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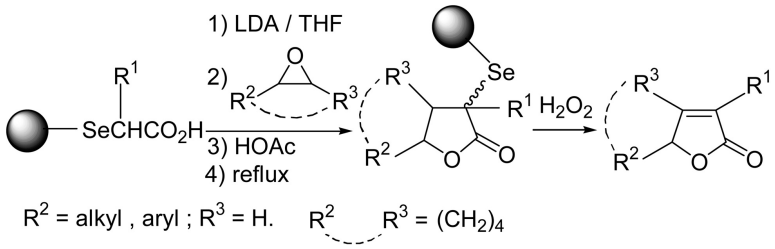

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A Facile Solid-Phase Synthesis of Substituted 2(5*H*)-Furanones from Polymer-Supported α-Selenocarboxylic Acids

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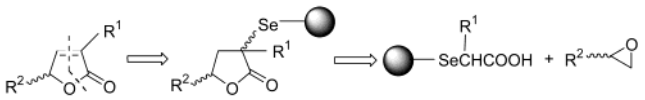
The synthesis of polystyrene-supported α-selenoacetic acid, α-selenopropionic acid, and α-selenophenylacetic acid is described. The reaction of the dilithio derivatives of polymer-supported α-selenocarboxylic acids with racemic epoxides or optically active styrene oxide afforded polystyrene-supported γ-substituted α-selenobutyrolactones. The α-alkylation reaction of γ-substituted polystyrene-supported α-selenobutyrolactones provided another route for the synthesis of polystyrene-supported α,γ-disubstituted α-selenobutyrolactones. Subsequent oxidation−elimination with an excess of 30% hydrogen peroxide at room temperature afforded substituted (3- and 5-mono-; 3,4- and 3,5-di) 2(5*H*)-furanones in high yields and good purities.

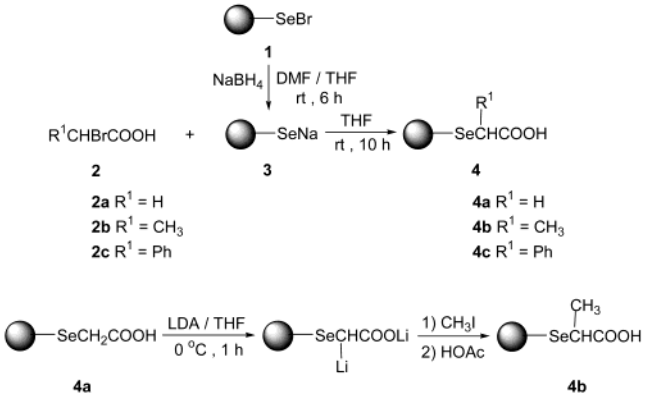
Introduction

Polymer-supported reagents have attracted growing interest because they can provide attractive and practical methods for the synthesis of libraries as a result of simple operation and the potential of automation.[1] Butenolides are a class of compounds of current interest because of the potential broad range of biological activities of natural and unnatural butenolide-containing products.[2] Several soild-phase butenolide syntheses have been reported.[3] However, it is still desirable to develop additional efficient solid-phase methodologies for the synthesis of butenolides. Polymers with selenium functionalities have been known for a long time.[4] It would be interesting to develop solid-phase organoselenium chemistry with a combined advantage of decreased volatility and simplification of product workup. Recently, selenium-based approaches for solid-phase organic synthesis have been reported by our group and others.[3a,3b,5] Fujita et al.[3a,3b] reported the preparation of the corresponding γ-substituted γ-lactones from (*E*)-4-phenyl-but-3-enoic acid and (*E*)-3-hexenoic acid using polystyrene-bound selenocyanate or selenenyl bromide. However, this solid-phase synthetic method seems to have some limitations, such as a lower yield and a higher reaction temperature. Furthermore, to the best of our knowledge, no SPOS method has been attempted for the synthesis of optically active butenolides so far. Herein, we wish to report a novel solid-phase approach to racemic or optically active butenolides[6] using polymer-supported α-selenocarboxylic acids (Scheme 1). A remarkable advantage of these new polymer-supported selenium compounds is their convenience of handing and totally odorless nature, as compared to the nonbound reagents.

