Additive and Medium Effects on Lewis Acid-Promoted Cationic π-Cyclizations of Alkenyl- and Alkynylcyclopentane-1,3-diones

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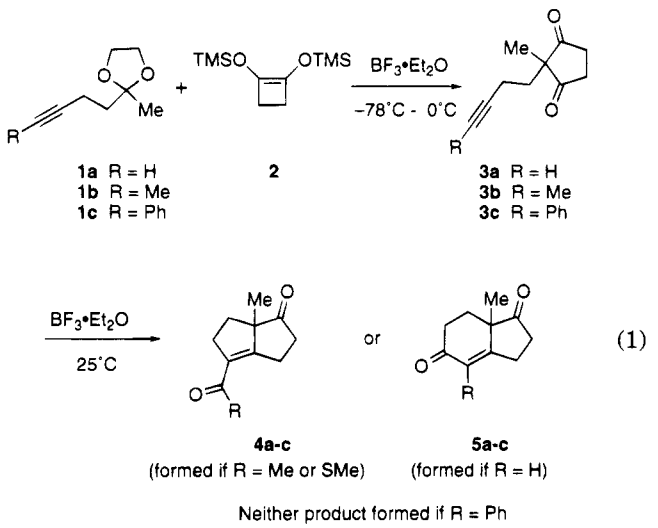
Received August 9, 1994[⊗]

The effects of nucleophilic additives, Lewis and Brønsted acids, and solvents on $BF_3{\cdot}Et_2O$-promoted cationic π-cyclizations of alkynyl- and alkenylcyclopentane-1,3-diones are reported. The rates and selectivities of alkynyl dione cyclizations were significantly effected by the addition of external nucleophiles or water, and the regioselectivity of cyclization was effected by the choice of reaction solvent. Cyclizations of alkenyl diones, which fail under standard non-nucleophilic conditions, were found to be successful in the presence of added nucleophiles or with Lewis acids other than $BF_3{\cdot}Et_2O$. The usefulness of these cationic π-cyclizations for producing bicyclic ring systems of various functionality was also explored.

Introduction

In the preceding paper,[1] we described a new ring-enlarging annulation reaction that converts an alkynyl acetal **1** and a bis(trimethylsilyl)acyloin **2** into an enedione **4** or **5** through the intermediacy of an alkynylcyclopentane-1,3-dione **3** (eq 1). In exploring the scope



(1)

of this transformation, we discovered a number of examples where reactions clearly failed (or appeared to fail) because the conversion of **3** to **4** or **5** did not occur. Since the precursors **1** and **2** are readily available and since their conversion to cyclopentanediones **3** is a very general reaction,[2] the discovery of modified conditions for cyclization of **3** would significantly expand the scope of this class of ring-enlarging annulations.

Our ideas for modified reaction conditions were based on work of Overman and co-workers.[3] In separate studies, they showed that the presence of nucleophilic additives could dramatically alter the results in cationic cyclizations of both alkynyl-[3a] and alkenyliminium salts.[3b] An insightful series of mechanistic experiments suggested that nucleophiles altered the reactions of these two classes of substrates in different ways. In the case of alkynyliminium salts, the nucleophiles served to accelerate the cationic cyclization.[3b] In the case of alkenyliminium salts, the nucleophiles did not alter the actual cationic cyclization, but dramatically changed the rates of trapping of cationic intermediates formed from the cyclizations.[3a] In the ring-enlarging annulation of eq 1, either type of alteration could be useful. Thus, we undertook a study of the effects of added nucleophiles on the cyclizations of both alkenyl- and alkynylcyclopentane-1,3-diones, the results of which are reported herein. The addition of nucleophiles like Bu_4NBr or Bu_4NI both expands the types of substrates that can be used successfully and alters the types of products that are formed. Changes in Lewis acid and solvent also have significant effects, as does the addition of water.

Effects of Nucleophiles on Alkynyl Cyclopentanedione Cyclizations. Alkynyl cyclopentanedione **3a** was prepared by reaction of the appropriate ketal **1a** with **2** (eq 1).[1,2] To prevent cyclization of **3a**, this reaction was only allowed to warm to 5 °C and was quenched with water after 10 min. To probe the effect of nucleophiles on the cyclization of **3a**, we adopted a standard set of conditions: distilled $BF_3{\cdot}Et_2O$ (10 equiv) was added to a methylene chloride solution (or, in some cases, suspension) of the nucleophile (10 equiv) and the dione **3a** (1 equiv, 0.15 M) at 0 °C. After 1 h, the reaction was warmed to 25°C. When **3a** was no longer present according to TLC and GC analysis, the reaction mixture was diluted with diethyl ether, quenched with saturated sodium bicarbonate, and then worked up. The products formed from the successful reactions were usually readily separable alcohols or enones. Purification of the crude mixtures was usually accomplished by flash chromatography on silica gel. Structures were established by standard spectroscopic means, and in two cases these assignments were confirmed by X-ray crystallography.

A number of nucleophilic additives proved uninteresting for assorted reasons. For example, Et_3SiH, TMSCN, and Bu_4NCN all superseded the cyclization and reacted directly with the dione to give isomeric mixtures of diols or bis-cyanohydrins. Inorganic salts like NaI had no effect, possibly because they were insoluble in the reac-

[⊗] Abstract published in *Advance ACS Abstracts,* January 1, 1995.

(1) Balog, A.; Curran, D. P. *J. Org. Chem.* **1995**, *60*, 337.

(2) (a) Shimada, J.; Hashimoto, K.; Kim, B. H.; Nakamura, E.; Kuwajima, I. *J. Am. Chem. Soc.* **1984**, *106*, 1759. (b) Wu, Y.-J.; Strickland, D. W.; Jenkins, T. J.; Liu, P.-Y.; Burnell, D. J. *Can. J. Chem.* **1993**, *71*, 1311. (c) Wu, Y.-J.; Strickland, D. W.; Jenkins, T. J.; Liu, P.-Y.; Burnell, D. J. *Can. J. Chem.* **1994**, *59*, 1485. (d) Pandey, B.; Khire, U. R.; Ayyangar, J. R. *Synth. Commun.* **1989**, *19*, 2741.

(3) (a) Overman, L. E.; Sharp, M. J. *J. Am. Chem. Soc.* **1988**, *110*, 612. (b) McCann, S. F.; Overman, L. E. *J. Am. Chem. Soc.* **1987**, *109*, 6107. (c) Overman, L. E.; Rodriguez-Campos, I. M. *Synlett* **1992**, 995.

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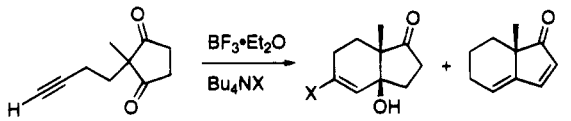
tion medium. $TMSN_3$ was not stable to the reaction conditions, and a gas (likely N_2) was liberated as soon as it was added. Thiophenol gave a complex mixture of products, as did reactions conducted in methanol or acetonitrile; however, reactions conducted in benzene were interesting (see below).

Although addition of Bu_4NCl to the reaction of **3a** had no effect, the effects of added Bu_4NBr and Bu_4NI were quite dramatic (eq 2). Cyclization of **3a** to **5a** mediated



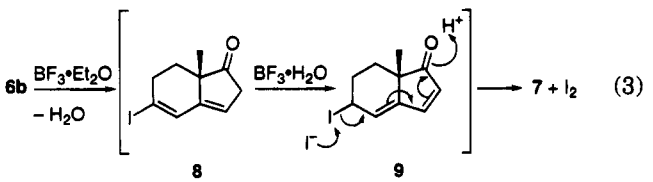
(2)

3a	X = Br X = I	6a (88%) 6b (65%)	not formed 7 (20%)

by $BF_3{\cdot}Et_2O$ required 18 h at 25 °C in the absence of any additive. However, when Bu_4NBr was added, the reaction was complete after 1 h and a new product, vinyl bromide **6a**, was formed. This product was isolated in 88% yield after flash chromatography. A control experiment showed that no reaction occurred when the $BF_3{\cdot}Et_2O$ was omitted. Attempts to develop a one-pot procedure for the transformation of **1a** and **2** through **3a** to **6a** were not successful. Therefore, subsequent reactions were conducted with isolated, purified dione precursors.

In the presence of Bu_4NI, the conversion of **3a** was somewhat slower (though still faster than with no additive). After 6.5 h, the reaction was complete and two separable products, alcohol **6b** and dienone **7**, were isolated in 65 and 20% yields, respectively. The enone **7** was unstable, but it was purified by rapid flash chromatography followed by HPLC. Though we never succeeded in obtaining a satisfactory HRMS of **7**, the NMR and IR spectra of the pure sample secured the structure.

