Natural Product Synthesis

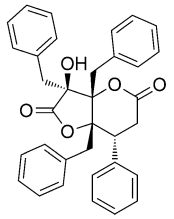
DOI: 10.1002/ange.201307835

Total Synthesis of (−)-Ophiodilactone A and (−)-Ophiodilactone B**

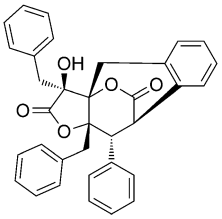
*Takaaki Matsubara, Keisuke Takahashi, Jun Ishihara, and Susumi Hatakeyama**

Abstract: *The first asymmetric total synthesis of (−)-ophiodilactone A and (−)-ophiodilactone B, isolated from the ophiuroid (Ophiocoma scolopendrina), is reported. The key features of the synthesis include the highly stereocontrolled construction of the structurally congested γ-lactone/δ-lactone skeleton through an asymmetric epoxidation, diastereoselective iodolactonization, and intramolecular epoxide-opening with a carboxylic acid, and biomimetic radical cyclization of ophiodilactone A to ophiodilactone B.*

In 2009, Matsunaga and co-workers reported the isolation of ophiodilactones A (**1**) and B (**2**) from *Ophiocoma scolopendrina*, a tropical and subtropical ophiuroid widely distributed in the Indo-Pacific. These compounds exhibit moderate cytotoxic activity against P388 murine leukemia cells with IC_{50} values of 5.0 and 2.2 $\mu g\,mL^{-1}$, respectively.[1] Intensive NMR studies led to the determination of their characteristic compact structures consisting of a fused γ-lactone/δ-lactone skeleton with four phenyl groups and four or five contiguous stereogenic centers containing three quaternary centers. The absolute structures of **1** and **2** were tentatively determined based on the analysis of the CD-spectroscopic data of **1**.[1]



(−)-ophiodilactone A (**1**)



(−)-ophiodilactone B (**2**)

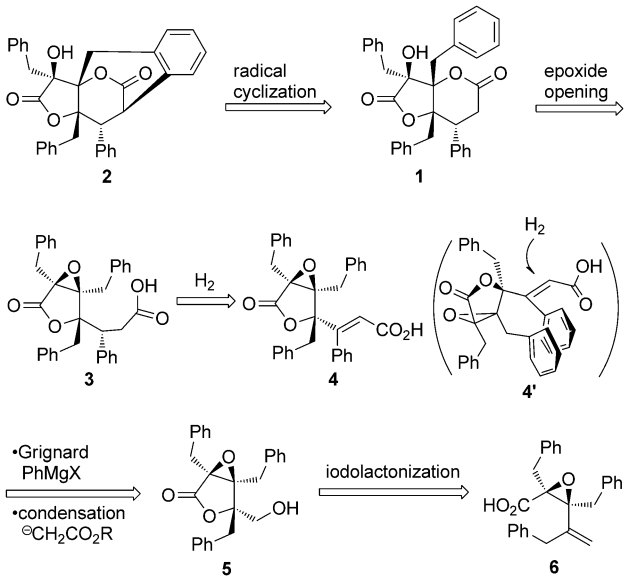
Their unique highly substituted dilactone structures and biological activities prompted us to investigate the synthesis of ophiodilactones.[2] Herein we describe the first total synthesis of (−)-ophiodilactone A (**1**) and (−)-ophiodilactone B (**2**), thereby unambiguously determining their absolute structures.

[*] T. Matsubara, Dr. K. Takahashi, Dr. J. Ishihara, Prof. Dr. S. Hatakeyama
Graduate School of Biomedical Sciences, Nagasaki University
1-14 Bunkyo-machi, Nagasaki 852-8521 (Japan)
E-mail: susumi@nagsaki-u.ac.jp

[**] We thank Prof. Shigeki Matsunaga (The University of Tokyo) for providing us copies of CD spectra of ophiodilactones A and B. This work was supported by the Grant-in-Aid (25253002 and 24659009) from JSPS and the Grant-in-Aid for Scientific Research on Innovative Areas "Advanced Molecular Transformations by Organocatalysis" (No. 2304) (24105526) and "Organic Synthesis based on Reaction Integration" (No. 2105) (24106736) from MEXT.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201307835.

