HETEROCYCLES, Vol. 82, No. 2, 2011, pp. 1327 - 1336. © The Japan Institute of Heterocyclic Chemistry
Received, 28th June, 2010, Accepted, 6th August, 2010, Published online, 1st December, 2010
DOI: 10.3987/COM-10-S(E)79

EFFICIENT PHENOLIC OXIDATIONS TO CONSTRUCT *ORTHO*-SPIROLACTONE STRUCTURES USING OXO-BRIDGED HYPERVALENT IODINE(III) COMPOUND

Naoko Takenaga,[†] Teruyoshi Uchiyama,[‡] Daishi Kato,[‡] Hiromichi Fujioka,[†] Toshifumi Dohi,[†,‡] and Yasuyuki Kita[‡,*]

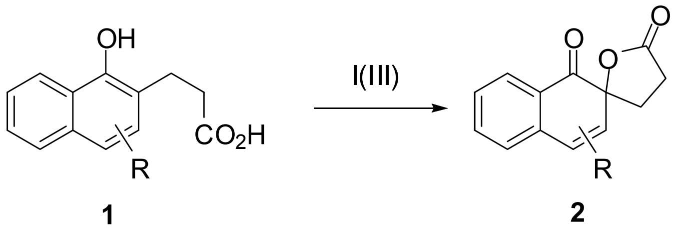
[†]Graduate School of Pharmaceutical Sciences, Osaka University, 1-6 Yamada-oka, Suita, Osaka, 565-0871, JAPAN
[‡]College of Pharmaceutical Sciences, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu, Shiga, 525-8577, JAPAN
[*]Corresponding author. Tel.: +81-77-561-5829; fax: +81-77-561-5829; e-mail: kita@ph.ritsumei.ac.jp (Y. Kita)

Abstract – The intramoleular *ortho*-spirocyclization of naphthols **1** bearing carboxylic acid moieties as internal nucleophiles using hypervalent iodine reagents is described. The use of the μ-oxo-bridged hypervalent iodine(III) compound is remarkably effective for this transformation, and spirolactones **2** were obtained in good to excellent yields using the μ-oxo-bis[trifluoroacetato-(phenyl)iodine] **4** [PhI(OCOCF$_3$)O(OCOCF$_3$)IPh].

This paper is dedicated to Professor Albert Eschenmoser on the occasion of his 85th birthday.

INTRODUCTION

Hypervalent iodine(III) reagents, such as PhI(OAc)$_2$ [phenyliodine diacetate, PIDA] and PhI(OCOCF$_3$)$_2$ [phenyliodine bis(trifluoroacetate), PIFA], are organo-oxidants having reactivities similar to those of the highly toxic heavy-metal oxidants, and are now recognized as useful tool for performing various environmentally benign oxidations.[1] Over the past 25 years, we have been engaged in the development of the hypervalent iodine(III)-mediated oxidation of phenol derivatives, and established its application for the synthesis of natural products.[2] In particular, for the efficient constructions of *para*-spirodienone structures, we have previously demonstrated the PIDA- and PIFA-mediated intramolecular oxidative cyclizations of phenols and their derivatives having pendent nucleophiles at the *para*-positions.[2a] In a continuation of our study on this theme,[3] we now report the intramoleular *ortho*-spirocyclization of naphthols **1** bearing carboxylic acid moieties as the nucleophilic side-chains (Scheme 1).

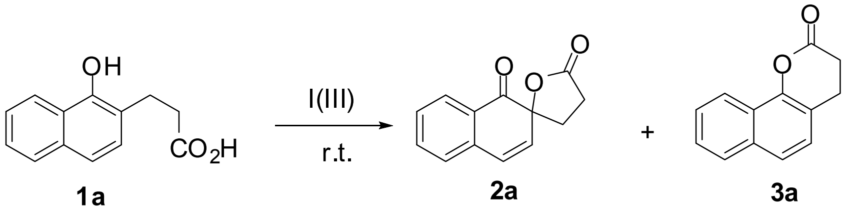


Scheme 1. *ortho*-Spirocyclization of naphthols **1** using hypervalent iodine(III) reagents.

