Highly Concise and Stereoselective Total Synthesis of (5*R*,7*S*)-Kurzilactone

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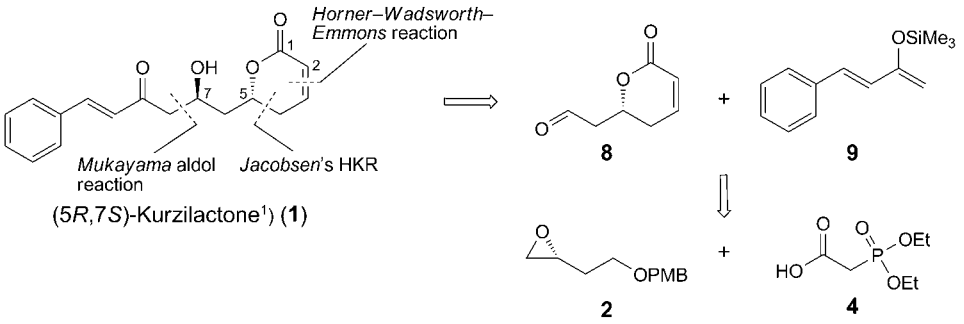
A highly concise and stereoselective total synthesis of (5*R*,7*S*)-kurzilactone (**1**) was performed by a convergent approach by means of a *Jacobsen*'s hydrolytic kinetic resolution, a *Horner–Wadsworth–Emmons* reaction for the construction of the α,β-unsaturated δ-lactone ring system, and a highly diastereoselective *Mukaiyama* aldol reaction for the introduction of the formal *anti*-1,3-diol unit (*Schemes 2* and *3*).

Introduction. – Natural products possessing 6-substituted α,β-unsaturated-δ-lactone moieties have attracted the attention of synthetic organic chemists due to their antitumor properties [1]. In addition, they inhibit HIV proteases [2], induce apopotosis [3][4], and were shown to be antileukemic [5], along with having many other relevant pharmacological properties [6]. (5*R*,7*S*)-Kurzilactone[1]) (**1**), an α,β-unsaturated δ-lactone, was isolated from the leaves of *Cryptocarya kurzii*, a plant that is indigenous to Malaysia. Kurzilactone showed a marked cytotoxicity against the KB human-carcinoma cell line ($IC_{50} = 1$ μg/ml) [7]. Initially, the stereogenic centers bearing the OH groups in the side chain and the O-atom of the δ-lacton were assigned a *syn*-relationship through NMR experiment but a corrected *anti*-relationship with (5*R*,7*S*) configuration of the C(5) and C(7) stereogenic centers were later assigned on the basis of a total synthesis [8]. The structural uniqueness of kurzilactone, coupled with its interesting bioactivity and our interest to verify the selectivity of the *Mukaiyama* aldol reaction in case of a δ-lactone-substituted aldehyde instead of an open-chain aldehyde as reported by our group, prompted us to revisit its total synthesis. The retrosynthetic analysis of **1** is described in *Scheme 1*.

Results and Discussion. – Our initial approach to aldehyde **8** employed the oxirane **2** [9] (*Scheme 2*), prepared by *Jacobsen*'s hydrolytic kinetic resolution (HKR) [10] of the racemate (*Scheme 2*) in the presence of [Co^{III}\{(*R*,*R*)-'salen'\}(OAc)] catalyst ('salen' = *N*,*N*′-bis[3,5-di(*tert*-butyl)salicylidene]cyclohexane-1,2-diaminato = {{2,2′-[(cyclohexane-1,2-diylbis(nitrilomethylidyne)]bis[4,6-di(*tert*-butyl)phenylato]}(2−)}. The 4-methoxybenzyl(PMB)-protected (2*R*)-oxirane **2** was obtained as a single enantionmer ($[\alpha]_D^{25} = +10.6$ ($c = 1.2$, $CHCl_3$), ([11]: $[\alpha]_D^{25} = -13.1$ ($c = 1.2$, $CHCl_3$) for the (2*S*)-enantiomer)), which was easily separated from the more polar diol. Oxirane **2** was treated with vinylmagnesium bromide in the presence of CuI to afford