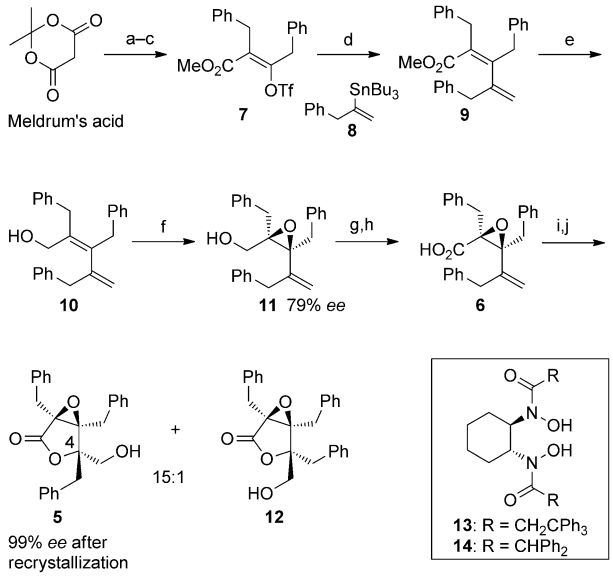
Matsunaga and co-workers proposed that ophiodilactone B (**2**) would be directly biosynthesized from ophiodilactone A (**1**) through a radical cyclization.[1] Inspired by this hypothesis, we envisioned **1** as a precursor of **2** (Scheme 1). Since, to our knowledge, such an intramolecular radical



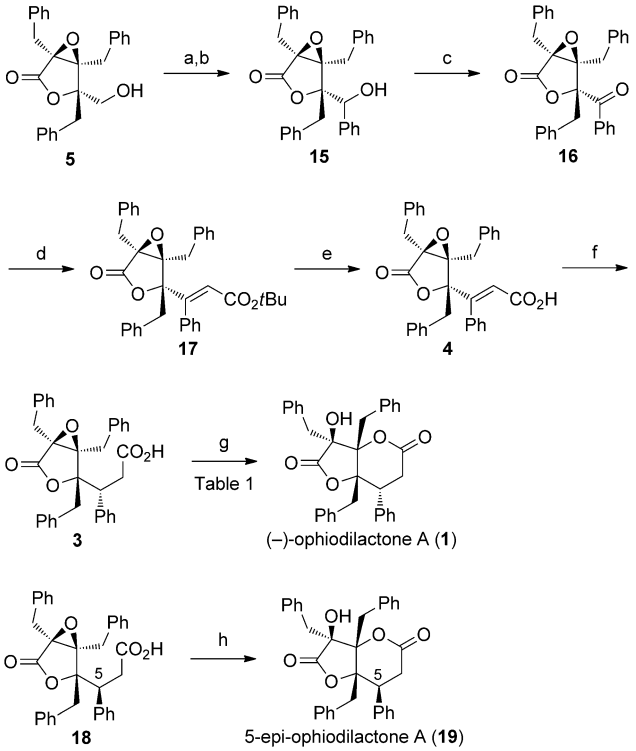
Scheme 1. Retrosynthetic analysis.

coupling between a benzene ring and a δ-lactone with site selectivity is unprecedented,[3,4] it would be a very challenging goal to accomplish this radical process. From a retrosynthetic perspective, we assumed that ophiodilactone A (**1**) would be accessible from **3** by intramolecular epoxide opening with a carboxylic acid group with inversion of stereochemistry. To access **3** we envisioned hydrogenation of **4**, which was expected to preferentially proceed with desired diastereoselectivity as depicted in **4′**.[5] We reasoned that compound **4** could be accessed from **6** via **5** by an approach involving diastereoselective iodolactonization and addition of phenyl and acetic acid units.

