Synthetic Methods

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Practical, Modular, and General Synthesis of Benzofurans through Extended Pummerer Annulation/Cross-Coupling Strategy**

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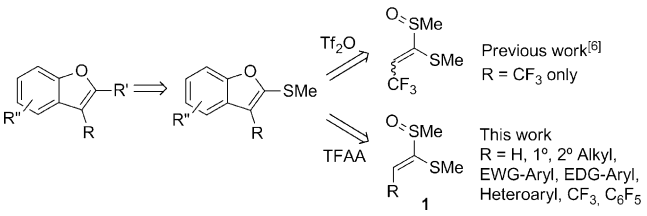
Abstract: *Operationally simple, efficient, and widely applicable Pummerer annulations of simple phenols with ketene dithioacetal monoxides, with the aid of trifluoroacetic anhydride, have been shown to provide a variety of benzofurans having a methylthio group at the 2-position. Subsequent and newly developed nickel-catalyzed arylation at the methylthio group culminates in diversity-oriented synthesis of multisubstituted benzofurans. Our extended Pummerer annulation/cross-coupling sequence is powerful enough to synthesize biologically active natural products as well as highly fluorescent benzofuran derivatives.*

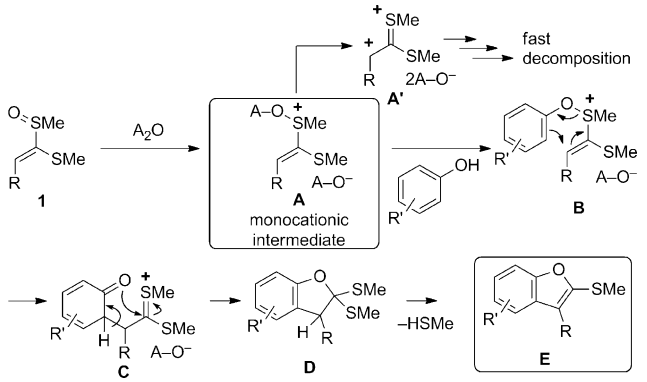


Scheme 1. Modular synthesis of substituted benzofurans. EDG = electron-donating group, EWG = electron-withdrawing group, Tf = trifluoromethanesulfonyl, TFAA = trifluoroacetic anhydride.

Benzofuran is an ubiquitous core found in various natural products,[1] biologically active molecules,[2] and organic functional molecules.[3] Development of straightforward and diversity-oriented reactions to construct benzofurans[4] would therefore have a big impact for pharmaceutical chemists as well as materials chemists who need libraries for novel molecules. While recent active investigations on direct two-component annulations of simple phenols describe an ideal route,[5] it has still been difficult to achieve modular and precise syntheses of substituted benzofurans.

We recently reported the synthesis of 3-trifluoromethylbenzofurans,[6] which have a convertible alkylthio group[7] at the 2-position, from simple phenols and perfluoroalkyl-substituted ketene dithioacetal monoxide (KDM) through an extended Pummerer annulation (Scheme 1).[8–10] Our diversity-oriented synthesis of substituted benzofurans was accomplished through an extended Pummerer annulation/cross-coupling[11] sequence. Although the annulation is metal-free, rapid, efficient, and regioselective, only perfluoroalkyl-substituted KDM is applicable and the scope is thus very limited. Naturally, we envisioned that the development of new extended Pummerer annulations, which proceed with a wide range of KDMs,[12] would provide a tailor-made[13] multisubstituted benzofurans.