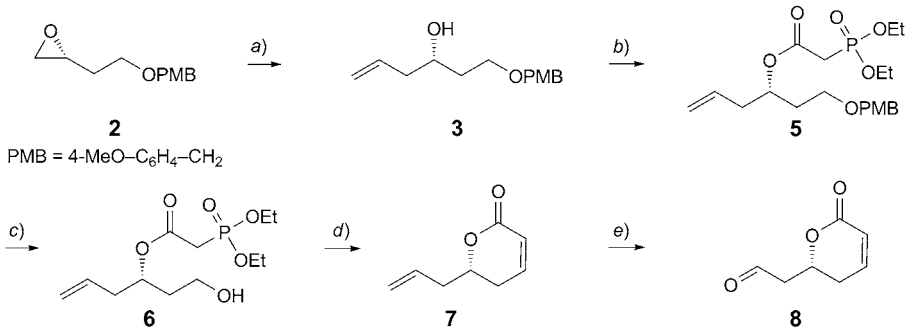
[1]) Trivial atom numbering; for the systematic name, see *Exper. Part.*

Scheme 1. *Retrosynthetic Analysis of (5*R,7S*)-Kurzilactone* (**1**)



the homoallyl alcohol **3** in 85% yield. The spectral and analytical data of **3** (ee 94% by HPLC)) were in good agreement with the literature values [12]. The C(3) stereogenic center was further confirmed by a modified *Mosher*'s method [13]. (3*S*)-Alcohol **3** was esterified with 2-(diethoxyphosphinyl)acetic acid **4** [14] in the presence of dicyclohexylcarbodiimide (DCC) and a catalytic amount of *N*,*N*-dimethylpyridin-4-amine (DMAP) to afford the (*S*)-ester **5** in 82% yield. Removal of the PMB group with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (=4,5-dichloro-3,6-dioxocyclohexa-1,4-diene-1,2-dicarbonitrile; DDQ) [15] in CH_2Cl_2 yielded hydroxy derivative **6** in 90% yield. Oxidation of **6** with 2-iodoxybenzoic acid (IBX) [16] followed by a *Horner–Wadsworth–Emmons* reaction provided α,β-unsaturated δ-lactone **7** in 68% yield over two steps. The one-step conversion of the terminal olefin moiety of **7** to give aldehyde **8** was achieved by a modified dihydroxylation followed by oxidative cleavage of the diol in 91% yield [17].

Scheme 2. *Synthesis of Aldehyde* **8**

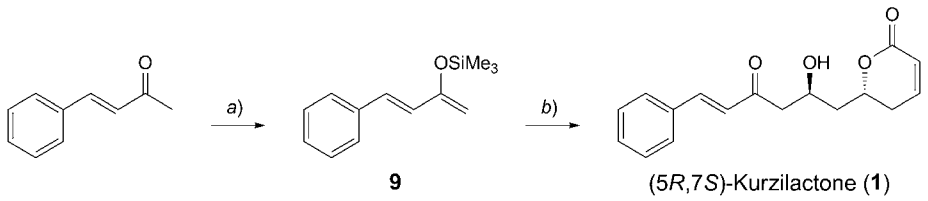


a) Vinylmagnesium bromide, CuI THF, 0° to r.t., 2 h; 85%. *b*) $(EtO)_2P(O)CH_2COOH$ (**4**), DCC, DMAP, CH_2Cl_2, r.t., 12 h; 62%. *c*) DDQ, CH_2Cl_2, H_2O, 0°, 2 h; 90%. *d*) 1. IBX, DMSO, THF, 0° to r.t., 6 h; 2. NaH, THF, 0°, 2 h; 68% over two steps. *e*) OsO_4, 2,6-lutidine (=2,6-dimethylpyridine), $NaIO_4$, dioxane, H_2O, r.t., 4 h; 91%.