Eq 3 suggests a mechanism for the formation of dienone **7**. Dehydration of **6b** promoted by $BF_3{\cdot}Et_2O$ may provide vinyl iodide **8**. Tautomerization of **8** to allyl

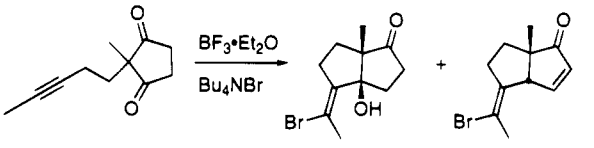


(3)

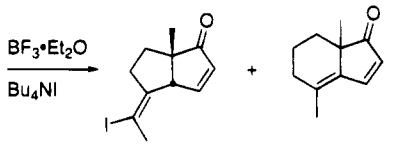
iodide **9** is probably catalyzed by the acidic $BF_3{\cdot}H_2O$[4] produced in the dehydration. Protic acid promoted reductive deiodination of **9** by I^- is a well-precedented type of reaction[5] and should provide dienone **7** (after enol–keto tautomerization) and molecular iodine. The very dark color of this reaction indeed suggests that iodine is a product.

In the reactions of **3a** (eq 2), the nucleophiles accelerated the conversion and changed the nature of the products, but the regioselectivity was not altered. All products, both with (**6a,b**, **7**) and without (**5**) nucleophiles result, from 6-*endo-dig* cyclizations. Similar to Overman's observations with alkynyl acyliminium ions,[3a] the results of the cyclizations of alkynyl ketone **3a** in the presence of Bu_4NBr and Bu_4NI seem to rule out the intermediacy of free vinyl cations and suggest instead that the nucleophile is directly involved in the cyclization.

Cyclization of internal alkyne **3b** in the absence of nucleophiles takes 18 h and provides a 9/1 ratio of 5-*exo-dig* product **4b** to 6-*endo-dig* product **5b** (eq 1). Addition of Bu_4NBr (eq 4) reduces the reaction time to 1 h and



3b 10 (61%) 11 (33%)



(4)

12 (42%) 13 (22%)

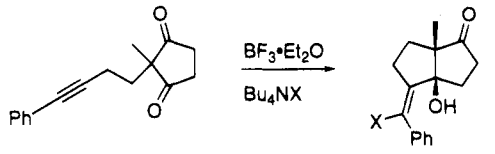
provides vinyl bromide **10** as the only product. A similar reaction that was allowed to run for 5 h gave a mixture of vinyl bromides **10** (61%) and **11** (33%). Both products result from 5-*exo-dig* cyclization. The primary product is alcohol **10**, which is partially dehydrated to provide **11** under the reaction conditions. Each product was a single vinyl bromide stereoisomer. The *E*-geometry, a result of net trans addition of the bromide and the ketone across the triple bond, was tentatively assigned by analogy to Overman's work,[3a] and this assignment was later supported by X-ray crystallography for a closely related product (see below).

The cyclization of **3b** in the presence of Bu_4NI took about 5 h and provided dehydrated product **12** (42%) resulting from 5-exo cyclization and the dienone **13** (22%). This dienone is similar to **7**, though it was somewhat more stable and was fully characterized. Dienone **13** must result from initial 6-*endo-dig* cyclization, and this is probably followed by a sequence of dehydration, tautomerization, and iodide reduction (similar to that shown in eq 3). The partial shift in regioselectivity in this experiment is consistent with direct participation of the nucleophile in the cyclization step, but other modes of action (such as trapping of reversibly formed intermediates) cannot be ruled out.

As described in the preceding paper,[1] reactions of phenylalkyne **1c** with **2** resulted in intractable mixtures, and there was no indication that dione **3c** was ever present. Therefore, **3c** was independently prepared from **3a** by a Castro–Stevens coupling.[6] Subjection of pure **3c** to the standard cyclization conditions in the absence of nucleophile gave complex mixtures. However, addition of either Bu_4NBr or Bu_4NI (eq 5) resulted in smooth conversion of **3c** to vinyl bromide **14** (80%) or vinyl iodide **15** (84%).[7]

The crude bromide **14** was purified by flash chromatography to yield a solid, which was crystallized from chloroform/ether to give clear monoclinic blocks. The X-ray crystal structure was solved (see supplementary material), and this proved that the ring fusion stereo-

(4) Massey, A. G. *Adv. Inorg. Chem. Radiochem.* **1967**, *10*, 1.
(5) Gemal, A. L.; Luche, J. L. *Tetrahedron Lett.* **1980**, *21*, 3195.
(6) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467.
(7) In this case a very small amount of the dehydrated nonreduced conjugated enone product was formed, but it was not purified for characterization.



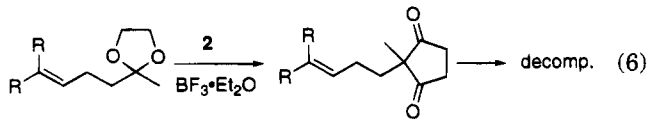
(5)

3c

14 X= Br (80%)
15 X = I (84%)

chemistry was cis and that the stereochemistry of the double bond was *E*. These were the first examples of a reaction that failed in the absence of nucleophiles but succeeded in their presence. While the results are consistent with a nucleophile-accelerated cyclization, in this case we cannot rule out an alternative mechanism of action where the nucleophile serves to trap an intermediate styrenyl cation that would have otherwise decomposed in its absence.

Effects of Nucleophiles on Alkenyl Cyclopentanedione Cyclizations. Alkenyl ketals **16** and **18** could not be successfully employed in the ring-enlarging annulation described in the preceding paper.[1] However, by controlling the reaction temperature and time, the conversions of **16** to **17** (67%) and **18** to **19** (71%) both occurred smoothly (eq 6). Extended exposure of **17** or



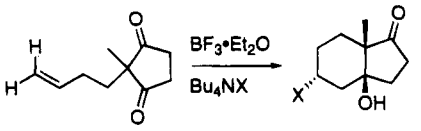
(6)

16 R = H
18 R = Me

17 R = H
19 R = Me

19 to BF_3•Et_2O without any nucleophile resulted in complete decomposition. Thus, we investigated the cyclizations of **17** and **19** with the goal of developing a two-step ring-enlarging annulation procedure in place of the unsuccessful one-step method.

Cyclization of **17** in the presence of BF_3•Et_2O and Bu_4NBr required 16 h but proceeded very cleanly to provide a single stereoisomeric bromide **20a** in 91% yield (eq 7).



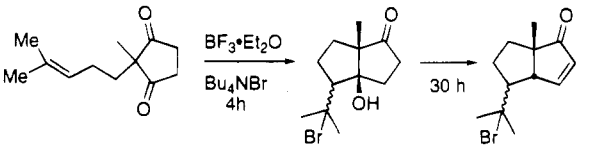
(7)

17

Bu4NBr **20a** X = Br, 91%
Bu4NI **20b** X = I, 74%
20c X = H

The ring structure, resulting from a 6-*endo-trig* cyclization, was confirmed by reductive debromination of **20a** with tributyltin hydride to provide the known bicycle **20c**.[8] The cyclization of **17** in the presence of Bu_4NI required 12 h and produced the analogous iodide **20b** in 74% yield. This was again reduced by tin hydride to form **20c**. The configuration of the carbon bearing the halide was assigned based on subsequent related observations of solvent-trapped products (see below).

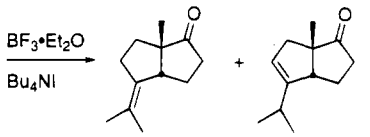
Cyclization of the trisubstituted olefin **19** with BF_3•Et_2O and Bu_4NBr required 2 h and produced an inseparable 6/1 stereoisomeric mixture of tertiary bromides **21** resulting from 5-*exo-trig* cyclization (eq 8). Due to steric hindrance on the endo face, we suspect that the major product bears the bromoalkyl group exo (β) on the



19

21, 6/1, 87%

22, 6/1, 80%



(8)

23 24

bicyclooctane ring. When a similar reaction was allowed to stand for 30 h prior to workup, dehydration and tautomerization occurred to provide enone **22**, again as a 6/1 mixture of isomers, in 80% yield. The reaction of **19** with Bu_4NI required 30 h and gave two products that were separated by HPLC. On the basis of the spectra, these products were assigned structures **23** (46%) and **24** (23%). These products probably result from dehydration of the first-formed iodo alcohol to provide an allylic iodide, which is then reduced by I^- as in eq 3.

