JOC Article

Electrooxidative Coupling of Furans and Silyl Enol Ethers: Application to the Synthesis of Annulated Furans

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The preparation of annulated furan systems as key synthetic intermediates through the application of a two-step annulation involving an electrochemical ring closure between a furan and a silyl enol ether has been studied. The reaction was shown to be quite general for the formation of six-membered rings in good yields and was tolerant of a variety of different functional groups. The ring closure was highly stereoselective, leading to the formation of cis-fused systems. Cyclic voltammetry and probe molecules were used to gain mechanistic insight into the reaction. These studies suggested that the key ring closure involved an initial oxidation of the silyl enol ether to a radical cation followed by a furan-terminated cyclization.

Introduction

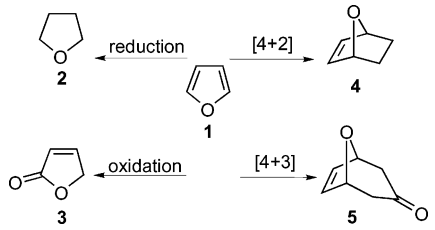
Simple furan derivatives are readily available and highly reactive and can serve as direct precursors to a wide range of different structural moieties.[1] Because of this high degree of synthetic flexibility, furans have frequently been employed in the total synthesis of natural products.[2]The furan ring is highly nucleophilic and undergoes the typical range of electrophilic aromatic substitution reactions. However, the furan ring can also participate in reactions that lead to an overall dearomatization of the nucleus (Scheme 1).

In addition to the products of reduction and oxidation (**2** and **3**), oxabicyclo[2.2.1]heptene **4** and oxabicyclo[3.2.1]-octene derivatives **5** are produced through cycloaddition reactions.[3] We have been especially interested[4] in these bridged systems since they can be readily transformed into a variety of carbocylic and oxacyclic systems by cleavage of one of the bridges in the bicyclic structures.

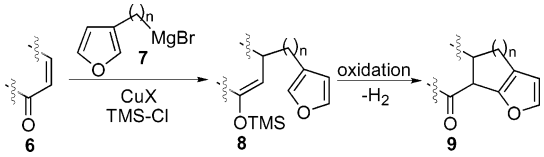
Application of these cycloadditions to annulated furans would be expected to produce much more complex systems than those routinely prepared from simple furan derivatives. Although the synthesis of annulated furans has been the focus of several investigations[5] and has found some use in total synthesis,[6] general methods for their construction are lacking. We have been interested in developing simple methodologies for the rapid assembly of annulated furans for use in the synthesis of terpenoid natural products. Along these lines, we envisioned a two-step sequence involving the initial conjugate addition of a furyl appended organometallic **7** to an α,β-unsaturated carbonyl compound **6** with in situ silylation to deliver an intermediate silyl enol ether **8** (Scheme 2).

The second step of the ring-forming procedure would involve the coupling of the α-carbon of the enol ether to

SCHEME 1. Some Important Transformations of Furan



SCHEME 2. General Strategy for the Assembly of Annulated Furans



* Corresponding author.

‡ To whom questions regarding NMR structures should be addressed at Dartmouth College.

§ University of Florida.

† Deceased August 7, 2003.

(1) Lisphutz, B. H. *Chem. Rev.* **1986**, *86*, 795.

(2) Wright, D. L. *Chem. Innovation* **2001,** *31*, 17.

(3) (a) For a review of furan [4+2] reactions see: Kappe, C. O.; Murphree, S. S.; Padwa, A. *Tetrahedron* **1997,** *53*, 14179. (b) For a review of furan [4+3] reactions see: Rigby, J. H.; Pigge, F. C. [4+3] Cycloaddition Reactions. In *Organic Reactions*; Paquette, L. A., Ed.; John Wiley & Sons: New York, 1997; Vol. 51, p 351.

(4) (a) Orugunty, R. S.; Wright, D. L.; Battiste, M. A.; Abboud, K. A. *Org. Lett.* **2002,** *4*, 1997. (b) Usher, L. C.; Jimenez-Estrella, M.; Ghiviriga, I.; Wright, D. L. *Angew. Chem., Int. Ed.* **2002**, 4742. (c) Wright, D. L.; Usher, L. C.; Jimenez-Estrella, M. *Org. Lett.* **2001**, *26*, 4275.

(5) Padwa, A.; Murphree, S. S. *Org. Prep. Proced. Int.* **1991**, *23*, 545.

(6) For some recent examples see: (a) Aso, M.; Ojida, A.; Yang, G.; Cha, O.-J.; Osawa, E.; Kanematsu, K. *J. Org. Chem.* **1993**, *58*, 3960. (b) Lee, K.; Cha, J. K. *J. Am. Chem. Soc.* **2001,** *123*, 5590. (c) Lee, J. C.; Cha, J. K. *Tetrahedron* **2000,** *56*, 10175−84. (d) Jacobi, P. A.; Lee, K.-A. *J. Am. Chem. Soc.* **1997**, *119*, 3409.

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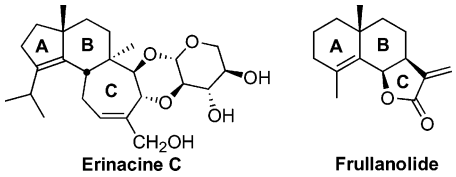
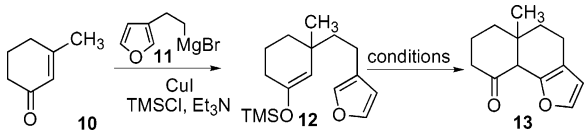


FIGURE 1. Targets for furan annulation strategy.

TABLE 1. Oxidative Cyclization Studies



entry	oxidant/conditions[a]	observations	yield of **13**
1	2.5 equiv of CAN/MeCN	hydrolysis[b]	N/A
2	10 equiv of CAN/MeCN	decomposition	N/A
3	2 equiv of $Mn(OAc)_3/Et_2O$	hydrolysis[b]	N/A
4	2 equiv of $VO(OCH_2CF_3)Cl_2$	decomposition	N/A
5	2 equiv of Ar_3NSbCl_6	cyclization	68%
6	carbon anode (1.5 V)	cyclization	76%

[a] 100 mg of the enol ether was treated with the oxidizing agent at room temperature and the reaction monitored by GC-MS and TLC. [b] Corresponding ketone was isolated.

the 2-position of the pendant heterocycle. This overall process is an oxidation and involves the formal loss of an equivalent of hydrogen. The ring closure involves the coupling of two nucleophilic carbons and requires an umpolong of one of these carbons to an electrophilic species through oxidation.

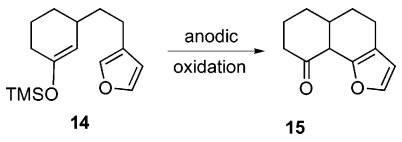
We have been interested in the application of this annulation strategy to the synthesis of terpenoid natural products such as erinacine C[7] and frullanolide[8] (Figure 1). In both cases, an A-ring enone would be annulated by the above strategy, using a furyl ethyl chain that would close the six-membered B-rings and install a furan as a latent form of the C-rings. A [4+3] cycloaddition can be used to construct the seven-membered C-ring of the erinacine C[9] while oxidation of the furan to a butenolide and methylenation would give the C-ring lactone of frullanolide.[10]

Results and Discussion

We initially examined the cyclization of a model enol ether **12**, derived from the copper-catalyzed addition of furylethylmagnesium bromide[11] to 3-methylcyclohexenone, under a variety of oxidative conditions (Table 1).

