Enediyne- and Tributyltin Hydride-Mediated Aryl Radical Additions onto Various Radical Acceptors

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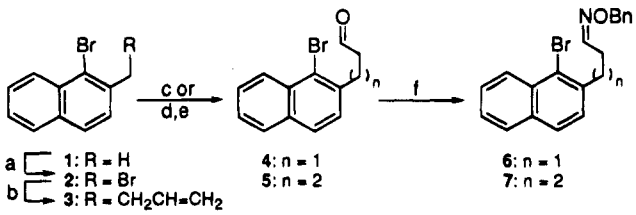
Tandem enediyne-radical cyclizations were carried out on substrates that contain nitrile and ketone radical acceptors. The products of these cyclizations and the previously reported tandem enediyne-radical cyclizations containing aldehyde and oxime ether radical acceptors were compared with tributyltin hydride-mediated aryl radical addition reactions with 1-bromonaphthalene derivatives containing aldehyde, oxime ether, nitrile, and ketone radical acceptors, since these substrates go through similar initial radical intermediates. Although many of the same products were observed using either method of aryl radical generation, there were distinct differences in the product composition and identity depending on which method was used. These differences can probably be primarily attributed to the temperature difference of the two modes of radical generation.

We have recently developed a new method of ring formation, in which a radical generated from an enediyne cyclization[1] undergoes a subsequent radical cyclization with a pendant olefin.[2] To expand the scope and utility of this tandem enediyne-radical cyclization, we have also investigated aldehydes and oxime ethers as radical acceptors.[3] Although there had been reports about alkyl radical cyclizations using aldehydes[4] and oxime ethers[5] as radical acceptors, these reactions[3] constituted the first examples of the addition of aryl radicals onto aldehyde and oxime ether radical acceptors. In order to investigate the impact of the specific reaction conditions, naphthyl bromides **4**–**7** were subjected to standard tributyltin hydride-mediated radical reaction conditions and the products were compared to those obtained from the previously reported tandem enediyne-radical cyclization of enediynes **30**, **31**, **38**, and **39**.[3] To further explore the differences between these two methods of aryl radical generation, ketones and nitriles were also employed in both the tandem enediyne-radical cyclization (substrates **17**, **18**, **21**, and **22**) and the tributyltin hydride-mediated radical cyclization (substrates **9**–**12**).

Synthesis of Naphthalene Precursors. Aldehydes **4** and **5**, as well as oxime ethers **6** and **7**, were readily available from 1-bromo-2-methylnaphthalene (**1**) (Scheme 1). Bromination of **1** with *N*-bromosuccinimide (NBS)[6] and subsequent reaction with allylmagnesium bromide[7] yielded olefin **3** in 56% overall yield, which, upon ozonolysis, gave aldehyde **4** in 74% yield. Attempts to synthesize aldehyde **5** in the same manner as aldehyde **4** by using homoallylmagnesium bromide instead of allylmagnesium bromide resulted in very low yields of the homologous substitution product, which proved difficult to purify. Alternatively, **5** could be obtained from **3** *via* hydroboration with 9-borabicyclo[3.3.1]nonane (9-BBN), followed by an oxidative workup (61%) and subsequent oxidation with pyridinium chlorochromate (PCC, 68%). Oxime ethers **6** and **7** could be obtained in excellent yields from aldehydes **4** and **5**, respectively, by condensing each with *O*-benzylhydroxylamine (Scheme 1, 97% for **6**, 92% for **7**).

Scheme 1



[a] (a) NBS, benzoyl peroxide, CCl_4, Δ (67%); (b) allylmagnesium bromide, Et_2O, rt, 2 d (84%); (c) O_3, CH_2Cl_2/MeOH (97/3), −78 °C (74%); (d) (i) 9-BBN, THF, rt; (ii) EtOH, NaOH, H_2O_2 (61%); (e) 1.2 equiv of PCC, CH_2Cl_2 (68%); (f) $BnONH_3Cl$, pyridine, CH_2Cl_2 (97% for **6**; 92% for **7**).

Ketone **9** and nitrile **10** were both readily available from 1-bromo-2-(bromomethyl)naphthalene (**2**) (Scheme 2). Conversion into the alcohol by treating **2** with calcium carbonate in a 1:1 mixture of 1,4-dioxane and water and subsequent PCC-oxidation gave rise to 1-bromonaphthalene-2-carboxaldehyde[8] (**8**) in 65% yield over two steps. Treatment of **8** under Wittig reaction conditions with acetonyl triphenylphosphorane in refluxing toluene followed by catalytic hydrogenation of the resulting enone gave ketone **9** in 61% overall yield. Nitrile **10** could be obtained *via* a Horner–Emmons reaction of **8** with

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(1) (a) Jones, R. R.; Bergman, R. G. *J. Am. Chem. Soc.* **1972**, *94*, 660. (b) Bergman, R. G. *Acc. Chem. Res.* **1973**, *6*, 25. (c) Lockhart, T. P.; Mallon, C. B.; Bergman, R. G. *J. Am. Chem. Soc.* **1980**, *102*, 5976. (d) Lockhart, T. P.; Comita, P. B.; Bergman, R. G. *J. Am. Chem. Soc.* **1981**, *103*, 4082. (e) Lockhart, T. P.; Bergman, R. G. *J. Am. Chem. Soc.* **1981**, *103*, 4091. (f) Bharucha, K. N.; Marsh, R. M.; Minto, R. E.; Bergman, R. G. *J. Am. Chem. Soc.* **1992**, *114*, 3120.

(2) (a) Grissom, J. W.; Calkins, T. L. *Tetrahedron Lett.* **1992**, *33*, 2315. (b) Grissom, J. W.; Calkins, T. L. *J. Org. Chem.* **1993**, *58*, 5422. (c) Grissom, J. W.; Calkins, T. L., McMillen, H. A. *J. Org. Chem.* **1993**, *58*, 6556. (d) Grissom, J. W.; Calkins, T. L., Egan, M. *J. Am. Chem. Soc.* **1993**, *115*, 11744. (e) Grissom, J. W.; Huang, D.; Calkins, T. L.; McMillen, H. A. *Tetrahedron* **1994**, *50*, 4635.

(3) Grissom, J. W., Klingberg, D. *J. Org. Chem.* **1993**, *58*, 6559.

(4) (a) Beckwith, A. L. J.; Raner, K. D. *J. Org. Chem.* **1992**, *57*, 4954. (b) Beckwith, A. L. J.; Hay, B. P. *J. Am. Chem. Soc.* **1989**, *111*, 2674. (c) Fraser-Reid, B.; Walton, R. *J. Am. Chem. Soc.* **1991**, *113*, 5791.

(5) (a) Marco-Contelles, J.; Pozuelo, C.; Jimeno, M. L.; Martínez, L.; Martínez-Grau, A. *J. Org. Chem.* **1992**, *57*, 2625. (b) Enholm, E. J.; Burroff, J. A.; Jaramillo, L. M. *Tetrahedron Lett.* **1990**, *31*, 3727. (c) Parker, K. A.; Spero, D. M.; Van Epp, J. *J. Org. Chem.* **1988**, *53*, 4628. (d) Bartlett, P. A.; McLaren, K. L.; Ting, P. C. *J. Am. Chem. Soc.* **1988**, *110*, 1633. (e) Hart, D. J.; Seely, F. L. *J. Am. Chem. Soc.* **1988**, *110*, 1631. (f) Corey, E. J.; Pyne, S. G. *Tetrahedron Lett.* **1983**, *24*, 2821.