A proposed mechanism of the extended Pummerer annulation with the acid anhydride A_2O is shown in Scheme 2. First, the KDM **1** is activated with A_2O to give the monocationic intermediate **A**. Unless an appropriate combination of A_2O and the R group is employed, **A** readily



Scheme 2. Proposed mechanism.

decomposes through the dicationic intermediate **A′**.[9d] The intermediate **A** reacts with a phenol to provide **B**. Charge-accelerated [3,3]-sigmatropic rearrangement of **B**[14] gives **C**, which smoothly cyclizes into **D**. Methanethiol is eliminated from **D** to afford the corresponding benzofuran **E**. Since the choice of acid anhydride directly affects the stability and reactivity of **A**, we first screened acid anhydrides. After the screening, we found trifluoroacetic anhydride (TFAA) to be the best activator (see the Supporting Information).

In contrast to the previous report[6,9a–d] where only CF_3-subtituted KDM could be applied, a wide variety of KDMs have become applicable with the aid of TFAA (Table 1). Treatment of 4-*tert*-butylphenol with **1a** in the presence of TFAA afforded the corresponding benzofuran **2a** in 87%

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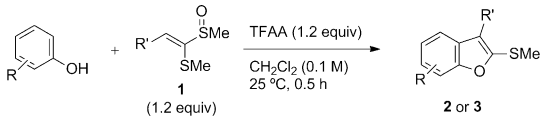
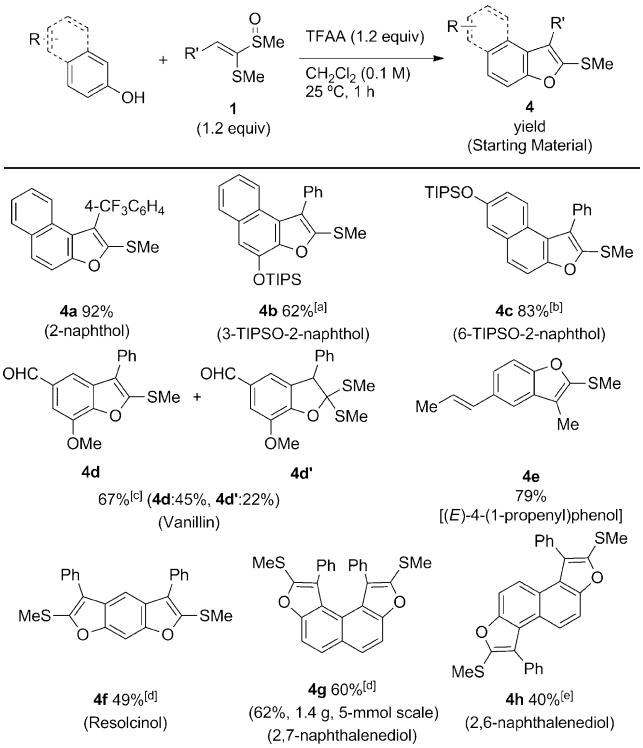
Table 1: Scope with regard to KDM and substituted phenol.



Entry	R	**1**: R′	**2** or **3**	Yield [%]
1	4-*t*Bu	**1a**: Ph	**2a**	87
2[a]	4-*t*Bu	**1b**: H	**2b**	67
3	4-*t*Bu	**1c**: Me	**2c**	78
4	4-*t*Bu	**1d**: Cyclohexyl	**2d**	63
5	4-*t*Bu	**1e**: 4-$CF_3C_6H_4$	**2e**	95
6	4-*t*Bu	**1f**: 4-$MeOC_6H_4$	**2f**	51
7	4-*t*Bu	**1g**: 4-ClC_6H_4	**2g**	96
8	4-*t*Bu	**1h**: 1-naphthyl	**2h**	78
9	4-*t*Bu	**1i**: 3-thienyl	**2i**	85
10[a,b]	4-*t*Bu	**1j**: C_6F_5	**2j**	54
11[a,b]	4-*t*Bu	**1k**: CF_3[c]	**2k**	61
12	4-Br	**1a**: Ph	**3a**	87
13	4-Bpin	**1a**: Ph	**3b**	76
14	4-CF_3	**1a**: Ph	**3c**	60
15[d]	4-MeO	**1a**: Ph	**3d**	72
16	4-EtO_2C	**1a**: Ph	**3e**	77
17[e]	4-CHO	**1a**: Ph	**3f**	60
18[a]	4-TIPSO	**1a**: Ph	**3g**	65
19	3-MeO	**1a**: Ph	**3h**[f]	63
20	2-Ph	**1a**: Ph	**3i**[g]	70