Traditional chemical oxidants such as CAN,[12] manganese triacetate,[13] or vanadium oxide,[14] all of which have been shown to oxidize electron-rich olefins, were ineffective in promoting cyclization to **13**. It was possible to effect cyclization with tris(4-bromophenyl)aminium hexachloroantimonate (BAHA),[15] a stable radical cation popularized by Bauld.[16] Exposure of the silyl enol ether to 2 equiv of the aminium salt promoted smooth oxidation to the annulated furan **13**. Although this reagent would effectively promote the oxidative cyclization, it was very difficult to remove the amine byproducts from the reaction and the reagent is fairly expensive. The best result for the conversion of enol ether **12** to the annulated furan was through the use of direct anodic oxidation on a carbon anode.[17] Moeller[18] and others[19] have shown that both furans and enol ethers can be oxidized to the corresponding radical cations under anodic conditions. Our optimized reaction conditions involve the use of a carbon anode in an acetonitrile solution containing lithium perchlorate as the supporting electrolyte, 2,6-lutidine as an acid scavanger, and 2-propanol as the cation trap. Methanol is traditionally used as the cation trap but these substrates underwent rapid methanolysis to yield the uncyclized ketones. However, the silyl enol ethers are stable for several days in the presence of the more sterically hindered 2-propanol. Another critical factor in these cyclizations was the current density of the anode. This is defined as the amount of charge passed per square centimeter of anode surface (Table 2).

TABLE 2. Effect of Current Density and Electrode Material on Cyclization Efficiency



entry[a]	anode	cathode	current density[b]	yield (%)
1	carbon	steel	0.5	68
2	carbon	steel	1.0	66
3	carbon	steel	5.0	35
4	carbon	steel	10	10
5	carbon	carbon	0.5	67
6	platinum	carbon	0.5	27
7	platinum	carbon	0.1	54
8	RVC	carbon	N/A	30
9	RVC	carbon	N/A	35

[a] Cyclizations were run on a 100-mg scale under the optimized conditions. [b] Expressed as mA/cm^2 and obtained by dividing the current passed by the surface area of the electrode.

A study on the ring closure of the enol ether **14**, derived from cyclohexenone, showed that as the current density was increased the yield of the cyclized product **15** decreased markedly. Attempted cyclizations at higher current densities produced large amounts of high molec-

(7) Kawagishi, H.; Shimada, A.; Shiraj, R.; Okamoto, K.; Ojima, F.; Sakamoto, H.; Ishiguro, Y.; Furukawa, S. *Tetrahedron Lett.* **1994**, *35*, 1569.

(8) Perold, G. W.; Ourisson, G.; Muller, J. C. *Tetrahedron* **1972**, *28*, 5797.

(9) Wright, D. L.; Whitehead, C. R.; Sessions, E. H.; Ghiviriga, I.; Frey, D. A. *Org. Lett.* **1999**, *1*, 1535.

(10) For a related strategy see: Tanis, S. P.; Robinson, E. D.; McMills, M. C.; Watt, W. *J. Am. Chem. Soc.* **1992**, *114*, 8349.

(11) Prepared from 3-bromofuran by lithiation and reaction with ethylene oxide followed by conversion to the bromide and then the Grignard reagent. See the Experimental Section for details.

(12) (a) Baciocchi, E.; Casu, A.; Ruzziconi, R. *Tetrahedron Lett.* **1989**, *30*, 3707. (b) Snider, B. B.; Shi, B.; Quickley, C. A. *Tetrahedron* **2000**, *56*, 10127.

(13) Snider, B. B. *Chem. Rev.* **1996**, *96*, 339.

(14) Ryter, K.; Livinghouse, T. *J. Am. Chem. Soc.* **1998**, *120*, 2668.

(15) Walter, R. I. *J. Am. Chem. Soc.* **1966**, *88*, 1923.

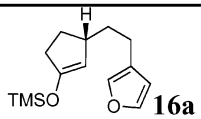
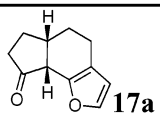
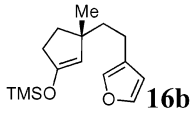
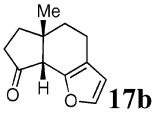
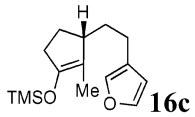
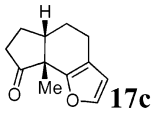
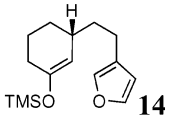
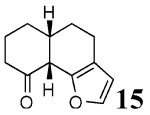
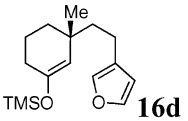
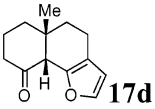
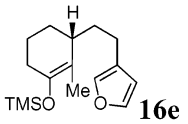
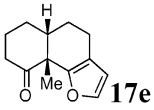
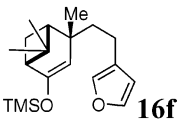
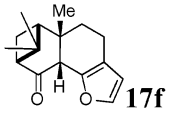
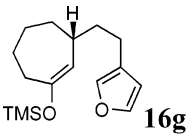
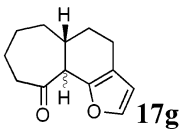
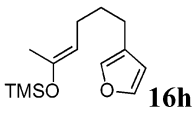
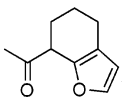
(16) (a) Gao, D. J.; Bauld, N. L. *J. Org. Chem.* **2000**, *65*, 6276. (b) Bauld, N. L.; Gao, D. *J. Chem. Soc., Perkin Trans. 2* **2000**, 931.

(17) (a) Wright, D. L.; Whitehead, C. R.; Sessions, E. H.; Ghiviriga, I.; Frey, D. A. *Org. Lett.* **1999**, *1*, 1535. (b) Whitehead, C. R.; Sessions, E. H.; Ghiviriga, I.; Wright, D. L. *Org. Lett.* **2002**, 3763.

(18) (a) Moeller, K. D.; New, D. G. *Tetrahedron Lett.* **1994**, *35*, 2857. (b) New, D. G.; Tesfai, Z.; Moeller, K. D. *J. Org. Chem.* **1996**, *61*, 1578.

(19) For an excellent review see: Moeller, K. D. *Tetrahedron* **2000**, *56*, 9527.

TABLE 3. Electrochemical Cyclizations

entry	enone	silyl enolether	product	yield[a]
1	cyclopentenone	 **16a**	 **17a**	70%
2	3-methylcyclopentenone	 **16b**	 **17b**	78%
3	2-methylcyclopentenone	 **16c**	 **17c**	64%
4	cyclohexenone	 **14**	 **15**	68%
5	3-methylcyclohexenone	 **16d**	 **17d**	76%
6	2-methylcyclohexenone	 **16e**	 **17e**	65%
7	verbenone	 **16f**	 **17f**	69%
8	cycloheptenone[b]	 **16g**	 **17g**	58%
9	methyl vinyl ketone	 **16h**	 **17h**	61%

[a] Yield is reported for two steps based on the enone as the limiting agent. [b] Isolated as an inseparable 4:1 mixture of trans:cis isomers.

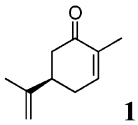
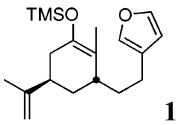
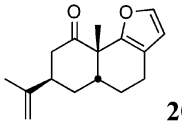
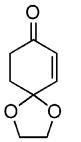
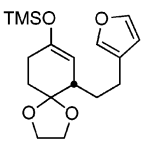
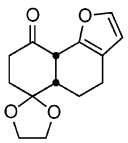
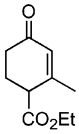
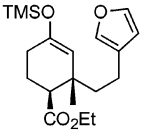
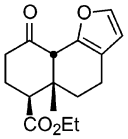
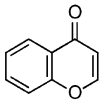
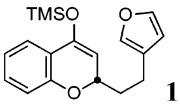
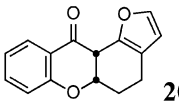
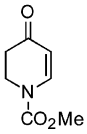
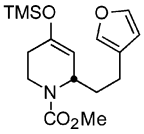
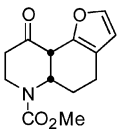
ular weight materials. This was attributed to the formation of polymers at the surface of the electrode. Since the current density is believed to determine the amount of electroactive species on the surface, higher current densities would favor bimolecular reactions.[20] Interestingly, reticulated vitrious carbon electrodes,[21] which have a very high surface area because of the porous nature of the material, were very inefficient at promoting the cyclization. It was found that the use of a carbon anode and a stainless steel cathode at a current density of 0.5 mA/cm^2 was the optimal arrangement and all reactions discussed below were performed under these conditions.