Scheme 1



Scheme 2



Results and Discussion

The polystyrene-supported α-seleno group was chosen since it appears (1) to facilitate the generation of the selenium-stabilized adjacent carbanion species, which would have sufficient nucleophilicity to react with epoxides or alkyl halides before or after the construction of the γ-lactone ring, and (2) to be a versatile traceless linker that can be easily cleaved by oxidation−elimination to form a double bond in the final products.

The polystyrene-supported α-selenocarboxylic acids **4** can be prepared by the reaction of polystyrene-supported sodium selenide **3**[5c,5l] with α-bromocarboxylic acids **2** (Scheme 2). Polystyrene-supported α-selenopropionic acid **4b** can also be synthesized by subsequently treating α-selenoacetic acid resin **4a** with lithium diisopropylamide and methyl iodide in high yield. The minimum loadings of COOH of resins **4a**−**4c**, verified by their FT-IR spectra showing a strong

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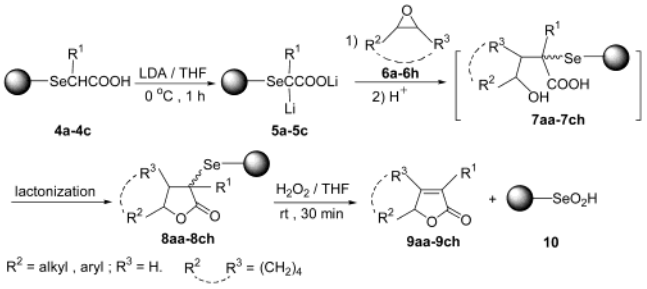
Scheme 3



carbonyl absorption at 1700−1710 cm^{-1}, were determined by acid−base titration [7] to be 1.27 mmol/g (**4a**, R^1 = H), 1.20 mmol/g (**4b**, R^1 = CH_3), and 1.12 mmol/g (**4c**, R^1 = Ph), respectively. Resin **4** can be stored at room temperature for a long period of time without diminution of capacity or the liberation of a foul smell.

The dianion resin **5a**−**5c** was easily generated by treating resins **4a**−**4c** with lithium diisopropylamide [8] (Scheme 3). Treatment of **5a**−**5c** with epoxides **6a**−**6h** in THF afforded γ-hydroxy-α-selenocarboxylic acid resins **7aa**−**7ch**. The lactonization of resins **7aa**−**7ch** would be the key for the success of this protocol. Here, the lactonization was investigated starting from α-selenoacetic acid resin **4a** and styrene oxide **6a**. When DCC/DMAP was used at room temperature or under reflux in CH_2Cl_2 or THF for 5 h or even for a longer time, the lactonization on solid-phase was not complete, as monitored by an FT-IR study, which showed two moderately strong peaks of carbonyl absorptions at 1702 and 1770 cm^{-1}. The lactonization with benzenesulfonyl chloride/pyridine [9] and EDAC/DMAP[6a] was better. However, the best result was obtained when the reaction suspension in THF was heated [6b] under reflux temperature for 8 h after being acidified with glacial acetic acid. The FT-IR spectrum of resin **8aa** showed a single strong carbonyl peak at 1770 cm^{-1} and the complete disappearance of carbonyl absorption at 1702 cm^{-1}.

As expected, oxidation-elimination of resins **8aa**−**8ch** was very rapid and efficient with excess of 30% hydrogen peroxide at room temperature to afford the corresponding substituted 2(5*H*)-furanones **9aa**−**9ch** in good yields (80−90%) and with high purity (Table 1). The residual resin, polystyrene-supported phenylseleninic acid **10**, was obtained as a byproduct whose infrared data was identical to the previously reported data[10] and showed no residual carbonyl absorption. Resin **10** could be converted to resin **4** for recycle by treatment of it with KI/$Na_2S_2O_3$[11] followed by $NaBH_4$[5p] and α-bromocarboxylic acids. Similarly, the treatment of **5a** with cyclohexene oxide **6f** gave 4,5-disubstituted 2(5*H*)-furanone **9af**, but the yield and purity were not satisfactory (entry 6, Table 1).

