Stereoselective Total Synthesis of Rugulactone[1])

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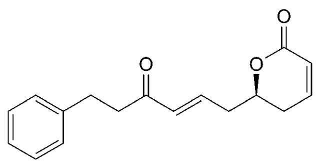
The stereoselective synthesis of the naturally occurring dihydropyranone rugulactone has been accomplished starting from 3-phenylpropan-1-ol employing *Maruoka* allylation and ring-closing metathesis as the key steps.

Introduction. – Natural products containing a dihydropyranone moiety are known to possess a wide range of biological properties, including antibacterial, antifungal, antifeedant, and cytotoxic activities [1]. Rugulactone (**1**), a member of this group, was isolated from *Cryptocarya rugulosa* [2]. The compound inhibits constitutive NF-κB activity in human lymphoma cell lines. Due to the interesting structural pattern and impressive bioactivity, the synthesis of this compound has been an important target for organic chemists [3–6]. In continuation of our work on the total synthesis of natural products [7–10], here we report an efficient approach for the stereoselective synthesis of compound **1**.



Rugulactone (**1**)

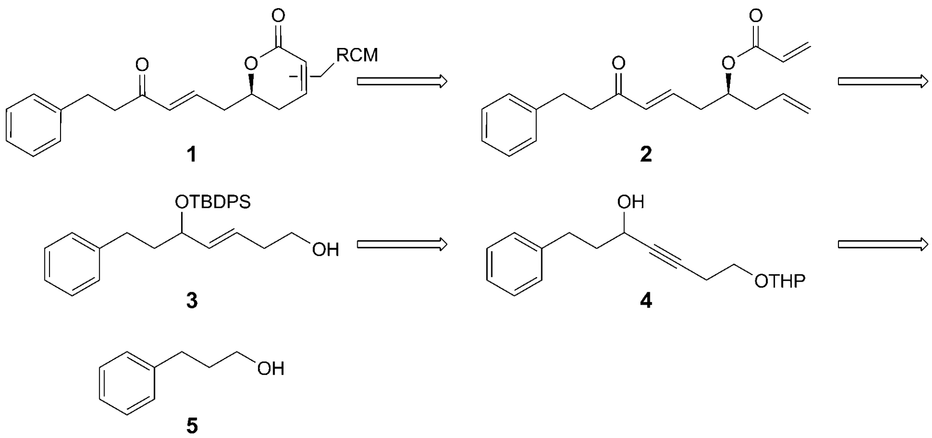
Results and Discussion. – The retrosynthetic analysis (*Scheme 1*) indicates that rugulactone (**1**) can be synthesized from the keto ester **2**. The latter, in turn, can be obtained from the alkenol **3** generated *via* an alkyne **4** from 3-phenylpropan-1-ol (**5**).

In the present synthesis (*Scheme 2*), the commercially available 3-phenylpropan-1-ol (**5**) was oxidized under *Swern* conditions, and the resulting aldehyde was treated with tetrahydro-2*H*-pyran-2-yl (THP) protected homopropargyl alcohol in the presence of BuLi to afford the secondary alcohol **4**.

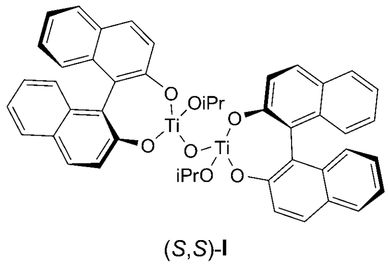
The alkyne moiety in **4** was reduced with $LiAlH_4$ in THF under reflux to furnish the alkenol **6**. The OH group was protected as (*t*-Bu)Ph_2Si (TBDPS) ether by reacting with TBDPSCl in the presence of 1*H*-imidazole to afford **7** in high yield. The THP group of **7** was removed by treatment with PPTS in MeOH to provide the primary alcohol **3**.

[1]) Part 42 in the series 'Synthetic Studies on Natural Products'.

