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Highly Efficient Synthesis of (+)-Bromoxone, (+)-Epiepoxydon and (+)-Epiepoformin†

Ming Yu Jin, Geum-Sook Hwang,‡ Hee Il Chae, Sun Hee Jung, and Do Hyun Ryu*

*Department of Chemistry, Sungkyunkwan University, Suwon 440-746, Korea. *E-mail: dhryu@skku.edu*
‡Graduate School of Analytical Science and Technology Chungnam National University and Korea Basic Science Institute, Seoul 136-701, Korea
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Epoxyquinols, a subclass of the cyclohexane epoxide (epoxyquinoids) family, show a wide range of impressive biological activities.[1] Interestingly, they exist in both monomeric and dimeric forms in nature. Among the monomeric forms, bromoxone (**1**),[2] epiepoxydon (**2**)[2f,3] and epiepoformin (**3**)[2f,3c,d,4] have the same chiral cyclohexene oxide skeleton (Fig. 1).

Bromoxone (**1**) and its acetate were isolated from the marine acorn worm in 1987.[5] The acetate of bromoxone has been shown to have potent antitumor activity against P388 cells *in vitro*. In addition, bromoxone and its iodo analogue provide an entry to synthesize more complex members of the epoxyquinol family such as harveynone,[4b,6] panepophenanthrin[7] and hexacyclinol[8] *via* a Pd-catalyzed coupling reaction. Two other members of this family, epiepoxydon (**2**) and epiepoformin (**3**), isolated from the culture filtrate of an unidentified fungus, showed inhibitory activity against the germination of lettuce seeds. Due to their broad range of biological properties and their usefulness as key intermediates, significant efforts have been put toward the stereoselective formation of these epoxyquinols.[1] Although several efficient synthetic methods have been developed,[1] there has been no report of the synthetic routes to **1**-**3** using a catalytic enantioselective process. Herein, we describe efficient synthesis of bromoxone (**1**), epiepoxydon (**2**) and epiepoformin (**3**) through the use of a catalytic asymmetric Diels-Alder reaction.

The chiral oxazaborolidium catalyst **4**[9] generated from the corresponding oxazaborolidines *via* protonation by trifluoromethanesulfonic acid was used as an excellent catalysts for an enantioselective Diels-Alder reaction with a variety of dienes and dienophiles, for example α,β-enones, esters and quinone monoketals (Fig. 2).[10]

Recently, it was found that the Diels-Alder reaction of cyclopentadiene and 2-iodo-1,4-quinone monoketal **5** with ***ent*-4** as catalyst generated solely the *endo*-cycloadduct **6** with excellent enantioselectivity (Scheme 1).[10g] Therefore, we envisioned that the chiral Diels-Alder adduct **6** could be a good starting material for the synthesis of **1**-**3**. With a readily available catalyst **4**, the enantioselective Diels-Alder reaction of cyclopentadiene and **5** was attempted. The reaction was carried out at −78 °C by stirring 2-iodo-1,4-quinone monoketal **5** and cyclopentadiene in the presence of **4** (10 mol %) in CH_2Cl_2 under nitrogen. The reaction was completed after 30 min. Only the *endo*-cycloadduct **6** was generated in 95% yield with 98% ee. The enantioselectivity was determined by HPLC analysis using a chiralcel OJ-H column with hexane-*i*PrOH (9:1) for elution (Scheme 1). Enantiomerically pure **6** was easily obtained from this product by one recrystallization from CH_2Cl_2-hexanes. The next stage in the synthesis was preparation of the key intermediate **11** from the chiral Diels-Alder *endo*-adduct **6** (Scheme 2). Removal of the iodo group was achieved using tributyltin hydride to afford compound **7** in high yield (88%). After a Luche reduction of **7** using sodium borohydride in the presence of cerium chloride,[10g] the generated alcohol **8** was subjected to an acidic condition to give the deprotected ketone **9** in 85% overall yield