It should be noted that in the case of α-selenopropionic acid resin **4b** (entries 8−11, Scheme 3 and Table 1), the oxidative cleavage of the corresponding α-seleno-γ-butyrolactone resins resulted in the exclusively formation of the corresponding 3,5-disubstituted 2(5*H*)-furanones **9ba**−**9be**, with no α-methylene-γ-butyrolactone being detected by ^{1}H NMR spectra. However, the reaction of the dianion **5b** with cyclohexene oxide **6f** (Scheme 4) followed by oxidation−elimination generated a 92:8 mixture (GLC analysis) of

Table 1. Yields and Purities of Substituted 2(5*H*)-Furanones

entry	R^1 (resin **4**)	(epoxide **6**) R^2, R^3	product[a] **9**	yield[b] (%)	purity[c] (%)
1	H (**4a**)	Ph, H(**6a**)	**9aa**	86	88
2	H (**4a**)	$C_6H_5OCH_2$, H (**6b**)	**9ab**	90	>95
3	H (**4a**)	*m*-$CH_3C_6H_4OCH_2$, H (**6c**)	**9ac**	85	91
4	H (**4a**)	$C_6H_5CH_2OCH_2$, H (**6d**)	**9ad**	83	>95
5	H (**4a**)	*n*-$BuOCH_2$, H (**6e**)	**9ae**	84	92
6	H (**4a**)	$-(CH_2)_4-$ (**6f**)	**9af**	76	85
7	H (**4a**)	CH_3, H (**6g**)	**9ag**	90	92
8	CH_3 (**4b**)	Ph, H (**6a**)	**9ba**	88	91
9	CH_3 (**4b**)	$C_6H_5OCH_2$, H (**6b**)	**9bb**	83	>95
10	CH_3 (**4b**)	$C_6H_5CH_2OCH_2$, H (**6d**)	**9bd**	80	>95
11	CH_3 (**4b**)	*n*-$BuOCH_2$, H (**6e**)	**9be**	83	>95
12	Ph (**4c**)	Ph, H (**6a**)	**9ca**	82	>95
13	Ph (**4c**)	CH_3, H (**6g**)	**9cg**	78	92

[a] All final products were characterized by ^{1}H NMR, IR, and MS spectra. [b] Overall yield based on the loading of resin **4**. [c] Purity determined by ^{1}H NMR spectra (400 MHz) of crude cleavage product using CH_2Br_2 as an internal standard.

Scheme 4

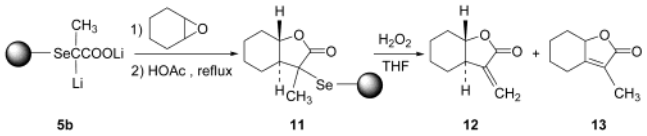


Table 2. Yields and Purities of Optically Active Substituted 2(5*H*)-Furanones

entry	resin **4**	epoxide **6**	product[a] **9**	yield[b] (%)	purity[c] (%)	% ee[d]
1	**4a**	**6h**	**9ah**	87	93	99.5
2	**4b**	**6h**	**9bh**	86	92	99.4
3	**4c**	**6h**	**9ch**	85	>95	99.4

[a] All final products were characterized by ^{1}H NMR, IR, and MS spectra. [b] Overall yield based on the loading of resin **4**. [c] Purity determined by ^{1}H NMR spectra (400 MHz) of crude cleavage product using CH_2Br_2 as an internal standard. [d] Determined by HPLC on a Chiralpak As column (4.6 mm × 250 mm), gradient elution with hexane/2-propanol.

trans-α-methylene-γ-butyrolactone **12** and bicyclic butenolide **13** in 80% overall yield based on resin **4b**, which is similar to the solution-phase process.[6c]

An attempt to use the anion of polystyrene-supported α-seleno ethyl acetate, prepared from ethyl bromoacetate with the sodium selenide resin **3**, for the reaction with propylene oxide gave an unsatisfactory result, 5-methyl-2(5*H*)-furanone being obtained in a low yield (45%).