Scheme 1



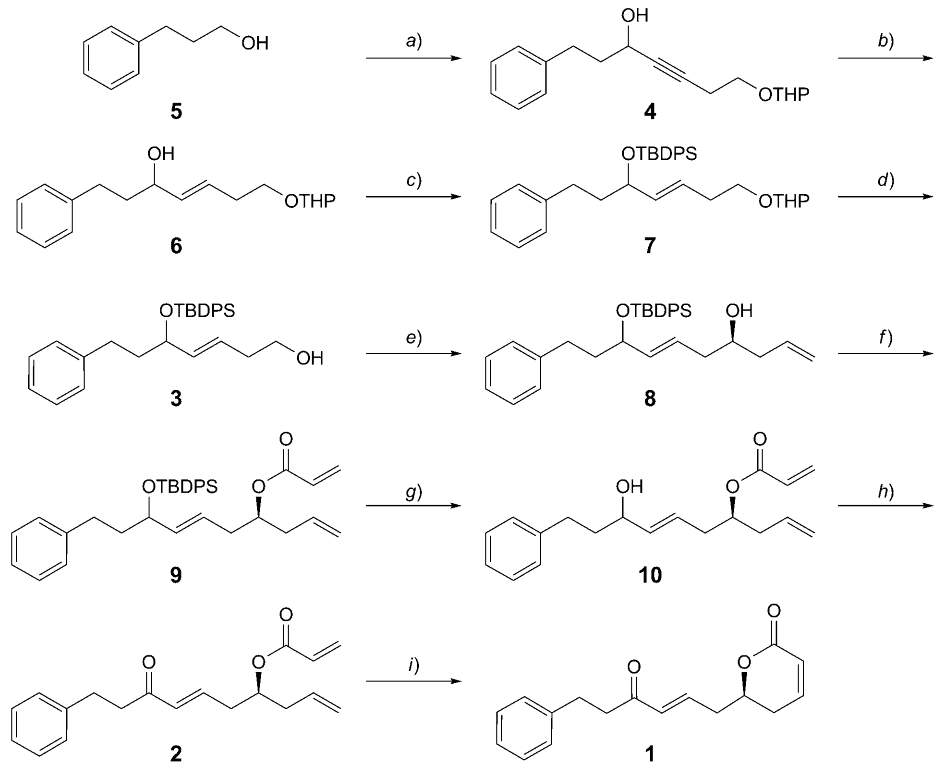
This alcohol was oxidized with 2-iodoxybenzoic acid (IBX) in dry DMSO to form the corresponding aldehyde, which, *via Maruoka* asymmetric allylation with the titanium complex (*S*,*S*)-**I** and (allyl)(tributyl)stannane, yielded the homoallylic alcohol **8** (97% ee) [11]. Compound **8** was esterified with acryloyl chloride in the presence of Et_3N to give the acryloyl ester **9** required for ring-closing metathesis [12][13]. The TBDPS group of **9** was removed with a catalytic amount of Bu_4NF (TBAF) to afford the alcohol **1**, which was oxidized with *Dess–Martin* periodinane (DMP) to afford the desired keto ester **2**. The ring-closing metathesis (RCM) of **2** was successfully achieved by using *Grubbs*' 2nd-generation catalyst (5 mol-%) to produce rugulactone (**1**). This RCM was described earlier in the first total synthesis of **1** [3] and also used by us in the synthesis of two similar natural products [7][8]. The structures of all the products involved in the present synthesis were established by their spectroscopic data (IR, ^1H- and ^{13}C-NMR, and MS). The physical and spectroscopic properties of the prepared **1** were identical to those reported earlier [2–6].



(*S*,*S*)-**I**

In conclusion, a new stereoselective total synthesis of the naturally occurring bioactive compound rugulactone (**1**) has been achieved starting from 3-phenylpropan-1-ol (**5**) by applying *Maruoka* asymmetric allylation and ring-closing metathesis as the key steps. This synthetic method can conveniently be utilized for the preparation of various analogs of rugulactone useful for biological evaluations.