(6) Newman, M. S.; Kosak, A. I. *J. Org. Chem.* **1949**, *14*, 375.

(7) Abeywickrema, A. N.; Beckwith, A. L. J.; Gerba, S. *J. Org. Chem.* **1987**, *52*, 4072.

(8) Smith, J. G.; Dibble, P. W.; Sandborn, R. E. *J. Org. Chem.* **1986**, *51*, 3762.

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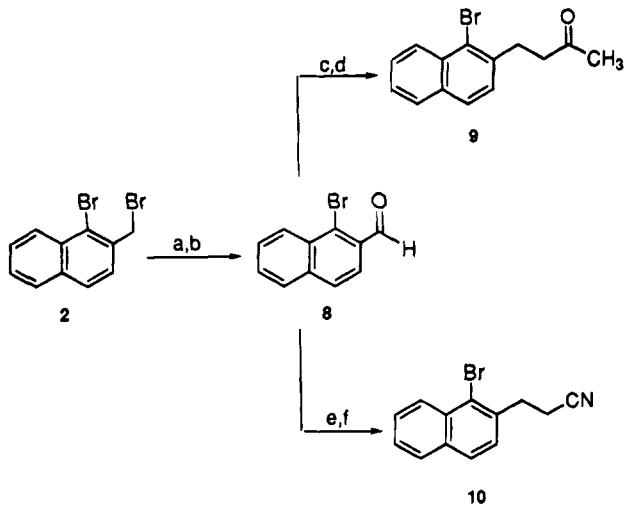
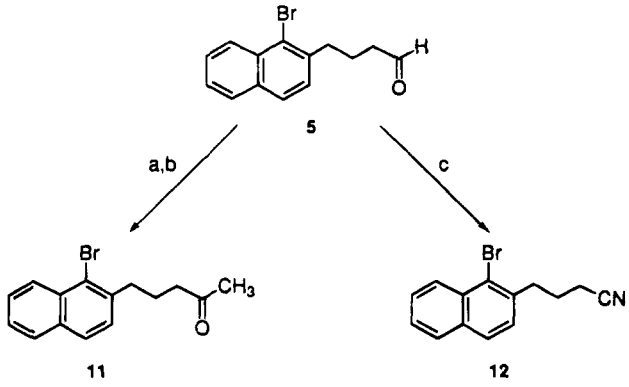
Scheme 2



[a] (a) $CaCO_3$, 1,4-dioxane/H_2O, Δ, 10 h (67%); (b) 1.2 equiv of PCC, CH_2Cl_2 (97%); (c) $Ph_3P{=}CHCOCH_3$, toluene, Δ (95%); (d) H_2, Pd/C, EtOAc (64%); (e) $(EtO)_2P(O)CH_2CN$, $(CH_3)_3COK$, THF (98%); (f) 1.5 equiv of $NaBH_4$, *i*-PrOH, Δ, 36 h (75%).

Scheme 3



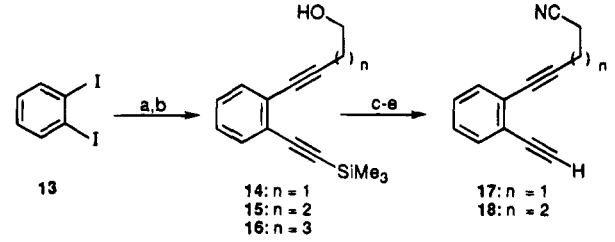
[a] (a) MeMgBr, Et_2O, 0 °C (86%); (b) 1.2 equiv of PCC, CH_2Cl_2 (87%); (c) (i) $HONH_3Cl$, H_2O, pyridine; (ii) $CuSO_4$, NEt_3, CH_2Cl_2; (iii) DCC, CH_2Cl_2 (69%).

diethyl (cyanomethyl)phosphonate in tetrahydrofuran (THF) (98%) followed by reduction of the intermediate conjugated nitrile with an excess of sodium borohydride in refluxing 2-propanol[9] (75%).

Aldehyde **5** was used as the precursor for the synthesis of ketone **11** and nitrile **12** (Scheme 3). A Grignard reaction of **5** with methylmagnesium bromide in diethyl ether and PCC-oxidation afforded ketone **11** in 75% yield starting from **5**. Nitrile **12** was obtained in 69% yield *via* formation of the oxime by condensing aldehyde **5** with hydroxylamine and subsequent dehydration of the oxime with copper(II) sulfate and 1,3-dicyclohexylcarbodiimide (DCC).[10]

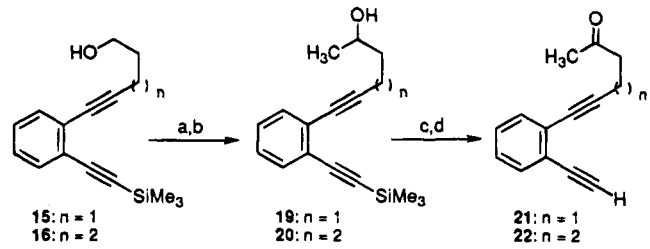
Synthesis of Precursors for the Tandem Enediyne-Radical Cyclizations. Enediyne nitriles **17** and **18** were synthesized in a straightforward manner from *o*-diiodobenzene (**13**) (Scheme 4). A palladium-catalyzed coupling reaction[11] of *o*-diiodobenzene (**13**) with 3-butynol followed by a second palladium-catalyzed coupling reaction with (trimethylsilyl)acetylene afforded alcohol **14** in an overall yield of 56%. Removal of the trimethylsilyl group with potassium carbonate in methanol in a yield of 97%, followed by tosylation of the alcohol with *p*-toluenesulfonyl chloride and pyridine in dichloromethane (81%) and nucleophilic substitution of the tosylate with sodium cyanide in dimethyl sulfoxide in 77% yield, gave enediyne nitrile **17**, along with a small amount of the respective elimination product. Nitrile **18** was synthesized in the same manner as nitrile **17** using 4-pentynol instead of 3-butynol in the first palladium-catalyzed coupling reaction with an overall yield of 41% starting from **13**.

Scheme 4



[a] (a) 1.5 equiv of 3-butynol or 4-pentynol or 5-hexynol, 0.03 equiv of $(Ph_3P)_2PdCl_2$, 0.1 equiv of CuI, 3.0 equiv of NEt_3, THF (58% for **14**/56% for **15**/48% for **16**); (b) 1.2 equiv of (trimethylsilyl)acetylene, same as (a) (96% for **14**/94% for **15**/94% for **16**); (c) K_2CO_3, MeOH (97%); (d) TsCl, pyridine, CH_2Cl_2 (81% for **17**/88% for **18**); (e) NaCN, DMSO, (77% for **17**/91% for **18**).