We began our studies of this annulation process by examining the reaction with a variety of simple enone starting materials that were devoid of any functionality that may be competitively oxidized under the electrochemical conditions. These studies revealed that the ring

(20) For example, the yield of Kolbe dimerization is enhanced at high current densities: Coleman, J. P.; Lines, R.; Utley, J. H. P. *J. Chem. Soc., Perkin Trans. 2* **1973**, 1064.

(21) Frey, D. A.; Wu, N.; Moeller, K. D. *Tetrahedron Lett.* **1996**, *37*, 8317.

TABLE 4. Electrochemical Cyclization of Functionalized Derivatives

entry	enone	silyl enolether	product	yield[a]
1	 **18a**	 **19a**	 **20a**	61 %
2	 **18b**[b]	 **19b**	 **20b**	69 %
3	 **18c**	 **19c**	 **20c**	76 %
4	 **18d**	 **19d**	 **20d**	67%
5	 **18e**[c]	 **19e**	 **20e**	65%

[a] Yield is reported for two steps based on the enone as the limiting agent. [b] Prepared according to ref 23. [c] Prepared according to ref 24. All other enones are commercially available

closure was fairly general and proceeded in a highly stereoselective manner (Table 3).

Under the optimized conditions, it was found that the silyl enol ethers **14** and **16a**−**h** could be oxidatively cyclized to yield the corresponding annulated furans **15** and **17a**−**h** in very good yields (58−78% over two steps) after a mild acidic workup.[22] There were also some important differences between substrates in terms of the initial conjugate addition reaction. As expected, addition to those enones without a β-alkyl substituent was considerably faster than that to those that were β,β-disubstituted at the enone. However, silylation was often incomplete in these cases and resulted in significant amounts of the nonsilylated enones being formed. Alternatively, the β,β-disubstituted enones, although slower to react, were more easily silylated and no intermediate, nonsilylated compounds were observed. The addition of TMEDA as an additive to the conjugate addition reaction accelerated the silylation resulting in silyl enol ethers being produced cleanly and in high yield. The crude silyl enol ethers were utilized directly in the electrochemical cyclizations without the benefit of further purification. The oxidations were conducted at a constant current, using a carbon anode and a stainless steel cathode. Upon completion of the reaction, the crude mixture was partitioned with dilute acid to break down any intermediate acetals that might form. Isolation of the compounds gave the annulated furans as single diastereomers, except in the case of **17g**.

Studies on Functional Group Tolerance. Our initial studies revealed that the cyclizations were very efficient and highly stereoselective with regard to the ring closure. We next turned to examining the tolerance of various functional groups to the annulation conditions. It is possible to oxidize additional functional groups under the present electrochemical conditions. However, one advantage of electrochemical reactions is the ability to tightly control the potential and thus limit the reaction to only the most easily oxidized or reduced functionality in a given molecule. To examine the potential for controlling the oxidation reactions, we prepared five additional enol ether substrates with additional functionality and exposed them to the annulation conditions (Table 4).

These studies demonstrate that the electrooxidative annulation can be carried out on substrates bearing potentially reactive functionality. Isolated olefins, acetals, esters, aryl ethers, and carbamates were all tolerated by the electrochemical conditions.

Structural Assignment of Annulation Products. When the annulation was onto a preexisting five- or six-membered ring, the only diastereomer formed was that resulting from a cis ring closure. The stereochemistry of the ring closures was assigned exclusively through NMR.

(22) We have found that the furyl ketone products are very susceptible to air oxidation at the activated bridgehead position and cannot be stored for long periods of time. Purging of chromatography and other solvents improves the yield by 10−15%. Subsequent reduction or ketalization of the ketone eliminates this problem.

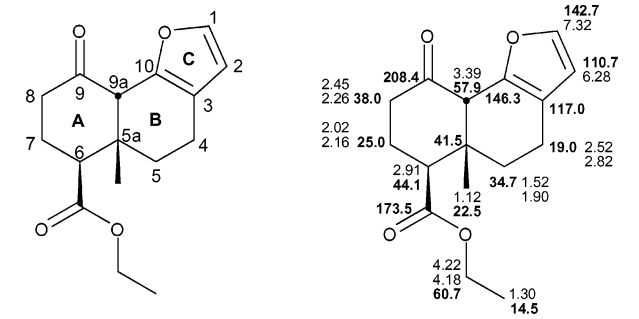
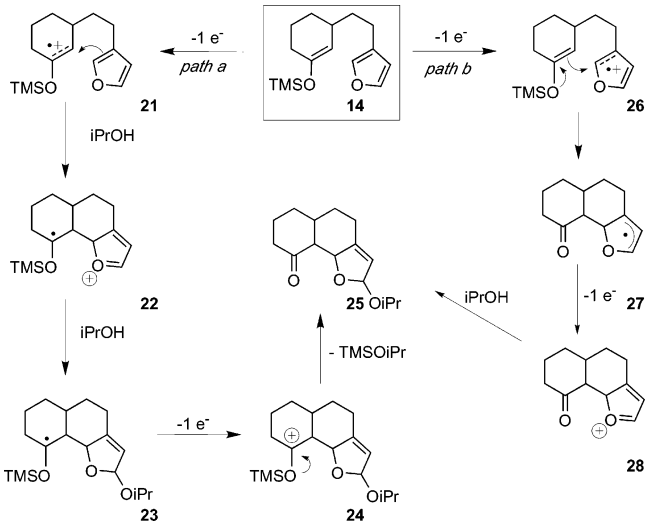


FIGURE 2. Numbering scheme and ^{1}H and ^{13}C (in bold) NMR assignments for adduct **20c**.

SCHEME 3. Possible Mechanisms of Oxidative Ring Closure



The case of compound **20c**, a typical example, is discussed below. The assignment of chemical shifts (shown in Figure 2) was made on the basis of proton−proton and proton−carbon couplings seen in the GHMQC, GHMBC, and DQCOSY spectra. Large vicinal couplings identified the chemical shifts of the axial protons at positions C4, C5, C6, C7, and C8 as 2.82, 1.52, 2.91, 2.16, and 2.26, correspondingly. An nOe between the axial protons at positions C4 and C6 indicated that the junction of rings A and B is cis; no such nOe would be expected for the trans stereochemistry. In the alternative trans configuration, the angular methyl group at C5a would be positioned between these two axial protons.

Similar strategies were used to determine the relative stereochemistry of the other adducts shown in Tables 3 and 4.

Mechanistic Considerations. The overall cyclization reaction leading from the silyl enol ether to the annulated furan requires the loss of two electrons and two protons. By eliminating the acidic workup, we have been able to isolate a dihydrofuran intermediate **25** that results from the addition of 2-propanol to a furyl cation (see Scheme 9). There are two main mechanistic pathways for the reaction to follow that are distinguished by the site of initial electron loss from the cyclization substrate. Although there are several minor variations on these two mechanistic formulations, the two pathways involve the same general steps, initiation to form a cationic center followed by nucleophilic ring closure (Scheme 3).