Scheme 2



a) 1. Oxalyl chloride, DMSO, Et_3N, $-78°$; 82%; 2. BuLi, dry THF, THP-protected homopropargyl alcohol (= but-3-yn-1-ol), $-78°$, 3 h; 87%. *b*) $LiAlH_4$, dry THF, 0° to reflux, 3 h; 78%. *c*) (*t*-Bu)Ph_2SiCl (TBDPSCl), 1*H*-imidazole, CH_2Cl_2, 0° to r.t., 2 h; 90%. *d*) Pyridinium *p*-toluenesulfonate (PPTS), MeOH, r.t., 12 h; 79%. *e*) 1. 2-Iodoxybenzoic acid (IBX), DMSO, dry CH_2Cl_2, 0° to r.t., 2 h; 76%, 2. (*S*,*S*)-**I**, allyl(tributyl)tin, -15 to 0°, 16 h; 74%. *f*) Acryloyl chloride (= prop-2-enoyl chloride), Et_3N, 4-(dimethylamino)pyridine (DMAP), CH_2Cl_2, 0° to r.t., 4 h; 78%. *g*) Bu_4NF (TBAF), dry THF, 0° to r.t., 1 h; 80%. *h*) *Dess–Martin* periodinane (DMP), dry CH_2Cl_2, 0° to r.t., 4 h; 77%. *i*) *Grubbs*' 2nd-generation catalyst (5 mol-%), CH_2Cl_2, reflux, 6 h; 75%.

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Experimental Part

General. Column chromatography (CC): silica gel (SiO_2; 100–200 mesh; *BDH*). TLC: silica gel GF_{254} precoated plates (*Merck*). Optical rotations: *Jasco Dip 360* digital polarimeter. IR Spectra: *Perkin-Elmer RX1* FT-IR spectrophotometer. NMR Spectra: *Varian Gemini* 200 MHz, *Bruker* 300-MHz (^{1}H) and 50-MHz (^{13}C) spectrometers. ESI-MS: *VG-Autospec micromass.*

*1-Phenyl-7-(tetrahydro-2*H*-pyran-2-yloxy)hept-4-yn-3-ol* (**4**). To a stirred soln. of oxalyl chloride (0.73 ml, 12.13 mmol) in dry CH_2Cl_2 (30 ml), DMSO (0.55 ml, 18.2 mmol) was added at $-78°$, and the mixture was stirred at the same temp. for 0.5 h. A soln. of *3-phenylpropan-1-ol* (**6**; 1 g, 6.06 mmol) in CH_2Cl_2 (20 ml) was added at $-78°$, and the mixture was stirred for 1.5 h at the same temp. Et_3N (4.21 ml, 30.33 mmol) was added at 0°, and the mixture was stirred for an additional 30 min. The mixture was diluted with H_2O (30 ml) and extracted with CH_2Cl_2 (2 × 50 ml). The combined org. layers were washed with brine (20 ml), dried (Na_2SO_4), and concentrated to give the corresponding aldehyde (0.80 g, 82%) as a colorless liquid. Because of extensive oxidation of the aldehyde to the corresponding acid, we have used it immediately for the next step.

Under N_2, a soln. of BuLi in hexane (6.0 ml, 9.62 mmol, 1.6M soln.) was added to a soln. of the THP ether of homopropargyl alcohol (0.99 g, 7.2 mmol) in THF (45 ml) at −78°, and the mixture was stirred for 30 min. Finally, a soln. of 3-phenylpropanal (0.80 g, 6.0 mmol) in dry THF (40 ml) was added. After stirring the mixture for 3 h at −78°, the reaction was quenched by adding sat. aq. NH_4Cl soln. (30 ml). The mixture was extracted with AcOEt (2 × 50 ml) and dried (anh. Na_2SO_4). Evaporation of the solvents gave the crude alcohol, which was purified by CC to afford the pure alcohol **4** (1.74 g, 87%). Light yellowish liquid. IR (neat): 3419, 2941, 2227, 1451, 1126, 1066, 1031. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.26–7.10 (*m*, 5 H); 4.63 (br. *t*, *J* = 3.0, 1 H); 4.28 (br. *t*, *J* = 6.2, 1 H); 3.88–3.73 (*m*, 2 H); 3.56–3.44 (*m*, 2 H); 2.76 (*t*, *J* = 7.7, 2 H); 2.52–2.43 (*m*, 2 H); 2.00–1.45 (*m*, 8 H). ^{13}C-NMR (50 MHz, $CDCl_3$): 141.4; 128.5; 125.9; 98.7; 82.6; 81.9; 65.7; 62.2; 61.8; 39.4; 31.4; 30.5; 25.3; 20.1; 19.3. ESI-MS: 308 ($[M + NH_4]^+$).