Scheme 5



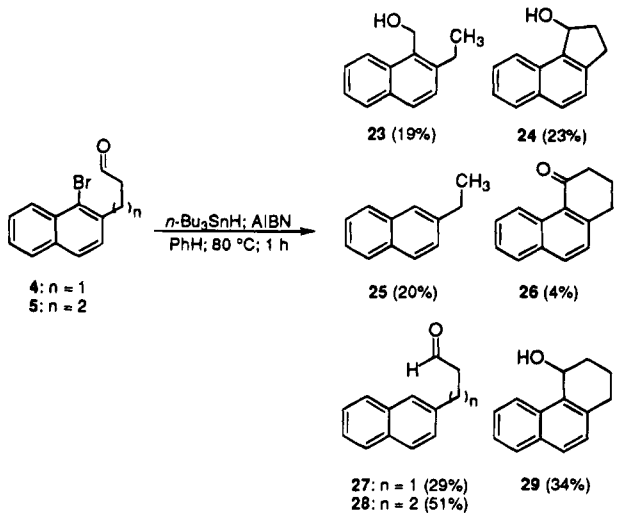
[a] (a) 1.2 equiv of PCC, CH_2Cl_2 (89% for **19**/88% for **20**); (b) MeMgBr, Et_2O, 0 °C (84% for **19**/67% for **20**); (c) K_2CO_3, MeOH (97%); (d) same as (a) (90% for **21**/94% for **22**).

Enediyne ketones **21** and **22** were obtained from alcohols **15** and **16**, respectively (Scheme 5). Oxidation of alcohol **15** with PCC gave the intermediate aldehyde (89%), which was subjected to a Grignard reaction with methylmagnesium bromide in diethyl ether to yield alcohol **19** in 84% yield. Removal of the trimethylsilyl group using a catalytic amount of potassium carbonate in methanol followed by a PCC-oxidation yielded the desired enediyne ketone **21** in 87% over two steps. Alcohol **16** was synthesized in 45% yield from *o*-diiodobenzene (**13**) *via* two sequential palladium-catalyzed coupling reactions with 5-hexynol and (trimethylsilyl)-acetylene (Scheme 4). Following the same protocol as for the preparation of **21**, enediyne ketone **22** could be obtained from alcohol **16** in an overall yield of 54% over four steps (Scheme 5).

Tributyltin Hydride-Mediated Radical Cyclization onto Aldehyde Acceptors. Aldehydes **4** and **5** were each treated with tributyltin hydride and a catalytic amount of 2,2′-azobis(2-methylpropanenitrile) (AIBN) in refluxing benzene for 1 h. In the tributyltin hydride-mediated radical cyclization of aldehyde **4**, four products were obtained (Scheme 6). The simple reduction product **27** could be isolated as the major product in 29% yield.

(9) Pépin, Y.; Nazémi, H.; Payette, D. *Can. J. Chem.* **1978**, *56*, 41.
(10) Vowinkel, E.; Bartel, J. *Chem. Ber.* **1974**, *107*, 1221.
(11) (a) Singh, R.; Just, G. *Tetrahedron Lett.* **1990**, *31*, 185. (b) Guillerm, D.; Linstrumelle, G. *Tetrahedron Lett.* **1985**, *26*, 3811. (c) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467.

Scheme 6



The desired tricyclic alcohol **24** was also obtained in 23% yield as well as 2-ethylnaphthalene (**25**) (20%) and naphthyl alcohol **23** (19%). The mechanism for the formation of these products is outlined in Scheme 7. The initial radical **A** can undergo intramolecular 1,5-hydrogen transfer and/or hydrogen abstraction from tributyltin hydride to form reduction product **27**. Alternatively, radical **A** can participate in a 5-*exo* radical cyclization to yield oxy-radical **B**, which can abstract hydrogen to give alcohol **24** or undergo a β-scission to yield the acyl transfer intermediate **C**. Subsequent hydrogen abstraction and reduction of the aldehyde by tributyltin hydride gives alcohol **23**. The formation of 2-ethylnaphthalene (**25**) came from decarbonylation of acyl radical **D** followed by hydrogen abstraction.

As described in our previous paper,[3] enediyne **30** undergoes enediyne cyclization followed by subsequent reactions to provide **32**, **27**, and **25** in 26, 20, and 41% yields, respectively (Scheme 8). A comparison of the low temperature tributyltin hydride 5-*exo* radical cyclization of **4** with the outcome of the corresponding high temperature tandem enediyne-5-*exo*-radical cyclization[3] of aldehyde **30** (Scheme 8) shows several interesting differences (Scheme 7). The formation of 2-ethylnaphthalene (**25**) *via* decarbonylation of the intermediate acyl radical **D** appears to be an unavoidable pathway in both types of radical reactions; this process, however, seems to become more prevalent at elevated temperatures. Noteworthy in the tributyltin hydride mediated radical reaction is the formation of naphthyl alcohol **23**, which constitutes a formyl transfer product. This product was not detected in the corresponding tandem enediyne-radical cyclization of aldehyde **30**;[3] therefore, for radical **B**, the hydrogen abstraction from 1,4-CHD must be faster than the β-scission. The cyclization product **24** was isolated in the low temperature cyclization, but underwent an elimination of water in the high temperature reaction to form benz[*e*]indenes **32**. Both tricyclic products **24** and **32** were isolated in comparable yields using either method. Overall it is remarkable that a wider variety of products originate from the radical reaction conducted at lower temperature.

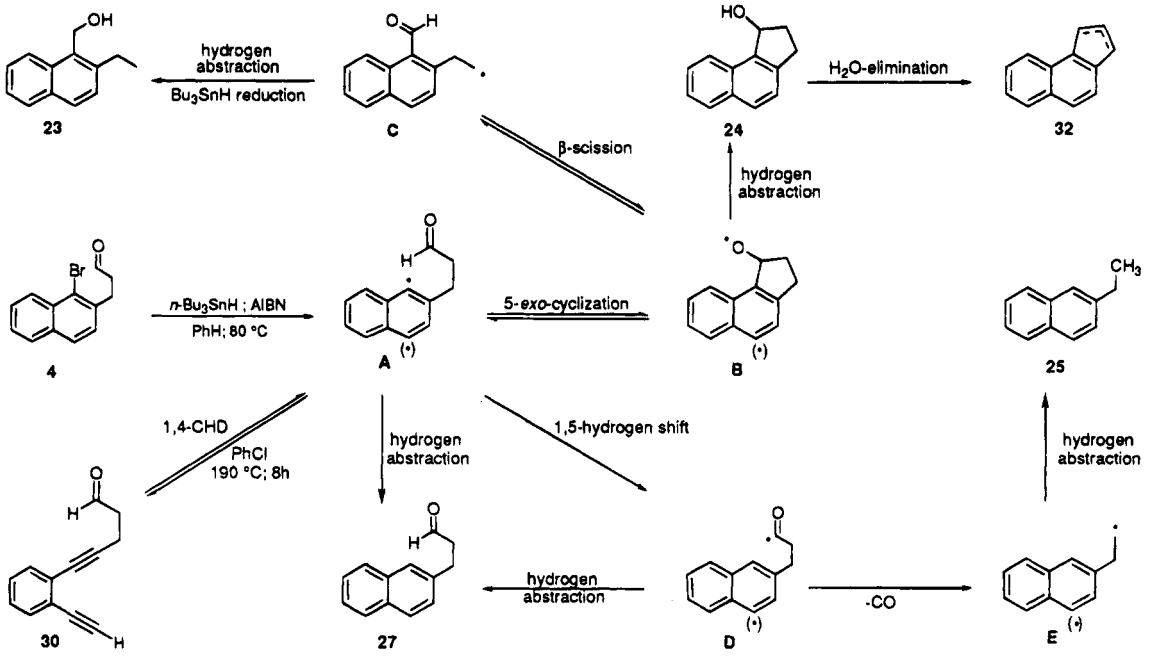
Subjecting the homologous aldehyde **5** to tributyltin hydride-mediated radical reaction conditions resulted in the formation of two major products (Scheme 6). Along with the direct cyclization product **29**, which was formed in 34% yield, the reduction product **28** could be isolated as the predominating product (51%). In addition to these two components, ketone **26** was formed in 4% yield. The possibility of an intramolecular 1,5-hydrogen shift is probably the reason for the predominance of reduction product **28** in this 6-*exo* radical cyclization. In spite of this competing process, the desired alcohol **29** was formed in a higher yield than the homologous alcohol **24** in the tributyltin hydride mediated 5-*exo* radical cyclization of aldehyde **4**.