Having aldehyde **8**, the stage was set to carry out the crucial *Mukaiyama* aldol reaction to verify the selectivity. The $BF_3 \cdot Et_2O$-mediated *Mukaiyama* aldol reaction of aldehyde **8** with trimethylsilyl enol ether **9** derived from (3*E*)-4-phenylbut-3-en-2-one

afforded the aldol adduct (5*R*,7*S*)-kurzilactone (**1**) as the only product in 95% yield (*Scheme 3*). It is noteworthy to mention here that in case of the α,β-unsaturated-δ-lactone-substituted aldehyde **8**, the cyclic transition state favored the attack from the opposite face of the lactone center leading to exclusive ($\geq 99\%$) formation of (5*R*,7*S*)-kurzilactone (**1**). The spectral and analytical data of the synthetic (5*R*,7*S*)-kurzilactone (**1**) were in good agreement with the reported value [8].

Scheme 3. *Synthesis of (5*R*,7*S*)-Kurzilactone* (**1**)



a) Et_3N, $CF_3SO_3SiMe_3$, CH_2Cl_2, $-10°$, 30 min. *b*) **8**, $BF_3 \cdot Et_2O$, CH_2Cl_2, $-78°$, 2 h; 81% over two steps.

Conclusions. – We achieved the total synthesis of (5*R*,7*S*)-kurzilactone (**1**) in five longest linear steps starting from a known oxirane by means of a *Horner–Wadsworth–Emmons* reaction for the construction of the α,β-unsaturated δ-lactone ring system and a highly diastereoselective *Mukaiyama* aldol reaction for the introduction of the formal *anti*-1,3-diol unit. Following the same protocol, (5*S*,7*R*)-kurzilactone (*ent*-**1**) could also be synthesized.

Experimental Part

General. Air- and/or moisture-sensitive reactions were carried out in anh. solvents under Ar in an oven- or flame-dried glassware. All anh. solvents were distilled prior to use: THF, benzene, toluene and Et_2O from Na and benzophenone; CH_2Cl_2, quinoline, and Et_3N from CaH_2; MeOH from Mg cake. Commercial reagents were used without purification. Column chromatography (CC): silica gel (SiO_2, 60–120 mesh). Specific optical rotations: $[\alpha]_D$ in 10^{-1} deg cm^2 g^{-1}. IR Spectra: in $CHCl_3$ or neat (as mentioned); $\tilde{\nu}$ in cm^{-1}. ^{1}H- and ^{13}C-NMR Spectra: at 300 (^{1}H) and 75 MHz (^{13}C); in $CDCl_3$; δ in ppm rel. to Me_4Si as internal standard, J in Hz.

*(*3S*)-1-[(4-Methoxyphenyl)methoxy]hex-5-en-3-ol* (**3**). To a stirred soln. of **2** (5.0 g, 24.22 mmol) and CuI (0.45 g, 2.40 mmol) in THF (30 ml) was added CH_2=CHMgBr (48 ml, 48.02 mmol) at $-10°$, and stirred at $-10°$ for 1 h. After completion of the reaction (TLC monitoring), it was quenched with sat. NH_4Cl soln. (20 ml). The mixture was extracted with AcOEt (2 × 60 ml), the combined org. layer washed with H_2O (100 ml) and brine (100 ml), dried (Na_2SO_4), and concentrated, and the residue purified by CC (SiO_2): **3** (4.8 g, 85%). Light yellow liquid. R_f (AcOEt/hexane 3:7) 0.4. $[\alpha]_D^{25} = -6.2$ ($c = 1.1$, $CHCl_3$) ([12]: $[\alpha]_D^{20} = -5.8$ ($c = 1.37$, $CHCl_3$)). IR (KBr): 2923, 2855, 2380, 1724, 1611, 1512, 1247, 1096, 1034, 822, 560. ^{1}H-NMR: 7.25 (*d*, $J = 8.4$, 2 H); 6.87 (*d*, $J = 8.4$, 2 H); 5.80–5.72 (*m*, 1 H); 5.14–5.06 (*m*, 2 H); 4.45 (*s*, 2 H); 3.89–3.82 (*m*, 1 H); 3.80 (*s*, 3 H); 3.73–3.57 (*m*, 2 H); 2.27–2.20 (*m*, 2 H); 1.82–1.70 (*m*, 2 H); ^{13}C-NMR: 159.1; 134.8; 129.9; 129.2; 117.4; 113.7; 72.8; 70.3; 68.5; 55.2; 41.8; 35.7. ESI-HR-MS: 259.1305 ($[M + Na]^+$, $C_{14}H_{20}NaO_3^+$; calc. 259.1306).