*(4*E*)-1-Phenyl-7-(tetrahydro-2*H*-pyran-2-yloxy)hept-4-en-1-ol* (**6**). To the suspension of $LiAlH_4$ (0.2 g, 5.22 mmol) in dry THF (16 ml) under N_2 at 0° was added **4** (1.5 g, 5.22 mmol) in dry THF (35 ml), and the mixture was stirred at r.t. for 3 h. The mixture was cooled to 0°, diluted with Et_2O, and the reaction was quenched with sat. Na_2SO_4 soln. (10 ml). When the effervescence subsided, the mixture was filtered through a pad of *Celite*, and washed with CH_2Cl_2 (30 ml) and hot AcOEt (30 ml). The filtrate was washed with brine (2 × 40 ml), dried (Na_2SO_4), and evaporated under vacuum, and the residue was purified by CC to furnish **6** (1.17 g, 78%). Colorless liquid. IR (neat): 3421, 2932, 2861, 1602, 1451, 1124, 1069, 1030. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.26–7.08 (*m*, 5 H); 5.71–5.50 (*m*, 2 H); 4.55 (br. *t*, *J* = 2.8, 1 H); 4.02 (*q*, *J* = 7.0, 1 H); 3.85–3.67 (*m*, 2 H); 3.50–3.34 (*m*, 2 H); 2.76–2.58 (*m*, 2 H); 2.31 (*q*, *J* = 7.0, 2 H); 1.91–1.44 (*m*, 9 H). ^{13}C-NMR (50 MHz, $CDCl_3$): 141.9; 134.7; 128.4; 128.3; 128.2; 125.6; 98.7; 72.1; 66.8; 62.3; 38.6; 32.6; 31.7; 30.6; 25.3; 19.5. ESI-MS: 291 ($[M + H]^+$).

*(*tert*-Butyl)(diphenyl){[(4*E*)-1-phenyl-7-(tetrahydro-2*H*-pyran-2-yloxy)hept-4-en-3-yl]oxy}silane* (**7**). To a stirred soln. of **6** (1.17 g, 4.05 mmol) and 1*H*-imidazole (0.63 g, 10.14 mmol) in dry CH_2Cl_2 (30 ml) was added TBDPSCl (1.33 g, 4.86 mmol) portionwise at 0°. The mixture was stirred at the same temp. for 2 h, and then the reaction was quenched with H_2O. The CH_2Cl_2 layer was separated, and the aq. layer was extracted with additional CH_2Cl_2 (2 × 20 ml). The combined org. layers were washed with H_2O (20 ml) and brine (20 ml), and dried (anh. Na_2SO_4). Solvent was removed *in vacuo*, and the residue was purified by CC to afford **7** (1.92 g, 90% yield). Colorless liquid. IR (neat): 2934, 2858, 1739, 1595, 1461, 1428, 1358, 1111, 1071, 1032. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.66–7.59 (*m*, 4 H); 7.41–7.27 (*m*, 6 H); 7.18–6.94 (*m*, 5 H); 5.49 (*dd*, *J* = 15.0, 7.0, 1 H); 5.33–5.31 (*m*, 1 H); 4.53–4.49 (*m*, 1 H); 4.14–4.10 (*m*, 1 H); 3.80–3.74 (*m*, 1 H); 3.63–3.59 (*m*, 1 H); 3.46–3.42 (*m*, 1 H); 3.25–3.19 (*m*, 1 H); 2.58–2.49 (*m*, 2 H); 2.22–2.12 (*m*, 2 H); 1.86–1.41 (*m*, 8 H); 1.06 (*s*, 9 H). ^{13}C-NMR (50 MHz, $CDCl_3$): 142.4; 135.9; 135.8; 134.2; 129.4; 129.3; 128.3; 128.2; 127.7; 127.6; 127.4; 127.2; 125.5; 98.7; 73.9; 66.8; 62.1; 39.6; 32.5; 31.0; 30.6; 27.0; 25.4; 19.5; 19.3. ESI-MS: 551 ($[M + Na]^+$).