The mechanism for the formation of the above mentioned products is outlined in Scheme 9 and is similar to that observed in the 5-*exo* aldehyde cyclizations. The initial radical **F** can undergo intramolecular 1,5- or 1,6-hydrogen transfer and/or hydrogen abstraction from tributyltin hydride to lead to reduction product **28**. A 6-*exo* radical cyclization of radical **F** followed by hydrogen abstraction yields alcohol **29**. The formation of ketone **26** is more difficult to explain. Oxyradical **G** could undergo a disproportionation reaction or acyl radical **H** could add into the aromatic ring followed by a disproportionation reaction. Alternatively, the air oxidation of alcohol **29** would lead to **26**, although this pathway seems less likely since the reaction was carried out under nitrogen.

As described in our previous paper,[3] enediyne **31** undergoes enediyne cyclization followed by additional reactions to give **28**, **33**, and **34** in 20, 57, and 11%, respectively (Scheme 8). A comparison of the low temperature tributyltin hydride 6-*exo* radical cyclization of **5** (Scheme 6) with the outcome of the corresponding high temperature tandem enediyne-6-*exo* radical cyclization of aldehyde **31** shows several interesting results (Scheme 9). Whereas the cyclization product **33** constituted the major product in the tandem enediyne-6-*exo* radical cyclization[3] of aldehyde **31**, the noncyclized reduction product **28** (51%) predominated in the tributyltin hydride-mediated 6-*exo* cyclization reaction. 2-Propylnaphthalene (**34**), which was isolated in the tandem enediyne-radical cyclization[3] of aldehyde **31**, was not observed in the tributyltin hydride-mediated cyclization of aldehyde **5**. While ketone **26** was isolated as a minor byproduct in the low temperature reaction, its formation was not observed in the high temperature reaction. It is difficult to determine whether ketone **26** comes from radical **G** or radical **H**. Although ketone **26** was formed in low yield, its formation in only the tributyltin hydride-mediated radical cyclization seems noteworthy, since similar radical addition products have been observed in other examples of the tandem enediyne-radical cyclization, arising from the addition of an acyl radical into the aromatic ring.[2e] Therefore, the formation of **26** in the tandem enediyne-radical cyclization would have been expected. The reaction conditions in the tributyltin hydride-mediated reaction do not favor a decarbonylation of the intermediate acyl radical **H** since under these conditions **34** was not observed. This result is in sharp contrast to the 5-*exo* cyclization of aldehyde **4**, in which the decarbonylation product **25** was seen in a significant yield.

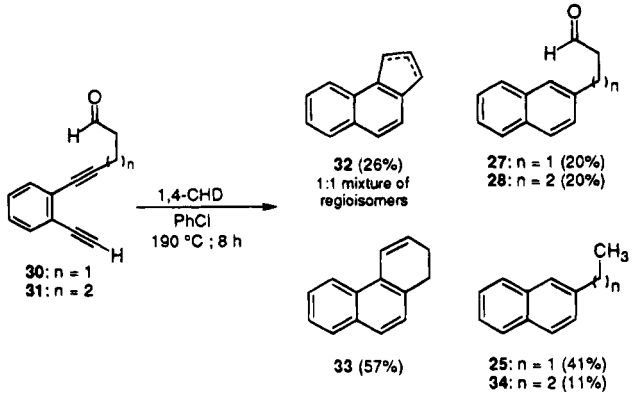
The results of both the enediyne and tributyltin hydride-mediated aryl radical reactions clearly show that the same trend is followed as in the respective alkyl radical cases, that the 6-*exo* cyclization is favored over the 5-*exo* cyclization onto aldehyde acceptors[4] despite the well-precedented possibility of an intramolecular 1,5-

Scheme 7

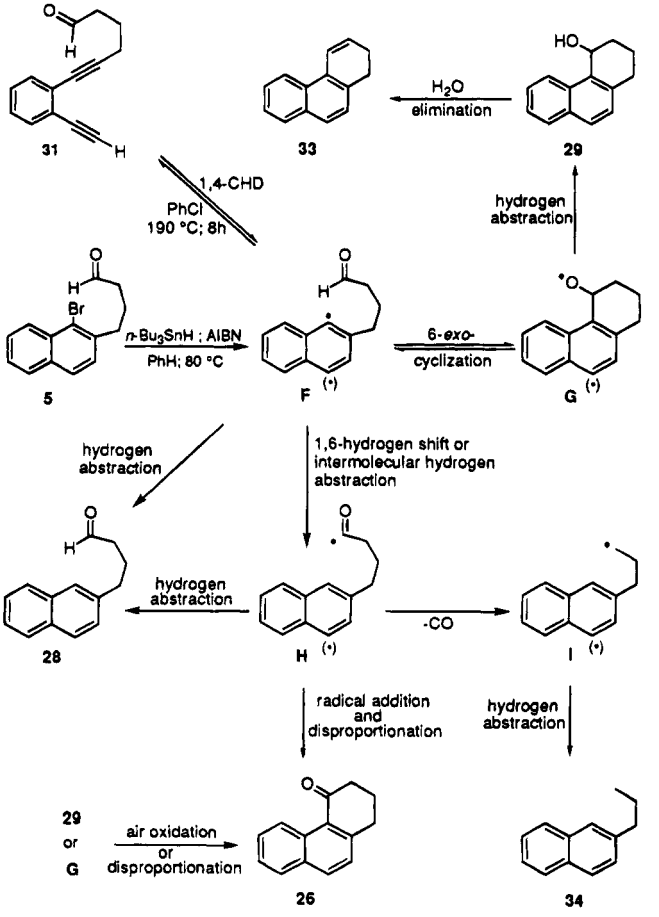


Note: Intermediates **A**, **B**, **D**, **E** can exist as the mono- or biradicals

Scheme 8



Scheme 9



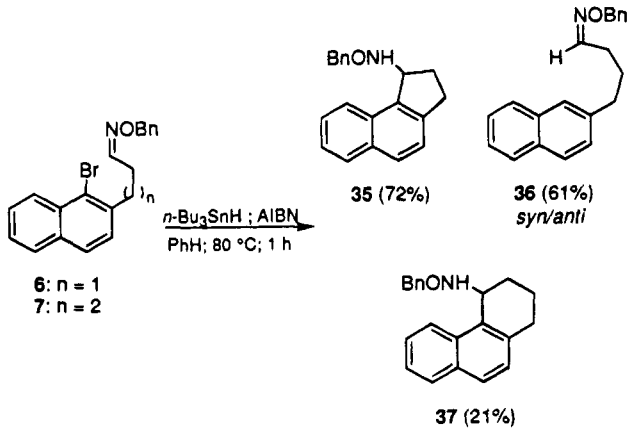
Note: Intermediates **F**-**I** can exist as the mono- or biradicals

hydrogen shift of the initially formed aryl radical.[12] The tandem enediyne-6-*exo*-radical cyclization of aldehyde **31** produced the desired cyclization product **33** in a higher yield than product **29** in the tributyltin hydride-mediated radical cyclization of aldehyde **5** under the given reaction conditions.