RESULTS AND DISCUSSION

A number of natural products having spirocyclic backbones exist, and most of them are attractive synthetic targets for organic chemists. In particular, *ortho*-spirolactone structures would be potentially useful subunits as precursors of bioactive compounds, such as lactonamycin and arnotin II.[4] For the purpose of developing the efficient synthesis of these *ortho*-spirolactone structures, we surveyed a suitable reaction condition, selecting naphthol carboxylic acid **1a** as the model case (Table 1). As shown in entries 1 and 2, all preliminary experiments based on our previous conditions for the *para*-spirocycliztions of phenols using PIDA and PIFA[2a] afforded the desired *ortho*-spirolactone product **2a** in low yields only. Particularly, formation of the six-membered aryl lactone **3a**, a dehydrative condensation product, occurred as an undesired background reaction when using PIFA in CH_2Cl_2 at room temperature (entry 2).

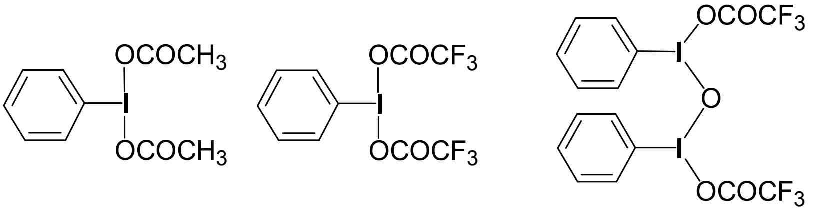
Table 1. *ortho*-Spirocyclization of **1a** using hypervalent iodine(III) reagents



entry	I(III)	solvent	time	**2a**	**3a**
1	$PhI(OAc)_2$ (PIDA)	CH_2Cl_2	1 h	11%	n.d.
2	$PhI(OCOCF_3)_2$(PIFA)	CH_2Cl_2	2 h	17%	45%
3	**4**	CH_2Cl_2	1 h	47%	n.d.
4	//	MeCN	1 h	58%	n.d.
5[a]	//	MeCN	1 h	73%	n.d.

[a] Reaction was performed at 0 °C.

Extensive examinations using PIDA and PIFA under the standard conditions did not produce any good result. In marked contrast, we found that a μ-oxo-bridged hypervalent iodine(III) reagent **4**[5] (Figure 1) is exceptionally effective for allowing the oxidative *ortho*-spirocyclization of **1a** leading to **2a** as shown in entry 3. Among the employed iodine reagents, reagent **4** afforded a very promising result. We then screened several solvents and conditions using **4**, and found that the use of MeCN at low temperature was remarkably effective for this transformation (entry 5). The use of fluoroalcohols such as $(CF_3)_2CHOH$ or CF_3CH_2OH, was not effective in this case and treatment of PIDA, PIFA, and the compound **4** in $(CF_3)_2CHOH$ did not show any distinct improvement of yield compared with the optimized reaction condition in entry 5.



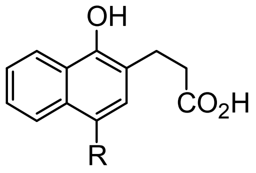
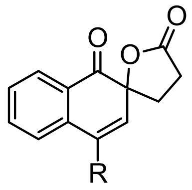
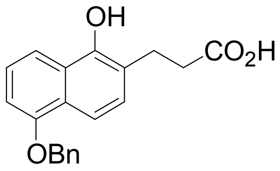
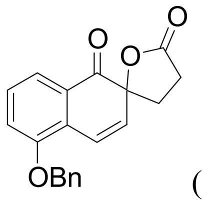
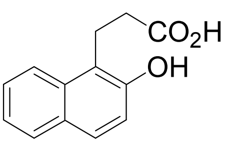
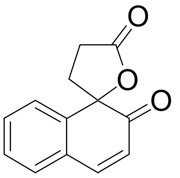
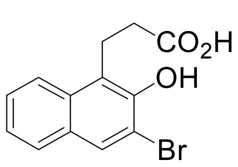
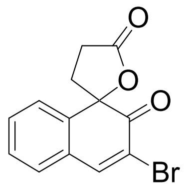
PIDA PIFA **4**

Figure 1. Hypervalent iodine(III) reagents for phenolic oxidations.