*(*1S*)-1-{2-[(4-Methoxyphenyl)methoxy]ethyl}but-3-en-1-yl 2-(Diethoxyphosphinyl)acetate* (**5**). To a stirred soln. of 2-(diethoxyphosphinyl)acetic acid (**4**; 4.5 g, 19.07 mmol) and DCC (7.9 g, 38.14 mmol) in CH_2Cl_2 (50 ml), was added DMAP (1.1 g, 9.05 mmol) at r.t. The mixture was stirred for 15 min before a soln. of **3** (7.4 g, 38 mmol) in CH_2Cl_2 (30 ml) was added at r.t. The mixture was stirred at r.t. for 12 h. After completion of the reaction (TLC monitoring), the mixture was quenched with H_2O (30 ml). The

aq. layer was extracted with CH_2Cl_2 (2 × 75 ml), the combined org. phase dried (Na_2SO_4), and concentrated, and the residue purified by CC (SiO_2): **5** (4.5 g, 62%). Colorless liquid. R_f (AcOEt/hexane 1:1) 0.3. $[\alpha]_D^{25} = +20.4$ ($c = 1.5$, $CHCl_3$). IR (KBr): 3328, 2926, 2853, 1666, 1734, 1625, 1250, 1029, 966, 610. ^{1}H-NMR: 7.24 (*d*, *J* = 8.4, 2 H); 6.86 (*d*, *J* = 8.4, 2 H); 5.73–5.69 (*m*, 1 H); 5.17–5.04 (*m*, 3 H); 4.39 (*s*, 2 H); 4.20–4.08 (*m*, 4 H); 3.82–3.76 (*s*, 3 H); 3.57–3.43 (*m*, 2 H); 2.92 (*d*, *J* = 21.5, 2 H); 2.42–2.27 (*m*, 2 H); 1.91–1.80 (*m*, 2 H); 1.34 (*dd*, *J* = 6.97, 0.37, 6 H). ^{13}C-NMR: 164.4; 158.3; 132.4; 129.6; 128.5; 117.3; 112.9; 71.8; 71.4; 65.2; 61.7; 54.4; 37.8; 34.4; 33.2; 15.6. ESI-HR-MS: 437.1705 ($[M+Na]^+$, $C_{20}H_{32}NaO_7P^+$; calc. 437.1726).

*(*1S*)-1-(2-Hydroxyethyl)but-3-en-1-yl 2-(Diethoxyphosphinyl)acetate* (**6**). To a stirred soln. of **5** (4.5 g, 10.81 mmol) in CH_2Cl_2/H_2O 9:1 (50 ml) was added DDQ (2.9 g, 13.12 mmol) at 0°, and the mixture was stirred for 2 h. After completion (TLC monitoring), the reaction was quenched with sat. aq. $NaHCO_3$ soln. (25 ml). The mixture was filtered through *Celite*, the aq. layer extracted with CH_2Cl_2 (2 × 40 ml), the combined org. phase washed with H_2O (50 ml) and brine (50 ml), dried (Na_2SO_4), and concentrated, and the residue purified by CC (SiO_2): **6** (2.87 g, 90%). Colorless liquid. R_f (AcOEt/hexane 4:1) 0.2. $[\alpha]_D^{25} = +10.6$ ($c = 1.7$, $CHCl_3$). IR (KBr): 2922, 2854, 2381, 1733, 1458, 1271, 1030, 970, 604, 494. ^{1}H-NMR: 5.79–5.72 (*m*, 1 H); 5.16–5.04 (*m*, 3 H); 4.23–4.10 (*m*, 4 H); 3.72–3.57 (*m*, 2 H); 3.02–2.80 (*m*, 2 H); 2.44–2.32 (*m*, 2 H); 1.89–1.80 (*m*, 1 H); 1.75–1.66 (*m*, 1 H); 1.40–1.33 (*m*, 6 H). ^{13}C-NMR: 165.9; 133.0; 118.0; 72.7; 63.0; 58.2; 38.7; 36.2; 33.5; 16.2. ESI-HR-MS: 295.1310 ($[M+H]^+$, $C_{12}H_{24}O_6P^+$; calc. 295.1305).