Tributyltin Hydride-Mediated Radical Cyclization onto Oxime Ether Acceptors. The tributyltin hydride mediated radical cyclization of oxime ether **6** (Scheme 10) gave exclusively the 5-*exo* cyclization product **35** (72%), which was also formed in the tandem enediyne-radical cyclization of enediyne **38** (25%, Scheme 11).[3] Due to the lower temperature employed in the tributyltin hydride mediated reaction, the elimination of *O*-benzylhydroxylamine from **35**, which gave rise to benz[*e*]indene (**32**), did not occur, as was observed in the tandem enediyne-radical cyclization. The formation of undesired byproducts was not seen in either the tandem enediyne-radical cyclization of oxime ether **38** or the tributyltin hydride-mediated radical cyclization of oxime ether **6**,

(12) For general references on free radical chemistry see: (a) Curran, D. P. *Synlett* **1991**, 63. (b) Hart, D. J. *Science* **1984**, *223*, 883. (c) Giese, B. *Radicals in Organic Chemistry*; Pergamon Press: New York, 1986. (d) Jasperse, C. P.; Curran, D. P.; Fevig, T. L. *Chem. Rev.* **1991**, *91*, 1237. (e) Curran, D. P. *Synthesis* **1988**, 417. (f) Curran, D. P. *Synthesis* **1988**, 489. (g) Neumann, W. P. *Synthesis* **1987**, 665. (h) Ramaiah, M. *Tetrahedron* **1987**, *43*, 3541. (i) *Houben-Weyl Methoden der Organischen Chemie*, Band 19a; Regitz, M.; Giese, B.; Thieme: Stuttgart, 1989.

Scheme 10



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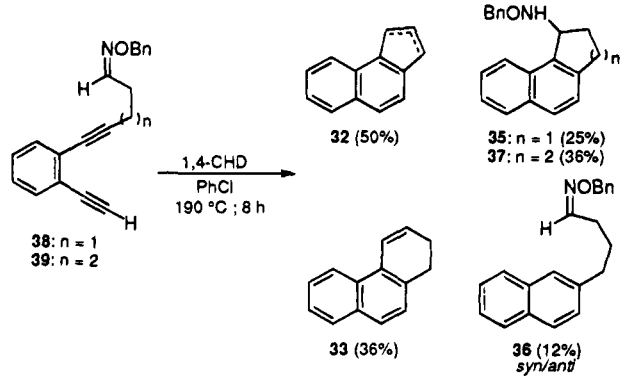
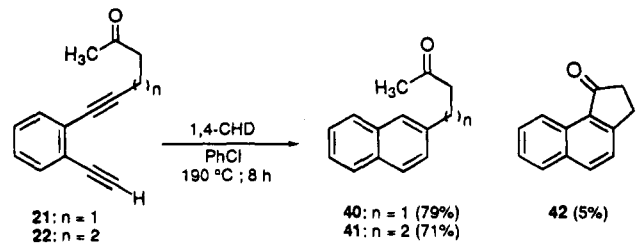


making both of these reactions synthetically useful. These reactions leave a site of functionality at the position where the radical addition took place thus allowing for further elaboration.

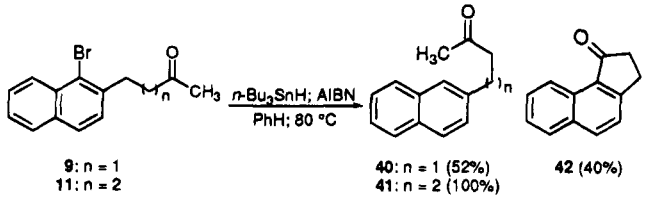
Unlike the 5-*exo* cyclization experiment, the tributyltin hydride-mediated 6-*exo* cyclization of oxime ether **7** gave rise to the noncyclized reduction product **36** (61%) along with the cyclization product **37** (21%) (Scheme 10). This result is in contrast with the tandem enediyne-radical cyclization, which gave cyclized products **33** and **37** in a combined yield of 72% and product **36** in only 12% yield (Scheme 11).

Due to the possibility of a 1,5-hydrogen transfer of the initially formed aryl radical in the 6-*exo* cyclization, the formation of the noncyclized reduction product **36** *via* hydrogen trapping by tributyltin hydride can effectively compete with the formation of *O*-benzylhydroxylamine **37**. These results show that oxime ethers follow the opposite trend of the respective cyclizations onto aldehyde acceptors in the tributyltin hydride-mediated radical cyclizations, that the 5-*exo* cyclization is favored over the 6-*exo* cyclization. Both the 5-*exo* and 6-*exo* cyclizations are favorable in the tandem enediyne-radical cyclizations. Comparing both modes of radical generation, in which the respective hydrogen atom donors were present from the beginning of the reaction, it is remarkable that in the tandem enediyne-radical cyclization of oxime ether **39** (E/Z = 3:2) the simple enediyne cyclized product **36** was formed in only 12% yield even though a large excess of the hydrogen atom donor 1,4-cyclohexadiene was used in the thermolysis reaction. It is possible that at higher temperatures the 6-*exo* cyclization process becomes kinetically favored over the competing hydrogen trapping reaction or 1,5-hydrogen shift of the initially formed aryl radical.

Scheme 12



Scheme 13

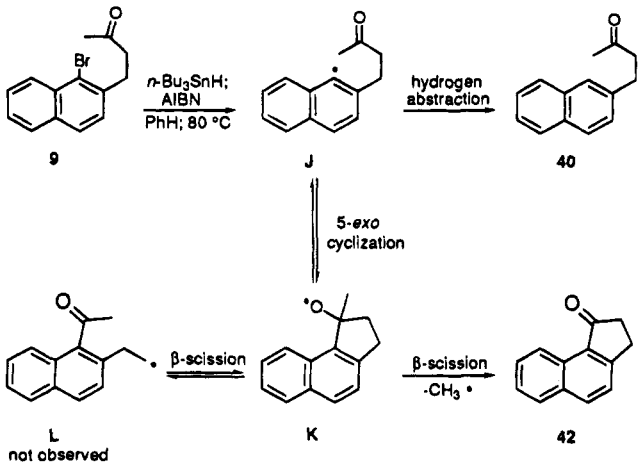


Tandem Enediyne-Radical Cyclization onto Ketone Acceptors. In order to test the feasibility of ketone radical acceptors in the tandem enediyne-radical cyclization we thermolyzed enediyne ketones **21** and **22** at 190 °C in chlorobenzene with an excess of 1,4-cyclohexadiene as a hydrogen atom donor (Scheme 12). Along with the simple enediyne cyclization product **40**, which could be isolated in 79% yield, the thermolysis of enediyne ketone **21** also gave rise to a 5% yield of ketone **42**. When thermolyzing enediyne ketone **22**, the simple endiyne cyclization product **41** was formed as the only product in a yield of 71%.