The μ-oxo-bridged hypervalent iodine(III) reagent **4** is a stable white powder and soluble in various organic solvents, such as CH_2Cl_2 and MeCN. The spirolactone **2a** was obtained using the following experimental protocol; a solution of **1a** (1.0 equiv) in MeCN was dropwise added to a stirred solution of **4** (0.55 equiv) in MeCN. The use of a half equivalent of **4** is enough to perform the reaction as the reagent has two reactive iodine(III) atoms in the molecule. The initially clear solution of the reaction mixture became slightly yellow as the reaction proceeded. After checking for the disappearance of the phenol **1a** by TLC, the mixture was quenched with saturated $NaHCO_3$ aq. and extracted several times with CH_2Cl_2. The organic layers were combined and evaporated in *vacuo*. From the residue, the co-product iodobenzene, which was produced from reagent **4**, was removed by column chromatography, giving the spirocyclized lactone **2a** in 73% yield.

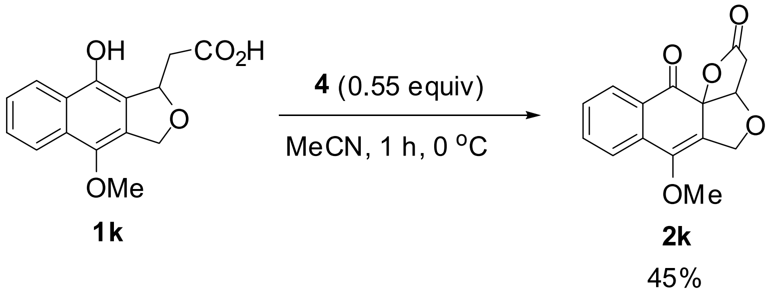
To confirm the high reactivity of the μ-oxo-bridged hypervalent iodine(III) reagent **4**, we further examined the scope of the substrates in the reactions. Selected examples are shown in Table 2. Electron-rich alkyl naphthols, such as **1b** and **1c**, afforded the corresponding spirolactones **2b** and **2c** in moderate yields (entries 2 and 3). On the other hand, naphthols bearing weak electron-withdrawing groups gave products **2d-g** in good to excellent yields (entries 4-7). Oxygen-atom containing naphthol **1h** was also applicable for the reaction (entry 8). Furthermore, the 2-naphthol derivatives also provided the expected spirolactones **2i** and **2j** (entries 9 and 10), respectively. These results clearly show the utility of

Table 2. *ortho*-Spirocyclization of various naphthols **1** using a hypervalent iodine(III) reagent **4**[a]

entry	Substrate	product	yield[b]
			
1	R = H (**1a**)	(**2a**)	73%
2	R = Et (**1b**)	(**2b**)	52%
3	R = Cy (**1c**)	(**2c**)	55%
4	R = Ph (**1d**)	(**2d**)	79%
5	R = Bn (**1e**)	(**2e**)	80%
6	R = Br (**1f**)	(**2f**)	93%
7	R = Bz (**1g**)	(**2g**)	99%
8	 (**1h**)	 (**2h**)	87%
9	 (**1i**)	 (**2i**)	63%
10	 (**1j**)	 (**2j**)	82%

[a] Reactions were performed using **4** (0.55 equiv.) in MeCN (0.05 M) at 0 °C for 1 h unless otherwise noted.
[b] Isolated yield after purification.

the present system using the μ-oxo-bridged hypervalent iodine(III) reagent **4** for the *ortho*-spirocyclization of the phenol derivatives. Finally, we demonstrated an example aiming at application of the method to natural product synthesis although this project is still currently underway. That is, the reaction system is applied to substrate **1k** to provide a tetracyclic compound **2k** containing the model ABCD rings of lactonamycin (Eq. 1).[4a]



(1)

Although the excellent role of reagent **4** over other iodine(III) reagents in the reactions remains unclear, we tentatively presume that its high reactivity would be derived from the unique μ-oxo-bridged structure. Previous report on the crystal structure of **4** revealed that the two types of I-O bond distances of the μ-oxo-bridged I-O and another I-$OCOCF_3$ are quite different.[5] Indeed, the I-O distance of the latter bond is remarkably longer than that of the former, which seems to facilitate the dissociation of the trifluoroacetoxy anion to produce the highly electrophilic iodine(III) center by the *trans* effect of the μ-oxo-bridged oxygen atom, resulting in the enhancement of the reactivity of **4** toward nucleophiles during the ligand exchange step.[7] We have confirmed the high reactivities of μ-oxo-bridged iodine(III) reagent **4** in many other reactions over the classical iodine(III) reagents, such as PIDA and PIFA.