In our preliminary study,[2] we have developed an eight-step synthesis of **6** from Meldrum's acid through Stille coupling[6] of **7** with **8**[7] and Katsuki–Sharpless asymmetric epoxidation[8] of **10** (Scheme 2). Although the diastereoselectivity and overall yield of this synthesis were satisfying, its enantioselectivity was disappointingly low (35% *ee*). Therefore, we first devoted our efforts to improving the asymmetric epoxidation step. After considerable experimentation,[9] we eventually found that the method developed by Yamamoto and co-workers[10] afforded epoxy alcohol **11** in acceptable enantioselectivity and yield although it proceeded very



Scheme 2. Reagents and conditions: a) $PhCH_2COCl$, pyridine, CH_2Cl_2, then MeOH, reflux, 99%; b) $PhCH_2Br$, NaH, benzene/DMF, 85 °C, 82%; c) Tf_2O, 5 M LiOH, hexane, 0 °C, 93%; d) **8**, $[Pd(PPh_3)_4]$ (0.1 equiv), CuCl, LiCl, DMSO, 80 °C, 94%; e) DIBAL-H, CH_2Cl_2, −78 °C, 97%; f) *t*BuOOH, **13** (0.1 equiv), $VO(OiPr)_3$ (0.05 equiv), toluene, 0 °C, 89%; g) Dess–Martin periodinane, $NaHCO_3$, CH_2Cl_2; h) $NaClO_2$, NaH_2PO_4, 2-methyl-2-butene, *t*BuOH/H_2O, 0 °C; i) I_2, aq $NaHCO_3$, CH_2Cl_2, 0 °C; j) 20 M NaOH, THF, 50 °C, then H_2SO_4, 0 °C, 94% (15:1 mixture), 65% (enantiomerically pure **5** after recrystallization) from **11** (4 steps).



Scheme 3. Reagents and conditions: a) $(COCl)_2$, DMSO, CH_2Cl_2, −78 °C, then Et_3N; b) PhMgCl, THF, −40 °C, 81% (2 steps); c) Dess–Martin periodinane, $NaHCO_3$, CH_2Cl_2, 92%; d) $Me_3SiCH_2CO_2tBu$, LHMDS, HMPA, −78 °C, 94%; e) TFA/CH_2Cl_2 (1:10), 60 °C; f) H_2, 20% $Pd(OH)_2$/C, AcOEt, 0 °C; g) $HOCH_2CH_2OH$, 150 °C, 55% from **17** (3 steps); h) H_2O, 150 °C, sealed tube, 40%.

sluggishly. Thus, when compound **10** was reacted with *tert*-butyl hydroperoxide using **13** (0.1 equiv) and $VO(OiPr)_3$ (0.05 equiv) in toluene at 0 °C for 6 days, **11** was obtained in 79% *ee*[11] and 89% yield. The use of **14** in place of **13** resulted in comparable enantioselectivity (78% *ee*) albeit the yield became lower (60%). Compound **11** was then subjected to Dess–Martin oxidation followed by Pinnick–Kraus oxidation to provide carboxylic acid **6** cleanly. Upon successive iodolactonization, alkaline hydrolysis, and acidic lactonization, **6** afforded γ-lactones **5** and **12** in a ratio of 15:1 in 94% yield from **11**. Interestingly, the ratio turned out to be sensitive to the final acidic lactonization conditions. When this process was carried out at 80 °C rather than 0 °C, the ratio diminished to 6:1,[2] implying the partial intervention of the C4 tertiary carbocation during lactonization of the corresponding dihydroxy carboxylic acid. At this stage enantiomerically pure **5** was obtained after recrystallization from benzene (65% from **11**). An X-ray structure[12] of the mesylate derived from **5** allowed us to unambiguously determine the absolute configuration of **5** as depicted.