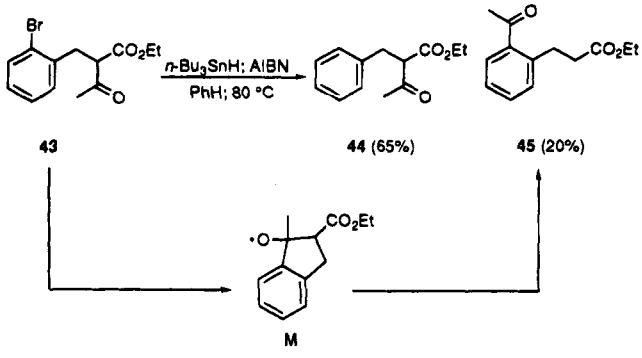
Tributyltin Hydride-Mediated Radical Cyclization onto Ketone Acceptors. The results in the respective tandem enediyne-radical cyclizations show a significantly lower rate of cyclization onto ketone radical acceptors than into aldehyde acceptors. Consequently we treated naphthalene derivatives **9** and **11** by slowly adding a solution of tributyltin hydride and a catalytic amount of AIBN in benzene *via* syringe pump over a period of 5 h to guarantee a low concentration of tributyltin hydride throughout the course of the reaction. When treating ketone **9** under these conditions, reduction product **40** could be isolated in 52% yield (Scheme 13). Surprisingly, cyclized ketone **42** was also isolated in 40% yield and there was no evidence for an acyl transfer product in this reaction.[13] Subjecting ketone **11** to the same conditions as ketone **9** led to the exclusive formation of the reduction product **41** in quantitative yield. The consistent results of both types of radical reactions in the respective 6-*exo* cyclization experiments show that a favorable 1,5-hydrogen shift of the initially formed aryl radicals prevents these substrates from forming any products deriving from a 6-*exo* cyclization onto the ketone and that sterically these radical cyclizations are disfavored as compared to the corresponding aldehyde substrates.

The significant yield of ketone **42** in the 5-*exo* tributyltin hydride-mediated radical cyclization experiment deserves comment (Scheme 14). Initially formed aryl radical **J** abstracts hydrogen to give reduction product **40**. The intermediate oxy-radical **K**, which is formed by a 5-*exo* cyclization of aryl radical **J** onto the carbonyl group, can undergo a β-scission in two different directions, one of which is a nonreversible cleavage of a methyl radical resulting in the formation of the observed product **42**. A β-scission, which cleaves the five-membered ring,

Scheme 14



Scheme 15



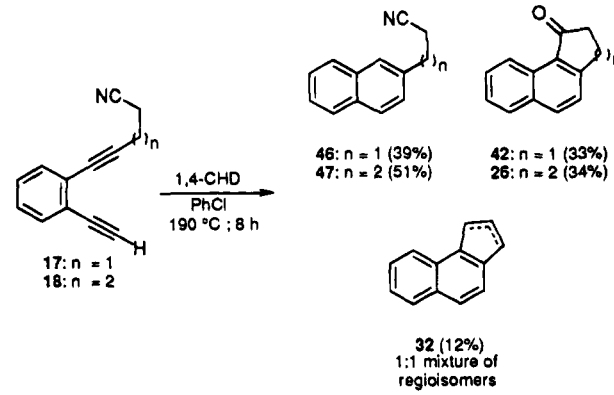
would create the primary alkyl radical **L** and lead to the formation of an acyl transfer product following hydrogen abstraction. This process, however, occurs reversibly, and the irreversible formation of ketone **42** shifts the equilibrium toward its formation, which explains the absence of an acyl transfer product in the product mixture.

Beckwith[13] has conducted similar experiments with β-keto ester **43** (Scheme 15). The presence of the stabilizing ester functionality in his substrate apparently makes the β-scission of the intermediate oxy-radical **M** irreversible and leads to the formation of acyl transfer product **45**. A product derived from the cleavage of a methyl radical from oxy-radical **M** was not observed. In the reaction of **K** (Scheme 14), it is the reversibility of this particular process that makes the energetically disfavored cleavage of a methyl radical the observed pathway. The low yield of ketone **42** in the enediyne mediated cyclization suggests that a low concentration of the hydrogen atom donor is necessary for the 5-*exo* radical cyclization to successfully compete with hydrogen abstraction by the aryl radical. The presence of a high concentration of 1,4-CHD in this reaction leads to a high yield of enediyne cyclization product **40**.

Tandem Enediyne-Radical Cyclization onto Nitrile Acceptors. Nitriles have already been successfully employed in radical cyclization reactions, especially in the 5-*exo* mode.[14] Clive employed several alkyl radicals in 5-*exo* cyclization reactions for the formation of cyclopentanone derivatives with varying yields.[14a] Fraser-

(13) (a) Beckwith, A. L. J.; O'Shea, D. M.; Gerba, S.; Westwood, S. W. *J. Chem. Soc., Chem. Commun.* **1987**, 666. (b) Beckwith, A. L. J.; O'Shea, D. M.; Westwood, S. W. *J. Am. Chem. Soc.* **1988**, *110*, 2565.

Scheme 16



Reid used a carbon–nitrogen triple bond in a tandem 5-*exo*-alkyl radical cyclization and isolated the cyclopentanone product in high yield.[14d] We have investigated enediyne nitriles **17** and **18** in the tandem enediyne-5-*exo* and 6-*exo* radical cyclizations to explore the behavior of carbon–nitrogen triple bonds in these high temperature radical cyclizations.

Subjecting enediyne nitrile **17** to tandem enediyne-radical cyclization conditions resulted in the formation of three products (Scheme 16). Along with the simple enediyne cyclization product **46**, which was isolated in 39% yield, ketone **42** as well as benz[*e*]indene (**32**), both of which result from a tandem enediyne-5-*exo*-radical cyclization, could be isolated in 33 and 12% yields, respectively.

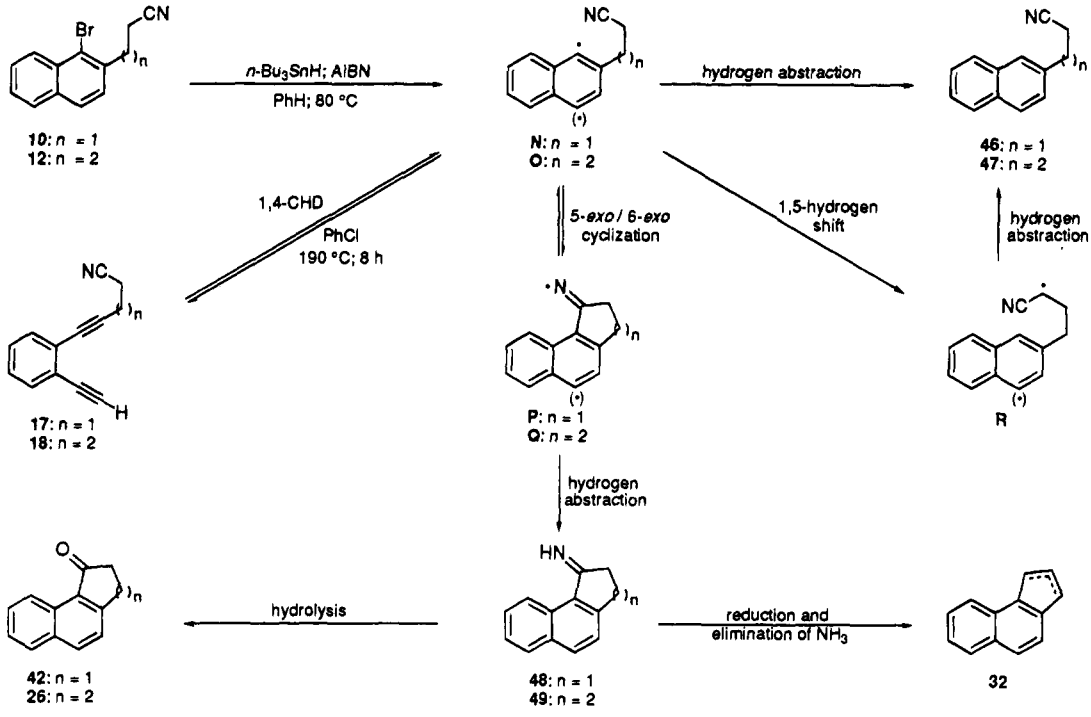
Ketone **42** was formed by the hydrolysis of the cyclized imine intermediate **48**, which came from a 5-*exo* radical cyclization of aryl radical **N** to give **P** followed by hydrogen abstraction (Scheme 17). The formation of **32** can be explained by the reduction of the cyclized imine intermediate **48** by 1,4-cyclohexadiene, followed by an elimination of ammonia. The initially formed 3*H*-dihydrobenz[*e*]indene then isomerizes to yield the 1:1 mixture of isomeric benz[*e*]indenes (**32**) (cf. reference 3). Encouraging is the fact that in this case the two products derived from a 5-*exo* radical cyclization of the intermediate aryl biradical (**32** and **42**) predominate over the simple enediyne cyclization product **46**.