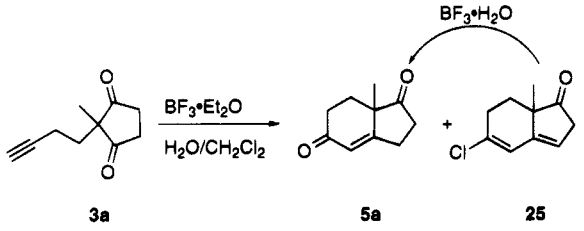
The role of the nucleophiles in the alkenyl 1,3-dione cyclizations is not clear. These reactions are not quite as fast as the previous alkynyl dione cyclizations, and in the absence of nucleophilic agents, the precursor decomposes over roughly the same time period as the reaction occurs in its presence. Thus, while it is clear that the nucleophiles are essential for formation of a clean product, there is no evidence that they actually accelerate the cyclization. It is possible that the nucleophiles in these reactions serve to trap the intermediates (presumably cations) that would otherwise decompose by other pathways. This tentative conclusion is consistent with the more clear-cut observations of Overman[3b] in alkenyliminium ion cyclizations and with our observations (see below) of solvent trapped products (which suggest that secondary and tertiary alkyl cations can be formed in these reactions).

Effects of Medium and Lewis Acid. Impetus for a study of medium and Lewis acid effects on these cyclizations came from an unexpected source. In experiments modeled after those of Harding,[9] alkynyl diones **3a** and **3b** were reacted with BF_3•Et_2O in the presence of 2 equiv of ^{18}O-labeled water to probe whether traces of water might be involved in trapping of vinyl cation intermediates. Unfortunately, this mechanistic probe was shown by control experiments to be inapplicable (the products of the reaction exchanged with $H_2{}^{18}O$ under the reaction conditions). However, we did notice that these reactions were significantly accelerated by the addition of water, and this led to some interesting experiments and observations.

When the cyclization of **3a** was conducted with BF_3•Et_2O under the standard conditions in the presence of 5 equiv of water, the reaction time was reduced from 24 to 1 h, and the expected product **5a** was formed in good yield alongside a small amount (about 10%) of a new unstable product (eq 9). This product was partially purified by chromatography, and its structure was tentatively as-

(8) Dev, S.; Patel, H. A. *Tetrahedron* **1981**, *37*, 1577.

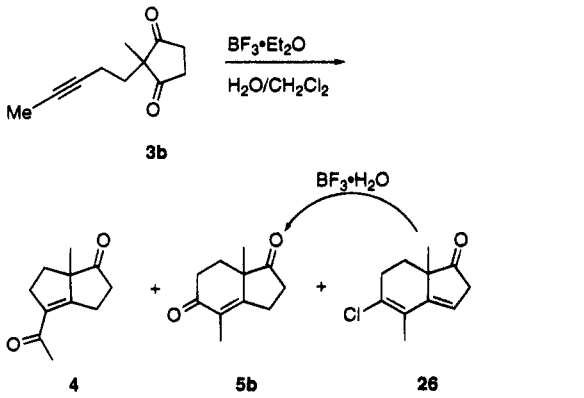
(9) (a) Harding, C. E.; Stanford, G. R., Jr. *J. Org. Chem.* **1989**, *54*, 3054. (b) Harding, C. E.; King, S. L. *J. Org. Chem.* **1992**, *57*, 883.



3a 5a 25 (9)

signed as dienyl chloride **25**. Resubjection of the partially purified sample of **25** to the reaction conditions provided **5a**,[10] thus suggesting that at least some of the **5a** formed in the original reaction came from **25**. By careful inspection of the mixture from an anhydrous reaction[1] (which takes 24 h for completion), we were able to detect **25** in about 1−2% yield in the crude product.

More conclusive experiments were conducted with the internal alkyne **3b** (eq 10). Cyclization of **3b** without

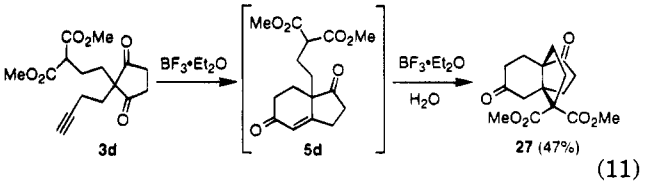


3b 4 5b 26 (10)

water required 24 h and provided 5-*exo-trig* product **4** and 6-*endo-trig* product **5b** in 94% yield in a 9/1 ratio.[11] In the presence of 2 equiv of water, the cyclization was again complete in 1 h, and a mixture of three products, **4**, **5b**, and **26**, was isolated in 94% yield. The ratio of these products was 18/6/1. By careful preparative TLC, we were able to isolate a small but very pure sample of **26**, which was completely characterized. The spectra of **26** were analogous to those of **25**, thereby confirming the tentative assignment of **25**. Resubjection of pure **26** to the reaction conditions (with water) for 4 h gave only **5b**.

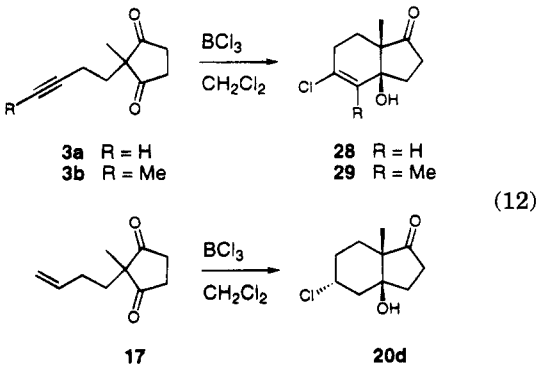
Though the reasons are unclear at present, the addition of water to these reactions has significant effects. Conversion rates are dramatically increased for both **3a** and **3b**, and vinyl chloride products **25** and **26** are produced. In the case of **3a**, the vinyl chloride hydrolyzes to the original product **5a**, but in the case of **3b**, it hydrolyzes to a regioisomer **5b** of the original product **4**. Thus, water can alter the regioselectivity. The only source of chloride in the reactions is the solvent, CH_2Cl_2, and related chloride abstractions are typical reactions of vinyl cations formed in non-nucleophilic media.[12] This suggests, at least in the presence of water, that vinyl cation intermediates are formed. It also suggests that water is not involved in the direct conversion of these vinyl cations to products **4** and **5**. This is probably because most of the available water is tied up as a complex with BF_3 (BF_3•H_2O). This BF_3•H_2O complex is a strong Brønsted acid,[4] and it probably promotes the hydrolysis of the vinyl chlorides to enones. It may also be responsible for some of the other effects of added water (such as acceleration of the rate). In the cyclizations of **3a** and **3b** with water, it is not clear how much of the enones **5a,b** are formed directly and how much are formed through the intermediacy of vinyl chlorides **25** and **26**. Similarly, the origin of **4** is not clear in the cyclization of **3b**. (We have no evidence for formation of the corresponding 5-*exo-trig* vinyl chloride, though its transient intermediacy cannot be ruled out.) The effects of water on these reactions merit further study; however, from a preparative standpoint they are already useful for accelerating the cyclizations.

Water also has significant effects on the outcome of the reaction of dione diester **3d**, shown in eq 11. Cyclization of **3d** under anhydrous conditions was very slow (72 h) and provided 5-*endo-dig* product **5d** in 20% yield alongside 10% of recovered **3d**. In contrast, cyclization with 5 equiv of water was complete after 4 h. In addition to a spot for **5d**, a new spot was observed on TLC. After 16 h, the spot for **5d** had disappeared, and only the new spot remained. The reaction was worked up as usual, and the new product was purified (47% yield) and was identified as a tricycle **27**. Apparently, **5d** suffered an acid catalyzed intramolecular Michael reaction. This reaction provides a rapid simple route to this class of tricycles.