In summary, we have developed an efficient oxidative *ortho*-spirocyclizing reaction by the appropriate choice of the highly reactive reagent, μ-oxo-bridged hypervalent iodine(III) compound **4**. The intriguing feature of the present transformation is the easy availability of the various *ortho*-spirolactones **2** from the readily prepared naphthol carboxylic acids **1**. The resulting five-membered spirolactones **2** would be promising intermediates for the syntheses of biologically active natural products. We are currently studying its synthetic application for the construction of some natural products as well as the design of new iodine reagents having the unique μ-oxo-bridged structures suitable for these types of transformations.

EXPERIMENTAL

Melting points (mp) are uncorrected. All ^1H and ^{13}C-NMR spectra of the products were measured in $CDCl_3$ using tetramethylsilane (δ 0.00 for ^1H and ^{13}C) as an internal standard. Data are reported as follows: chemical shift in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, brs = broad singlet, m = multiplet), coupling constant (Hz), and integration. Infrared spectra (IR) were obtained on a Hitachi 270-50 spectrometer; absorptions are reported in reciprocal centimeters. The high resolution mass spectra and elemental analysis were performed by the Elemental Analysis Section of Osaka University. Flash column chromatography was performed with SiO_2 (Merck Silica Gel 60 (230-400 mesh)).

Preparation of μ-oxo-bridged hypervalent iodine(III) reagent 4

μ-Oxo-bridged hypervalent iodine(III) reagent **4** was prepared according to the literature procedure.[5]

Synthesis of naphthol carboxylic acids 1[3]

1a was prepared by hydrolysis of 3,4-dihydro-2*H*-naphtho[1,2-*b*]pyran-2-one[8] under basic conditions. Other naphthol carboxylic acids (**1b-1j**) were obtained from the corresponding naphthols by similar procedures.[9] Tricyclic **1k** was synthesized according to the reported method.[4a]

General procedure for the experiments in Table 2 (*ortho*-spirolactonization)

To a stirred solution of μ-oxo-bridged hypervalent iodine(III) reagent **4** (35.8 mg, 0.11 x 1/2 mmol) in MeCN (1.0 mL) a solution of 3-(1-hydroxy-2-naphthyl)propionic acid **1a** (21.6 mg, 0.10 mmol) in MeCN (1.0 mL) was added dropwise at 0 °C. The reaction mixture was stirred for 1 h at the same temperature. After the reaction completion, saturated $NaHCO_3$ aq. was added to the mixture, and it was then extracted with CH_2Cl_2. The combined organic layers were washed with brine and dried over anhydrous Na_2SO_4. After removal of the solvents, the residue was subjected to column chromatography on silica-gel (eluents: *n*-hexane/AcOEt = 2/1) to give **2a** (15.6 mg, 0.073 mmol) in 73% yield.

3,4-Dihydrospiro[furan-2(5*H*),2'(1'*H*)-naphthalene]-1',5-dione (2a)

White powder; mp 104-105 °C; IR (KBr, cm^{-1}): 1788, 1693, 1597, 1481, 1454, 1323, 1296, 1178, 1123, 1032, 930, 787, 696; ^{1}H-NMR (300 MHz, $CDCl_3$): 2.13-2.25 (m, 1H), 2.39-2.47 (m, 1H), 2.55-2.65 (m, 1H), 2.85-2.98 (m, 1H), 6.21 (d, J = 9.9 Hz, 1H), 6.66 (d, J = 9.9 Hz, 1H), 7.26 (d, J = 7.2 Hz, 1H), 7.41 (t, J = 7.5 Hz, 1H), 7.64 (t, J = 7.5 Hz, 1H), 8.02 (d, J = 7.8 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.4, 31.0, 83.4, 127.1, 127.5, 127.8, 127.9, 128.8, 132.1, 135.6, 136.7, 176.5, 196.5; HRMS (FAB) calcd for $C_{13}H_{11}O_3$ (M^+ + H): 215.0708, found: 215.0694.