*(*6S*)-5,6-Dihydro-6-(prop-2-en-1-yl)-2*H*-pyran-2-one* (**7**). To a stirred soln. of iodoxybenzoic acid (3.7 g, 13.22 mmol) in dry DMSO (10 ml), was added a soln. of **6** (2.6 g, 8.84 mmol) in anh. THF (35 ml) at r.t. and stirred for 6 h. After completion of the reaction (TLC monitoring), the mixture was quenched with H_2O (20 ml) and filtered through *Celite*. The filtrate was extracted with AcOEt (3 × 50 ml). The combined org. phase was washed with brine (75 ml), dried (Na_2SO_4), and concentrated, and the resulting crude aldehyde (2.75 g) was used as such without further purification for the next step. To a suspension of NaH (0.32 g, 13.62 mmol) in dry THF (60 ml), the crude aldehyde (2.75 g, 8.06 mmol) in THF (200 ml) was added at 0°, and the mixture was stirred for 2 h. After completion of the reaction (TLC monitoring), it was quenched with H_2O (30 ml). THF was removed, the aq. layer extracted with AcOEt (3 × 50 ml), the combined org. phase dried (Na_2SO_4) and concentrated, and the residue purified by CC (SiO_2): **7** (0.64 g, 68% over two steps). Colorless liquid. R_f (AcOEt/hexane 3:7) 0.7. $[\alpha]_D^{25} = +84$ ($c = 2.1$, $CHCl_3$). IR (KBr): 2923, 2855, 1726, 1459, 1280, 1071, 526. ^{1}H-NMR: 6.87–6.79 (*m*, 1 H); 6.00 (*dt*, *J* = 9.8, 1.5, 1 H); 5.88–5.79 (*m*, 1 H); 5.20–5.11 (*m*, 2 H); 4.49–4.42 (*m*, 1 H); 2.62–2.40 (*m*, 2 H); 2.37–2.31 (*m*, 2 H). ^{13}C-NMR: 164.2; 144.9; 132.2; 121.2; 118.8; 77.0; 39.0; 28.6. ESI-MS: 138 (M^+).

*(2*R*)-3,6-Dihydro-6-oxo-2*H*-pyran-2-acetaldehyde* (**8**). To a stirred soln. of **7** (0.2 g, 1.42 mmol) in dioxane/H_2O 3:1 (8 ml), 2,6-lutidine (0.31 g, 2.89 mmol), OsO_4 (0.007 g, 0.028 mmol), and $NaIO_4$ (1.23 g, 5.79 mmol) were added. The mixture was stirred at r.t. for 4 h (TLC monitoring). The mixture was quenched with H_2O (10 ml) and extracted with CH_2Cl_2 (3 × 30 ml). The combined org. phase was washed with brine (50 ml), dried (Na_2SO_4), and concentrated, and the resulting crude **8** (208 mg, 91%) was used as such without further purification in the next step.

*{(1*E*)-3-[(Trimethylsilyl)oxy]buta-1,3-dien-1-yl}benzene* (**9**). To a stirred soln. of (3*E*)-4-phenylbut-3-en-2-one (0.5 g, 3.44 mmol) and Et_3N (0.47 ml, 5.17 mmol) in freshly prepared anh. CH_2Cl_2 (10 ml) at −10° was added dropwise $CF_3SO_3SiMe_3$ (0.8 ml, 4.10 mmol). The mixture was stirred at −10° for 30 min and quenched with sat. aq. $NaHCO_3$ soln. The aq. layer was extracted with CH_2Cl_2 (2 × 25 ml), the combined org. phase dried (Na_2SO_4) and concentrated at r.t., and the resulting crude **9** (0.46 g) was used as such for the next step without purification.