With the desired γ-lactone **5** in hand, we next investigated the synthesis of ophiodilactone A (**1**; Scheme 3). Compound **5** was subjected to Swern oxidation followed by Grignard reaction using phenylmagnesium chloride to give alcohol **15**, which was then oxidized to **16**. Peterson olefination[13] of **16** proceeded smoothly to afford unsaturated ester **17** in 94% yield with excellent *E* selectivity, whereas either Horner–Wadsworth–Emmons or Wittig olefination did not produce **17** at all. As expected from the conformational analysis by molecular mechanics calculations, **17** did not undergo hydrogenation because of the steric bulkiness of the *tert*-butyl ester group. In fact, we successfully obtained the hydrogenated compound **3** from sterically less hindered carboxylic acid **4**. Notably, this hydrogenation took place with excellent diastereoselectivity at 0 °C and the corresponding C5-epimer **18** was not observed in the ^1H NMR, whereas the reaction at room temperature afforded a 7:1 mixture of **3** and **18**. To complete the total synthesis of ophiodilactone A (**1**), we explored the crucial intramolecular epoxide-opening reaction of **3** under various conditions (Table 1). Even acid-catalyzed conditions required higher temperatures, which caused the partial decomposition of **3** or **1** leading to the lower yield of

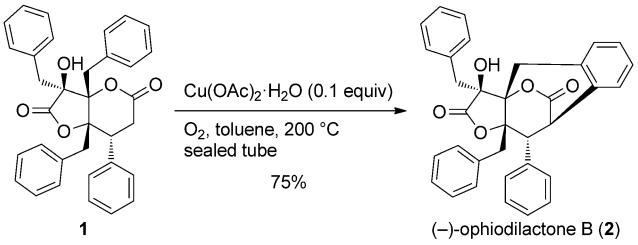
Table 1: Synthesis of ophiodilactone A from **3**.

Entry	Conditions	Yield [%][a]
1[b]	CSA (1 equiv), TFA (5equiv), CH_2Cl_2, 160 °C, 4 h, sealed tube	0[c]
2	TFA, 100 °C, 3 days, sealed tube	15
3	TFA, 150 °C, 4 h, sealed tube	38
4	H_2O, 150 °C, 12 h, sealed tube	50
5	$HOCH_2CH_2OH$, 150 °C, 5 h	55

[a] Overall yield from **17** (3 steps). [b] Conditions reported by Trost and Krische for the similar cyclization.[17] [c] Compound **3** was recovered in 50% yield. CSA = camphorsulfonic acid.

1 (Table 1, entries 1–3). However, we gratifyingly found that the epoxide-opening reaction proceeded under neutral conditions when **3** was simply heated at 150 °C in a protic solvent such as water and ethylene glycol (Table 1, entries 4,5).[14,15] The best result was obtained under the conditions listed in entry 5, which produced (−)-ophiodilactone A (**1**) in 55% yield from **17**. The spectral data of the synthetic ophiodilactone A were identical to those of the natural specimen[1] in all respects. It is important to add that upon exposure of **18**[16] to the conditions listed in entry 4, the cyclization took place sluggishly to produce 5-epi-ophiodilactone (**19**). The comparison of the spectral data of **1** and **19** allowed us to further confirm that hydrogenation of **4** occurred with desired diastereofacial selectivity.