[a] **1** (1 equiv), TFAA (2 equiv), phenol (2 equiv). [b] 40 °C, 1.5 h. [c] The *E*/*Z* ratio of **1k** was 4:1. [d] **1a** (1 equiv), TFAA (1.2 equiv), phenol (1.2 equiv). [e] **1a** (1 equiv), TFAA (2 equiv), phenol (2 equiv), K_2CO_3 (2 equiv), 1 h. [f] 6-Methoxy-2-methylthio-3-phenylbenzo[*b*]furan. [g] 2-Methylthio-3,7-diphenylbenzo[*b*]furan. TIPS = triisopropylsilyl.

Table 2: Reaction of various hydroxyaromatics.

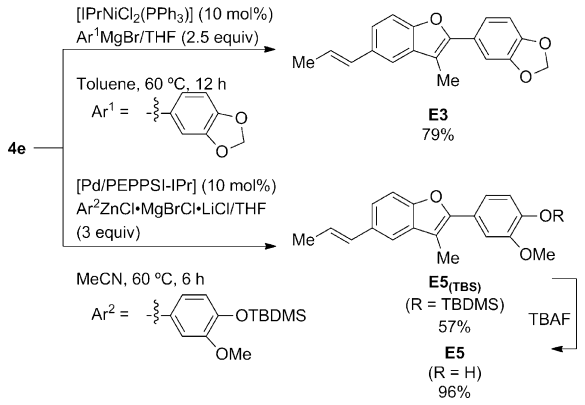


[a] Alcohol (2 equiv), **1** (1 equiv) TFAA (2 equiv). [b] Alcohol (1 equiv), **1** (2 equiv), TFAA (2 equiv). [c] Vanillin (2 equiv), **1a** (1 equiv), TFAA (2 equiv), K_2CO_3 (2 equiv). [d] Diol (1 equiv), **1** (3 equiv), TFAA (3 equiv). [e] Diol (2 equiv), **1a** (1 equiv), TFAA (1.5 equiv).

yield. The unsubstituted KDM **1b** or KDM having other alkyl groups such as methyl and bulky cyclohexyl groups participated to give **2b**–**d** in good yields (entries 2–4). The reactions with various substituents on the aryl groups of the KDMs, groups such as electron-withdrawing and electron-donating moieties and halogens, were successful (entries 5–7). Bulky 1-naphthyl- and heteroaryl-substituted **1h** and **1i** reacted to provide **2h** and **2i**, respectively, in high yields (entries 8 and 9). KDMs having perfluorinated substituents also reacted similarly (entries 10 and 11). The scope of substituted phenols was also studied and showed high functional-group compatibility (entries 12–20). Phenols having halogen, boron, electron-withdrawing, or electron-donating groups smoothly reacted (entries 12–15). While the reaction of 4-ethoxycarbonylphenol provided **3e** with the ester group intact (entry 16), a formyl group did not tolerate the original reaction conditions because the resulting trifluoroacetic acid catalyzed dithioacetalization of the carbonyl moiety with methanethiol. An addition of K_2CO_3 suppressed this side reaction to afford **3f** (entry 17). A bulky triisopropylsiloxy group remained untouched (entry 18). To our delight, the reaction of 3-methoxyphenol proceeded at the 6-position, the less crowded *ortho* position, regioselectively to yield 6-methoxy-2-methylthio-3-phenylbenzo[*b*]furan (**3h**) (entry 19). Bulky *ortho*-substituted 2-phenylphenol reacted smoothly (entry 20).