When the homologous enediyne nitrile **18** was thermolyzed under the same conditions as enediyne nitrile **17**, there was no evidence for a product analogous to reduction/elimination product **32** (Scheme 16). Along with the enediyne-cyclized nitrile **47**, which could be isolated as the major product in 51% yield, product **26** coming from a tandem enediyne-6-*exo*-radical cyclization and subsequent hydrolysis could also be isolated in 34% yield.

These results suggest that both the 5-*exo* and the 6-*exo* radical cyclization onto carbon–nitrogen triple bonds can effectively compete with the hydrogen trapping of the intermediate aryl radicals **N** or **O**. However, due to the possibility of a 1,5-hydrogen shift of aryl radical **O** in the tandem enediyne-6-*exo*-radical cyclization, the formation of the tandem enediyne-radical cyclized product **26** occurred in lower yield than the formation of the respec-

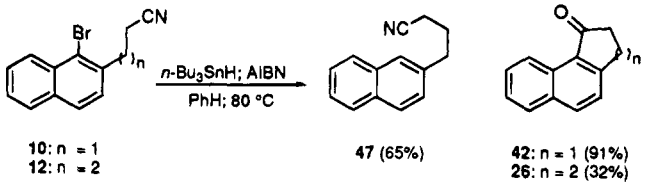
(14) For examples of radical cyclizations onto nitriles, see: (a) Clive, D. L. J.; Beaulieu, P. L.; Set, L. *J. Org. Chem.* **1984**, *49*, 1313. (b) Griller, D.; Schmid, P.; Ingold, K. U. *Can. J. Chem.* **1979**, *57*, 831. (c) Chenera, B; Chuang, C.-P.; Hart, D. J.; Hsu, L.-Y. *J. Org. Chem.* **1985**, *50*, 5409 and references therein. (d) Tsang, R.; Fraser-Reid, B. *J. Am. Chem. Soc.* **1986**, *108*, 2116.

Scheme 17



Note: Intermediates N-R can exist as the mono- or biradicals

Scheme 18



tive tandem enediyne-radical cyclization products (**32** and **42**) in the 5-*exo* case.

Tributyltin Hydride-Mediated Radical Cyclization onto Nitrile Acceptors. When nitrile **10** was treated with tributyltin hydride and AIBN *via* syringe pump addition, ketone **42** was isolated as the exclusive product after a hydrolytic workup in a yield of 91% (Scheme 18). There was no evidence for reduction product **46**, which was seen in the tandem enediyne-radical cyclization of nitrile **17**. Cyano transfer products that could result from a β-scission of radical **P** were not observed (Scheme 17).

Subjecting the homologous nitrile **12** to the same radical reaction conditions as nitrile **10** gave rise to the reduction product **47** in 65% yield. Cyclized ketone **26** could also be isolated in 32% yield after a hydrolytic workup with acetic acid.

A comparison between the low temperature tributyltin hydride-mediated radical cyclization of **10** and the high temperature tandem enediyne-radical cyclization of **17** shows that a low concentration of the hydrogen atom donor is crucial in the 5-*exo* cyclizations for the success of the radical cyclization onto nitrile acceptors. When the concentration of Bu_3SnH was kept low using a syringe pump, there was no evidence for reduction product **46**. An excess of 1,4-cyclohexadiene, however, is necessary in the tandem enediyne-radical cyclization to prevent the intermediate radicals from polymerizing; therefore, the yield of reduction product **46** is higher. This ratio suggests that the rate of the 5-*exo* radical cyclization onto a nitrile is comparable to the rate of hydrogen abstraction and that the rate is slower than the rate of addition to the corresponding oxime ether.[3] The formation of the reduction/elimination product **32** was not observed in the respective tributyltin hydride-mediated radical cyclization of nitrile **10**. The similar product distribution in both the tandem enediyne-radical cyclization and the tributyltin hydride-mediated radical cyclization in the 6-*exo* case indicates that the product distribution in both reactions is probably determined by the competition of the 6-*exo* radical cyclization and 1,5-hydrogen shift of aryl radical **O** to give radicals **P** and **R**, respectively (Scheme 17) and is less likely to be influenced by the concentration of the hydrogen atom donor.

Conclusion

In summary, aryl radicals generated from treatment of naphthyl bromides with tributyltin hydride or from enediyne cyclizations can undergo cyclizations with aldehyde, ketone, nitrile, and oxime ether radical acceptors.

In the 5-*exo* radical cyclization, the synthetically useful reaction is the addition of aryl radicals onto oxime ether acceptors. Both the enediyne and tributyltin hydride generated aryl radicals undergo exclusive radical cyclization and no undesired byproducts are observed. Also useful in the 5-*exo* cyclization is the use of tributyltin hydride under high dilution conditions in the radical cyclization onto a nitrile acceptor. The corresponding enediyne-generated radical cyclization onto a nitrile resulted in a high amount of reduction product thus suggesting that the rate of 5-*exo* cyclization is comparable to the rate of hydrogen abstraction of 1,4-CHD. The use of aldehydes and ketones as radical acceptors in both types of radical additions also led to large amounts of reduction products.

In the 6-*exo* radical cyclizations it is interesting that the only synthetically useful reaction results from the tandem enediyne-radical cyclization onto an oxime ether acceptor. The corresponding tributyltin hydride-mediated radical cyclization onto the same acceptor yielded predominantly reduction product. There is a modest selectivity for cyclization in the tandem enediyne-radical cyclization using an aldehyde acceptor. In all cases using tributyltin hydride, the reduction product is the predominant one. This result suggests that, with tributyltin hydride, the rate of hydrogen abstraction by the aryl radical is faster than the 6-*exo* cyclization. There is a possibility that much of the reduction products in the tandem enediyne 6-*exo* radical cyclization comes from 1,5-hydrogen transfers and that at high temperature it is the intramolecular rather than the intermolecular hydrogen abstraction that is competing with the 6-*exo* radical cyclization.

There are major differences in the reactions of tributyltin hydride- and enediyne-generated aryl radicals. Although many similar products were observed using either method of radical generation, there were also products seen that were unique to each method. It is difficult to tell how much of this difference can be attributed to the large difference in temperature between the two methods. Efforts to use these radical acceptors in lower temperature variants of the enediyne cyclization are underway.