4'-Ethyl-3,4-dihydrospiro[furan-2(5*H*),2'(1'*H*)-naphthalene]-1',5-dione (2b)

White powder; mp 96-97 °C; IR (KBr, cm^{-1}): 2968, 2937, 2878, 1787, 1693, 1597, 1452, 1294, 1211, 1175, 1032, 931, 849, 750, 707; ^{1}H-NMR (300 MHz, $CDCl_3$): 1.26 (t, *J* = 7.2 Hz, 3H), 2.13-2.22 (m, 1H), 2.36-2.45 (m, 1H), 2.54-2.64 (m, 3H), 2.82-2.96 (m, 1H), 6.00 (s, 1H), 7.42 (t, *J* = 7.5 Hz, 1H), 7.46 (d, *J* = 8.1 Hz, 1H), 7.68 (dd, *J* = 7.8 Hz, 1.5 Hz, 1H), 8.05 (dd, *J* = 7.8 Hz, 1.5 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 12.2, 24.8, 26.7, 31.4, 83.7, 124.2, 127.0, 127.3, 127.8, 128.4, 135.4, 137.3, 138.1, 176.5, 196.8; HRMS (EI) calcd for $C_{15}H_{14}O_3$ (M^+): 242.0943, found: 242.0941.

4’-Cyclohexyl-3,4-dihydrospiro[furan-2(5*H*),2’(1’*H*)-naphthalene]-1’,5-dione (2c)

White powder; mp 151-152 °C; IR (KBr, cm^{-1}): 2928, 2853, 1789, 1693, 1593, 1450, 1294, 1175, 1034, 935, 712; ^{1}H-NMR (300 MHz, $CDCl_3$): 1.21-1.51 (m, 5H), 1.75-2.13 (m, 5H), 2.16-2.20 (m, 1H), 2.36-2.44 (m, 1H), 2.53-2.65 (m, 2H), 2.80-2.92 (m, 1H), 5.97 (s, 1H), 7.40 (t, *J* = 7.2 Hz, 1H), 7.49 (d, *J* = 7.8 Hz, 1H), 7.67 (dd, *J* = 7.8 Hz, 1.5 Hz, 1H), 8.04 (dd, *J* = 7.5 Hz, 1.5 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.2, 26.7, 31.5, 32.5, 32.8, 38.5, 83.9, 124.0, 125.9, 127.7, 128.1, 128.2, 135.3, 137.0, 141.8, 176.5, 196.9; HRMS (FAB) calcd for $C_{19}H_{21}O_3$ (M^+ + H): 297.1412, found: 297.1505.

3,4-Dihydro-4’-phenylspiro[furan-2(5*H*),2’(1’*H*)-naphthalene]-1’,5-dione (2d)

White powder; mp 172-174 °C; IR (KBr, cm^{-1}): 3554, 3059, 3032, 2982, 2930, 2253, 1965, 1944, 1788, 1769, 1745, 1682, 1643, 1593, 1566, 1493, 1479, 1454, 1443; ^{1}H-NMR (300 MHz, $CDCl_3$): 2.21-2.33 (m, 1H), 2.48-2.67 (m, 2H), 2.85-2.96 (m, 1H), 6.12 (s, 1H), 7.15 (d, *J* = 7.7 Hz, 1H), 7.34-.7.35 (m, 2H),7.40-7.44 (m, 4H) 7.55 (t, *J* = 7.4 Hz, 1H), 8.05 (d, *J* = 7.4 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.8, 31.5, 83.7, 127.2, 127.4, 128.0, 128.3, 128.5, 128.8, 130.4, 135.2,137.2, 137.4, 139.7, 187.2, 196,2; HRMS (EI) calcd for $C_{19}H_{14}O_3$ (M^+): 290.0943, found: 290.0960.