To achieve biomimetic transformation of ophiodilactone A (**1**) to ophiodilactone B (**2**), we focused on direct oxidative coupling reactions of C–H and Ar–H bonds. Although such reactions have been widely investigated, they were mostly executed under basic conditions.[4] However, owing to the extreme instability of **1** under basic conditions, we had to intensively seek appropriate neutral or weekly acidic conditions for our endgame. As a result, we found that when a solution of **1** in toluene was heated with $Cu(OAc)_2{\cdot}H_2O$ (0.1 equiv) at 200 °C under oxygen by modifying the procedure reported by Taylor and co-workers,[4g,18] the radical cyclization cleanly took place to furnish (−)-ophiodilactone B (**2**) in 75% yield (Scheme 4). The reaction



Scheme 4. Synthesis of ophiodilactone B.

proceeded with excellent site selectivity and no other cyclized products were observed. Note that when the reaction was conducted at 170 °C, the yield was dramatically diminished to 6% and the unreacted **1** was recovered in 91% yield. The synthetic ophiodilactone B exhibited spectral properties identical in all respects to those reported for the natural product.[1]

In conclusion, we have accomplished the first total synthesis of (−)-ophiodilactone A (**1**) and (−)-ophiodilactone B (**2**) in enantiomerically pure forms in 14% (17 steps) and 10% (18 steps) overall yields from Meldrum's acid, respectively. The present work illustrates the prowess of the copper-catalyzed radical cyclization to enable biomimetic transformation of **1** to **2**.

Received: September 6, 2013
Revised: October 16, 2013
Published online: December 11, 2013

Keywords: asymmetric synthesis · bioinspired synthesis · radical coupling · total synthesis

[1] R. Ueoka, T. Fujita, S. Matsunaga, *J. Org. Chem.* **2009**, *74*, 4396.
[2] T. Matsubara, K. Takahashi, J. Ishihara, S. Hatakeyama, *Heterocycles* **2012**, *86*, 155.
[3] For reviews on direct C–H bond functionalization reactions, see: a) C. S. Yeung, V. M. Dong, *Chem. Rev.* **2011**, *111*, 1215; b) J. Yamaguchi, A. D. Yamaguchi, K. Itami, *Angew. Chem.* **2012**, *124*, 9092; *Angew. Chem. Int. Ed.* **2012**, *51*, 8960.
[4] For related radical coupling reactions, see: a) P. S. Baran, J. M. Richter, *J. Am. Chem. Soc.* **2004**, *126*, 7450; b) P. S. Baran, J. M. Richter, D. W. Lin, *Angew. Chem.* **2005**, *117*, 615; *Angew. Chem. Int. Ed.* **2005**, *44*, 609; c) J. M. Richter, B. W. Whitefield, T. J. Maimone, D. W. Lin, M. P. Castroviejo, P. S. Baran, *J. Am. Chem. Soc.* **2007**, *129*, 12857; d) A. Perry, R. J. K. Taylor, *Chem. Commun.* **2009**, 3249; e) Y.-X. Jia, E. P. Kündig, *Angew. Chem.* **2009**, *121*, 1664; *Angew. Chem. Int. Ed.* **2009**, *48*, 1636; f) D. S. Pugh, J. E. M. N. Klein, A. Perry, R. J. K. Taylor, *Synlett* **2010**, 934; g) J. E. M. N. Klein, A. Perry, D. S. Pugh, R. J. K. Taylor, *Org. Lett.* **2010**, *12*, 3446; h) V. Bhat, J. A. MacKay, V. H. Rawal, *Org. Lett.* **2011**, *13*, 3214; i) J. E. M. N. Klein, R. J. K. Taylor, *Eur. J. Org. Chem.* **2011**, 6821; j) S. Ghosh, S. De, B. N. Kakde, S. Bhunia, A. Adhikary, A. Bisai, *Org. Lett.* **2012**, *14*, 5864; k) C. L. Moody, V. Franckevičius, P. Drouhin, J. E. M. N. Klein, R. J. K. Taylor, *Tetrahedron Lett.* **2012**, *53*, 1897.