The reactions were applied to various hydroxy-substituted aromatics (Table 2). The reactions of 2-naphthols regioselectively proceeded to give **4a**–**c** in high yield.[15] In the presence of K_2CO_3, vanillin participated to furnish the corresponding benzofuran **4d** in 45% yield with concomitant formation of **4d′** in 22% yield. The reaction of 4-[(*E*)-1-propenyl]phenol with **1c** smoothly proceeded in the presence of TFAA to give **4e** in 79% yield. Gratifyingly, the reactions of dihydroxylated arenes such as resolcinol and naphthalenediols afforded the corresponding difurans **4f**–**h** directly in one pot. Since the solubility of 2,6-naphthodiol in dichloromethane is poor, employment of an excess amount of 2,6-naphthodiol provided the corresponding difuran **4h** in moderate yield. To demonstrate the robustness of the extended Pummerer annulation, the reaction of 2,6-naphthalenediol was performed on a 5 mmol scale, thus affording 1.4 grams of **4g** after simple filtration though a pad of silica gel and recrystallization from CH_2Cl_2/MeOH (1:2).

We applied the Pummerer annulation/coupling strategy toward the diversity-oriented syntheses of Eupomatenoids (Scheme 3),[16] which were first isolated from *Eupomatia laurina* and have interesting biological activities such as anticancer[17a] or anti-*Trypanosoma cruzi* activity.[17b] In the recent report by Bach and Bartels,[18] the linear syntheses of eupomatenoids started from the arylation of the bromo group at the 2-position of 2,3,5-tribromobenzo[*b*]furan. Since the eupomatenoid family has variety of aryl groups, installation of an aryl group at the 2-position should be ideally done at the late stage of a synthesis. In contrast, our convergent strategy centers on the synthesis of the core benzofuran (i.e., **4e**), which is then transformed into eupomatenoids. To realize the



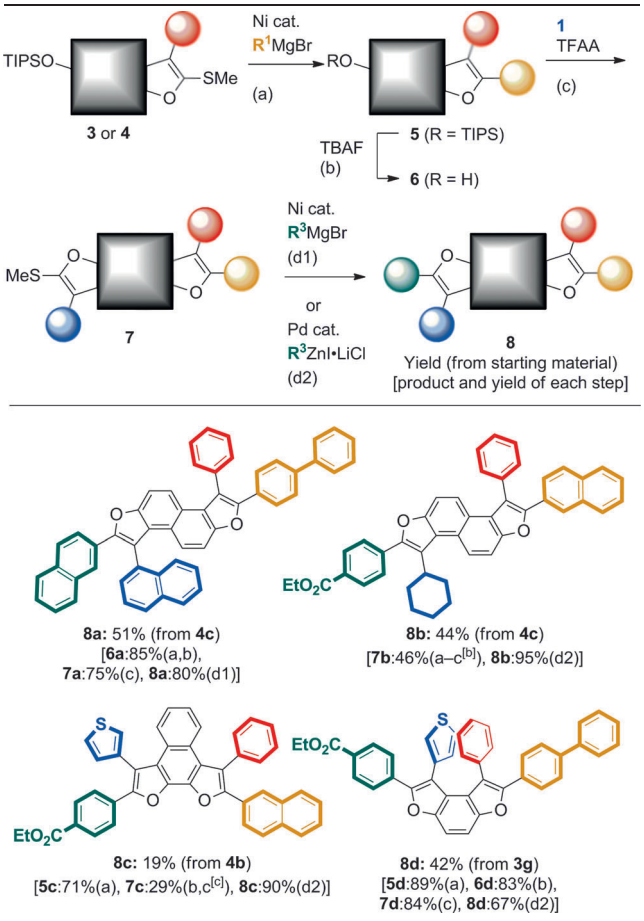
Scheme 3. Syntheses of Eupomatenoids. IPr = 1,3-bis(2,6-diisopropylphenyl)-1,3-dihydro-2 H-imidazol-2-ylidene, PEPPSI = pyridine-enhanced precatalyst preparation stabilization and initiation, TBDMS = *tert*-butyldimethylsilyl.