3,4-Dihydro-4’-(phenylmethyl)spiro[furan-2(5*H*),2’(1’*H*)-naphthalene]-1’,5-dione (2e)

White powder; mp 159-160 °C; IR (KBr, cm^{-1}): 3061, 3028, 1790, 1693, 1597, 1495, 1452, 1294, 1211, 1172, 1032, 930, 735, 700, 654; ^{1}H-NMR (300 MHz, $CDCl_3$): 2.11-2.23 (m, 1H), 2.40-2.47 (m, 1H), 2.52-2.62 (m, 1H), 2.82-2.95 (m, 1H), 3.89 (s, 2H), 5.90 (s, 1H), 7.23-7.42 (m, 7H), 7.59 (t, *J* = 7.8 Hz, 1H), 8.05 (d, *J* = 7.8 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.6, 31.4, 38.5, 83.6, 125.0, 126.7, 127.4, 127.9, 128.57, 128.64, 130.7, 135.4, 135.7, 137.0, 137.3, 176.4, 196.5; HRMS (FAB) calcd for $C_{20}H_{17}O_3$ (M^+ + H): 305.1099, found: 305.1168.

4’-Bromo-3,4-dihydrospiro[furan-2(5H),2’(1’H)-naphthalene]-1’,5-dione (2f)

Pale yellow powder; mp 156 °C (decomposed); IR (KBr, cm^{-1}): 3684, 3622, 3018, 2945, 2895, 2399, 1788, 1697, 1628, 1591; ^{1}H-NMR (300 MHz, $CDCl_3$): 2.16-2.31 (m, 1H), 2.45 (t, *J* = 11.0 Hz, 1H), 2.61

(dd, *J* = 17.2, 9.3 Hz, 1H), 2.81-2.95 (m, 1H), 6.66 (s, 1H), 7.46-7.52 (m, 1H), 7.74 (d, *J* = 3.8 Hz, 2H), 8.02 (d, *J* = 7.6 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.4, 31.1, 84.2, 122.4, 127.3, 127.9, 128.8, 130.1, 133.4, 135.1, 135.9, 175.7, 194.7; Anal. Calcd for $C_{13}H_9BrO_3$: C, 53.27; H, 3.09; Br, 27.26. Found: C, 53.03; H, 3.02; Br, 27.09.

4'-Benzoyl-3,4-dihydrospiro[furan-2(5*H*),2'(1'*H*)-naphthalene]-1',5-dione (2g)

White powder; mp 97-98 °C; IR (KBr, cm^{-1}): 2925, 1791, 1665, 1595, 1450, 1276, 1244, 1172, 1033, 990, 937, 913, 775, 735, 662; ^{1}H-NMR (400 MHz, $CDCl_3$): 2.22- 2.30 (m, 1H), 2.47-2.63 (m, 2H), 2.85-2.94 (m, 1H), 6.37 (s, 1H), 7.39 (d, *J* = 7.8 Hz, 1H), 7.44-7.50 (m, 3H), 7.57-7.65 (m, 2H), 7.95 (dd, *J* = 8.3, 1.2 Hz, 2H), 8.11 (dd, *J* = 7.8, 1.2 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.3, 31.2, 82.7, 126.9, 127.4, 128.5, 128.9, 129.8, 130.1, 134.0, 134.2, 134.3, 135.8, 135.9, 137.5, 175.9, 194.5, 195.2; HRMS (EI) calcd for $C_{20}H_{14}O_4$ (M^+): 318.0892, found: 318.0888.

5'-Benzyloxy-3,4-dihydrospiro[furan-2(5*H*),2'(1'*H*)-naphthalene]-1',5-dione (2h)

Pale yellow powder; mp 173-174 °C; IR (KBr, cm^{-1}): 2918, 1789, 1689, 1590, 1455, 1266, 1178, 1033, 939, 749; ^{1}H-NMR (400 MHz, $CDCl_3$): 2.08-2.20 (m, 1H), 2.37-2.42 (m, 1H), 2.53-2.59 (m, 1H), 2.81-2.91 (m, 1H), 5.12 (s, 2H), 6.14 (d, *J* = 10.0 Hz, 1H), 7.14 (d, *J* = 10.0 Hz, 1H), 7.19 (d, *J* = 8.3 Hz, 1H), 7.29-7.43 (m, 6H), 7.61 (d, *J* = 7.8 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.5, 29.7, 31.3, 70.9, 83.5, 118.8, 119.8, 121.8, 126.1, 127.4, 128.3, 128.7, 129.6, 131.1, 136.1, 154.4, 176.5, 196.9; HRMS (EI) calcd for $C_{20}H_{16}O_4$ (M^+): 320.1049, found: 320.1051.