[5] Conformer **4′** was suggested to be the energetically most stable by molecular mechanical calculations (MMFF, Macro Model 8.6). Other optimum thirteen conformers within 3.0 kcal mol^{-1} difference still have the similar steric environment around the olefinic double bond.
[6] X. Han, B. M. Stoltz, E. J. Corey, *J. Am. Chem. Soc.* **1999**, *121*, 7600.
[7] Prepared from styrene: 1) $CHBr_3$, 50% NaOH; 2) EtMgBr, THF; 3) nBu$_3$SnH, $B(C_6F_5)_3$, toluene. See the Supporting Information.
[8] Y. Gao, R. M. Hanson, J. M. Klunder, S. Y. Ko, H. Masamune, K. B. Sharpless, *J. Am. Chem. Soc.* **1987**, *109*, 5765.
[9] Asymmetric nucleophilic epoxidations of **9** and the corresponding unsaturated aldehyde were unsuccessful owing to their poor electrophilicity; a) C. L. Elston, R. F. W. Jackson, S. J. F. MacDonald, P. J. Murray, *Angew. Chem.* **1997**, *109*, 379; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 410; b) O. Jacques, S. J. Richards, R. F. W. Jackson, *Chem. Commun.* **2001**, 2712; c) M. Marigo, J. Franzén, T. B. Poulsen, W. Zhuang, K. A. Jørgensen, *J. Am. Chem. Soc.* **2005**, *127*, 6964; d) S. Lee, D. W. C. MacMillan, *Tetrahedron* **2006**, *62*, 11413.
[10] a) W. Zhang, A. Basak, Y. Kosugi, Y. Hoshino, H. Yamamoto, *Angew. Chem.* **2005**, *117*, 4463; *Angew. Chem. Int. Ed.* **2005**, *44*, 4389; b) W. Zhang, H. Yamamoto, *J. Am. Chem. Soc.* **2007**, *129*, 286; c) A. U. Barlan, W. Zhang, H. Yamamoto, *Tetrahedron* **2007**, *63*, 6075; d) Z. Li, W. Zhang, H. Yamamoto, *Angew. Chem.* **2008**, *120*, 7630; *Angew. Chem. Int. Ed.* **2008**, *47*, 7520; e) Z. Li, H. Yamamoto, *J. Am. Chem. Soc.* **2010**, *132*, 7878; f) Z. Li, H. Yamamoto, *Acc. Chem. Res.* **2013**, *46*, 506.
[11] Determined by HPLC analysis of **5** on a chiral stationary phase.
[12] CCDC 950641 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.
[13] a) M. W. Rathke, D. F. Sullivan, *Synth. Commun.* **1973**, *3*, 67; b) M. Duraisamy, H. M. Walborsky, *J. Am. Chem. Soc.* **1983**, *105*, 3252; c) D. J. Ager, *Org. React.* **1990**, *38*, 1.
[14] In light of the model reported by Jamison and Vilotijevic of epoxide-opening reactions promoted by water or ethylene glycol, we assumed that the reaction of **3** to **1** would be

accelerated by hydrogen-bond activation. I. Vilotijevic, T. F. Jamison, *Science* **2007**, *317*, 1189.

[15] For related epoxide-opening reactions, see: a) Z. Wang, Y.-T. Cui, Z.-B. Xu, J. Qu, *J. Org. Chem.* **2008**, *73*, 2270; b) J. M. Wurst, G. Liu, D. S. Tan, *J. Am. Chem. Soc.* **2011**, *133*, 7916; c) J. J. Mousseau, C. J. Morten, T. F. Jamison, *Chem. Eur. J.* **2013**, *19*, 10004.

[16] Compound **18** was partly obtained in pure form from a 7:1 mixture of **3** and **18** by preparative TLC (SiO_2, AcOEt) albeit poor separation was achieved.

[17] B. M. Trost, M. J. Krische, *J. Am. Chem. Soc.* **1999**, *121*, 6131.

[18] When the reaction was conducted using $Cu(OAc)_2{\cdot}H_2O$ (0.1 equiv) in mesitylene at 165 °C for 5 h under O_2 according to the method reported by Taylor and co-workers,[4g] ophiodilactone B was not produced but appreciable decomposition of **1** was observed.