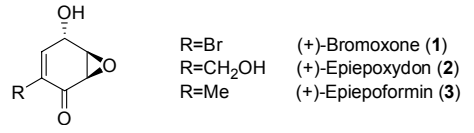


Figure 1

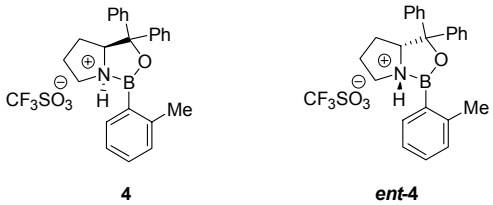
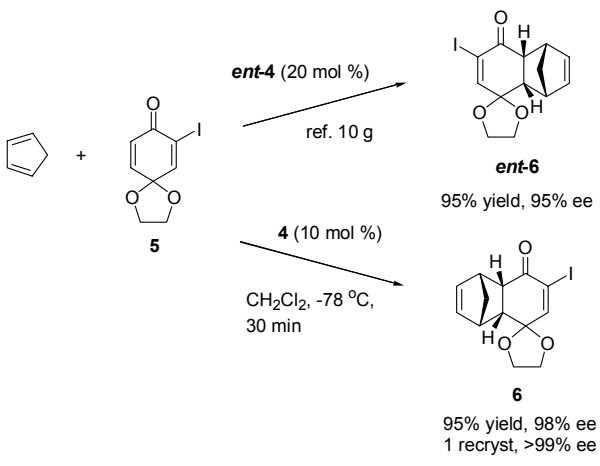
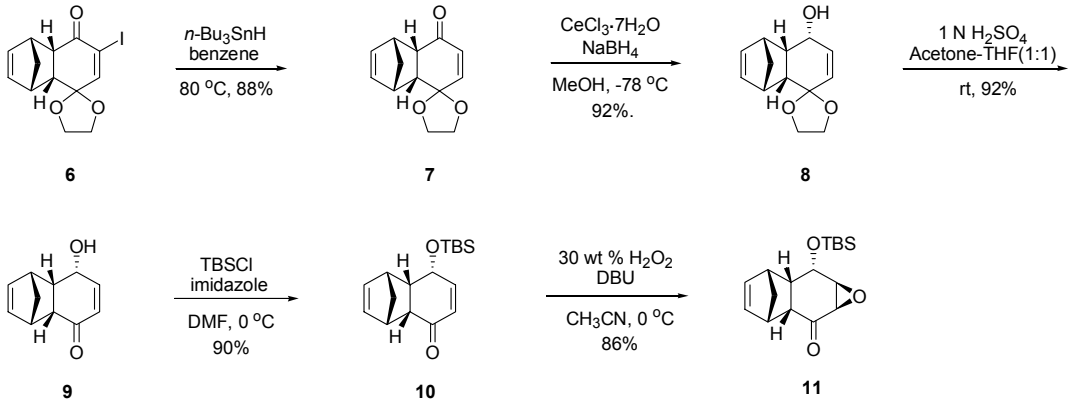