*(3*E*)-5-{[(*tert*-Butyl)(diphenyl)silyl]oxy}-7-phenylhept-3-en-1-ol* (**3**). To a stirred soln. of **8** (1.92 g, 3.63 mmol) in MeOH (20 ml) was added a cat. amount of PPTS (0.2 g, 0.90 mmol). The mixture was stirred at r.t. for *ca.* 12 h. MeOH was removed under reduced pressure. The crude residue was purified by CC to afford **3** (1.43 g, 79%). Viscous liquid. IR (neat): 3365, 2933, 2958, 1666, 1596, 1463, 1427, 1363, 1108. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.63–7.55 (*m*, 4 H); 7.38–7.24 (*m*, 6 H); 7.19–6.96 (*m*, 5 H); 5.45 (*dd*, *J* = 15.0, 7.0, 1 H); 5.13–5.11 (*m*, 1 H); 4.16–4.08 (*m*, 1 H); 3.37 (*t*, *J* = 6.3, 2 H); 2.51 (*t*, *J* = 7.3, 2 H); 2.06 (*q*, *J* = 6.3, 2 H); 1.87–1.64 (*m*, 2 H); 0.99 (*s*, 9 H). ^{13}C-NMR (50 MHz, $CDCl_3$): 142.2; 135.9; 135.8; 135.6; 134.3; 134.2; 129.5; 129.4; 128.3; 128.2; 127.5; 127.3; 127.2; 125.6; 73.9; 61.7; 39.7; 35.4; 31.1; 26.9; 19.3. ESI-MS: 467 ($[M + Na]^+$).

*(4*S*,6*E*)-8-{[(*tert*-Butyl)(diphenyl)silyl]oxy}-10-phenyldeca-1,6-dien-4-ol* (**8**). To an ice-cooled soln. of 2-iodoxybenzoic acid (1.06 g, 1.28 mmol) in DMSO (1.35 ml, 28.9 mmol) was added a soln. of **3** (1.43 g, 3.219 mmol) in anh. CH_2Cl_2 (10 ml). The mixture was stirred at r.t. for 2 h, then filtered through a *Celite* pad, and washed with Et_2O (100 ml). The combined org. filtrates were washed with H_2O (15 ml)

and brine (15 ml), dried (anh. Na_2SO_4), and concentrated *in vacuo*. The crude product was purified by CC to afford aldehyde as a colorless liquid (1.08 g, 76%).