With our successful synthesis of racemic 2(5*H*)-furanones based on the polystyrene-supported α-selenocarboxylic acids, we studied the reaction of (*R*)-styrene oxide **6h** with the dianion resins **5a**−**5c** in the same procedure as that of racemic epoxides. The results are summarized in Table 2. We found that the reaction proceeded smoothly to give the

Scheme 5

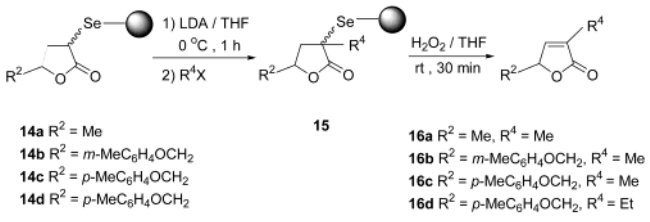


Table 3. Synthesis of 3,5-Disubstituted 2(5*H*)-Furanones Starting from Resin **14**

entry	R^2 (resin **14**)	R^4X	product[a] **16**	yield (%)[b]	purity[c] (%)
1	CH_3 (**14a**)	CH_3I	**16a**	81	>95
2	*m*-$CH_3C_6H_4OCH_2$ (**14b**)	CH_3I	**16b**	80	92
3	*p*-$CH_3C_6H_4OCH_2$ (**14c**)	CH_3I	**16c**	78	>95
4	*p*-$CH_3C_6H_4OCH_2$ (**14d**)	EtBr	**16d**	75	ND[d]

[a] All final products were characterized by ^{1}H NMR, IR, and MS spectra. [b] Overall yield based on the loading of the resin **4**. [c] Purity determined by ^{1}H NMR spectra (400 MHz) of crude cleavage product using CH_2Br_2 as an internal standard. [d] Not determined.

expected products (*5R*)-2(5*H*)-furanones **9ah**−**9ch** with retention of configuration (>99.0% ee) in good yields and high purities.

Finally, the one-pot reaction of α-alkylation to the polystyrene-supported α-selenobutyrolactones **14** followed by oxidation−elimination as above led to the 3,5-disubstituted 2(5*H*)-furanones **16** in moderate to good yields. Typical examples are shown in Scheme 5 and Table 3.

In conclusion, we have developed an efficent method for the solid-phase construction of 5-mono-, 3,5-, and 4,5-disubstituted 2(5*H*)-furanones in high yields and good purities employing a selenium-based traceless linker strategy. Although an excess amount of reagents was required, higher yields were achieved, as compared to those of the corresponding solution-phase synthesis. The considerably simplified workup procedure replaces the time-consuming isolation and purification steps in the corresponding solution-phase synthesis. Furthermore, the described technology and sequence has potential applications in combinatorial synthesis of butenolide-containing natural product libraries for chemical biological screening and the drug discovery process.

Experimental Section

General Methods. Starting materials were obtained from commercial suppliers and used without further purification. THF was distilled under N_2 from sodium/benzophenone immediately prior to use. (*R*)-Styrene oxide and polystyrene (H 1000, 100−200 mesh, cross-linked with 1% divinylbenzene) for the preparation of selenenyl bromide resin (1.45 mmol Br/g) according to the procedure described by Nicolaou and co-workers[5c] was purchased from commercial sources. Other epoxides were prepared according to the literature procedures.[12,13] Melting points were uncorrected.^{1}H NMR (400 MHz) and ^{13}C NMR (100 MHz) spectra were recorded on a Bruker Avance (400 MHz) spectrometer using $CDCl_3$ as the solvent and TMS as the internal standard. Mass spectra (EI, 70 eV) were recorded on a HP5989B mass spectrometer. Infrared spectra were recorded on a Bruker Vector 22 spectrometer. Microanalyses were performed with a Carlo-Erba 1106 elemental analyzer. The samples were further purified by TLC for ^{13}C NMR and microanalyses.

General Procedure for the Preparation of Polystyrene-Supported α-Selenocarboxylic Acids 4. Under a positive pressure of nitrogen, to polystyrene-supported selenium bromide **1** (1.0 g, 1.45 mmol Br/g) swelled in THF (15 mL) and DMF (2 mL) for 30 min was added $NaBH_4$ (3 mmol). After 6 h with stirring at room temperature, α-bromo carboxylic acid **2** (2 mmol) in 2 mL of THF was added slowly, and the mixture was stirred for 10 h. The resin was collected on a filter and washed successively with saturated $NaHCO_3$ solution (10 mL), H_2O (2 × 20 mL), THF (2 × 5 mL), and CH_2Cl_2 (2 × 5 mL) and then dried under vacuum overnight to afford resin **4**.