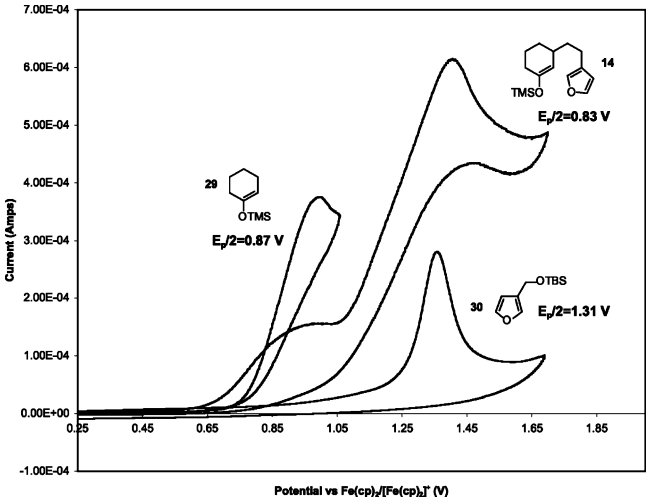
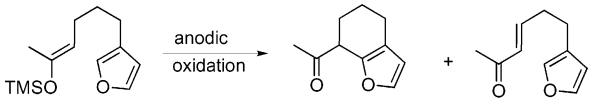


FIGURE 3. Cyclic voltammograms of model substrates.

SCHEME 4. A Byproduct of the Electrochemical Cyclization



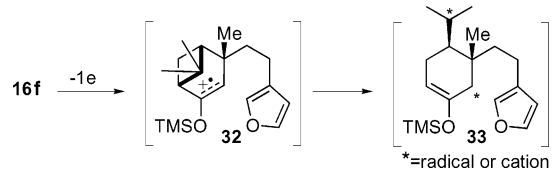
Initial loss of an electron from the silyl enol ether **14** would lead to radical cation **21** that would be attacked by the pendant furan to generate **22**. Trapping of the oxonium ion with alcohol and the loss of a second electron from the radical would lead to **24**, which generates the initial product **25** through loss of the silyl group. Alternatively, the initial electron loss could occur from the furan to generate radical cation **26**, which would be subsequently attacked by the nucleophilic silyl enol ether to produce an intermediate furyl radical **27**. Loss of a second electron would then give the oxonium ion **28**, which is trapped by solvent to give the intermediate **25**.

The initial site of oxidation should be governed by the relative oxidation potentials of the two functional groups with the most easily oxidized group being that with the lowest potential. To examine this, silyl enol ether **14** was studied along with two model substrates by cyclic voltammetry (Figure 3).

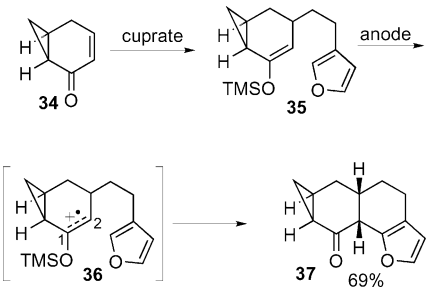
Model substrate **14** was found to have an oxidation potential resembling that of simple silyl enol ether **29** rather than a 3-substituted furan **30**. The silyl enol ether of cyclohexanone has an oxidation potential significantly lower than that of the monosubstituted furan (0.87 V vs 1.31 V as measured against ferrocene). The analysis of the CV data suggested that the silyl enol ether was more readily oxidized than the furan. Further evidence that the silyl enol ether was the primary site of oxidation was found through the identification of a minor byproduct (Scheme 4).

Enone **31** was identified in the crude reaction mixture as a minor byproduct from the oxidation of **16h**. The origin of this product was attributed to the loss of a proton from an intermediate radical cation analogous to **21**, which may also rationalize the slightly higher yields obtained when there is a quaternary center at the γ-position (see Table 3).

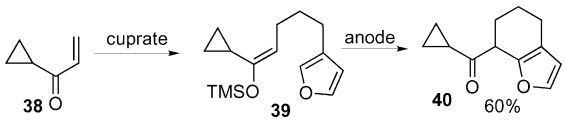
SCHEME 5. Reactive Intermediate Derived from Verbenone



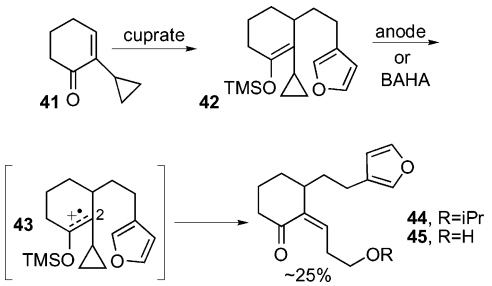
SCHEME 6. A Mechanistic Probe Molecule



SCHEME 7. An Acyclic Probe Molecule



SCHEME 8. An Alternative Probe Molecule



In light of this mechanistic proposal, the uneventful cyclization of enol ether **16f** seemed surprising because the analogous intermediate would place a radical or cationic center adjacent to a relatively strained ring (Scheme 5).

Loss of an electron from the silyl enol ether moiety of **16f** would be expected to produce radical cation **32**. It has been documented both in the case of radicals[25] and cations[26] that intermediates of this type promote rapid scission of the bridging isopropylidine system to give intermediates such as **33**. However, no evidence for this type of fragmentation was observed in the cyclization of **16f**. To examine this process in greater detail, a more reactive probe molecule **35** was prepared from the known[27] enone **34** (Scheme 6).

Oxidation of **35** would be expected to produce **36**, which places a radical cation at the cyclopropylcarbinyl carbon C1. Although less well studied than either cyclopropylcarbinyl cations[28] or radicals,[29] the ring opening of **36** would be expected to be rapid. However, ring closure to **37** proceeded in excellent yield with no evidence of ring fragmentation observed. There was some concern that the absence of fragmentation was due to poor overlap between the reactive intermediate and the σ bond of the strained ring. To eliminate this possibility, an acyclic probe molecule was prepared and subjected to electrochemical oxidation (Scheme 7).

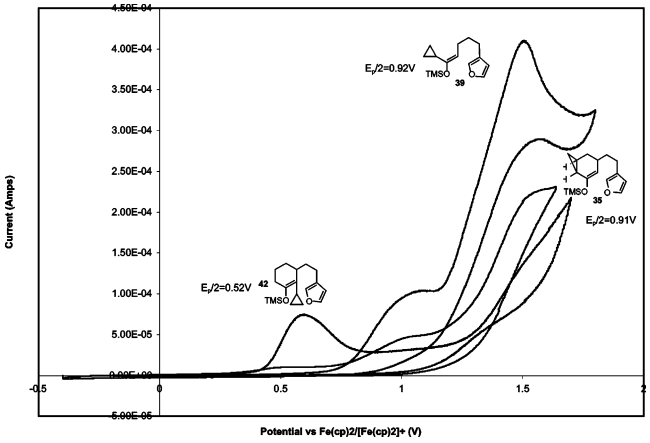


FIGURE 4. Cyclic voltammograms of probe molecules.

Oxidation of the silyl enol ether **39**, prepared from known[30] enone **38**, led to a good yield (60% over two steps) of the ring-closed product without evidence of fragmentation. A possible explanation for these results lies with the siloxy group at the cyclopropylcarbinyl center stabilizing the reactive intermediate so effectively that ring opening was not favored. A further extension of this could involve a rapid loss of the trimethylsilyl group upon oxidation to directly produce a ketone. Whatever the nature of the stabilization, it should not be present at the adjacent carbon, C2. To examine this position, known[31] enone **41** was converted to silyl enol ether **42** and reacted under standard conditions (Scheme 8).

The presumed radical-cation intermediate **43**, derived from oxidation, contains a reactive cyclopropylcarbinyl radical cation without the benefit of oxygen stabilization. When **42** was oxidized under electrochemical conditions, several compounds were produced. Analysis of the crude reaction mixture indicated that there was no longer a cyclopropane moiety among the crude materials. Purification gave a low yield of ketone **44**. This compound is believed to result from ring opening of **43** followed by trapping of a cationic intermediate with 2-propanol. The same types of ring-opened products could be obtained from BAHA oxidation. Addition of 2 equiv of the aminium salt to **43** gave low yields of **44** as well as alcohol **45** that arises from trapping of the cation by adventitious water. The difference in behavior between C1 and C2 cyclopropyl substitution can also be seen in the corresponding cyclic voltammograms (Figure 4).