3d 5d 27 (47%) (11)

In our previous work,[1] we had surveyed a number of Lewis acids ($TiCl_4$, $SnCl_4$) without identifying a substitute for BF_3•Et_2O. The presence of chloride-containing products in the above reactions suggested that BCl_3 might be a useful Lewis acid for these reactions. This indeed proved to be the case. Cyclization of **3a** in the presence of 2 equiv of BCl_3 (no water) was complete in only 6 min, and the vinyl chloride **28** resulting from 6-endo-trig cyclization was isolated in 93% yield (eq 12). More



3a R = H **28** R = H
3b R = Me **29** R = Me

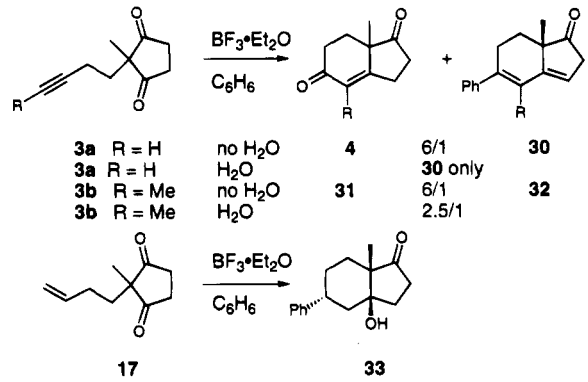
17 20d (12)

stunning was the reaction of **3b**, which required 2 h for completion, but produced none of the expected 5-*exo-trig*

(10) Hudlicky, M. *Coll. Czech. Chem. Commun.* **1993**, *58*, 2229.
(11) In the preceding paper (ref 1), product **5b** was not detected in the one-step ring-enlarging annulation route to **4**. It is not clear whether **5b** was not formed, whether it decomposed under the prolonged reaction time, or whether it simply was not detected.
(12) (a) White, E. H.; Tiwari, H. P., Todd, M. J. *J. Am. Chem. Soc.* **1968**, *90*, 4734. (b) Johnson, W. S.; Gravestock, M. B.; Parry, R. J.; Okorie, D. A. *J. Am. Chem. Soc.* **1972**, *94*, 3013. (c) Lansbury, P. T.; Demmin, T. R.; DuBois, G. E.; Haddon, V. R. *J. Am. Chem. Soc.* **1975**, *97*, 394. (d) Mellor, M.; Santos, A.; Scovell, E. G.; Sutherland, J. K. *J. Chem. Soc., Chem. Commun.* **1978**, 528. (e) Johnson, W. S.; Ward, C. E.; Boots, S. G.; Gravestock, M. B.; Markezich, R. L.; McCarry, B. E.; Okorie, D. A.; Parry, R. J. *J. Am. Chem. Soc.* **1988**, *110*, 88.

product. Instead, the 6-*endo-trig* product **29** was isolated in 98% yield. Cyclization of the alkene **17** with BCl_3 required only 1 h and provided the chloride **20d** in 91% yield. This very brief survey suggests that BCl_3 has excellent potential as a reagent in this type of reaction.

The presence of the chloride-containing products in the $BF_3{\cdot}Et_2O$ reactions also suggested that the use of other weakly nucleophilic solvents in place of CH_2Cl_2 would be interesting. This also proved to be the case. Treatment of **3a** with $BF_3{\cdot}Et_2O$ in benzene (no water present) provided after 20 h the original product **4** and the solvent-alkylated product **30** in a ratio of 6/1 in 76% yield (eq 13). Similar reaction of **3b** over 20 h provided rearranged



(13)

and alkylated 6-*endo-dig* products **31** and **32** in a ratio of 6/1 and 92% yield; no 5-*exo-dig* products were observed. Addition of water to this reaction again decreased the reaction time to 1 h and increased the amount of solvent-alkylated product: **31/32** = 2.5/1 (92%). Cyclization of alkene **17** also required the presence of water, and after 1 h the solvent-alkylated product **33** was formed in 85% yield. This product was crystallized, and the X-ray structure was solved (see supplementary material). This proved that the ring fusion was cis, and the phenyl group derived from the solvent was trans to the ring fusion.

Conclusions

Even though the mechanistic details are not yet completely understood, the effects of additives, Lewis and Brønsted acids, and solvents that have been uncovered considerably extend the scope of the alkynyl and alkenyl ketone cyclizations. Substrates that failed to produce cyclic products under the original conditions (phenylalkynes and -alkenes) can now be employed successfully under the modified conditions. Substrates that cyclized to produce a single product can now be coaxed to produce an assortment of products, depending on conditions (Figure 1). For example, the methyl-substituted alkyne **3b** produced only the 5-exo enedione **4**. But with appropriate choices of solvent, additive, and Lewis acid, it can now lead to (among others) 5-exo products **10-12** and 6-endo products **5b**, **28**, and **32**. To date, we have made no effort to optimize any of these individual processes, so it seems probable that some yields could be improved.

This work shows that cationic π-cyclizations of both alkenes and alkynes to cyclic 1,3-diones have excellent potential for synthetic applications.

Experimental Section

General. All reactions were performed under an atmosphere of nitrogen or argon. Methylene chloride, chlorotrimethylsilane, $BF_3{\cdot}Et_2O$, 1,2-dimethoxyethane, and triethylamine were all distilled from CaH_2. Benzene, toluene, diethyl ether and THF were all distilled from sodium/benzophenone. IR spectra were recorded on thin films. All ^1H NMR spectra were recorded in $CDCl_3$ at 300 MHz, and all ^{13}C NMR spectra were recorded in $CDCl_3$ at 75 MHz.

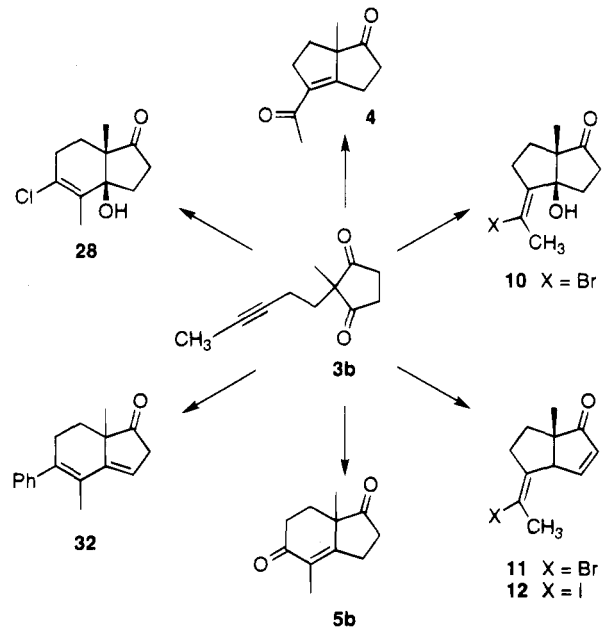


Figure 1. Products available from dione **3b**.

Standard Procedure for Dione Formation.[13] **2-Methyl-2-(3-butynyl)-1,3-cyclopentanedione (3a).** Ketal **1a** (1.053g, 7.52 mmol) was dissolved in dry CH_2Cl_2 (75 mL), and cooled to −78 °C. $BF_3{\cdot}Et_2O$ (7.99 mL, 75.2 mmol) was then added very slowly. After 10 min, succinoin **2** (2.51 mL, 9.78 mmol) was added slowly via syringe. The reaction was kept at −78 °C for 3 h and then allowed to warm slowly to 5 °C. After 10 min, the mixture was diluted with Et_2O (50 mL) and H_2O (50 mL) and extracted three times with Et_2O (50 mL). The combined organic layers were washed once with brine (25 mL) and dried over anhydrous $MgSO_4$. Evaporation of the solvent gave the crude dione **3a**. This was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 1717, 1453, 1422 cm^{-1}; ^1H NMR δ 2.83 (4 H, s), 2.19 (2 H, m), 1.96 (3 H, m), 1.13 (3 H, s); ^{13}C NMR δ 215.45, 82.24, 70.33, 59.79, 55.13, 34.56, 32.00, 20.06; MS *m/e* 164, 125, 112, 97, 69.

2-Methyl-2-(3-pentynyl)-1,3-cyclopentanedione (3b) was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 1717, 1453, 1420 cm^{-1}; ^1H NMR δ 2.77 (4 H, m), 2.07 (2 H, m), 1.93 (2 H, t, J = 6.8 Hz), 1.68 (3 H, t, J = 2.4 Hz), 1.09 (3 H, s); ^{13}C NMR δ 215.91, 78.16, 77.84, 55.43, 34.72, 33.52, 20.91, 14.34, 3.05.

2-Methyl-2-(3-butenyl)-1,3-cyclopentanedione (17) was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 1723, 1453, 1422 cm^{-1}; ^1H NMR δ 5.62, (1 H, m), 4.93 (2 H, m), 2.73 (4 H, m), 1.94 (2 H, m), 1.76 (2 H, m), 1.11 (3 H, s); ^{13}C NMR δ 216.56, 137.30, 115.74, 56.19, 35.04, 34.04, 29.12, 20.04; MS *m/e* 166, 125, 112, 97, 69; exact mass calcd for $C_{10}H_{14}O_2$ 166.1005, found 166.0999.