General Procedure for the Preparation of 2(5*H*)-Furanone 9. Resin **4a** (0.787 g, 1.0 mmol) was swelled in THF (15 mL) at room temperature for 30 min. After cooling to 0 °C, a solution of LDA (1.1 mL, 2.0 M) was added under nitrogen, and the mixture was stirred for 1 h at the same temperature. Then a solution of styrene oxide **6a** (0.132 g, 1.1 mmol) in THF (2 mL) was added, and the reaction mixture was warmed to room temperature and stirred for 5 h. The suspension was treated with glacial acetic acid (0.5 mL) and heated under reflux for 8 h, cooled to room temperature, and filtered. The resin was washed successively with saturated $NaHCO_3$ solution (10 mL), H_2O (2 × 20 mL), THF (2 × 5 mL), MeOH (2 × 5 mL) and CH_2Cl_2 (2 × 5 mL). The washed resin **8aa** was preswollen with THF (15 mL), followed by the treatment with 30% hydrogen peroxide (1 mL, 11.6 mmol). The reaction suspension was stirred at room temperature for 30 min, and then the resin was filtered off and rinsed with THF (4 × 3 mL). The filtrate was then neutralized with saturated $NaHCO_3$ solution and extracted with ether. The organic extracts were washed with water, dried over anhydrous Na_2SO_4, and concentrated to afford product 5-phenyl-2(5*H*)-furanone (0.138 g, 86% overall yield), **(9aa)**.[15] ^{1}H NMR δ 7.54−7.33(m, 5H), 7.28−7.26 (m, 1H), 6.24 (dd, J = 6.4, 2.0 Hz, 1H), 6.01 (s, 1H). MS (*m*/*e*) 160 (M^+, 62), 131 (95), 115 (32), 105 (100), 77 (81), 51 (54). IR (neat) 1756, 1622, 1602, 1493, 1158, 1091, 1032 cm^{-1}. The following compounds were synthesized using the above protocol.

5-Phenoxymethyl-2(5*H*)-furanone (9ab). mp 81−82 °C (lit.[14] 82−83 °C). ^{1}H NMR δ 7.61 (dd, J = 5.9, 1.5 Hz, 1H), 7.31−7.26 (m, 2H), 7.02−6.98 (m, 1H), 6.90−6.88 (m, 2H), 6.24 (dd, J = 5.7, 1.9 Hz, 1H), 5.35 (m, 1H), 4.29−4.25 (m, 1H), 4.16−4.12 (m, 1H). MS (*m*/*e*) 190 (M^+), 107 (100), 77 (93), 51 (34); IR (neat) 1762, 1599, 1492, 1251, 1162 cm^{-1}.

5-(*m*-Methylphenoxymethyl)-2(5*H*)-furanone (9ac). Colorless oil. ^{1}H NMR δ 7.59 (d, J = 4.5 Hz, 1H), 7.15 (t, J = 6.4 Hz, 1H), 7.78 (d, J = 7.1 Hz, 1H), 6.68 (t, J = 7.8 Hz, 2H), 6.21 (s, 1H), 5.32 (s, 1H), 4.21−4.18 (m, 1H), 4.14−4.10 (m, 1H), 2.30 (s, 3H). ^{13}C NMR 173.6, 158.0, 153.8, 139.8, 129.4, 122.8, 122.6, 115.6, 111.5, 81.3, 67.3, 21.5. MS (*m*/*e*) 204 (M^+), 121 (100), 91 (91), 77 (22), 65 (33). Anal. Calcd for $C_{12}H_{12}O_3$: C, 70.57; H, 5.92. Found: C, 70.55; H, 6.01. IR (neat) 1762, 1605, 1511, 1288, 1158 cm^{-1}.

5-Benzyloxymethyl-2(5*H*)-furanone (9ad).[14] Colorless oil; ^{1}H NMR δ 7.50 (dd, J = 5.7, 1.4 Hz, 1H), 7.37−7.30 (m, 5H), 6.16 (dd, J = 5.7, 1.8 Hz, 1H), 5.18−5.16 (m, 1H), 4.57 (s, 2H), 3.75−3.67 (m, 2H). MS (*m*/*e*) (M^+ + 1, 17), 204 (M^+, 3), 181 (34), 91 (100). IR (neat) 1760, 1600, 1497, 1204, 1096 cm^{-1}.