Addition of a cyclopropane at the C2 position as in **42** causes a significant lowering of the oxidation potential

(23) Kerr, W. J.; McLaughlin, M.; Morrison, A. J.; Pauson, P. L. *Org. Lett.* **2001**, *3*, 2945.
(24) Comins, D. L.; Foley, M. A. *Tetrahedron Lett.* **1988**, *29*, 6711.
(25) Nguyen, T. M.; Seifert, R. J.; Mowrey, D. R.; Lee, D. *Org. Lett.* **2002**, *4*, 3959.
(26) Kusakari, T.; Ichiyanagi, T.; Kosugi, H.; Kato, M. *Tetrahedron: Asymmetry* **1999**, *10*, 339.
(27) Corey, E. J.; Chaykorsky, M. *J. Am. Chem. Soc.* **1965**, *87*, 1353.
(28) Friedric, L. E.; Schuster, G. B. *Tetrahedron Lett.* **1971**, *34*, 3171.
(29) Kantorowki, E. J.; Borhan, B.; Nazarian, S.; Kurth, M. J. *Tetrahedron Lett.* **1998**, *39*, 2483.
(30) Gras, J. L. *Tetrahedron Lett.* **1978**, 2955.
(31) Pattenden, G.; Whybrow, D. *J. Chem. Soc., Perkin Trans. 1* **1981**, 3147.

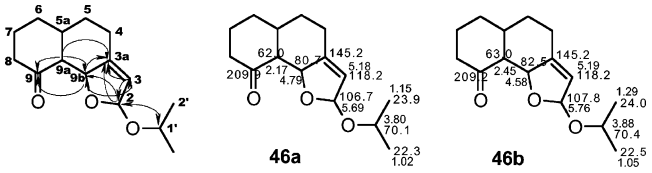
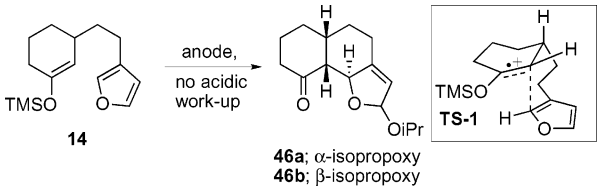


FIGURE 5. Numbering scheme and ^{1}H and ^{13}C chemical shifts in compounds **46a**,**b**. The arrows represent a long-range coupling between a proton and a carbon (at the tip).

SCHEME 9. Isolation of a Dihydrofuran Intermediate



by 0.4 V while a cylcopropane at C1 (**35** or **39**) alters the potential little relative to model enol ether **14**. These mechanistic studies suggest that the mechanism occurs through oxidation of the silyl enol ether function (path a, Scheme 2). In addition to these studies, it also proved possible to isolate a key intermediate in the reaction, dihydrofuran **43** (Scheme 9).

If the standard acidic workup was omitted, a relatively stable dihydrofuran acetal **46** could be isolated in high yield without any furan formation. The relative stereochemistry of this compound was determined by NMR spectroscopy (Figure 5).

Compound **46** was isolated as an equimolar mixture of diastereomers (**46a** and **46b**). The presence of an isopropoxy group at C2 and the closure of the six-membered ring between C9a and C9b were demonstrated by the proton−carbon long-range couplings seen in the GHMBC spectrum and presented in Figure 5. The chemical shifts for positions C4−C8 could not be assigned due to severe overlap; however, the cross-peak of H9a and H9b in the DQCOSY spectrum showed that 9a has a 10 Hz coupling with 9b and a coupling of less than 3 Hz with 5a. These coupling constants indicate that protons 5a, 9a, and 9b are correspondingly equatorial, axial, and axial to ring B, therefore the junction of rings A and B is cis. The coupling constant H2−H9b was 4.0 Hz in **46a** and 1.1 Hz in **46b**, indicating that these protons are trans in the former and cis in the latter.[32]

The exclusive formation of the syn/anti relationship at the ring junctions suggests that the cyclization proceeds through a cis-exo transition state such as **TS-1** whereby the furan closes on the radical cation through an exo orientation.

A general method for the formation of annulated furans has been developed through a two-step process that involves an initial conjugate addition of a furyl-substituted cuprate followed by an electrochemical cyclization. The reaction has been shown to be effective for the formation of six-membered rings during the cyclization and proceeds to give primarily cis-fused products. In addition, the reaction is tolerant of a wide range of functionality including protected amines. Mechanistic studies suggest an initial oxidation of the silyl enol ether followed by a furan-terminated cyclization. Current efforts are focused on the extension of this annulation to other ring sizes and other heterocycles. The application of this method to the synthesis of terpenoid natural products is also ongoing.

Experimental Section

3-(2-Bromoethyl)furan. A solution of 3-bromofuran[33] (5.4 mL, 60.6 mmol) in THF (100 mL) was cooled to −78 °C, then a solution of *n*-BuLi (2.6 M, 23.3 mL, 60.6 mmol) was added slowly via an addition funnel over 30 min. The resulting solution was stirred for 1 h. A solution of ethylene oxide (3.2 g, 72 mmol) in THF (20 mL) was added over 5 min, and then $BF_3{\cdot}OEt_2$ (9.2 mL, 72.7 mmol) was added via addition funnel over 30 min. The resulting solution was stirred for 5 h. Saturated $NaHCO_3$ was added slowly over 15 min, and the semisolid mixture was allowed to warm slowly to room temperature over 3 h. The aqueous phase was extracted with EtOAc (2 × 30 mL), and the combined organic phases were washed with saturated $NaHCO_3$ and brine. The solution was dried with Na_2SO_4, and after evaporation of solvent the crude product was distilled (64−68 °C, 2.5 mmHg) to provide the alcohol as a clear liquid (4.3 g, 62%) having physical and spectroscopic properties consistent with those reported. The alcohol was then converted to the bromide utilizing the method of Tanis.[34]

General Procedure for Cuprate Addition and Electrolysis. A solution of 2-(3-furyl)ethylbromide (1.0 g, 5.8 mmol) in THF (6.0 mL) was purged with argon while the solution was stirred for 10 min. This solution was then added to a flask containing Mg turnings (0.17 g, 7.0 mmol). After 2.5 h the majority of the Mg had dissolved and a clear dark solution had formed. The solution was cooled to 0 °C and CuI (0.165 g, 0.87 mmol) was added. After being stirred for 5 min the turbid black solution was cooled to −78 °C. A 1:1 mixture of TMSCl/Et_3N (6.0 mL) was added, followed by *N*,*N*,*N*,*N*-tetramethylethylenediamine (0.95 mL, 5.8 mmol). Dropwise addition of the enone (4.5 mmol) produced a bright yellow solution. The mixture was allowed to warm to room temperature over 5 h and then placed in the refrigerator overnight. The black mixture was then poured into an ice-cold mixture of hexanes (100 mL) and saturated aqueous NH_4Cl (50 mL). The hexanes layer was separated and washed with $NaHCO_3$, then brine, and dried over Na_2SO_4. Removal of solvent provided the crude enol ether (1.2 g). A 250-mL beaker was charged with the crude enol ether and 225 mL of an electrolyte solution (4:1 MeCN: 2-propanol, 0.1 M $LiClO_4$, and 0.08 M 2,6-lutidine) and the mixture was stirred until homogeneous. An electrode system (see the Supporting Information for details) consisting of alternating plates of carbon (anode) and steel (cathode) was inserted and charged with a constant current of 45.0 mA. There was ∼90 cm^2 of carbon charged as the anode. The reaction mixture was partially covered with PTFE tape to slow evaporation of solvent, and after 7.5 h the current was turned off. The volatiles were removed under vacuum, and the crude material was dissolved in ether (150 mL) and washed with 1 M HCl. The aqueous phase was extracted with Et_2O (2 × 25 mL), and the combined organic phases were washed with water, $NaHCO_3$, and brine and dried over Na_2SO_4.