Figure 2

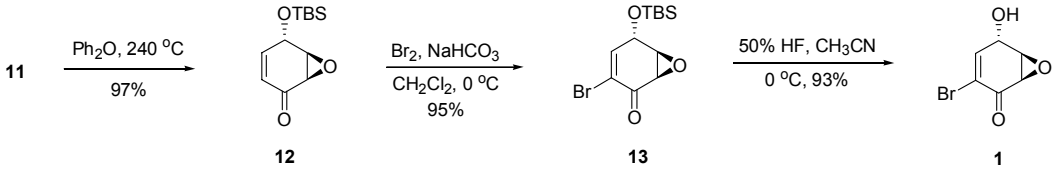


Scheme 1

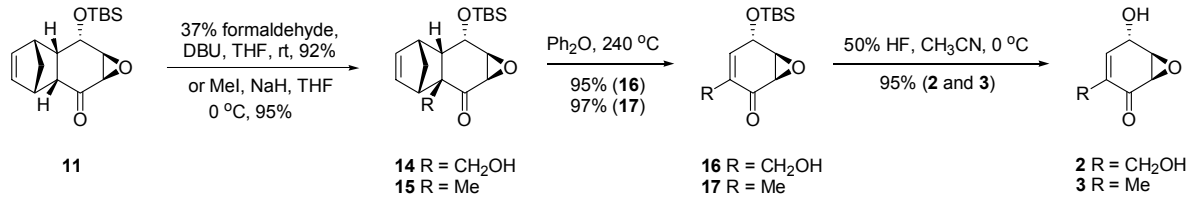
†This paper is dedicated to Professor Sunggak Kim on the occasion of his honorable retirement.



Scheme 2



Scheme 3



Scheme 4

from **7**. To induce the formation of the epoxide with the correct stereochemistry, the free hydroxyl group in **9** was protected with a bulky TBS group to afford **10** in 90% yield. Base-mediated epoxidation of enone **10** was attempted under various conditions. It was found that the epoxidation with hydrogen peroxide and DBU at 0 °C occurred from the convex face to provide only the *exo*-epoxide **11** in 86% yield.[3f]

The retro-Diels-Alder reaction of **11** furnished epoxycyclohexenone **12** in 97% yield. Treatment of **12** with bromine and $NaHCO_3$ as a base gave TBS protected bromoxone **13**. Finally, deprotection of the TBS group afforded the natural product (+)-bromoxone (**1**)[2] in 93% yield (Scheme 3). Identity of the synthetic material is fully established through the comparison of the ^1H and ^{13}C NMR spectra and specific rotations, $[\alpha]^{24}_D$ = +205 (*c* 0.1, acetone), (> 99% ee). [lit.[2g] $[\alpha]^{20}_D$ = +205.7 (*c* 0.32, acetone)]. This is an efficient enantioselective synthesis of (+)-bromoxone[11] with an overall yield of 47% in a total of 9 steps.

The key intermediate **11** was readily elaborated to (+)-epiepoxydon (**2**) and (+)-epiepoformin (**3**) using Ogasawara's previously reported protocol (Scheme 4).[3f,4a]

Treatment of **11** with formaldehyde and DBU gave the hydroxymethyl compound **14** in 92% yield. Whereas, α-methylation provided the *exo*-methylated product **15** in 95% yield. The retro-Diels-Alder reaction and the following deprotection of the TBS group afforded optically pure (+)-epiepoxydon (**2**) and (+)-epiepoformin (**3**). The spectral data and optical rotations of the synthetic compounds were in well accord with the previously reported values.[2f,4d] Overall yields of **2** and **3** were 46% and 48%, respectively, in a total of 9 steps.

In summary, we demonstrated that the chiral Diels-Alder adduct **6** is a useful starting material for the asymmetric synthesis of natural cyclohexenone epoxides. As a result, efficient enantioselective synthesis of (+)-bromoxone, (+)-epiepoxydon and (+)-epiepoformin has been achieved. Further use of this method for the synthesis of additionally functionalized cyclohexane-epoxide natural products is now in progress.

Experimental

Unless stated otherwise, reactions were carried out under a dry argon atmosphere in vacuum-flame dried glassware. Thin-layer chromatography (TLC) was performed on Merck silica gel 60 F254. Flash chromatography was performed using E. Merck silica gel (40 ~ 60 μm particle size). ^1H and ^{13}C NMR spectra were recorded on a Varian at 300 and 75 MHz. Infrared spectra were recorded on a Bruker Vertex 70. HRMS were recorded on JEOL JMS-SX102A mass spectrometer with EI

or FAB resource. Analytical high performance liquid chromatography (HPLC) was performed on FUTECS NS 4000 at 256 nm using the indicated chiral column (4.6 mm × 25 cm). Optical rotations were determined on a Perkin-Elmer Polarimeter Model 343 plus at 589 nm. Commercial grade reagents and solvents were used without further purification.