strategy, we developed new Kumada–Tamao–Corriu conditions for bulky thioethers[7,8,19] catalyzed by [IPrNiCl$_2$(PPh$_3$)].[20] Treatment of **4e** with a Grignard reagent in toluene at 60 °C for 12 h in the presence of the [IPrNiCl$_2$(PPh$_3$)] catalyst furnished Eupomatenoid-3 (**E3**) in 79 % yield. Since methoxy moieties are not tolerated by the highly active Ni/IPr catalyst,[20c] the synthesis of Eupomatenoid-5 (**E5**) was accomplished under our Negishi conditions.[6] The reaction of **4e** with the 3-methoxy-4-siloxyphenylzinc reagent[21] provided TBS-protected **E5**$_{(TBS)}$ in 57 % yield, and was smoothly deprotected with TBAF to give **E5** in 96 % yield.

Finally, we performed modular and tailor-made syntheses of multisubstituted difurans because substituents on the furan cores significantly alter their photophysical properties.[3,6] Our iterative Pummerer annulation/cross-coupling strategy leads to the construction multisubstituted difurans at will (Table 3). The details of the strategy are as follows. The siloxy-substituted 2-methylthiofuran **3** or **4** is subjected to our [IPrNiCl$_2$(PPh$_3$)]-catalyzed Kumada–Tamao–Corriu coupling with an organomagnesium reagent. The siloxy group on furan **5** is then removed with TBAF to yield **6**. The second furan structure is constructed under the extended Pummerer annulation conditions with the KDM **1**. The resulting difuran **7** is then converted, by the Kumada–Tamao–Corriu or Negishi reaction, to afford the tetrasubstituted difuran **8**. By using this strategy, we synthesized various multisubstituted difurans which have four different substituents at the designated positions. The structure of **8a** was confirmed by X-ray crystallographic analysis (Figure S7 in the Supporting Information). Gratifyingly, the resulting multisubstituted furans **8** showed a bright blue fluorescence with high quantum yields [quantum yield $\Phi_F = 0.71$ (**8a**), 0.81 (**8b**), 0.71 (**8c**), 0.62 (**8d**); see the Supporting Information]. Overall, the results clearly demonstrate the iterative annulation/coupling strategy is promising for accessing a library of multisubstituted difurans for materials science.

In summary, we invented the extended Pummerer annulation/coupling strategy toward diversity-oriented syntheses of multisubstituted benzofurans. Our improved nickel-catalyzed Kumada–Tamao–Corriu and palladium-catalyzed Negishi conditions were broadly applicable to the bulky thioethers. The newly developed strategy was powerful enough to synthesize highly fluorescent benzofuran molecules and Eupomatenoid natural products.

Table 3: Tailor-made synthesis of difurans.[a]



[a] Reaction conditions: a) [IPrNiCl$_2$(PPh$_3$)] (10 mol %), R^{1}MgBr/THF (1 M, 2.5 equiv), toluene (0.1 M), 100 °C, 12 h; b) TBAF/THF (1 M, 3 equiv), THF (0.1 M), 25 °C, 3 h; c) **1** (2 equiv), TFAA (2 equiv), CH_2Cl_2, 25 °C, 1 h; d1) [IPrNiCl$_2$(PPh$_3$)] (10 mol %), R^{3}MgBr/THF (1 M, 2.5 equiv), toluene (0.1 M), 100 °C, 12 h; d2) [Pd/PEPPSI-IPr] (10 mol %), R^{3}ZnI·LiCl/THF[21] (1 M, 2.5 equiv), toluene/MeCN (1:1, 0.05 M), 60 °C, 12 h. [b] *E*/*Z* ratio of **1d** used in this reaction was 3:2. [c] CH_2Cl_2/MeCN (5:1, 0.08 M) was used as a solvent. TBAF = tert-*n*-butylammonium fluoride.

