinyl-4,5-dihydrofuran-2(3*H*)-one (**13b**): Colorless oil. Yield: 93%. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1770 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 2.50 (2H, t, $J=8$ Hz, $C\underline{H}_2Ph$), 2.90—3.50 (1H, m, C_4-H), 3.85 (1H, d, $J=4$ Hz, C_3-H), 3.65—4.55 (2H, m, C_5-H_2), 7.20 (5H, s, $CH_2C_6\underline{H}_5$), 7.50 (5H, s, SOC_6H_5). MS *m/e*: 301 (M^++1).

4-Methyl-3-phenylsulfinyl-4,5-dihydrofuran-2(3*H*)-one (**13c**): Colorless oil. Yield: 92%. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1760 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.70 and 1.25 (3H, each d, $J=6$ Hz, CH_3), 2.80—3.45 (1H, m, C_4-H), 3.70 (1H, d, $J=5$ Hz, C_3-H), 3.80—4.40 (2H, m, C_5-H_2), 7.50 (5H, s, ArH). MS *m/e*: 224 (M^+).

4-Isopropyl-3-phenylsulfinyl-4,5-dihydrofuran-2(3*H*)-one (**13d**): Colorless oil. Yield: 95%. IR $\nu_{max}^{CHCl_3}$ cm^{-1}: 1760 (C=O). ^{1}H-NMR ($CDCl_3$) δ: 0.58 and 0.64 (2 × 1.5H, each d, $J=6$ Hz, $C(C\underline{H}_3)_2$), 0.95 (3H, d, $J=6$ Hz, $C(CH_3)_2$), 1.40—2.00 (1H, m, $CH(CH_3)_2$), 2.60—2.90 (1H, m, C_4-H), 3.30 (1H, d, $J=3$ Hz, C_3-H), 3.75—4.50 (2H, m, C_5-H_2), 7.50 (5H, s, ArH). MS *m/e*: 252 (M^+).

4-Alkyl-2(5*H*)-furanone (14a—d): General Procedure——A solution of the sulfoxide (**13a**—**d**) (30 mmol) in toluene (90 ml) containing $NaHCO_3$ (45 mmol) was refluxed for 1 h. After cooling, the reaction mixture was diluted with $CHCl_3$ and the organic layer was washed with water and brine, dried over Na_2SO_4 and evaporated to dryness *in vacuo*. The residue was chromatographed on silica gel using CH_2Cl_2 as the eluant.

4-Ethyl-2(5*H*)-furanone (**14a**): White solid, mp 35—36 °C (from benzene–hexane) [lit.,6) mp 36 °C]. Yield: 79%. Its spectroscopic data were identical with those reported.6)

4-Benzyl-2(5*H*)-furanone (**14b**): Colorless oil. Yield: 78%. Its spectroscopic data were identical with those reported.24)

4-Methyl-2(5*H*)-furanone (**14c**): Colorless oil. Yield: 75%. Its spectroscopic data were identical with those reported.6)

4-Isopropyl-2(5*H*)-furanone (**14d**): Colorless oil. Yield: 80%. Its spectroscopic data were identical with those reported.25)

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