(1'*R*,4'*S*,4'a*R*,8'*R*,8'a*S*)-4',4'a,8',8'a-Tetrahydro-spiro-{1,3-dioxolane-2,5'(1'H)-[1,4]methanonaphthalen}-8'-ol (8). To a solution of **7** (623 mg, 2.85 mmol) in methanol (10 mL) at 0 °C was added the $CeCl_3 \cdot 7H_2O$ (1.06 g, 2.85 mmol). After 30 min at 0 °C, $NaBH_4$ (215.5 mg, 5.7 mmol) was added to the mixture at −78 °C. The reaction mixture was stirred at −78 °C for 1 h and then quenched with Et_3N (3.42 mmol, 0.48 mL) and saturated aqueous solution of $NaHCO_3$. The aqueous phase was extracted with CH_2Cl_2 (3 × 10 mL). The organic layers were combined and dried over anhydrous sodium sulfate. The mixture was filtered and the solvent was evaporated under reduced pressure. The concentrated crude product was purified by flash column chromatography (hexanes/ethyl acetate, 3:1) affording **8** as viscous oil (578.4 mg, 92%). $[\alpha]_D^{20}$ −194.9 (*c* 1.0, acetone); IR (film) ν_{max} 3459, 2980, 2874, 1476, 1454, 1381, 1240, 1111, 1063, 1021, 948, 735 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.99 (dd, *J* = 5.7, 3 Hz, 1H), 5.80-5.73 (m, 2H), 5.47 (dd, *J* = 9.9, 2.4 Hz, 1H), 4.57-4.48 (m, 1H), 4.07-3.89 (m, 4H), 3.04-3.01 (m, 2H), 2.88-2.79 (m, 1H), 2.71 (dd, *J* = 9.6, 3.3 Hz, 1H), 1.69 (d, *J* = 6.9 Hz, 1H), 1.41-1.34 (m, 1H), 1.30 (d, *J* = 8.1 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 136.5, 135.4, 134.7, 130.1, 106.7, 66.4, 65.1, 64.1, 49.5, 46.4, 45.9, 45.2, 42.4; HRMS (EI) calcd for $C_{13}H_{16}O_3$: 220.1099. found 220.1097.

(1*R*,4*S*,4a*R*,8*R*,8a*S*)-8-hydroxy-4,4a',8,8a'-Tetrahydro-[1,4]methanonaphthalen}-5(1H)-one (9). To a solution of **8** (72.1 mg, 0.33 mmol) in THF (3 mL) was added acetone (2.5 mL) and 1 N H_2SO_4 (2 mL). The reaction mixture was stirred at room temperature for 10 min and then quenched with saturated aqueous solution of $NaHCO_3$. The aqueous phase was extracted with CH_2Cl_2 (3 × 5 mL). The organic layers were combined and dried over anhydrous sodium sulfate. The mixture was filtered and the solvent was evaporated under reduced pressure. The concentrated crude product was purified by flash column chromatography (hexanes/ethyl acetate, 1:1) affording **9** as solid (53.1 mg, 92%). $[\alpha]_D^{20}$ −341.4 (*c* 1.0, acetone); mp 79 ~ 81 °C; IR (film) ν_{max} 3406, 3310, 2992, 2974, 1668, 1637, 1619, 1374, 1301, 1252, 1064, 1036, 852 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.54 (dd, *J* = 10.5, 2.1 Hz, 1H), 6.17 (dd, *J* = 5.7, 3 Hz, 1H), 5.84 (dd, *J* = 5.7, 3 Hz, 1H), 5.79 (dd, *J* = 10.2, 2.4 Hz, 1H), 4.84-4.74 (m, 1H), 3.41 (s, 1H), 3.24 (s, 1H), 3.10-2.97 (m, 2H), 1.78 (d, *J* = 6.6 Hz, 1H), 1.49-1.41 (m, 1H), 1.34 (d, *J* = 8.4 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 201.1, 151.1, 135.8, 135.5, 130.3, 65.7, 51.1, 49.1, 48.1, 46.1, 40.9; HRMS (FAB) ($[M + Na]^+$) calcd for $C_{11}H_{12}O_2$: 199.0735, found: 199.0732.