Experimental Section

Preparation of **2a** is representative (Table 1). A dichloromethane (2 mL) solution of 4-*tert*-butylphenol (30 mg, 0.20 mmol) and **1a** (51 mg, 0.24 mmol) was placed in a flask. Trifluoroacetic anhydride (33 μL, 0.24 mmol) was added at 25 °C, and the resulting mixture was stirred for 30 min. The mixture was filtered through a pad of alumina and concentrated in vacuo. Purification by chromatography on silica gel (*n*-hexane/CH_2Cl_2 = 5:1) provided 5-*tert*-butyl-2-methylthio-3-phenylbenzo[*b*]furan (**2a**, 51 mg, 0.17 mmol, 87 %).

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[1] a) A. L. Ososki, E. J. Kennelly, *Phytother. Res.* **2003**, *17*, 845; b) K. Baba, K. Takeuchi, F. Hamasaki, M. Kozawa, *Chem. Pharm. Bull.* **1985**, *33*, 416.

[2] a) D. A. Horton, G. T. Bourne, M. L. Smythe, *Chem. Rev.* **2003**, *103*, 893; b) B. L. Flynn, G. S. Gill, D. W. Grobelny, J. H. Chaplin, D. Paul, A. F. Leske, T. C. Lavranos, D. K. Chalmers, S. A. Charman, E. Kostewicz, D. M. Shackleford, J. Morizzi, E. Hamel, M. K. Jung, G. Kremmidiotis, *J. Med. Chem.* **2011**, *54*, 6014.

[3] a) H. Tsuji, C. Mitsui, L. Ilies, Y. Sato, E. Nakamura, *J. Am. Chem. Soc.* **2007**, *129*, 11902; b) H. Tsuji, C. Mitsui, Y. Sato, E. Nakamura, *Adv. Mater.* **2009**, *21*, 3776; c) S. Shinamura, I. Osaka, E. Miyazaki, A. Nakao, M. Yamagishi, J. Takeya, K. Takimiya, *J. Am. Chem. Soc.* **2011**, *133*, 5024; d) C. Mitsui, J. Soeda, K. Miwa, H. Tsuji, J. Takeya, E. Nakamura, *J. Am. Chem. Soc.* **2012**, *134*, 5448.

[4] Reviews: a) G. Zeni, R. C. Larock, *Chem. Rev.* **2006**, *106*, 4644; b) O. Miyata, N. Takeda, T. Naito, *Heterocycles* **2009**, *78*, 843; c) S. Cacchi, G. Fabrizi, A. Goggiamani, *Org. Biomol. Chem.* **2011**, *9*, 641; Recent examples: d) M. Furusawa, T. Imahori, K. Igawa, K. Tomooka, R. Irie, *Chem. Lett.* **2013**, *42*, 1134; e) H. Tsuji, K. Shoyama, E. Nakamura, *Chem. Lett.* **2012**, *41*, 957; f) W. Yuan, S. Ma, *Org. Lett.* **2014**, *16*, 193; g) L. Meng, G. Zhang, C. Liu, K. Wu, A. Lei, *Angew. Chem.* **2013**, *125*, 10385; *Angew. Chem. Int. Ed.* **2013**, *52*, 10195.