*(*6R*)-5,6-Dihydro-6-[(*2S,5E*)-2-hydroxy-4-oxo-6-phenylhex-5-en-1-yl]-2*H*-pyran-2-one* (**1**). Aldehyde **8** (0.208 g, 1.4 mmol) and silyl enol ether **9** (0.46 g, 2.12 mmol) were taken up in freshly prepared anh. CH_2Cl_2 (20 ml), and the mixture was cooled to −78°. $BF_3 \cdot Et_2O$ (0.30 ml, 2.12 mmol) in freshly prepared anh. CH_2Cl_2 (5 ml) was added slowly. The mixture was stirred at −78° for additional 2 h and quenched with sat. aq. $NaHCO_3$ soln. (10 ml). The the aq. layer was extracted with CH_2Cl_2 (2 × 25 ml), the combined org. phase washed with H_2O (40 ml) and brine (40 ml), dried (Na_2SO_4), and concentrated, and the residue purified by CC (SiO_2): **1** (382 mg, 81% over two steps). White solid. R_f (AcOEt/hexane 1:3) 0.3. M.p. 73–74°. $[\alpha]_D^{25} = +82.4$ ($c = 1.0$, $CHCl_3$) ([8]: $[\alpha]_D^{20} = +84$ ($c = 0.231$, $CHCl_3$). IR (KBr):

3453, 3028, 2924, 2854, 1712, 1604, 1384, 1252, 1049, 781, 508. ^{1}H-NMR: 7.58 (*d*, *J* = 16.0, 1 H); 7.56 – 7.52 (*m*, 2 H); 7.43– 7.36 (*m*, 3 H); 6.94 – 6.91 (*m*, 1 H); 6.77 – 6.68 (*d*, *J* = 16.0, 1 H); 6.02 (*dd*, *J* = 9.8, 2.0, 1 H); 4.85 – 4.75 (*m*, 1 H); 4.54 – 4.46 (*m*, 1 H); 2.93 (*dd*, *J* = 17.3, 3.0, 1 H); 2.81 (*dd*, *J* = 17.3, 9.0, 1 H); 2.44 – 2.30 (*m*, 2 H); 1.93 – 1.78 (*m*, 2 H). ^{13}C-NMR: 200.3; 164.2; 145.2; 143.8; 134.0; 130.8; 128.9; 128.4; 125.9; 121.3; 74.8; 63.9; 46.8; 41.6; 29.9. ESI-HR-MS: 309.1102 ($[M+Na]^+$, $C_{17}H_{18}NaO_4^+$; calc. 309.1109).

REFERENCES

[1] H. M. R. Hoffmann, J. Rabe, *Angew. Chem., Int. Ed.* **1985**, *24*, 94.

[2] K. R. Romines, R. A. Chrusciel, *Curr. Med. Chem.* **1995**, *2*, 825; P. A. Aristoff, *Drugs Future* **1998**, *23*, 995; S. Hagen, J. V. N. V. Prasad, B. D. Tait, *Adv. Med. Chem.* **2000**, *5*, 159; S. E. Hagen, J. Domagala, C. Gajda, M. Lovdahl, B. D. Tait, E. Wise, T. Holler, D. Hupe, C. Nouhan, A. Urumov, G. Zeikus, E. Zeikus, E. A. Lunney, A. Pavlovsky, S. J. Gracheck, J. Saunders, S. VanderRoest, J. Brodfuehrer, *J. Med. Chem.* **2001**, *44*, 2319; V. K. Agrawal, J. Singh, K. C. Mishra, P. V. Khadikar, Y. A. Jaliwala, *Arkivoc* **2006**, *ii*, 162.

[3] S. H. Inayat-Hussain, A. B. Osman, L. B. Din, N. Taniguchi, *Toxicol. Lett.* **2002**, *131*, 153; S. H. Inayat-Hussain, B. O. Annuar, L. B. Din, A. M. Ali, D. Ross, *Toxicol. In Vitro* **2003**, *17*, 433; K. M. Chan, N. F. Rajab, M. H. A. Ishak, A. M. Ali, K. Yusoff, L. B. Din, S. H. Inayat-Hussain, *Chem.-Biol. Interact.* **2006**, *159*, 129.