(1*R*,4*S*,4a*R*,8*R*,8a*S*)-8-{[(1,1-Dimethylethyl)dimethylsilyl]oxy}-4,4a,8,8a-tetrahydro[1,4]methanonaphthalen}-5(1H)-one (10). To a solution of **9** (260 mg, 1.48 mmol) in DMF (5 mL) was added the imidazole (503.5 mg, 7.4 mmol). After 30 min at room temperature, TBSCl (557.7 mg, 3.7 mmol) was added to the mixture at 0 °C. The reaction mixture was stirred at 0 °C for 4 h and then quenched with distilled water. The aqueous phase was extracted with hexanes (3 × 10 mL), The organic layers were combined and dried over anhydrous sodium sulfate. The mixture was filtered and the solvent was evaporated under reduced pressure. The concentrated product was purified by flash column chromatography (hexanes/ethyl acetate, 3:1) affording **10** (385.7 mg, 90%). $[\alpha]_D^{20}$ −210.1 (*c* 1.0, acetone); IR (film) ν_{max} 2955, 2930, 2857, 1668, 1471, 1387, 1253, 1085, 1043, 876, 837 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.42-6.34 (m, 1H), 6.12 (dd, *J* = 5.7, 3 Hz, 1H), 5.77-5.68 (m, 2H), 4.73-4.65 (m, 1H), 3.36 (s, 1H), 3.17 (s, 1H), 2.99-2.85 (m, 2H), 1.41-1.33 (m, 1H), 1.28 (d, *J* = 8.4 Hz, 1H), 0.96 (s, 9H), 0.13 (d, *J* = 8.4 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 200.9, 152.3, 136.7, 134.4, 129.7, 66.1, 51.5, 48.6, 48.1, 46.9, 41.2, 26.1, 18.4, −4.5, −4.6; HRMS (EI) calcd for $C_{17}H_{26}O_2Si$: 290.1702, found 290.1698.

[1a*R*-(1a,2aβ,3β,6β,6aβ,7α,7aα)]-7-{[(1,1-Dimethylethyl)dimethylsiyl]oxy}-2a,3,6,6a,7,7a-hexahydro[3,6]methanonaphth[2,3-b]oxiren-2(1aH)-one (11). To a solution of **10** (86.1 mg, 0.3 mmol) in CH_3CN (2 mL) at 0 °C was added DBU (0.31 mL, 2.1 mmol) and 30% H_2O_2 (0.4 mL, 3.9 mmol). The reaction mixture was stirred at 0 °C for 10 min and then quenched with saturated aqueous solution of NH_4Cl. The aqueous phase was extracted with CH_2Cl_2 (3 × 3 mL). The organic layers were combined and dried over anhydrous sodium sulfate. The mixture was filtered and the solvent was evaporated under reduced pressure. The concentrated product was purified by flash column chromatography (hexanes/ethyl acetate, 1:1) affording **11** as solid (78.1 mg, 86%). $[\alpha]_D^{20}$ −56.4 (*c* 1.0, acetone); IR (film) ν_{max} 2974, 2931,1719, 1462, 1243, 1099, 1067, 837, 776, 732 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.01 (s, 2H), 4.66 (dd, *J* = 5.1, 3.3 Hz, 1H), 3.37 (dd, *J* = 4.5, 3.3 Hz, 1H), 3.23 (d, *J* = 4.2 Hz, 1H), 3.09-3.02 (m, 2H), 2.89-2.82 (m, 2H), 1.36 (d, *J* = 8.4 Hz, 1H), 1.22 (d, *J* = 8.1 Hz, 1H), 0.85 (s, 9H), 0.11 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 207.5, 136.8, 132.6, 67.3, 59.9, 54.9, 51.0, 49.5, 45.4, 45.3, 42.9, 26.2, 18.4, -4.0, -4.7; HRMS (FAB) ($[M + H]^+$) calcd for $C_{17}H_{26}O_2Si$: 307.1724, found: 307.1729.