3,4-Dihydrospiro[furan-2(5*H*),1'(2'*H*)-naphthalene]-2',5-dione (2i)

White powder; mp 137-138 °C; IR (KBr, cm^{-1}): 2957, 1786, 1680, 1568, 1244, 1173, 1038, 902, 832, 757, 462; ^{1}H-NMR (400 MHz, $CDCl_3$): 2.08 (m, 1H), 2.59-2.67 (m, 2H), 2.78-2.87 (m, 1H), 6.15 (d, *J* = 9.8 Hz, 1H), 7.32-7.40 (m, 2H), 7.43-7.47 (m, 2H), 7.53 (d, *J* = 7.7 Hz, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.6, 35.8, 53.4, 85.8, 122.6, 125.8, 129.1, 129.7, 131.0, 140.6, 146.0, 176.4, 197.5; HRMS (EI) calcd for $C_{13}H_{10}O_3$ (M^+): 214.0630, found: 214.0646.

3'-Bromo-3,4-dihydrospiro[furan-2(5*H*),1'(2'*H*)-naphthalene]-2',5-dione (2j)

White powder; mp 135-136 °C; IR (KBr, cm^{-1}): 2925, 1790, 1692, 1345, 1160, 1038, 912, 797, 744, 670, 582, 468; ^{1}H-NMR (300 MHz, $CDCl_3$): 2.11-2.20 (m, 1H), 2.62-2.68 (m, 2H), 2.80-2.90 (m, 1H), 7.27 (d, *J* = 7.2 Hz, 1H), 7.40 (dd, *J* = 7.4, 1.2 Hz, 1H), 7.48-7.54 (m, 2H), 7.89 (s, 1H); ^{13}C-NMR (75 MHz, $CDCl_3$): 26.4, 36.1, 86.4, 118.3, 126.0, 128.9, 129.4, 129.6, 131.4, 139.9, 147.3, 175.8, 191.2 ; HRMS (EI) calcd for $C_{13}H_{14}BrO_3$ (M^+): 291.9735, found: 291.9725.

Danishefsky's lactone 2k[4a]

White powder; mp 142.5 °C (decomposed); IR (KBr, cm^{-1}): 3153, 2939, 2851, 2359, 2340, 1790, 1693, 1666, 1595; ^{1}H-NMR (300 MHz, CDCl$_3$): 2.83 (d, J = 18.0 Hz, 1H), 3.18 (dd, J = 18.0 Hz, 4.8 Hz, 1H), 3.98 (s, 3H), 4.75 (d, J = 4.8 Hz, 1H), 4.92, 5.08 (ABq, J = 12.8 Hz, 2H), 7.45 (td, J = 7.1 Hz, 2.0 Hz, 1H), 7.64-7.71 (m, 2H), 7.90 (d, J = 7.1 Hz, 1H); ^{13}C-NMR (75 MHz, CDCl$_3$): 37.9, 59.3, 69.0, 79.4, 88.4, 110.6, 124.1, 127.4, 128.3, 129.5, 135.47, 135.52, 149.9, 174.7, 192.1. HRMS (FAB) calcd for $C_{15}H_{13}O_5$ (M^++H) 273.0763, found: 273.0762.

ACKNOWLEDGEMENTS

This work was partially supported by Grant-in-Aid for Scientific Research (A) from the Japan Society for the Promotion of Science (JSPS), Young Scientists (B) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), and Ritsumeikan Global Innovation Research Organization (R-GIRO) project. T.D. also acknowledges support from the Industrial Technology Research Grant Program from the New Energy and Industrial Technology Development Organization (NEDO) of Japan. N.T. thanks the research fellowship of JSPS for Young Scientists.