General Procedure for Tris(4-bromophenyl)aminium Hexachloroantimonate Cyclization. To a solution of tris-(4-bromophenyl)aminium hexachloroantimonate (295 mg, 0.36

(32) (a) Alves, M. J.; Azoia, N. G.; Bickley, J. F.; Fortes, A. G.; Gilchrist, T. L.; Mendonca, R. *J. Chem. Soc., Perkin Trans. 1* **2001**, 2969. (b) Guizzardi, B.; Mella, M.; Fagnoni, M.; Albini, A. *Tetrhedron* **2000**, *56*, 9383.

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mmol) in 10 mL of a 4:1 MeCN:^{i}PrOH solution with 0.2 M 2,6-lutidine at 0 °C was added the silyl enol ether (0.18 mmol) dropwise. After 10 min, the solvent was evaporated and the crude mixture was taken up in 20 mL of 1 M HCl and 15 mL of diethyl ether. The aqueous layer was extracted thrice and any solids rinsed with 20 mL of Et_2O. The combined organic layers were washed with 20 mL of saturated sodium bicarbonate and dried over sodium sulfate. The compounds were purified by silica gel chromatography.

***cis*-4,5,5a,6,7,8a-Hexahydro-1-oxa-*as*-indacen-8-one (17a).** With use of the general procedure as described above, 2-cyclopenten-1-one (0.065 mL, 0.78 mmol) was reacted to give **17a** as a pale yellow oil (88 mg, 70%) after chromatography: R_f(10:1 hexanes:EtOAc) 0.30; IR (neat) ν_{max} 2855, 1743, 1627, 1454, 1122, 1094 cm^{-1}; ^{1}H NMR δ 7.36 (dd, J = 0.6, 2.0 Hz, 1H), 6.21 (d, J = 2.0 Hz, 1H), 3.38 (d, J = 7.3 Hz, 1H), 2.75 (m, 1H), 2.51 (m, 2H), 2.36 (m, 2H), 2.12 (m, 1H), 1.90 (m, 2H), 1.68 (m, 1H); ^{13}C NMR δ 215.2, 144.7, 142.6, 118.1, 110.3, 48.3, 36.7, 36.3, 25.7, 25.5, 20.2; EI-HRMS m/z calcd for $C_{11}H_{12}O_2$ (M^+) 176.0837, found 176.0839.

5a-Methyl-4,5,5a,6,7,8a-hexahydro-1-oxa-*as*-indacen-8-one (17b). With use of the general procedure as described above, 3-methylcyclopentenone (0.065 mL, 0.78 mmol) was reacted to give **17b** as a white solid (116 mg, 78%): mp 42−43 °C; R_f(9:1 hexanes: EtOAc) 0.27; IR (KBr pellet) ν_{max} 2959, 2862, 1742, 1625, 1550, 1050, cm^{-1}; ^{1}H NMR δ 7.35 (dd, J = 1.9, Hz, 1H), 6.21 (J = 1.9 Hz, 1H), 3.00 (s, 1H), 2.51 (m, 2H), 2.41 (m, 2H), 2.00 (m, 1H), 1.81 (m, 1H), 1.62 (m, 2H), 1.19 (s, 3H); ^{13}C NMR δ 215.1, 144.7, 142.6, 116.7, 110.0, 54.9, 40.2, 35.5, 33.1, 31.7, 25.5, 19.0; EI-HRMS m/z calcd for $C_{12}H_{14}O_2$ (M^+) 190.0994, found 190.0993.

***cis*-8a-Methyl-4,5,5a,6,7,8a-hexahydro-1-oxa-*as*-indacen-8-one (17c).** With use of the general procedure as described above, 2-methylcyclopentenone (0.023 mL, 0.24 mmol) was reacted to give the ketone **17c** as a colorless oil (29 mg, 64%) after chromatography: R_f(9:1 hexanes:EtOAc) 0.27; IR (neat) ν_{max} 2927, 2854, 1745, 1629, 1227, 1054 cm^{-1}; ^{1}H NMR δ 7.31 (d, J = 1.8 Hz, 1H), 6.17 (d, J = 1.8 Hz, 1H), 2.55−2.45 (m, 2H), 2.40−2.22 (m, 3H), 2.00−1.75 (m, 2H), 1.38 (s, 3H); ^{13}C NMR δ 18.9, 21.3, 22.4, 23.2, 36.2, 44.3, 49.9, 110.2, 117.5, 142.5, 147.8, 217.8; EI-HRMS m/z calcd for $C_{12}H_{14}O_2$ (M^+) 190.0994, found 190.0989.

***cis*-4,5a,6,7,8,9a-Hexahydro-5*H*-naphtho[1,2-*b*]furan-9-one (15).** With use of the general procedure as described above, cyclohexenone (0.039 mL, 0.4 mmol) was reacted to give the ketone **15** as a white solid (52 mg, 68%): R_f(9:1 hexanes: EtOAc) 0.26; IR (neat) ν_{max} 2930, 1715, 1631, 1503, 1253, 1107 cm^{-1}; ^{1}H NMR δ 7.32 (d, J = 1.9 Hz, 1H), 6.23 (d, J = 1.9 Hz, 1H), 3.63 (d, J = 5.7 Hz, 1H), 2.61−2.43 (m, 3H), 2.42−2.28 (m, 2H), 2.00−1.84 (m, 3H), 1.84−1.72 (m, 1H), 1.72−1.60 (m, 2 H); ^{13}C NMR δ 209.8, 147.0, 142.2, 117.7, 110.4, 50.6, 40.7, 38.8, 28.6, 26.7, 24.1, 20.5; EI-HRMS m/z calcd for $C_{12}H_{14}O_2$ (M^+) 190.0994, found 190.0999.

***cis*-5a-Methyl-4,5a,6,7,8,9a-hexahydro-5*H*-naphtho[1,2-*b*]furan-9-one (17d).** With use of the general procedure as described above, 3-methyl-2-cyclohexen-1-one (0.77 mL, 7.2 mmol) was reacted to give the ketone **17d** as a pale yellow oil (1.12 g, 76%) after chromatography: R_f(9:1 hexanes:EtOAc) 0.27; IR (neat) ν_{max} 2924, 1716, 1632, 1455, 1230 cm^{-1}; ^{1}H NMR δ 7.31 (d, J = 1.8 Hz, 1H), 6.23 (d, J = 1.8 Hz, 1H), 3.23 (s, 1H), 2.52 (m, 2H), 2.30 (m, 2H), 1.88 (m, 3H), 1.71 (m, 1H), 1.48 (m, 2H), 1.09 (s, 3H); ^{13}C NMR δ 210.3, 147.3, 142.4, 116.5, 110.4, 56.9, 39.8, 39.7, 34.3, 33.4, 26.7, 22.3,19.0; EI-HRMS m/z calcd for $C_{13}H_{16}O_2$ (M^+) 204.1150, found 204.1172.

***cis*-9a-Methyl-4,5a,6,7,8,9a-hexahydro-5*H*-naphtho[1,2-*b*]furan-9-one (17e).** With use of the general procedure as described above, 2-methyl-2-cyclohexen-1-one (20 mg, 0.18 mmol) was reacted to give **17e** as a colorless oil (24 mg, 65%) after chromatography: R_f(9:1 hexanes:EtOAc) 0.28; IR (neat) ν_{max} 2927, 2851, 1707, 1628, 1163 cm^{-1}; ^{1}H NMR δ 7.31 (d, J = 1.9 Hz, 1H), 6.24 (d, J = 1.9 Hz, 1H), 2.62−2.40 (m, 4H), 2.22 (m, 1H), 2.09 (m, 1H), 2.20−1.66 (m, 5H), 1.47 (s, 3H); ^{13}C NMR δ 20.0, 22.4, 24.7, 25.8, 26.8, 39.2, 45.2, 51.3, 110.5, 116.3, 142.1, 151.3, 211.9; EI-HRMS m/z calcd for $C_{13}H_{16}O_2$ (M^+) 204.1150, found 204.1166.