To a stirred soln. of $TiCl_4$ (0.01 ml, 0.12 mmol) in CH_2Cl_2 (5 ml) was added dried $Ti(O^iPr)_4$ (0.102 ml, 0.22 mmol) at 0° under N_2. The soln. was allowed to warm to r.t. After 1 h, Ag_2O (0.05 g, 0.24 mmol) was added at r.t., and the mixture was stirred for 5 h under exclusion of direct light. The mixture was diluted with CH_2Cl_2 (10 ml) and treated with (*S*)-binaphthol (0.14 g, 0.49 mmol) at r.t. for 2 h to furnish chiral bis[Ti(IV)oxide] (*S*,*S*)-**I**. The *in situ* generated (*S*,*S*)-**I** catalyst was cooled to −15° and treated sequentially with the above prepared aldehyde (1.08 g 2.43 mmol) in CH_2Cl_2 (50 ml) and allyl(tributyl)tin (1.06 g, 3.16 mmol) at −15°. The whole mixture was allowed to warm to 0° and stirred for 16 h. The reaction was quenched with sat. $NaHCO_3$ (10 ml), and the mixture was extracted with Et_2O (100 ml). The org. extracts were dried (Na_2SO_4). Evaporation of solvents and purification of the residue by CC afforded **8** (0.94 g, 74%). Colorless liquid. IR (neat): 3386, 3028, 2921, 2852, 1674, 1634, 1406, 1268, 1191, 1048. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.76–7.63 (*m*, 5 H); 7.53–7.32 (*m*, 7 H); 7.24–7.08 (*m*, 3 H); 5.83–5.66 (*m*, 3 H); 5.18–5.06 (*m*, 2 H); 4.32–4.28 (*m*, 1 H); 3.83–3.79 (*m*, 1 H); 2.58–2.20 (*m*, 4 H); 1.99–1.51 (*m*, 2 H); 1.12 (*s*, 9 H). ^{13}C-NMR (50 MHz, $CDCl_3$): 142.0; 134.1; 132.3; 130.2; 130.0; 129.8; 129.5; 129.3; 128.4; 128.2; 126.0; 115.8; 75.5; 74.1; 42.5; 41.2; 40.5; 31.7; 25.8; 19.5. ESI-MS: 485 ([*M*+H]$^+$).

*(4*S*,6*E*)-8-{[(*tert*-Butyl)(diphenyl)silyl]oxy}-10-phenyldeca-1,6-dien-4-yl Prop-2-enoate* (**9**). To a stirred soln. of **8** (0.94 g, 1.94 mmol) in CH_2Cl_2 (30 ml) was added acryloyl chloride (0.26 g, 2.92 mmol) and Et_3N (0.39 g, 3.89 mmol) at 0°. The mixture was allowed to warm to r.t., and stirred for 4 h. The mixture was diluted with H_2O (10 ml) and extracted with CH_2Cl_2 (4 × 10 ml). The combined org. layer was dried (Na_2SO_4), and the solvent was removed under vacuum to obtain the crude residue, which was purified by CC to afford pure **9** (1.51 g, 78%). Colorless oil. IR (neat): 3028, 2921, 2852, 1724, 1675, 1633, 1407, 1269, 1190, 1049. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.75–7.60 (*m*, 5 H); 7.50–7.32 (*m*, 7 H); 7.24–7.08 (*m*, 3 H); 6.41–6.39 (*m*, 1 H); 6.22–6.00 (*m*, 2 H); 5.92–5.85 (*m*, 4 H); 5.17–5.06 (*m*, 3 H); 4.50–4.48 (*m*, 1 H); 4.02–4.0 (*m*, 1 H); 2.66–2.36 (*m*, 6 H); 1.96–1.66 (*m*, 2 H); 1.12 (*s*, 9 H). ESI-MS: 539 ([*M*+H]$^+$).

*(4*S*,6*E*)-8-Hydroxy-10-phenyldeca-1,6-dien-4-yl Prop-2-enoate* (**10**). To a soln. of **9** (0.80 g, 1.48 mmol) in dry THF (10 ml) was added TBAF (1.48 ml, 1.48 mmol, 1M soln. in THF) dropwise at 0°, and the mixture was stirred for 1 h. H_2O (20 ml) was added, and the mixture was extracted with AcOEt (50 ml). The org. extracts were washed with brine (30 ml) and dried (Na_2SO_4). Evaporation of the solvent afforded **10** (0.35 g, 80%). Colorless liquid. IR (neat): 3429, 3028, 2921, 2852, 1723, 1674, 1634, 1406, 1268, 1191, 1048. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.37–7.15 (*m*, 5 H); 6.76–6.72 (*m*, 1 H); 6.39 (*dd*, *J* = 17.3, 1.5, 1 H); 6.18–6.02 (*m*, 2 H); 5.87–5.67 (*m*, 2 H); 5.16–5.04 (*m*, 2 H); 4.46–4.44 (*m*, 1 H); 4.11–4.07 (*m*, 1 H); 2.71–2.57 (*m*, 2 H); 2.48–2.39 (*m*, 2 H); 2.30–2.23 (*m*, 2 H); 1.88–1.69 (*m*, 2 H). ^{13}C-NMR (50 MHz, $CDCl_3$): 166.4; 140.9; 131.8; 129.6; 126.9; 124.4; 116.3; 77.1; 71.9; 39.9; 37.8; 32.2; 29.0. ESI-MS: 301 ([*M*+H]$^+$).