2-Methyl-2-(4-methyl-3-pentenyl)-1,3-cyclopentanedione (19) was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR (film) 1718, 1455, 1420 cm^{-1}; ^1H NMR δ 4.90 (1 H, t, J = 1.2 Hz), 2.71 (4 H, m), 1.84 (2 H, m), 1.72 (2 H, m), 1.61 (3 H, s), 1.50 (3 H, s), 1.09 (3 H, s); ^{13}C NMR δ 216.39, 132.58, 123.07, 55.97, 35.17, 34.69, 25.16, 23.07, 19.63, 17.25; MS *m/e* 194, 113, 82, 67; exact mass calcd for $C_7H_9O_2$ 125.0581, found 125.0583.

2-Methyl-2-(4-phenyl-3-butynyl)-1,3-cyclopentanedione (3c) was prepared by a Castro–Stevens reaction.[6] A

(13) (a) Wu, Y.-J.; Burnell, D. J. *Tetrahedron Lett.* **1988**, *29*, 4369. (b) Burnell, D. J.; Wu, Y.-J. *Can. J. Chem.* **1990**, *68*, 804.

mixture of dione **3a** (0.200 mg, 1.22 mmol), CuI (0.0114 mg, 0.006 mmol), $(Ph_3P)_2PdCl_2$ (0.0085 g, 0.0122 mmol), PhI (0.14 mL, 1.22 mmol), and diethylamine (20 mL) was stirred rapidly at 25 °C for 16 h. After evaporation of the solvent, the residue was purified by flash chromatography on silica gel eluting with hexanes/ethyl acetate (4:1) to yield 61% of **3c**: IR 1721, 1491, 1453, 1420 cm^{-1}; ^1H NMR δ 7.32 (5 H, m), 2.75 (4 H, m), 2.42 (2 H, t, J = 8.0 Hz) 2.09 (2 H, t, J = 8.0 Hz) 1.18 (3 H, s); ^{13}C NMR δ 215.95, 131.15, 128.21, 127.92, 122.87, 88.74, 82.92, 55.52, 34.75, 33.06, 21.42, 15.15; MS m/e (CI) 241, 225, 213, 195, 128, 113, 105.

Preparation of Dimethyl 3-(ethylenedioxy)-6-heptynyl-1,1-dicarboxylate. 3-(Ethylenedioxy)-6-heptynol (17.9 g, 105 mmol) was dissolved in CH_2Cl_2 (400 mL), and MsCl (15.7 mL, 157 mmol) was added. The solution was then cooled to 0 °C followed by careful addition of TEA (43.9 mL, 315 mmol). After 2 h, the reaction was diluted with Et_2O (100 mL) and quenched with H_2O (300 mL). This was extracted with Et_2O (3 × 150 mL). The organics were washed once with H_2O (200 mL) and once with brine (100 mL) and dried over $MgSO_4$. The solution was filtered through a 2 in. plug of silica gel and the solvent evaporated to give the crude mesylate. This was taken on without purification.

NaH (60% suspension in mineral oil, 11.4 g, 284 mmol) was added to dry DME (200 mL) and cooled to 0 °C. Dimethyl malonate (33.6 mL, 294 mmol) was added very slowly and then the solution heated to reflux. The crude mesylate (approximately 100 mmol) was then slowly added. After 4 h, the reaction was cooled to 25 °C and quenched with H_2O (200 mL). The mixture was extracted with Et_2O (3 × 150 mL). The organics were washed once with H_2O (100 mL) and once with brine (100 mL) and dried over $MgSO_4$. Purification by flash chromatography on silica gel eluting with hexanes/ethyl acetate (3:1) gave 19.6 g (66%) of the desired ketal; IR 3290, 1734, 1437 cm^{-1}; ^1H NMR δ 3.92 (4 H, s), 3.72 (6 H, s), 3.38 (1 H, t, J = 7.6 Hz), 2.22 (2 H, dt, J = 2.6, 7.6 Hz), 1.92 (5 H, m), 1.62 (2 H, m); ^{13}C NMR δ 169.49, 109.84, 83.92, 67.97, 64.88, 52.33, 51.31, 35.70, 34.07, 23.01, 12.85; MS m/e 253, 231, 173, 125, 99; exact mass calcd for $C_{10}H_{15}O_6$ 231.0869, found 231.0867.

Preparation of 2-(3-Butynyl)-2-(1,1-bis(methoxycarbonyl)-3-propyl)-1,3-cyclopentanedione (3d). The ketal (3.99 g, 14.1 mmol) was dissolved in CH_2Cl_2 (140 mL) and cooled to −78 °C. $BF_3{\cdot}Et_2O$ (13.85 mL, 112.6 mmol) was then slowly added. After 10 min, bis((trimethylsilyl)oxy)cyclobutene (5.41 mL, 21.1 mmol) was added slowly. The reaction was kept at −78 °C for 3 h and then allowed to slowly warm to 10 °C. After 15 min at 10°C, the reaction was diluted with Et_2O (50 mL) and H_2O (200 mL). This was extracted with Et_2O (3 × 70 mL). The organics were washed once with brine (50 mL) and dried over $MgSO_4$. Solvent evaporation gave the crude dione as a yellow oil. Generally, **3d** was produced cleanly and was simply passed through a plug of silica gel eluting with hexanes/ethyl acetate (1:1) to give 4.01 g (93%) of dione **3d**: IR 3285, 1725, 1437; ^1H NMR δ 3.72 (6 H, s), 3.23 (1 H, t, J = 7.0 Hz), 2.81 (4 H, d, J = 2.1 Hz), 2.14 (2 H, dt, J = 2.5, 7.0 Hz), 2.93 (3 H, m), 1.78 (2 H, m), 1.59 (2 H, m); ^{13}C NMR δ 215.30, 168.90, 82.34, 70.79, 59.11, 52.63, 51.19, 35.69, 32.55, 31.21, 23.05, 14.05; MS m/e 308, 256, 176, 145, 125; exact mass calcd for $C_{16}H_{20}O_6$ 308.1259, found 308.1228.

Preparation of 7,7a-Dihydro-7a-(1,1-bis(methoxycarbonyl)-3-propyl)-1,5(6*H*)-indenedione (5d). The ketal (0.538 g, 1.89 mmol) was dissolved in CH_2Cl_2 (15 mL) and cooled to −78 °C. $BF_3{\cdot}Et_2O$ (2.32 mL, 18.9 mmol) was then slowly added. After 10 min, succinoin **2** (0.63 mL, 2.46 mmol) was added. The reaction was kept at −78 °C for 3 h and then slowly warmed to 25 °C. After 78 h the reaction was diluted with Et_2O (25 mL) and quenched with H_2O (50 mL). This was extracted with Et_2O (3 × 50 mL). The organics were washed once with brine (25 mL) and dried over $MgSO_4$. Solvent evaporation gave the crude bicycle **5d** (20%) and the dione precursor **3d** (10%). Flash chromatography on silica gel eluting with hexanes ethyl acetate (2:1) gave the bicycle **5d** mixed with a small impurity. All attempts to remove this impurity failed to give pure **5d**: IR 1736, 1667, 1455; ^1H NMR δ 5.97 (1 H, t, J = 1.7 Hz), 3.72 (6 H, s), 3.30 (1 H, t, J = 6.4 Hz), 2.94 (1 H, m), 2.73 (2 H, m), 2.42 (2 H, m), 2.25 (2 H, m), 1.95 (2 H, m), 1.71 (3 H, m); ^{13}C NMR δ 215.52, 198.44, 169.70, 169.31, 124.62, 52.92, 51.99, 51.15, 35.89, 32.71, 30.73, 26.92, 25.91, 23.68; MS m/e 308, 277, 245, 176, 135.

Standard Procedure for Cyclizations with Tetrabutylammonium Bromide or Iodide: (3aα,4α,6aα)- and (3aα,4β,6aα)-4-(2-Bromoisopropyl)-4,5,6,6a-tetrahydro-*cis*-6a-methyl-1(2*H*)-pentalenone (22). Dione **19** (0.201 g, 1.04 mmol) was dissolved in dry CH_2Cl_2 (15 mL), and tetrabutylammonium bromide (3.32 g, 10.4 mmol) was added. The solution was cooled to 0 °C and $BF_3{\cdot}Et_2O$ (1.06 mL, 10.4 mmol) was slowly added. The reaction was kept at 0 °C for 1 h and then allowed to warm to 25 °C. After 29 h, the reaction was carefully quenched with saturated $NaHCO_3$ (10 mL), diluted with Et_2O (15mL) and water (10 mL), and extracted three times with Et_2O (20 mL). The combined organic layers were washed with brine (10 mL) and dried over anhydrous $MgSO_4$. The solution was filtered through a 2 in. plug of silica gel and rinsed repeatedly with dry Et_2O. Evaporation of the solvent yielded the crude **19** as a brown oil. This was isolated as a 6:1 ratio of unseparable diastereomers (80%) after flash chromatography on silica gel eluting with hexanes/ethyl acetate (3:1): IR 1707, 1653, 1458 cm^{-1}; ^1H NMR δ 7.57 (1 H, dd, J = 5.7, 2.6 Hz), 5.95 (1 H, dd, J = 1.8, 5.7 Hz), 3.00 (1 H, dt, J = 1.8, 6.7 Hz), 1.95 (2 H, m), 1.85 (3 H, s), 1.77 (3 H, s), 1.64 (2 H, m), 1.25 (3 H, s); ^{13}C NMR δ 213.58, 165.22, 129.93, 70.95, 59.04, 57.46, 54.59, 34.38, 34.04, 32.26, 31.84, 21.26; MS m/e 258, 256, 177, 133, 117, 91, 69, 55; exact mass calcd for $C_{12}H_{17}OBr$ 258.0481, found 258.0477.