5-(*n*-Buoxymethyl)-2(5*H*)-furanone (9ae).[14] Colorless oil. ^{1}H NMR δ 7.48 (dd, J = 6.4, 1.2 Hz, 1H), 6.11 (dd, J = 6.4, 2.0 Hz, 1H), 5.12−5.09 (m, 1H), 3.64 (Oct ABX, J_{AB} = 12.4 Hz, J_{AX} = 10.8 Hz, J_{BX} = 6.4 Hz, 1H), 3.57 (Oct ABX, J_{AB} = 12.4 Hz, J_{AX} = 10.8 Hz, J_{BX} = 6.3 Hz, 1H), 3.47−3.40 (m, 2H), 1.51−1.46 (m, 2H), 1.27 (q, J = 7.81 Hz, 2H), 0.84 (t, J = 7.20 Hz, 3H); MS (*m*/*e*) 171 (M^+ + 1, 100), 97 (18), 57 (27), 41 (26); IR (neat) 1759, 1602, 1161, 1205, 1101 cm^{-1}.

4,5-Tetramethylene-2(5*H*)-furanone (9af).[15] Colorless oil. ^{1}H NMR δ 5.69 (s, 1H), 4.47−4.62 (m, 1H), 2.85−2.82 (m, 1H), 2.53−2.50 (m, 1H), 2.27−2.22 (m, 1H), 2.01−1.98 (m, 1H), 1.91−1.86 (m, 1H), 1.46−1.20 (m, 3H). MS (*m*/*e*) 138 (M^+, 36), 109 (100), 81 (64), 53 (36), 41 (33). IR (neat) 1753, 1647, 1448, 1168, 1087, 1036 cm^{-1}.

5-Methyl-2(5*H*)-furanone (9ag).[16] Colorless oil. ^{1}H NMR δ 7.46 (d, J = 6.0 Hz, 1H), 6.11 (d, J = 5.2 Hz, 1H), 5.15 (m, 1H), 1.46 (d, J = 6.8 Hz, 3H). MS (*m*/*e*) (M^+ + 1, 77), 98 (M^+, 22), 83 (37), 55 (100), 43 (47). IR (neat) 1756, 1601, 1168, 1108, 1075 cm^{-1}.

3-Methyl-5-phenyl-2(5*H*)-furanone (9ba).[16] Colorless oil. ^{1}H NMR δ 7.47−7.24 (m, 5H), 7.12 (d, J = 1.1 Hz, 1H), 5.86 (d, J = 1.1 Hz, 1H), 1.99 (s, 3H); MS (*m*/*e*) 174 (M^+, 58), 145 (40), 115 (42), 105 (100), 77 (62), 51 (50). IR (neat) 1765, 1602, 1495, 1090, 1046 cm^{-1}.

3-Methyl-5-phenoxymethyl-2(5*H*)-furanone (9bb). mp 65−66 °C. ^{1}H NMR δ 7.30−7.27 (m, 2H), 7.17 (d, J = 3.0 Hz, 1H), 6.70−6.87 (m, 3H), 5.22−5.18 (m, 1H), 4.17 (Oct ABX, J_{AB} = 26.4 Hz, J_{AX} = 9.46 Hz, J_{BX} = 5.45 Hz, 1H), 4.06 (Oct ABX, J_{AB} = 26.5 Hz, J_{AX} = 9.66 Hz, J_{BX} = 5.32 Hz, 1H), 1.96 (s, 3H). ^{13}C NMR δ 173.2, 157.5, 145.2, 131, 129.1, 121.1, 114.2, 78.3, 67.3, 10.3. MS (*m*/*e*) 204 (M^+, 15), 107 (100), 77 (63), 51 (20). Anal. Calcd for $C_{12}H_{12}O_3$: C, 70.57; H, 5.92. Found: C, 70.51; H, 5.97. IR (KBr) 1759, 1602, 1460, 1374, 1161, 1102, 819 cm^{-1}.

3-Methyl-5-benzyloxymethyl-2(5*H*)-furane (9bd). Colorless oil. ^{1}H NMR δ 7.37−7.30 (m, 5H), 5.05−5.02 (m, 1H), 4.6 (s, 2H), 4.57 (d, J = 3.2 Hz, 1H), 3.64 (dd, J = 1.6, 1.6 Hz, 2H), 1.93 (s, 3H). ^{13}C NMR δ 173.9, 146.1, 137.5, 131.2, 128.5, 128.0, 127.7, 80.1, 73.8, 70.0, 10.8. MS (*m*/*e*) 219 (M^+ + 1, 22), 218 (M^+, 5), 181 (33), 91 (100), 65 (14). Anal. Calcd for $C_{13}H_{14}O_3$: C, 71.54; H, 6.47. Found: C, 71.58; H, 6.50. IR (neat) 1760, 1600, 1453, 1204, 1102, 1069 cm^{-1}.