REFERENCES

1. Recent reviews and publications: a) P. J. Stang and V. V. Zhdankin, *Chem. Rev.*, 1996, **96**, 1123; b) Y. Kita, T. Takada, and H. Tohma, *Pure Appl. Chem.*, 1996, **68**, 627; c) A. Kirschning, *Eur. J. Org. Chem.*, 1998, 2267; d) V. V. Zhdankin and P. J. Stang, *Chem. Rev.*, 2002, **102**, 2523; e) *Hypervalent Iodine Chemistry*; T. Wirth, Ed.; Springer-Verlag: Berlin, Heidelberg, 2003; f) H. Tohma and Y. Kita, *Top Curr. Chem.*, 2003, **224**, 209; g) V. V. Zhdankin and P. J. Stang, *Chem. Rev.*, 2008, **108**, 5299; h) T. Dohi and Y. Kita, *Chem. Commun.*, 2009, 2073.
2. Our previous works for phenolic oxidations: a) Y. Tamura, T. Yakura, J. Haruta, and Y. Kita, *J. Org. Chem.*, 1987, **52**, 3927; b) Y. Kita, H. Tohma, K. Kikuchi, M. Inagaki, and T. Yakura, *J. Org. Chem.*, 1991, **56**, 435; c) Y. Kita, H. Tohma, M. Inagaki, K. Hatanaka, and T. Yakura, *J. Am. Chem. Soc.*, 1992, **114**, 2175; d) Y. Kita, M. Arisawa, M. Gyoten, M. Nakajima, R. Hamada, H. Tohma, and T. Takada, *J. Org. Chem.*, 1998, **63**, 6625; e) H. Tohma, Y. Harayama, M. Hashizume, M. Iwata, M. Egi, and Y. Kita, *Angew. Chem.*, 2002, **114**, 358; *Angew. Chem. Int. Ed.*, 2002, **41**, 348; f) T. Dohi, A. Maruyama, M. Yoshimura, K. Morimoto, H. Tohma, and Y. Kita, *Angew. Chem. Int. Ed.*, 2005, **44**, 6193; g) T. Dohi, Y. Minamitsuji, A. Maruyama, S. Hirose, and Y. Kita, *Org. Lett.*, 2008, **10**, 3559; h) Y. Minamitsuji, D. Kato, H. Fujioka, T. Dohi, and Y. Kita, *Aust. J. Chem.*, 2009, **62**, 648.
3. a) T. Dohi, A. Maruyama, N. Takenaga, K. Senami, Y. Minamitsuji, H. Fujioka, S. B. Caemmerer, and Y. Kita, *Angew. Chem. Int. Ed.*, 2008, **47**, 3787; b) T. Dohi, Y. Kita, and A. Maruyama, *Jpn.*

Kokai Tokkyo Koho, 2009149564A, 2009.

4. For recent reports of natural product syntheses containing the *ortho*-spirolactone structures, see: a) C. Cox and S. J. Danishefsky, *Org. Lett.*, 2000, **2**, 3493; b) T. Siu, C. D. Cox, and S. J. Danishefsky, *Angew. Chem.*, 2003, **115**, 5787; *Angew. Chem. Int. Ed.*, 2003, **42**, 5629; c) D. A. Henderson, P. N. Collier, G. Pave, P. Rzepa, A. J. P. White, J. N. Burrows, and A. G. M. Barrett, *J. Org. Chem.*, 2006, **71**, 2434; d) F. Konno, T. Ishikawa, M. Kawahata, and K. Yamaguchi, *J. Org. Chem.*, 2006, **71**, 9818.
5. For previous report on the structure of **4**, see: J. Gallos, A. Varvoglis, and N. W. Alcock, *J. Chem. Soc., Perkin Trans. 1*, 1985, 757.
6. In contrast, the cyclohexa-2,4-dienones obtained from the oxidations of simple phenol carboxylic acids are generally quite reactive and have high propensity toward self-dimerization through the Diels-Alder process. For selected example, see: I. Drutu, J. T. Njardarson, and J. L. Wood, *Org. Lett.*, 2002, **4**, 493.
7. a) R. M. Moriarty and O. Prakash, *Acc. Chem. Res.*, 1986, **19**, 244; b) A. Varvoglis, *hypervalent Iodine in Organic Synthesis*, Academic Press, San Diego, CA, 1997; c) *Ligand Coupling Reaction with Het eroatomic Compounds*, ed. Finet, P. Tetrahedron Organic Chemistry Series, Pergamon, Oxford, 1998, vol. 18.
8. J. Posakony, M. Hirao, S. Stevens, J. A. Simon, and A. Bedalov, *J. Med. Chem.*, 2004, **47**, 2635.
9. Y. Kitani, A. Morita, T. Kumamoto, and T. Ishikawa, *Helv. Chim. Acta*, 2002, **85**, 1186.