[5] Reaction with ketoesters: a) X. Guo, R. Yu, H. Li, Z. Li, *J. Am. Chem. Soc.* **2009**, *131*, 17387; b) U. A. Kshirsagar, R. Parnes, H. Goldshtein, R. Ofir, R. Zarivach, D. Pappo, *Chem. Eur. J.* **2013**, *19*, 13575; Reaction with 1,2-diol: c) D.-H. Lee, K.-H. Kwon, C. S. Yi, *J. Am. Chem. Soc.* **2012**, *134*, 7325; Reaction with alkene: d) U. Sharma, T. Naveen, A. Maji, S. Manna, D. Maiti, *Angew. Chem.* **2013**, *125*, 12901; *Angew. Chem. Int. Ed.* **2013**, *52*, 12669; Reaction with alkyne: e) M. R. Kuram, M. Bhanuchandra, A. K. Sahoo, *Angew. Chem.* **2013**, *125*, 4705; *Angew. Chem. Int. Ed.* **2013**, *52*, 4607; f) W. Zeng, W. Wu, H. Jiang, L. Huang, Y. Sun, Z. Chen, X. Li, *Chem. Commun.* **2013**, *49*, 6611; g) R. Zhu, J. Wei, Z. Shi, *Chem. Sci.* **2013**, *4*, 3706.

[6] a) T. Kobatake, D. Fujino, S. Yoshida, H. Yorimitsu, K. Oshima, *J. Am. Chem. Soc.* **2010**, *132*, 11838; b) Y. Ookubo, A. Wakamiya, H. Yorimitsu, A. Osuka, *Chem. Eur. J.* **2012**, *18*, 12690.

[7] Reviews on transformations of alkylthio groups: a) S. R. Dubbaka, P. Vogel, *Angew. Chem.* **2005**, *117*, 7848; *Angew. Chem. Int. Ed.* **2005**, *44*, 7674; b) T.-Y. Luh, Z.-J. Ni, *Synthesis* **1990**, 89; c) T.-Y. Luh, *Acc. Chem. Res.* **1991**, *24*, 257; d) F. Pan, Z.-J. Shi, *ACS Catal.* **2014**, *4*, 280.

[8] Reviews: a) L. H. S. Smith, S. C. Coote, H. F. Sneddon, D. J. Procter, *Angew. Chem.* **2010**, *122*, 5968; *Angew. Chem. Int. Ed.* **2010**, *49*, 5832; b) S. Akai, Y. Kita, *Top. Curr. Chem.* **2007**, *274*, 35; c) K. S. Feldman, *Tetrahedron* **2006**, *62*, 5003; d) S. K. Bur, A. Padwa, *Chem. Rev.* **2004**, *104*, 2401; e) *Sulfur-Mediated Rearrangements I* (Ed.: E. Schaumann), Springer, Heidelberg, **2007**; f) H. Yorimitsu, *J. Synth. Org. Chem. Jpn.* **2013**, *71*, 341.

[9] Recent examples from our group: a) S. Yoshida, H. Yorimitsu, K. Oshima, *Chem. Lett.* **2008**, *37*, 786; b) S. Yoshida, H. Yorimitsu, K. Oshima, *Org. Lett.* **2007**, *9*, 5573; c) S. Yoshida, H. Yorimitsu, K. Oshima, *Org. Lett.* **2009**, *11*, 2185; d) T. Kobatake, S. Yoshida, H. Yorimitsu, K. Oshima, *Angew. Chem.* **2010**, *122*, 2390; *Angew. Chem. Int. Ed.* **2010**, *49*, 2340; e) K. Murakami, J. Imoto, H. Matsubara, S. Yoshida, H. Yorimitsu, K. Oshima, *Chem. Eur. J.* **2013**, *19*, 5625.

[10] From other groups: a) A. J. Eberhart, C. Cicoira, D. J. Procter, *Org. Lett.* **2013**, *15*, 3994; b) X. Huang, N. Maulide, *J. Am. Chem. Soc.* **2011**, *133*, 8510; c) X. Huang, M. Patil, C. Fares, W. Thiel, N. Maulide, *J. Am. Chem. Soc.* **2013**, *135*, 7312; d) A. J. Eberhart, J. E. Imbriglio, D. J. Procter, *Org. Lett.* **2011**, *13*, 5882; e) A. J. Eberhart, D. J. Procter, *Angew. Chem.* **2013**, *125*, 4100; *Angew. Chem. Int. Ed.* **2013**, *52*, 4008; f) K. S. Feldman, M. D. Fodor, *J. Org. Chem.* **2009**, *74*, 3449; g) S. Akai, N. Kawashita, Y. Wada, H. Satoh, A. H. Alinejad, K. Kakiguchi, I. Kuriwaki, Y. Kita, *Tetrahedron Lett.* **2006**, *47*, 1881.