3-Methyl-5-(*n*-buoxymethyl)-2(5*H*)-furanone (9be). Colorless oil. ^{1}H NMR δ 7.02 (dd, J = 3.6, 1.2 Hz, 1H), 4.95−4.91 (m, 1H), 3.52 (dd, J = 1.6, 1.6 Hz, 1H), 3.43−3.36 (m, 2H), 1.84 (s, 3H), 1.49−1.42 (m, 2H), 1.29−1.24 (m, 2H), 0.80 (t, J = 3.2, 3H). ^{13}C NMR δ 174.0, 146.3, 130.7, 80.2, 71.7, 70.6, 31.5, 19.1, 13.8, 10.5. MS (*m*/*e*) 185 (M^+ +.1, 100), 111 (40), 57 (28). Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.19; H, 8.75. Found: C, 65.22; H, 8.80; IR (neat) 1760, 1660, 1378, 1125, 1070 cm^{-1}.

3,5-Diphenyl-2(5*H*)-furanone (9ca).[17] mp 108−109 °C (lit. 108−109 °C). ^{1}H NMR δ 7.90−7.88 (m, 2H), 7.62 (d, J = 1.6 Hz, 1H), 7.44−7.31 (m, 8H), 6.01 (d, J = 1.6 Hz, 1H); MS (*m*/*e*) 236 (M^+, 74), 105 (100), 77 (90), 51 (78), 41 (50). IR (KBr) 1740, 1625, 1120, 1050 cm^{-1}.

3-Phenyl-5-methyl-2(5*H*)-furanone (9cg).[16] Colorless oil. ^{1}H NMR δ 8.14−7.5 (m, 2H), 7.56 (d, J = 1.5 Hz, 1H), 7.44−7.38 (m, 3H), 5.18−5.13 (m, 1H), 1.52 (d, J = 6.8 Hz, 3H). MS (*m*/*e*) 174 (M^+, 32), 105 (31), 103 (100), 84 (85), 77 (41), 51 (30). IR (neat) 1756, 1602, 1493, 1450, 1321, 1132, 1114, 973 cm^{-1}.

(5*R*)-5-Phenyl-2(5*H*)-furanone (9ah).[17] Colorless oil. ^{1}H NMR δ 7.50 (dd, J = 6.4, 1.2 Hz, 1H), 7.38−7.35 (m, 3H), 7.72−7.23 (m, 2H), 6.19 (dd, J = 6.4, 1.6 Hz, 1H), 6.01 (s, 1H). MS (*m*/*e*) 160 (M^+, 62), 131 (95), 115 (32), 105 (100), 77 (81), 51 (54). IR (neat) 1756, 1624, 1600, 1495, 1158, 1090, 1030 cm^{-1}.

(5*R*)-3-Methyl-5-phenyl-2(5*H*)-furanone (9bh).[17] Colorless oil. ^{1}H NMR δ 7.35−7.21 (m, 5H), 7.10 (d, J = 1.2 Hz, 1H), 5.83 (d, J = 1.2 Hz, 1H), 1.95 (s, 3H). MS (*m*/*e*) 174 (M^+, 58), 145 (40), 115 (42), 105 (100), 77 (62), 51 (50). IR (neat) 1760, 1602, 1496, 1092, 1047 cm^{-1}.

(5*R*)-3,5-Diphenyl-2(5*H*)-furanone (9ch).[17] mp 107−108 °C (lit. 108−109 °C). ^{1}H NMR δ 7.91−7.88 (m, 2H), 7.61 (d, J = 1.9 Hz, 1H), 7.44−7.32 (m, 8H), 6.02 (d, J = 1.9 Hz, 1H). MS (*m*/*e*) 236 (M^+, 74), 105 (100), 77 (90), 51 (78), 41 (50). IR (KBr) 1739, 1626, 1119, 1055 cm^{-1}.