[1a*S*-(1aα,2aβ,3β,6β,6aβ,7α,7aα)]-3a-Hydroxymethyl-7-{[(1,1-dimethylethyl)dimethylsiyl]oxy}-2a,3,6,6a,7,7a-hexahydro-[3,6]methanonaphth[2,3-b]oxiren-2(1aH)-one (14). To a solution of **11** (157 mg, 0.51 mmol) in THF (2 mL) at 0 °C were added DBU (0.092 mL, 0.61 mmol) and 37 wt % formaldehyde (0.38 mL, 5.1 mmol). The reaction mixture was stirred at room temperature for 3 h and then quenched with saturated aqueous solution of NH_4Cl. The aqueous phase was extracted with CH_2Cl_2 (3 × 5 mL). The organic layers were combined and dried over anhydrous sodium sulfate. The mixture was filtered and the solvent was evaporated under reduced pressure. The concentrated product was purified by flash column chromatography (hexanes/ethyl acetate, 3:1) affording **14** as solid (158.6 mg, 92%). $[\alpha]_D^{20}$ +26.4(*c* 1.0, acetone); IR (film) ν_{max} 3513, 3141, 3044, 2958, 1696, 1470, 1343, 1256, 1065, 856, 829, 777 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.15 (dd, *J* = 5.4, 3 Hz, 1H), 5.97 (dd, *J* = 5.4, 3 Hz, 1H), 4.64, (dd, *J* = 8.1, 2.1 Hz, 1H), 3.93 (dd, *J* = 11.1, 7.5 Hz, 1H), 3.72 (dd, *J* = 11.1, 5.1 Hz, 1H), 3.31 (dd, *J* = 3.6, 2.1 Hz, 1H), 3.23 (d, *J* = 3.9 Hz, 1H), 3.08 (s, 1H), 2.95 (s, 1H), 2.55 (dd, *J* = 8.1, 3.3 Hz, 1H), 2.15 (dd, *J* = 7.5, 5.1 Hz, 1H), 1.41 (d, *J* = 9.3 Hz, 1H), 1.37-1.30 (m, 1H), 0.92 (s, 9H), 0.16 (d, *J* = 3 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 208.2, 138.5, 134.0, 70.1, 66.0, 61.8, 60.7, 54.8, 49.0, 48.2,

46.2, 45.6, 26.2, 18.5, −4.2, −4.7; HRMS (FAB) ($[M+H]^+$) calcd for $C_{18}H_{28}O_4Si$: 337.1835, found 337.1837.