***cis*-3a-Hydroxy-5-bromo-3a,6,7,7a-tetrahydro-7a-methyl-1(2*H*)-indenone (6a)** was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 3426, 1736, 1647 cm^{-1}; ^1H NMR δ 6.09 (1 H, d, J = 1.1 Hz), 2.42 (3 H, m), 2.15 (3 H, m), 1.95 (1 H, m), 1.89 (1 H, s), 1.58 (1 H, m), 1.05 (3 H, s); ^{13}C NMR δ 219.57, 132.76, 126.88, 78.21, 50.95, 34.53, 32.94, 32.04, 28.09, 17.31; MS m/e 246, 244, 231, 229, 165, 147, 108, 69, 57.

***cis*-3a-Hydroxy-5-iodo-3a,6,7,7a-tetrahydro-7a-methyl-1(2*H*)-indenone (6b)** was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 3421, 1740, 1649, 1269 cm^{-1}; ^1H NMR δ 6.38 (1 H, d, J = 1.6 Hz), 2.43 (2 H, m), 2.14 (4 H, m), 1.84 (1 H, m), 1.55 (1 H, m), 1.02 (3 H, s); ^{13}C NMR δ 219.47, 140.98, 101.47, 78.97, 50.72, 36.27, 34.56, 32.82, 29.06, 17.33; MS m/e 292, 236, 165, 108; exact mas calcd for $C_{10}H_{13}O_2I$ 291.9947, found 291.9948.

7,7a-Dihydro-7a-methyl-1-indenone (7) was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (5:1) and then further purified by semipreparative HPLC using hexanes/ethyl acetate (95:5): ^1H NMR δ 7.59 (1 H, d, J = 5.5 Hz), 5.96 (1 H, d, J = 5.5 Hz), 5.79 (1 H, t, J = 4.0 Hz), 2.33 (1 H, m), 2.07 (1 H, m), 1.80 (4 H, m), 1.14 (3 H, s); ^{13}C NMR δ 211.48, 155.24, 145.66, 128.70, 124.04, 45.04, 27.08, 24.53, 22.39, 17.38.

***cis*-3a-Hydroxy-4(*E*)-(bromomethylmethylidene)-3,-3a,4,5,6,6a-hexahydro-6a-methyl-1(2*H*)-pentalenone (10)** was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 3435, 2965, 1732 cm^{-1}; ^1H NMR δ 2.56 (3 H, s), 2.48 (1 H, t, J = 8.2 Hz), 2.34 (2 H, m), 2.27 (3 H, m), 1.94 (1 H, s), 1.80 (1 H, m), 1.50 (1 H, m), 1.06 (3 H, s); ^{13}C NMR δ 220.57, 144.42, 120.96, 88.06, 62.02, 36.31, 34.71, 31.78, 31.51, 25.24, 14.66; MS m/e 260, 258, 204, 202, 179, 73, 61, 45; exact mass calcd for $C_{11}H_{15}O_2Br$ 258.0262, found 258.0262.

***cis*-4(*E*)-(Bromomethylmethylidene)-3a,5,6,6a-tetrahydro-6a-methyl-1-pentalenone (11)** was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (5:1): IR 1711, 1448, 1143, 1072 cm^{-1}; ^1H NMR δ 7.45 (1 H, dd, J = 3.1, 5.6 Hz), 6.14 (1 H, dd, J = 1.1, 5.6 Hz), 3.52 (1 H, s), 2.56 (1 H, dd, J = 8.2, 14.1 Hz), 2.39 (3 H, s), 2.00 (2 H, m), 1.55 (1 H, m), 1.22 (3 H, s); ^{13}C NMR δ 213.76, 160.78, 139.12, 132.32, 114.07, 58.01, 55.84, 34.81, 33.46, 25.28, 22.23; MS m/e 242, 240, 227, 199, 176, 161, 91, 61; exact mass calcd for $C_{11}H_{13}OBr$ 240.0127, found 240.0124.

***cis*-4(*E*)-(Iodomethylmethylidene)-3a,5,6,6a-tetrahydro-6a-methyl-1-pentalenone (12)** was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (3:1): IR 1711, 1586, 1449, 1055 cm^{-1}; ^1H NMR δ 7.45 (1 H,

dd, J = 3.0, 5.5 Hz), 6.13 (1 H, dd, J = 1.7, 5.5 Hz), 3.60 (1 H, s), 2.58 (3 H, t, J = 1.7 Hz), 2.49 (1 H, m), 2.14 (1 H, m), 2.00 (1 H, ddd, J = 2.0, 8.0, 12.8 Hz), 1.55 (1 H, td, J = 8.0, 14.5), 1.2 (3 H, s); ^{13}C NMR δ 213.74, 160.75, 144.97, 132.19, 90.36, 57.23, 56.29, 38.67, 34.41, 29.93, 22.36; MS m/e 288, 161, 143, 133, 59, 45; exact mass calcd for $C_{11}H_{13}OI$ 288.0007, found 288.0008.

5,7a-Dimethyl-7,7a-dihydro-1-indenone (13) was isolated first by flash chromatography on silica gel eluting with hexanes/ethyl acetate (3:1) followed by semipreparative HPLC using hexanes/ethyl acetate (97:3): IR 1703, 1664, 1532, 1455, 625 cm^{-1}; ^{1}H NMR δ 7.90 (1 H, d, J = 5.7 Hz), 5.98 (1 H, d, J = 5.7 Hz), 2.28 (1 H, dd, J = 7.4, 19.5 Hz), 2.05 (1 H, m), 1.84 (5 H, m), 1.23 (2 H, m), 1.13 (3 H, s); ^{13}C NMR δ 212.48, 152.99, 139.47, 132.58, 127.76, 45.68, 30.38, 27.15, 22.80, 18.71, 17.90; MS m/e 162, 147, 119, 105, 91, 77, 65; exact mass calcd for $C_{11}H_{14}O$ 162.1049, found 162.1045.

***cis*-3a-Hydroxy-4(*E*)-(bromobenzylidene)-3,3a,4,5,6,6a-hexahydro-6a-methyl-1(2*H*)-pentalenone (14)** was isolated as a single isomer by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 3621, 1736, 1522 cm^{-1}; ^{1}H NMR δ 7.40 (5 H, m), 2.80 (1 H, m), 2.60 (1 H, ddd, J = 4.0, 8.8, 18.3 Hz), 2.37 (2 H, m), 2.15 (1 H, m), 1.84 (2 H, m), 1.60 (1 H, m), 1.46 (1 H, s), 1.05 (3 H, s); ^{13}C NMR δ 219.11, 147.00, 139.30, 129.05, 128.95, 128.60, 118.96, 88.45, 62.28, 35.61, 34.49, 34.01, 30.42, 13.99; MS m/e 320, 264, 241, 164, 84, 69; exact mass calcd for $C_{16}H_{17}O_2Br$ 322.0411, found 322.0409; mp 149.1 - 154.8 °C.

***cis*-3a-Hydroxy-4(*E*)-(iodobenzylidene)-3,3a,4,5,6,6a-hexahydro-6a-methyl-1(2*H*)-pentalenone (15)** was isolated as a single isomer by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 3619, 1730, 1454, 1269, 1230, 1070 cm^{-1}; ^{1}H NMR δ 7.36 (5 H, m), 2.77 (1 H, dd, J = 7.9, 16.9 Hz), 2.58 (1 H, ddd, J = 3.4, 8.8, 18.1 Hz), 2.37 (2 H, m), 2.16 (1 H, m), 1.82 (2 H, m), 1.59 (1 H, m), 1.33 (1 H, s), 1.06 (3 H, s); MS m/e 368, 313, 241, 105; exact mass calcd for $C_{16}H_{17}O_2I$ 241.1229, found 241.1212; mp 154.5−156.0 °C.