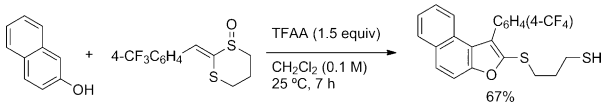
[11] *Applied Cross-Coupling Reactions* (Ed.: Y. Nishihara), Springer, Heidelberg, **2013**.

[12] a) K. Murakami, H. Yorimitsu, A. Osuka, *Bull. Chem. Soc. Jpn.* **2013**, *86*, 1193; b) K. Murakami, H. Yorimitsu, A. Osuka, *Bull. Chem. Soc. Jpn.* **2014**, *87*, 441; c) K. Ogura, Y. Ito, G. Tsuchihashi, *Bull. Chem. Soc. Jpn.* **1979**, *52*, 2013.

[13] a) K. Itami, J. Yoshida, *Bull. Chem. Soc. Jpn.* **2006**, *79*, 811; b) S. Tani, T. N. Uehara, J. Yamaguchi, K. Itami, *Chem. Sci.* **2014**, *5*, 123.

[14] a) R. F. de La Pradilla, M. Tortosa, A. Viso, *Top. Curr. Chem.* **2007**, *275*, 103; b) X. Huang, S. Klimczyk, N. Maulide, *Synthesis* **2012**, 175.

[15] The reaction of KDMs which have cyclic structure also proceeded smoothly to provide the corresponding benzofuran.



[16] B. F. Bowden, E. Ritchie, W. C. Taylor, *Aust. J. Chem.* **1972**, *25*, 2659.

[17] a) G. B. Longato, L. Y. Rizzo, I. M. de Oliveira Sousa, S. V. Tinti, A. Possenti, G. M. Figueira, A. L. T. G. Ruiz, M. A. Foglio, J. E. de Carvalho, *Planta Med.* **2011**, *77*, 1482; b) P. S. Luize, T. Ueda-Nakamura, B. P. Filho, G. D. Cortéz, C. V. Nakamura, *Biol. Pharm. Bull.* **2006**, *29*, 2126.

[18] T. Bach, M. Bartels, *Synthesis* **2003**, 925.

[19] Recent examples: a) S. Kanemura, A. Kondoh, H. Yorimitsu, K. Oshima, *Synthesis* **2008**, 2659; b) K. Itami, D. Yamazaki, J. Yoshida, *J. Am. Chem. Soc.* **2004**, *126*, 15396; c) A. Ghaderi, T. Iwasaki, A. Fukuoka, J. Terao, N. Kambe, *Chem. Eur. J.* **2013**, *19*, 2951.

[20] a) K. Matsubara, K. Ueno, Y. Shibata, *Organometallics* **2006**, *25*, 3422; b) S. Tanaka, D. Tanaka, G. Tatsuta, K. Murakami, S. Tamba, A. Sugie, A. Mori, *Chem. Eur. J.* **2013**, *19*, 1658; c) M. J. Iglesias, A. Prieto, M. C. Nicasio, *Org. Lett.* **2012**, *14*, 4318.

[21] a) A. Krasovskiy, V. Malakhov, A. Gavryushin, P. Knochel, *Angew. Chem.* **2006**, *118*, 6186; *Angew. Chem. Int. Ed.* **2006**, *45*, 6040; b) F. M. Piller, A. Metzger, M. A. Schade, B. A. Haag, A. Gavryushin, P. Knochel, *Chem. Eur. J.* **2009**, *15*, 7192.