[1a*R*-(1aα,2aβ,3β,6β,6aβ,7α,7aα)]-3a-Methyl-7-{[(1,1-dimethylethyl)dimethylsiyl]oxy}-2a,3,6,6a,7,7a-hexahydro-[3,6]methanonaphth[2,3-b]oxiren-2(1aH)-one (15). To a solution of **11** (31.7 mg, 0.1 mmol) in THF (1 mL) at 0 °C were added NaH (12 mg, 0.5 mmol) and MeI (0.0156 mL, 0.25 mmol). The reaction mixture was stirred at 0 °C for 2 h and then quenched with saturated aqueous solution of NH_4Cl. The aqueous phase was extracted with CH_2Cl_2 (3 × 3 mL). The organic layers were combined and dried over anhydrous sodium sulfate. The mixture was filtered and the solvent was evaporated under reduced pressure. The concentrated product was purified by flash column chromatography (hexanes/ethyl acetate, 3:1) affording **15** as viscous oil (31.5 mg, 95%). $[\alpha]_D^{20}$ +37.0 (*c* 1.0, acetone); IR (film) ν_{max} 2961, 2932, 1704, 1474, 1360, 1338, 1255, 1149, 1108, 1062, 860, 830, 780 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.07 (dd, *J* = 5.7, 3 Hz, 1H), 5.98 (dd, *J* = 5.7, 3 Hz, 1H), 4.70 (dd, *J* = 7.5, 2.4 Hz, 1H), 3.31 (dd, *J* = 3.9, 2.4 Hz, 1H), 3.20 (d, *J* = 3.9 Hz, 1H), 2.85 (s, 1H), 2.75 (s, 1H), 2.49 (dd, *J* = 7.8, 3.3 Hz, 1H), 1.49-1.44 (m, 4H), 1.36-1.28 (m, 1H), 0.90 (s, 9H), 0.15 (d, *J* = 2.1 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 210.1, 137.4, 134.1, 66.7, 60.8, 55.3, 54.6, 53.6, 51.7, 46.6, 45.8, 28.6, 26.2, 18.5, −4.1, −4.8; HRMS (FAB) ($[M+H]^+$) calcd for $C_{18}H_{28}O_3Si$: 321.1886, found 321.1884.