3a-Hydroxy-5-bromo-3a,4,5,6,7,7a-hexahydro-7a-methyl-1-indenone ((3aα,5β,7aα)-20a) was isolated as a single diastereomer by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 3464, 1734, 1456, 1375, 1163; ^{1}H NMR δ 4.22 (1 H, tt, J = 3.7, 11.6 Hz), 2.55 (1 H, ddd, J = 3.7, 8.3, 19.8 Hz), 2.36 (1 H, m), 2.26 (1 H, m), 2.13 (1 H, m), 2.03 (1 H, s), 1.98 (2 H, m), 1.76 (2 H, dd, J = 11.6, 14.0 Hz), 1.15 (1 H, m), 0.96 (3 H, s); ^{13}C NMR δ 217.92, 79.23, 60.47, 51.93, 47.36, 46.72, 34.47, 32.94, 29.45, 18.67; MS m/e 246, 192, 166, 149, 107, 93; exact mass calcd for $C_{10}H_{15}O_2Br$ 246.0228, found 246.0230.

3a-Hydroxy-5-iodo-3a,4,5,6,7,7a-hexahydro-7a-methyl-1-indenone ((3aα,5α,7aα)-20b) was isolated as a single diastereomer by flash chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 2950, 1732, 1456 cm^{-1}; ^{1}H NMR δ 4.27 (1 H, tt, J = 3.6, 12.3 Hz), 2.53 (2 H, m), 2.29 (2 H, m), 2.05 (4 H, m), 1.71 (2 H, m), 1.40 (1 H, m), 0.94 (3 H, s); ^{13}C NMR δ 218.01, 79.62, 51.77, 49.70, 36.79, 34.47, 32.71, 30.64, 23.07, 19.19; MS m/e 294, 209, 167, 125, 112, 69.

(3aα,4α,6aα)- and (3aα,4β,6aα)-3a-hydroxy-4-(2-bromoisopropyl)-3,3a,4,5,6,6a-hexahydro-6a-methyl-1(2*H*)-pentalenone (21) was isolated as a 6:1 mixture of unseparable diastereomers by preparative thin-layer chromatography on silica gel eluting with hexanes/ethyl acetate (2:1): IR 3441, 1732, 1454, 1365, 1174 cm^{-1}; ^{1}H NMR δ 2.92 (1 H, dd, J = 9.6, 14.5 Hz), 2.64 (3 H, m), 2.41 (2 H, m), 1.85 (3 H, m), 1.60 (1 H, broad s), 1.37 (3 H, s), 1.35 (3 H, s), 1.44 (3 H, s); ^{13}C NMR δ 219.89, 140.64, 72.08, 62.25, 53.42, 40.14, 34.67, 32.14, 29.87, 29.22, 21.39, 20.26; MS m/e 258, 221, 138, 123, 82.

***cis*-4-Isopropyl-3,3a,6,6a-tetrahydro-6a-methyl-1(2*H*)-pentalenone (23)** was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (5:1) followed by HPLC using hexanes/ethyl acetate (98:2): IR 1736, 1458, 1125 cm^{-1}; ^{1}H NMR δ 5.25 (1 H, s), 3.03 (1 H, s), 2.55 (1 H, dd, J = 2.0, 16.4 Hz), 2.08 (6 H, m), 1.56 (3 H, s), 1.08 (3 H, d, J = 6.8 Hz), 1.02 (3 H, d, J = 6.8 Hz); ^{13}C NMR δ 225.68, 151.21, 121.41, 55.17, 55.00, 43.00, 36.43, 27.42, 22.39, 21.52, 20.94, 20.87; MS m/e 178, 150, 135, 74, 59; exact mass calcd for $C_{12}H_{18}O$ 178.1341, found 178.1343.

***cis*-4-(Dimethylmethylidene)-3,3a,4,5,6,6a-hexahydro-6a-methyl-1(2*H*)-pentalenone (24)** was isolated by flash chromatography on silica gel eluting with hexanes/ethyl acetate (5:1) followed by semipreparative HPLC using hexanes/ethyl acetate (98:2): IR 1738, 1455, 1372 cm^{-1}; ^{1}H NMR δ 2.86 (1 H, t, J = 7.5 Hz), 2.25 (6 H, m), 1.87 (1 H, dt, J = 7.5, 12.7 Hz), 1.70 (3 H, s), 1.62 (3 H, s), 1.47 (1 H, m), 1.08 (3 H, s); ^{13}C NMR δ 223.22, 138.25, 123.45, 56.39, 52.16, 37.63, 34.59, 29.61, 25.27, 21.03, 20.84, 20.14; MS m/e 178, 163, 122, 107, 93, 79; exact mass calcd for $C_{12}H_{18}O$ 178.1363, found 178.1363.

5-Chloro-7,7a-dihydro-7a-methyl-1(2*H*)-indenone (25); ^{1}H NMR δ 6.36 (1 H, d, J = 2.1 Hz), 5.72 (1 H, S), 3.07 (1 H, dd, J = 23.1, 115.2 Hz), 2.65 (1 H, m), 2.44 (1 H, dd, J = 6.1, 13.1 Hz), 1.61 (2 H, m), 1.14 (3 H, s).

4,7a-Dimethyl-7,7a-dihydro-1,5(6*H*)-indenedione (5b) and 4,7a-dimethyl-5-chloro-7,7a-dihydro-1(2*H*)-indenone (26). Dione **3b** (0.0395 g, 0.22 mmol) was dissolved in dry CH_2Cl_2 (1.5 mL) followed by addition of H_2O (0.04 mL, 2.2 mmol). BF_3·Et_2O (0.41 mL, 3.33 mmol) was then added dropwise. After 1 h, the reaction was quenched with H_2O (5 mL), diluted with Et_2O (10 mL), and extracted three times with Et_2O (20 mL). The combined organic layers were washed one time with brine (10 mL) and dried over anhydrous $MgSO_4$. Evaporation of the solvent yielded the crude mixture of **5b** and **26** as an orange oil. Preparative thin-layer chromatography eluting with hexanes/ethyl acetate (4:1) gave pure dienyl chloride **26** and 5,6-dienone **5b** as clear oils.

5,6-Dienone 5b: IR 1746, 1663, 1356, 1115 cm^{-1}; ^{1}H NMR δ 2.81 (3 H, m), 2.52 (3 H, m), 2.05 (1 H, ddd, J = 2.5, 4.9, 13.4 Hz), 1.83 (1 H, m), 1.77 (3 H, s), 1.28 (3 H, s); ^{13}C NMR δ 217.66, 197.89, 162.44, 129.80, 48.86, 35.40, 32.75, 28.77, 24.46, 21.23, 10.75; MS m/e 178, 151, 136, 93, 79; exact mass calcd for $C_{11}H_{14}O_2$ 178.0995, found 178.0994.

Dienyl chloride 26: IR 2962, 1755, 1624, 1458 cm^{-1}; ^{1}H NMR δ 5.82 (1 H, s), 3.24 (1 H, d, J = 24.1 Hz), 2.89 (1 H, dd, J = 2.5, 24.1 Hz), 2.72 (1 H, m), 2.51 (1 H, m), 1.96 (3 H, s), 1.86 (1 H, dd, J = 5.7, 13.0 Hz), 1.58 (1 H, m), 1.12 (3 H, s); ^{13}C NMR δ 218.73, 146.11, 131.83, 125.65, 115.98, 48.89, 41.80, 31.29, 27.92, 20.48, 14.37; MS m/e 198, 196, 170, 168, 155, 153, 133, 91; exact mass calcd for $C_{11}H_{13}OCl$ 196.0655, found 196.0655.

Preparation of Dimethyl 3,7-dioxotricyclo[4.3.3.0]-dodecane-10,10-dicarboxylate (27). The dione **3d** (0.460 mg, 1.49 mol) was dissolved in CH_2Cl_2 (9.9 mL). Water (0.134 mL, 7.45 mmol) was added followed by BF_3·Et_2O (3.67 mL, 29.87 mmol). The dione was not present by TLC after 4 h (only the 5,6-enedione was present). After 16 h the run was complete and was diluted with Et_2O (50 mL) and quenched with H_2O (50 mL). This was extracted with Et_2O (3 × 50 mL). The combined organics were washed with brine (30 mL) and dried over $MgSO_4$. Purification by silica gel chromatography eluting with hexanes/ethyl acetate (3:1) gave 0.210 g of tricycle **27** (47%): IR 1732, 1435, 1669, 1145 cm^{-1}; ^{1}H NMR δ 3.21 (3 H, s), 3.66 (3 H, s), 3.09 (1 H, d, J = 15.9 Hz), 2.45 (1 H, m), 2.44 (1 H, d, J = 15.9 Hz), 2.38 (2 H, m), 2.18 (4 H, m), 1.96 (2 H, m), 1.80 (3 H, m); ^{13}C NMR 220.34, 209.85, 171.27, 169.97, 68.82, 59.27, 56.26, 52.74, 52.48, 45.46, 36.40, 36.17, 33.52, 32.27, 31.61, 29.13; MS m/e 308, 277, 176, 149, 91; exact mass calcd for $C_{16}H_{20}O_6$ 308.1260, found 308.1314.