3,5-Dimethyl-2(5*H*)-furanone (16a).[16] ^{1}H NMR δ 7.08 (d, J = 1.6 Hz, 1H), 5.05−4.99 (m, 1H), 1.95 (d, J = 1.7 Hz, 3H), 1.36 (s, 3H). MS (*m*/*e*) 112 (M^+, 8), 97 (11), 69 (29), 55 (51), 43 (100). IR (neat) 1752, 1600, 1449, 1323, 1209, 1082, 1028, 998 cm^{-1}.

3-Methyl-5-(*m*-methylphenoxymethyl)-2(5*H*)-furanone (16b). Colorless oil. ^{1}H NMR δ 7.17−7.14 (m, 2H), 6.79 (d, J = 7.5 Hz, 1H), 6.69 (t, J = 8.0 Hz, 2H), 5.19 (s, 1H), 4.19−4.15 (m, 1H), 4.08−4.04 (m, 1H), 2.32 (s, 3H), 1.96 (s, 3H). ^{13}C NMR δ 174.1, 158.4, 146.2, 140.1, 131.9, 130.0, 122.9, 116.0, 111.9, 79.3, 68.2, 21.9, 11.2. MS (*m*/*e*) 218 (M^+, 23), 121 (100), 91 (78), 77 (19), 65 (27). Anal. Calcd for $C_{13}H_{14}O_3$: C, 71.54; H, 6.47. Found: C, 71.50; H, 6.51. IR (neat) 1761, 1603, 1585, 1490, 1176, 1106, 1075 cm^{-1}.

3-Methyl-5-(*p*-methylphenoxymethyl)-2(5*H*)-furanone (16c). mp 78−79 °C. ^{1}H NMR δ 7.15 (d, J = 1.5 Hz, 1H), 7.07 (d, J = 8.3 Hz, 2H), 6.81 (d, J = 8.3 Hz, 2H), 5.18 (m, 1H), 4.14−4.11 (m, 1H), 4.07−4.03 (m, 1H), 2.27 (s, 3H), 1.94 (s, 3H). ^{13}C NMR δ 173.8, 156.0, 145.8, 131.4, 130.9, 130.0, 114.5, 79.0, 68.1, 20.4, 10.7. MS (*m*/*e*) 218 (M^+, 24), 121 (100), 91 (70), 77 (19), 65 (26). Anal. Calcd for $C_{13}H_{14}O_3$: C, 71.54; H, 6.47. Found: C, 71.52; H, 6.45. IR (KBr) 1751, 1612, 1513, 1444, 1296, 1237, 1114, 1076 cm^{-1}.

3-Ethyl-5-(*p*-methylphenoxymethyl)-2(5*H*)-furanone (16d). mp 91−92 °C. ^{1}H NMR δ 7.21 (d, J = 1.5 Hz, 1H), 7.16 (d, J = 8.3 Hz, 2H), 6.86 (d, J = 8.5 Hz, 2H), 5.29 (m, 1H), 4.26−4.22 (m, 1H), 4.14−4.10 (m, 1H), 2.44 (q, J = 1.9 Hz, 2H), 2.36 (s, 3H), 1.27 (t, J = 7.4 Hz, 3H). ^{13}C NMR δ 173.2, 156.0, 144.3, 137.5, 130.9, 130.0, 114.6, 79.1, 68.2, 20.4, 18.8, 11.7. MS (*m*/*e*) 232 (M^+, 24), 121 (100), 91 (58), 77 (17), 65 (18), 41 (17). Anal. Calcd for

$C_{14}H_{16}O_3$: C, 72.39; H, 6.94. Found: C, 72.41; H, 6.97. IR (KBr) 1751, 1612, 1514, 1255, 1110, 1076, 817 cm^{-1}.

4,5-Tetramethylene-α-methylene Lactone (12).[6d] Colorless oil. ^{1}H NMR δ 6.02 (d, $J = 3.21$ Hz, 1H), 5.35 (d, $J = 3.20$ Hz, 1H), 3.71−3.65 (m, 1H), 2.40−1.18 (m, 9H). MS (*m*/*e*) 153 ($M^+ + 1$, 100), 135 (33), 124 (30), 95 (25), 53 (18), 41 (16). IR (neat) 1771, 1671, 1447, 1251, 1206, 996 cm^{-1}.

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Supporting Information Available. ^{1}H NMR for all compounds and ^{13}C NMR for new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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