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References

1. For reviews see: (a) Marco-Contelles, J.; Molina, M. T.; Anjum, S. *Chem. Rev.* **2004**, *104*, 2857. (b) Shoji, M.; Hayashi, Y. *Eur. J. Org. Chem.* **2007**, 3783. (c) Ogasawara, K. *J. Synth. Org. Chem. Jpn.* **1999**, *57*, 957.
2. (a) Gautier, E. C. L.; Lewis, N. J.; McKillop, A.; Taylor, R. J. K. *Tetrahedron Lett.* **1994**, *35*, 8759. (b) Johnson, C. R.; Miller, M. W. *J. Org. Chem.* **1995**, *60*, 6674. (c) Adelt, S.; Plettenburg, O.; Stricker, R.; Reiser, G.; Altenbach, H.-J.; Vogel, G. *J. Med. Chem.* **1999**, *42*, 1262. (d) Altenbach, H.-J. In *Antibiotics and Antiviral Compounds*; Krohn, K., Kirst, H., Maas, H., Eds.; VCH: Weinheim, 1993; pp 359-372. (e) Block, O.; Klein, G.; Altenbach, H.-J.; Brauer, D. J. *J. Org. Chem.* **2000**, *65*, 716. (f) Tachihara, T.; Kitahara, T. *Tetrahedron* **2003**, *59*, 1773. (g) Barros, M. T.; Matias, P. M.; Maycock, C. D.; Ventura, M. R. *Org. Lett.* **2003**, *5*, 4321.
3. (a) Ichihara, A.; Kimura, R.; Oda, K.; Sakamura, S. *Tetrahedron Lett.* **1976**, *17*, 4741. (b) Teh-Wei Chou, D.; Ganem, B. *J. Am. Chem. Soc.* **1980**, *102*, 7987. (c) Ichihara, A.; Kimura, R.; Oda, K.; Moriyasu, K.; Sakamura, S. *Agric. Biol. Chem.* **1982**, *46*, 1879. (d) Ichihara, A. *Synthesis* **1987**, 207. (e) Nagata, T.; Ando, Y.; Hiroto, A. *Biosci. Biotechnol. Biochem.* **1992**, *56*, 810. (f) Kamikubo, T.; Hiroya, K.; Ogasawara, K. *Tetrahedron Lett.* **1996**, *37*, 499. (g) Genski, T.; Taylor, R. J. K. *Tetrahedron Lett.* **2002**, *43*, 3573. (h) Mehta, G.; Ramesh, S. S. *Tetrahedron Lett.* **2004**, *45*, 1985. (i) Mehta, G.; Pujar, S. R.; Ramesh, S. S.; Islam, K. *Tetrahedron Lett.* **2005**, *46*, 3373.
4. Kamikubo, T.; Ogasawara, K. *Tetrahedron Lett.* **1995**, *36*, 1685. (b) Barros, M. T.; Maycock, C. D.; Ventura, M. R. *Chem. Eur. J.* **2000**, *6*, 3991. (c) Shimizu, H.; Okamura, H.; Yamashita, N.; Iwagawa, T.; Nakatani, M. *Tetrahedron Lett.* **2001**, *42*, 8649. (d) Carreño, M. C.; Merino, E.; Ribagorda, M.; Somoza, Á.; Urbano, A. *Org. Lett.* **2005**, *7*, 1419.
5. Higa, T.; Okuda, R. K.; Severns, R. M.; Scheuer, P. J.; He, C-H.; Changfu, X.; Clardy, J. *Tetrahedron* **1987**, *43*, 1063.
6. Li, J.; Park, S.; Miller, R. L.; Lee, D. *Org. Lett.* **2009**, *11*, 4290.
7. (a) Moses, J. E.; Commeiras, L.; Baldwin, J. K.; Adlington, R. M. *Org. Lett.* **2003**, *5*, 2987. (b) Mehta, G.; Islam, K. *Tetrahedron Lett.* **2004**, *45*, 7683. (c) Matsuzawa, M.; Kakeya, H.; Yamaguchi, J.; Shoji, M.; Onose, R.; Osada, H.; Hayashi, Y. *Chem. Asian J.* **2006**, *1*, 845.
8. (a) Porco, J. A., Jr.; Su, S.; Lei, X.; Bardhan, S.; Rychnovsky, S. D. *Angew. Chem., Int. Ed.* **2006**, *45*, 5790. (b) Mehta, G.; Roy, S. *Tetrahedron Lett.* **2008**, *49*, 1458.
9. (a) Corey, E. J. *Angew. Chem., Int. Ed.* **2009**, *48*, 2100. (b) Senapati, B. K.; Hwang, G.-S.; Lee, S.; Ryu, D. H. *Angew. Chem., Int. Ed.*, **2009**, *48*, 4398. (c) Gao, L.; Hwang, G.-S.; Lee, M. Y.; Ryu, D. H. *Chem. Commun.* **2009**, 5460.
10. (a) Ryu, D. H.; Zhou, G.; Corey, E. J. *Org. Lett.* **2005**, *7*, 1633. (b) Ryu, D. H.; Zhou, G.; Corey, E. J. *J. Am. Chem. Soc.* **2004**, *126*, 8106. (c) Ryu, D. H.; Corey, E. J. *J. Am. Chem. Soc.* **2003**, *125*, 6388. (d) Ryu, D. H.; Lee, T. W.; Corey, E. J. *J. Am. Chem. Soc.* **2002**, *124*, 9992. (e) Ryu, D. H.; Kim, K. H.; Sim, J. Y.; Corey, E. J. *Tetrahedron Lett.* **2007**, *48*, 5735. (f) Sim, J. Y.; Hwang, G.-S.; Kim, K. H.; Ko, E. M.; Ryu, D. H. *Chem. Commun.* **2007**, 5064. (g) Lee, M. Y.; Kim, K. H.; Jiang, S.; Jung, Y. H.; Sim, J. Y.; Hwang, G.-S.; Ryu, D. H. *Tetrahedron Lett.* **2008**, *49*, 1965. (h) Kim, J. Y.; Hwang, G.-S.; Lee, S. M.; Han, J. H.; Kim, E. Y.; Ryu, D. H. *Bull. Korean Chem. Soc.* **2009**, *30*, 289.