Standard Procedure for Reactions with BCl_3. *cis*-3a-Hydroxy-4,7a-dimethyl-5-chloro-3a,5,6,7-tetrahydro-1-indenone (29). Dione **3b** (0.057 g, 0.32 mmol) was dissolved in dry CH_2Cl_2 (2.1 mL), and BCl_3 (0.64 mL of 1.0M solution) was added slowly. After 5 min, the reaction was quenched with H_2O (10 mL) and diluted with Et_2O (20 mL). The mixture was extracted three times with Et_2O (10 mL). The combined organic layers were washed with brine (10 mL) and dried over anhydrous $MgSO_4$. Filtration through a 5 cm silica plug and subsequent solvent evaporation yielded the crude product **28** as a yellow oil. This was isolated as a single isomer by flash chromatography on silica gel eluting with hexanes/ethyl acetate (3:1): IR 3459, 1736, 1239, 1073 cm^{-1}; ^{1}H NMR δ 2.52 (4 H, m), 2.21 (3 H, m), 2.08 (3 H, s), 1.84 (1 H, dt, J = 7.1, 12.7 Hz), 1.57 (1 H, dt, J = 7.1, 12.7 Hz), 1.08 (3 H, s); ^{13}C NMR δ 220.76, 140.86, 124.20, 87.42, 60.99, 36.54, 32.50,

32.00, 30.61, 24.33, 14.79; MS *m/e* 214, 178, 158, 109,77, 53; exact mass calcd for $C_{11}H_{15}O_2Cl$ 214.0754, found 214.0760.

***cis*-3a-Hydroxy-5-chloro-3a,6,7,7a-tetrahydro-7a-methyl-1-indenone (28)** was isolated by preparative thin-layer chromatography eluting with hexanes/ethyl acetate (2:1): IR 3436, 1732, 1651, 1454 cm^{-1}; ^1H NMR δ 5.84 (1 H, t, J = 1.5 Hz), 2.43 (1 H, m), 2.23 (4 H, m), 2.06 (1 H, m), 1.95 (1 H, t, J = 5.1, 13.6 Hz), 1.77 (1 H, broad s), 1.56 (1 H, dt, J = 8.0, 13.6 Hz), 1.04 (3 H, s); ^{13}C NMR δ 219.21, 137.01, 128.56, 77.58, 51.10, 34.59, 33.18, 29.77, 27.44, 17.33; MS *m/e* 200, 165, 144, 129, 105, 91, 77, 57; exact mass cald for $C_{10}H_{13}O_2Cl$ 200.0604, found 200.0610.

3a-Hydroxy-5-chloro-3a,4,5,6,7,7a-hexahydro-7a-methyl-1-indenone ((3aα,5β,7aα)-20d) was isolated as a single diastereomer by flash chromatography on silica gel eluting with hexanes/ethyl acetate (3:1): IR 3463, 1732, 1456, 1040 cm^{-1}; ^1H NMR δ 4.09 (1 H, tt, J = 3.5, 11.1 Hz), 2.55 (1 H, m), 2.40 (1 H, m), 2.24 (2 H, m), 2.01 (6 H, m), 1.61 (1 H, dd, J = 11.1, 14.8 Hz), 1.41, (1 H, m), 0.96 (3 H, s); ^{13}C NMR δ 218.28, 78.65, 55.13, 52.03, 46.14, 34.42, 33.30, 32.95, 28.41, 18.22; MS *m/e* 202, 166, 146, 106, 93; exact mass cald for $C_{10}H_{15}O_2Cl$ 202.0761, found 202.0753.

Standard Procedure for Reactions in Benzene. 5-Phenyl-7a-methyl-7,7a-dihydro-1(2*H*)-indenone (30). Dione **3a** (0.128 g, 0.781 mmol) was dissolved in dry benzene. Water (0.021 mL, 1.17 mmol) was then added followed by slow addition of $BF_3{\cdot}Et_2O$ (0.96 mL, 7.8 mmol). After 0.5 h the reaction was diluted with Et_2O and water and extracted three times with Et_2O (30 mL). The organic layers were washed once with brine and dried over anhydrous magnesium sulfate. This solution was filtered through a 2 in. plug of silica gel and concentrated to give **30** as the only product in 76% yield: IR 1746, 1445, 1053 cm^{-1}; ^1H NMR δ 7.49 (2 H, d, J = 7.6 Hz), 7.36 (2 H, t, J = 7.0 Hz), 7.28 (1 H, t, J = 7.0 Hz), 6.68 (1 H, bs), 5.83 (1 H, bs), 3.32 (1 H, d, J = 23.4 Hz), 2.90 (1 H, d, J = 23.4 Hz), 2.70 (2 H, m), 2.04 (1 H, ddd, J = 2.2, 4.8, 12.9 Hz), 1.62 (1 H, m), 1.18 (3 H, s); ^{13}C NMR δ 219.08, 145.71, 140.34, 136.63, 128.31, 127.56, 125.17, 119.47, 117.47, 48.47, 41.67, 27.21, 24.79, 20.45; MS *m/e* 224, 196, 181, 165, 115, 91, 77; exact mass calcd for $C_{16}H_{16}O$ 224.1201, found 224.1183.

4,7a-Dimethyl-5-phenyl-7,7a-dihydro-1(2*H*)-indenone (32) was isolated as a single isomer by flash chromatography on silica gel eluting with hexanes/ethyl acetate (5:1): IR 1742, 1713, 1454 cm^{-1}; ^1H NMR δ 7.35 (2 H, t, J = 6.8 Hz), 7.27 (1 H, t, J = 6.8 Hz), 7.16 (2 H, d, J = 6.8 Hz), 5.85 (1 H, br, s), 3.30 (1 H, d, J = 23.3 Hz), 2.93 (1 H, dd, J = 2.7, 23.3 Hz), 2.65 (1 H, m), 2.48 (1 H, m), 1.94 (1 H, dd, J = 7.0, 13.1 Hz), 1.78 (3 H, s), 1.61 (1 H, td, J = 6.1, 12.4 Hz), 1.19 (3 H, s); ^{13}C NMR, (75 MHz, $CDCl_3$ δ 220.31, 147.88, 142.51, 137.02, 128.21, 128.08, 126.72, 124.46, 115.19, 49.05, 41.87, 29.69, 27.73, 20.55, 14.86.

3a-Hydroxy-5-phenyl-3a,4,5,6,7,7a-hexahydro-7a-methyl-1-indenone (33) was isolated as a single isomer by flash chromatography on silica gel eluting with hexanes/ethyl acetate (5:1): IR 3464, 1727, 1455, 1279 cm^{-1}; ^1H NMR δ 7.31 (2 H, t, J = 7.7 Hz), 7.20 (1 H, d, J = 8.0 Hz), 7.16 (2 H, d, J = 8.0 Hz), 2.82 (1 H, tt, J = 2.9, 12.5 Hz), 2.57 (1 H, dq, J = 1.8, 10.5 Hz), 2.27 (2 H, m), 2.14 (2 H, m), 2.00 (1 H, m), 1.91 (1 H, m), 1.73 (1 H, m), 1.46 (2 H, m), 1.30 (1 H, m), 1.05 (3 H, s); ^{13}C NMR δ 219.05, 145.74, 128.34, 126.59, 126.11, 77.42, 52.44, 44.81, 38.21, 34.62, 32.93, 30.28, 29.19, 19.45; MS *m/e* 244, 226, 184, 104, 91; exact mass calcd for $C_{16}H_{20}O_2$ 244.1463, found 244.1455.

Acknowledgment. We thank the National Institutes of Health for funding this work. A.B. thanks Wyeth-Ayerst, Inc., for a fellowship.

Supplementary Material Available: Copies of ^1H and ^{13}C NMR spectra for all new products and details of the X-ray crystal structures of **14** and **33** (65 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

JO941389+