2,2,8a-Trimethyloctahydro-1,3-menthanonaphtho[6,7-*b*]furan-4-one (17f). With use of the general procedure as described above, verbenone (50% ee, 0.031 mL, 0.20 mmol) was reacted to provide the ketone **17f** as a yellow solid (72 mg, 69%) after chromatography: R_f(11:1 hexane:EtOAc) 0.29; mp 121 °C dec; IR (KBr) ν_{max} 2906, 1711, 1633, 1179, 1029 cm^{-1}; ^{1}H NMR δ 7.42 (dd, J = 1.0, 1.9 Hz, 1H), 6.23 (d, J = 1.9 Hz, 1H), 3.45 (s, 1H), 2.70 (3 line m, 1H), 2.58 (5 line m, 1H), 2.50 (m, 1H), 2.48 (dd, J = 1.7, 3.8 Hz, 1H), 2.04 (3 line m, 1H), 1.87 (m, 1H), 1.69 (d, J = 11.3 Hz, 1H), 1.43 (s, 3H), 1.35 (dt, J = 4.3, 3.3 Hz, 1H), 1.24 (d, J = 1.0 Hz, 3H), 1.23 (s, 3H); ^{13}C NMR δ 209.0, 146.4, 142.7, 118.5, 110.1, 58.8, 54.2, 50.6, 40.3, 37.8, 34.8, 28.1, 26.8, 25.8, 25.7, 18.7; EI-HRMS m/z calcd for $C_{16}H_{20}O_2$ (M^+) 244.1463, found 244.1463.

4,5,5a,6,7,8,9,10a-Octahydro-1-oxa-cyclohepta[*e*]inden-10-one (17 g). With use of the general procedure as described above, 2-cyclohepten-1-one (0.405 mL, 3.64 mmol) was reacted to give **17g** as a mixture of two isomers in a 4:1 ratio isolated as a colorless oil (430 mg, 58%) after chromatography. The two isomers could not be separated but the major isomer could be characterized by NMR. Major (*trans*-**17g**): R_f(9:1 hexanes: EtOAc) 0.25; IR (neat) ν_{max} 2925, 1711, 1637, 1504, 1158 cm^{-1}; ^{1}H NMR δ 7.29 (dd, J = 0.9, 1.7 Hz, 1H), 6.21 (d, J = 1.7 Hz, 1H), 3.92 (d, J = 9.7 Hz), 2.76 (m, 1H), 2.50 (m, 2H), 2.08−1.94 (m, 2H), 1.94−1.76 (m, 2H), 1.76−1.55 (m, 2H), 1.38−1.55 (m, 2H), 1.38−1.20 (m, 2H); ^{13}C NMR δ 212.2, 148.1, 141.9, 120.3, 110.2, 52.1, 44.7, 40.8, 38.7, 32.3, 27.7, 23.2, 21.9; EI-HRMS m/z calcd for $C_{13}H_{16}O_2$ (M^+) 204.2649, found 204.2661.

1-(4,5,6,7-Tetrahydrobenzofuran-7-yl)ethanone (17h). With use of the general procedure as described above, methyl vinyl ketone (87 mg, 1.24 mmol) was reacted to give ketone **17h** (124 mg, 0.76 mmol, 61%) as a colorless oil after chromatography: R_f(3:1 pentane:diethyl ether) 0.50; IR (neat) ν_{max} 2934, 2855, 1715, 1356 cm^{-1}; ^{1}H NMR ($CDCl_3$, 500 mHz) δ 7.32 (dd, J = 2.0, 1.2 Hz, 1H), 6.25 (d, J = 2.0 Hz, 1H), 3.66 (t, J = 6.1 Hz, 1H), 2.42−2.53 (m, 2H), 2.20 (s, 3H), 2.06−2.13 (m, 1H), 1.90−1.97 (m, 1H), 1.69−1.84 (m, 2H); ^{13}C δ 208.3, 147.2, 141.7, 119.5, 110.7, 48.1, 28.9, 26.3, 22.1, 22.4; EI-HRMS m/z calcd for $C_{10}H_{12}O_2$ (M^+) 164.0837, found 164.0837.

7-Isopropenyl-9a-methyl-4,5a,6,7,8,9a-hexahydro-5*H*-naphtho[1,2-*b*]furan-9-one (20a). With use of the general procedure as described above, carvone (50 mg, 0.53 mmol) was reacted to give ketone **20a** (77 mg, 0.32 mmol, 60%) as a viscous, colorless oil after chromatography: R_f(20:1 pentane: diethyl ether) 0.31; IR (neat) ν_{max} 3084, 2975, 2935, 1714, 1499, 1266 cm^{-1}; ^{1}H NMR (500 mHz, $CDCl_3$) δ 7.25 (d, J = 1.9 Hz, 1H), 6.21 (d, J = 1.9 Hz, 1H), 4.72 (m, 1H), 4.64 (m, 1H), 2.60−2.64 (m, 1H), 2.47−2.54 (m, 2H), 2.37−2.41 (m, 1H), 1.71−1.85 (m, 2H), 1.69 (s, 3H), 1.40 (s, 3H); ^{13}C δ 210.3, 150.5, 147.5, 141.8, 115.3, 110.5, 109.5, 49.8, 44.5, 44.2, 43.5, 32.2, 24.5, 22.4, 20.6, 18.4; EI-HRMS m/z calcd for $C_{16}H_{20}O_2$ (M^+) 244.1463, found 244.1458.

***cis*-4,5a,6,7,8,9a-Hexahydro-5*H*-naphtho[1,2-*b*]furan-4,9-dione-4-monoethylene Ketal (20b).** With use of the general procedure as described above, ketal **18b** (380 mg, 2.5 mmol) was reacted to give ketone **20b** (420 mg, 1.7 mmol, 69%) as a white solid after chromatography and recrystallization from pentane:ether: R_f(1:1 hexane:ethyl acetate) 0.48; mp 116−118 °C; IR (KBr) ν_{max} 3054, 2954, 1715, 1501, 1324 cm^{-1}; ^{1}H NMR (500 mHz, $CDCl_3$) δ 7.36 (d, J = 1.9 Hz, 1H), 6.23 (d, J = 2.0 Hz, 1H), 4.04−4.09 (m, 4H), 3.93 (d, J = 5.6 Hz, 1H), 2.81 (dt, 1H), 2.53−2.58 (m, 1H), 2.36−2.45 (m, 2H), 2.30−2.34 (m, 1H), 2.09−2.12 (m, 2H), 1.95−2.00 (m, 1H), 1.31−1.40 (m, 1H); ^{13}C δ 208.3, 146.9, 142.5, 118.5, 110.2, 108.7, 65.3, 64.6, 47.7, 46.7, 38.0, 30.9, 23.4, 21.7; EI-HRMS m/z calcd for $C_{14}H_{16}O_4$ (M^+) 248.1049, found 248.1050.