*(4*S*,6*E*)-8-Oxo-10-phenyldeca-1,6-dien-4-yl Prop-2-enoate* (**2**). To a stirred soln. of **10** (0.35 g, 0.66 mmol) in dry CH_2Cl_2 (15 ml), *Dess–Martin* periodinane (0.40 g, 0.972 mmol) was added at 0° and the mixture was stirred for 4 h at r.t. The reaction was quenched with sat. $NaHCO_3$ soln./hypo soln. = $Na_2S_2O_3$ soln. (1:1; 15 ml) and stirred for 30 min and then extracted with CH_2Cl_2 (2 × 20 ml). The combined org. layers were washed with H_2O (10 ml), dried (anh. Na_2SO_4), and concentrated. The crude residue was purified by CC to afford pure (0.26 g, 77%). Viscous liquid. IR (neat): 3429, 3028, 2921, 2852, 1723, 1674, 1634, 1406, 1268, 1191, 1048. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.32–7.26 (*m*, 3 H); 7.21–7.18 (*m*, 2 H); 6.77–6.71 (*m*, 1 H); 6.39 (*dd*, *J* = 17.2, 1.4, 1 H); 6.17–6.04 (*m*, 2 H); 5.83 (*dd*, *J* = 10.2, 1.2, 1 H); 5.76–5.72 (*m*, 1 H); 5.14–5.06 (*m*, 2 H); 4.56–4.50 (*m*, 1 H); 2.97–2.82 (*m*, 4 H); 2.56–2.47 (*m*, 2 H); 2.37 (*t*, *J* = 6.6, 2 H). ^{13}C-NMR (50 MHz, $CDCl_3$): 199.1; 165.5; 141.6; 132.8; 132.7; 131.1; 128.5; 128.3; 126.1; 118.5; 71.7; 41.7; 38.1; 36.5; 30.0; 29.7. ESI-MS: 321 ([*M*+Na]$^+$).

*(6*R*)-6-[(2*E*)-4-Oxo-6-phenylhex-2-en-1-yl]-5,6-dihydro-2*H*-pyran-2-one* (**1**) [3]. To a stirred soln. of benzylidine[1,3-bis(2,4,6-trimethylphenyl)imidazolidin-2-ylidene]dichloro(tricyclohexylphosphine)-ruthenium (*Grubbs*' 2nd-generation catalyst; 8 mg, 5 mol-%) in CH_2Cl_2 (40 ml) at 55° was added to **2** (0.26 g, 0.07 mmol) dissolved in CH_2Cl_2 (10 ml). The resulting mixture was stirred for 6 h, after which time all of the starting material had been consumed (TLC). The solvent was removed under reduced

pressure to yield a crude product, which was purified by CC to give pure **1** (0.182 g, 75%). Yellow oil. IR (neat): 3444, 2924, 2854, 1717, 1631, 1450, 1382, 1244, 1039. ^{1}H-NMR (200 MHz, $CDCl_3$): 7.33 – 7.23 (*m*, 3 H); 7.23 – 7.17 (*m*, 2 H); 6.92 – 6.73 (*m*, 2 H); 6.20 (*d*, *J* = 15.8, 1 H); 6.05 (*d*, *J* = 9.0, 1 H); 4.57 – 4.53 (*m*, 1 H); 2.98 – 2.88 (*m*, 4 H); 2.71 – 2.60 (*m*, 2 H); 2.40 – 2.31 (*m*, 2 H). ^{13}C-NMR (50 MHz, $CDCl_3$): 199.0; 163.7; 144.6; 141.0; 140.0; 133.5; 128.5; 128.4; 126.1; 121.5; 76.1; 41.7; 37.2; 29.9; 28.9. ESI-MS: 288 ($[M + NH_4]^+$).

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