[4] N. B. Blatt, G. D. Glick, *Bioorg. Med. Chem.* **2001**, *9*, 1371; Z. Huang, *Chem. Biol.* **2002**, *9*, 1059.

[5] H. Kikuchi, K. Sasaki, J. Sekiya, Y. Maeda, A. Amagai, Y. Kubohara, Y. Ohsima, *Bioorg. Med. Chem.* **2004**, *12*, 3203.

[6] S. S. Stampwala, R. H. Bunge, T. R. Hurley, N. E. Willmer, A. J. Brankiewicz, C. E. Steinman, T. A. Smitka, J. C. French, *J. Antibiot.* **1983**, *36*, 1601; H. Nagashima, K. Nakamura, T. Goto, *Biochem. Biophys. Res. Commun.* **2001**, *287*, 829; G. E. Raoelison, C. Terreaux, E. F. Queiroz, F. Zsila, M. Simonyi, S. Antus, A. Randriantsoa, K. Hostettmann, *Helv. Chim. Acta* **2001**, *84*, 3470; D. S. Lewy, C.-M. Gauss, D. R. Soenen, D. L. Boger, *Curr. Med. Chem.* **2002**, *9*, 2005; A. K. Larsen, A. E. Escargueil, A. Skladanowski, *Pharmacol. Ther.* **2003**, *99*, 167; A. Richetti, A. Cavallaro, T. Ainis, V. Fimiani, *Immunopharmacol. Immunotoxicol.* **2003**, *25*, 441; F. Koizumi, H. Ishiguro, K. Ando, H. Kondo, M. Yoshida, Y. Matsuda, S. Nakanishi, *J. Antibiot.* **2003**, *56*, 603.

[7] X. Fu, T. Sévenet, A. Hamid, A. Hadi, F. Remy, M. Païs, *Phytochemistry* **1993**, *33*, 1272.

[8] B. Jiang, Z. Chen, *Tetrahedron: Asymmetry* **2001**, *12*, 2835.

[9] J. A. Marshall, G. Schaaf, A. Nolting, *Org. Lett.* **2005**, *7*, 5331.

[10] L. P. C. Nielsen, C. P. Stevenson, D. G. Blackmond, E. N. Jacobsen, *J. Am. Chem. Soc.* **2004**, *126*, 1360.

[11] M. J. Gaunt, A. S. Jessiman, P. Orsini, H. R. Tanner, D. F. Hook, S. V. Ley, *Org. Lett.* **2003**, *5*, 4819.

[12] D.-R. Li, D.-H. Zhang, C.-Y. Sun, J.-W. Zhang, L. Yang, J. Chen, B. Liu, C. Su, W.-S. Zhou, G.-Q. Lin, *Chem.–Eur. J.* **2006**, *12*, 1185.

[13] I. Ohtani, J. Kusumi, Y. Kashman, H. Kakisawa, *J. Am. Chem. Soc.* **1991**, *113*, 4092; W. Y. Yoshido, P. J. Bryan, B. J. Baker, J. B. McClintock, *J. Org. Chem.* **1995**, *60*, 780.

[14] A. Friese, K. Hell-Momeni, I. Zündorf, T. Winckler, T. Dingermann, G. Danhardt, *J. Med. Chem.* **2002**, *45*, 1535; A. B. Smith, III, I. G. Safonov, R. M. Corbett, *J. Am. Chem. Soc.* **2002**, *124*, 11102; K. C. Nicolaou, Y.-P. Sun, R. Guduru, B. Banerji, D. Y.-K. Chen, *J. Am. Chem. Soc.* **2008**, *130*, 3633; K. Ando, K. Narumiya, H. Takada, T. Teruya, *Org. Lett.* **2010**, *12*, 1460.

[15] Y. Oikawa, T. Yushioka, O. Yonemitsu, *Tetrahedron Lett.* **1982**, *23*, 885.

[16] M. Frigeno, M. Santagostino, *Tetrahedron Lett.* **1994**, *35*, 8019.

[17] W. Yu, Y. Mei, Y. Kang, Z. Hua, Z. Jin, *Org. Lett.* **2004**, *6*, 3217.

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