5a-Methyl-9-oxo-4,5,5a,6,7,8,9,9a-octahydronaphtho-[1,2-*b*]furan-6-carboxylic Acid Ethyl Ester (20c). With use of the general procedure as described above, Hageman's ester

(98 mg, 0.54 mmol) was reacted to give ketone **20c** (114 mg, 0.41 mmol, 76%) as a white solid after chromatography and recrystallization from pentane:ether: R_f(10:1 pentane:ethyl acetate) 0.45; mp 72−74 °C; IR (KBr) ν_{max} 3056, 2960, 2916, 1754, 1719, 1476, 1301 cm^{-1}; ^{1}H NMR (500 mHz, $CDCl_3$) δ 7.40 (d, J = 1.8 Hz, 1H), 6.28 (d, J = 1.8 Hz, 1H), 4.18−4.25 (m, 2H), 3.39 (s, 3H), 2.91 (dd, J = 11.4, 3.9 Hz, 1H), 2.80−2.87 (m, 1H), 2.50−2.58 (m, 1H), 2.45 (dt, J = 13.9, 4.1 Hz, 1H), 2.26 (td, J = 13.4, 6.2 Hz, 1H), 2.13−2.22 (m, 1H), 2.00−2.06 (m, 1H), 1.88−1.94 (m, 1H), 1.50−1.59 (m, 1H), 1.30 (t, J = 7.2 Hz, 3H), 1.12 (s, 3H); ^{13}C δ 208.5, 173.5, 146.3, 142.7, 117.0, 110.6, 60.8, 57.8, 44.0, 41.4, 38.0, 34.7, 25.0, 22.5, 19.0, 14.5; EI-HRMS m/z calcd for $C_{16}H_{20}O_2$ (M^+) 276.1362, found 276.1367.

4,5,5a,11a-Tetrahydro-1,6-dioxa-cyclopenta[*a*]anthracen-11-one (20d). With use of the general procedure as described above, chromone (240 mg, 1.6 mmol) was reacted to give ketone **20d** (253 mg, 1.1 mmol, 67%) after chromatography: R_f(5:1 hexane:ethyl acetate) 0.25; mp 153 °C dec; IR (KBr) ν_{max} 3016, 2954, 2928, 1688, 1607 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.96 (dd, J = 7.9, 1.8 Hz, 1H), 7.47 (ddd, J = 8.6, 7.2, 1.9 Hz, 1H), 7.34 (dd, J = 1.8, 1.1 Hz, 1H), 7.00 (ddd, J = 7.9, 7.2, 1.1 Hz, 1H), 6.94 (dd, J = 8.4, 1.0 Hz, 1H), 6.25 (d, J = 1.9 Hz), 5.04 (ddd, J = 6.2, 4.3, 2.0, 1H), 3.82−3.90 (m, 1H), 2.84−2.92 (m, 1H), 2.56−2.65 (m, 1H), 2.39−2.48 (m, 1H), 1.91−2.00 (m, 1H); ^{13}C NMR δ 189.5, 161.1, 143.1, 142.3, 136.5, 127.8, 121.6, 119.5, 118.3, 118.2, 110.6, 75.6, 46.8, 26.9, 18.2; EI-HRMS m/z calcd for $C_{15}H_{12}O_3$ (M^+) 240.0786, found 240.0788.

9-Oxo-5,5a,7,8,9,9a-hexahydro-4*H*-furo[2,3-*f*]quinoline-6-carboxylic Acid Methyl Ester (20e). With use of the general procedure as described above, pyridone **18e** (186 mg, 1.2 mmol) was reacted to give ketone **20e** (198 mg, 0.80 mmol, 65%) as a viscous, colorless oil. R_f(3:1 diethyl ether:pentane) 0.26; IR (neat) ν_{max} 3114, 2950, 2860, 1698, 1509 cm^{-1}; ^{1}H NMR (500 mHz, $CDCl_3$) δ 7.36 (d, J = 2.0 Hz, 1H), 6.23 (d, J = 2.0 Hz), 4.86 (br, 1H), 4.45 (br, 1H), 3.75 (s, 3H), 3.73 (d, J = 3.2 Hz, 1H), 3.31 (t, J = 12 Hz, 1H), 2.62 (m, 1H), 2.55 (dd, J = 5.5, 5.1 Hz), 2.39 (d, J = 14.1 Hz), 1.77−1.84 (m, 2H); ^{13}C NMR δ 205.7, 155.9, 145.1, 143.4, 118.3, 110.2, 54.4, 53.4, 49.7, 40.7, 25.8, 20.5; EI-HRMS m/z calcd for $C_{13}H_{15}NO_4$ (M^+) 249.1001, found 249.1010.

4,5,5a,6,6a,7,7a,8a-Octahydro-1-oxa-cyclopenta[*a*]-cyclopropa[*g*]naphthalene-8-one (37). With use of the general procedure as described above, enone **34** (120 mg, 1.1 mmol) was reacted to give ketone **37** (156 mg, 0.77 mmol, 69%) as a white solid after chromatography and recrystallization from pentane:ether: R_f(5:1 pentane:ethyl acetate) 0.33; mp 69−70 °C; IR (KBr) ν_{max} 3013, 2930, 2860, 1682, 1501 cm^{-1}; ^{1}H NMR (500 mHz, $CDCl_3$) δ 7.28 (dd, J = 2.0, 1.2 Hz, 1H), 6.19 (d, J = 2.0 Hz, 1H), 3.56 (br s, 1H), 2.62−2.67 (m, 1H), 2.55−2.60 (m, 1H), 2.41−2.46 (m, 1H), 2.00−2.06 (m, 1H), 1.65−1.81 (m, 5H), 1.10−1.15 (m, 1H), 0.30 (dd, J = 11.0, 4.8 Hz, 1H); ^{13}C δ 207.6, 146.0, 141.9, 116.0, 110.6, 48.5, 36.9, 27.4, 24.5, 22.9, 18.8, 18.5, 18.1; EI-HRMS m/z calcd for $C_{13}H_{14}O_2$ (M^+) 203.1073, found 203.1071.

Cyclopropyl(4,5,6,7-tetrahydrobenzofuran-7-yl)methanone (40). With use of the general procedure as described above, cyclopropyl vinyl ketone (62 mg, 0.65 mmol) was reacted to give ketone **40** (75 mg, 0.39 mmol, 60%) as a colorless oil R_f(20:1 pentane:ether) 0.22; IR (neat) ν_{max} 2930, 2849, 1713, 1366 cm^{-1}; ^{1}H NMR (500 mHz, $CDCl_3$) δ 7.32 (dd, J = 2.0, 0.7 Hz, 1H), 6.25 (d, J = 1.9 Hz, 1H), 3.81 (t, J = 6.1 Hz, 1H), 2.42−2.53 (m, 2H), 2.12−2.16 (m, 1H), 1.97−2.07 (m, 2H), 1.70−1.89 (m, 1H), 1.02−1.10 (m, 2H), 0.84−0.93 (m, 2H); ^{13}C δ 210.3, 147.6, 141.8, 119.6, 110.7, 48.4, 26.8, 22.3, 21.5, 19.3, 11.8, 11.6; EI-HRMS m/z calcd for $C_{12}H_{14}O_2$ (M^+) 190.0944, found 190.0943.

3-Furan-3-ylmethyl-3-(3-isopropoxypropylidene)-cyclohexanone (44). With use of the general procedure as described above, enone **41** (44 mg, 0.32 mmol) was reacted to give enone **44** (22 mg, 25%) as a colorless oil. R_f(3:1 pentane:ether) 0.25; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.35 (d, J = 1.7 Hz, 1H), 7.24 (s, 1H), 6.3 (t, J = 7.4 Hz, 1H), 6.24 (s, 1H), 3.57 (7 line multiplet, J = 6.1 Hz, 1H), 3.53 (m, 2H), 3.01 (m, 1H), 2.57 (m, 1H), 2.31−2.48 (m, 6H), 1.69−1.82 (m, 5H), 1.54−1.58 (m, 1H), 1.18 (d, J = 6.3 Hz, 6H); ^{13}C δ 203.0, 143.3, 143.1, 139.0, 134.7, 124.7, 111.0, 71.9, 66.9, 40.7, 35.7, 34.3, 29.2, 28.0, 22.6, 22.4, 22.3, 19.3; IR (neat) ν_{max} 2968, 2933. 1687, 1920, 1501.

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Supporting Information Available: Electrode schematic and copies of ^{1}H and ^{13}C NMR spectra for compounds **15**, **17a**−**h**, **20a**−**e**, **37**, and **40**. This material is available free of charge via the Internet at http://pubs.acs.org.

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