Experimental Section[15]

1-Bromo-2-(bromomethyl)naphthalene[6] (2). A mixture of 1-bromo-2-methylnaphthalene (**1**) (5.45 g, 24.65 mmol), *N*-bromosuccinimide (4.61 g, 25.9 mmol), and benzoyl peroxide (0.03 g, 0.1 mmol) in 30 mL of carbon tetrachloride was heated to reflux for 2 h. After that, the reaction mixture was allowed to cool to room temperature and was filtered; the residue was washed with carbon tetrachloride. The filtrate was concentrated and the crude product recrystallized from hexanes to give 4.95 g (67%) of **2** as a pale yellow solid: TLC R_f 0.31 (hexanes); ^{1}H NMR δ 4.83 (2H, s), 7.46 (1H, d, J = 8.4 Hz), 7.51 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.58 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.73 (1H, d, J = 8.7 Hz), 7.77 (1H, d, J = 8.7 Hz), 8.31 (1H, d, J = 8.3 Hz); ^{13}C NMR δ 134.8, 134.0, 132.3, 128.2, 128.0, 127.7, 127.6, 127.4, 127.1, 124.9, 34.8.

1-Bromo-2-but-3-enylnaphthalene[7] (3). A solution of 1-bromo-2-(bromomethyl)naphthalene (**2**) (1.34 g, 4.5 mmol) in 30 mL of diethyl ether was added dropwise to a Grignard solution prepared from allyl bromide (1.44 g, 11.9 mmol) and magnesium turnings (0.32 g, 13.2 mmol) in 50 mL of diethyl ether. The reaction mixture was stirred at room temperature for 2 d. The solvent was removed *in vacuo* and the residue passed through a short silica gel column using a 1:1 mixture of hexanes/ethyl acetate. The crude product was subjected to radial chromatography with pentane to give 0.975 g (84%) of **3** as a colorless oil: TLC R_f 0.37 (hexanes); ^{1}H NMR δ 2.48 (2H, m), 3.10 (2H, t, J = 8.0 Hz), 5.05 (1H, dd, J = 10.2, 1.2 Hz), 5.12 (1H, dq, J = 17.1, 1.7 Hz), 5.96 (1H, ddt, J = 17.1, 10.2, 6.6 Hz), 7.34 (1H, d, J = 8.4 Hz), 7.49 (1H, ddd, J = 8.1, 6.6, 1.2 Hz), 7.59 (1H, ddd, J = 8.4, 6.9, 1.5 Hz), 7.77 (2H, dd, J = 12.3, 8.4 Hz), 8.36 (1H, d, J = 8.6 Hz); ^{13}C NMR δ 139.3, 137.7, 133.2, 132.6, 128.1, 128.0, 127.4, 127.2, 125.8, 123.7, 115.2, 36.8, 34.0.

1-Bromo-2-naphthalenepropanal (4). 1-Bromo-2-but-3-enylnaphthalene (**3**) (0.200 g, 0.77 mmol) was dissolved in 10 mL of a 97:3 mixture of dichloromethane/methanol and the solution cooled to −78 °C. After that, ozone was introduced, until the starting material was no longer visible by TLC. The reaction mixture was quenched with 1 mL of dimethyl sulfide and allowed to stir overnight. After removal of the solvent *in vacuo*, the residue was passed through a short Florisil column with a 1:1 mixture of hexanes/ethyl acetate. Purification by radial chromatography with a 90:10 mixture of hexanes/ethyl acetate yielded 0.150 g (74%) of **4** as a pale yellow oil: TLC R_f 0.51 (3:1 hexanes/ethyl acetate); IR (neat) ν 3055, 2822, 2724, 1724 cm^{-1}; ^{1}H NMR δ 2.87 (2H, td, J = 7.7, 1.4 Hz), 3.29 (2H, t, J = 7.7 Hz), 7.35 (1H, d, J = 8.4 Hz), 7.48 (1H, ddd, J = 8.4, 6.9, 1.5 Hz), 7.58 (1H, ddd, J = 8.1, 6.9, 1.5 Hz), 7.73 (1H, d, J = 8.1 Hz), 7.79 (1H, d, J = 8.1 Hz), 8.29 (1H, d, J = 8.4 Hz), 9.85 (1H, t, J = 1.4 Hz); ^{13}C NMR δ 201.0, 137.9, 133.3, 132.5, 128.0, 128.0, 127.9, 127.5, 127.1, 126.1, 123.7, 43.8, 29.9; HRMS (EI) calcd for $C_{13}H_{11}BrO$ (M^+) 261.9993, found 261.9984.

1-Bromo-2-naphthalenebutanol. A solution of 1-bromo-2-but-3-enylnaphthalene (**3**) (0.633 g, 2.44 mmol) in 1.3 mL of THF was added to a 0.5 M solution of 9-borabicyclo[3.3.1]-nonane (9-BBN) (4.885 mL, 0.298 g, 2.44 mmol) in THF and the reaction mixture was stirred for 1 h. Then 3 mL of ethanol, 0.5 mL of a 6 M aqueous sodium hydroxide solution, and 1 mL of an aqueous hydrogen peroxide solution (30%) were slowly added. The reaction mixture was stirred for an additional 15 min at room temperature and for 10 min at 50 °C. After saturation of the aqueous layer with potassium carbonate, the organic layer was separated, the solvent removed *in vacuo*, and the residue dissolved in diethyl ether. The aqueous layer was extracted twice with diethyl ether and the combined organic layers were dried over potassium carbonate. After filtration the organic solvent was removed *in vacuo* and the residue passed through a short silica gel column with a 1:1 mixture of hexanes/diethyl ether. The crude product was purified by radial chromatography with an 85:15 mixture of hexanes/diethyl ether to yield 0.417 g (61%) of the alcohol as a colorless oil: TLC R_f 0.17 (3:1 hexanes/ethyl acetate); IR (neat) ν 3351 (br), 3054, 2936, 2872 cm^{-1}; ^{1}H NMR δ 1.35 (1H, s, br), 1.62−1.82 (4H, m), 3.00 (2H, t, J = 7.5.Hz), 3.68 (2H, t, J = 6.3 Hz), 7.32 (1H, d, J = 8.4 Hz), 7.46 (1H, ddd, J = 8.4, 6.9, 1.2 Hz), 7.56 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.71 (1H, d, J = 8.1 Hz), 7.78 (1H, d, J = 8.1 Hz), 8.30 (1H, d, J = 8.4 Hz); ^{13}C NMR δ 139.7, 133.1, 132.5, 128.0, 127.9, 127.5, 127.2, 127.2, 125.8, 123.6, 62.6, 36.9, 32.3, 26.2; HRMS (EI) calcd for $C_{14}H_{15}BrO$ (M^+) 278.0306, found 278.0305.

1-Bromo-2-naphthalenebutanal (5). 1-Bromo-2-naphthalenebutanol (0.105 g, 0.38 mmol) was dissolved in 10 mL of dichloromethane, and pyridinium chlorochromate (0.097 g, 0.45 mmol) was added portionwise under vigorous stirring. After the addition was completed, the reaction mixture was allowed to stir at room temperature, until the alcohol was no longer visible by TLC (5−7 h). The mixture was passed through a short Florisil column with dichloromethane. Purification by radial chromatography with a 95:5 mixture of hexanes/ethyl acetate afforded 0.071 g (68%) of **5** as a pale yellow oil: TLC R_f 0.45 (3:1 hexanes/ethyl acetate); IR (neat) ν 3054, 2822, 2722, 1723 cm^{-1}; ^{1}H NMR δ 2.04 (2H, quintet, J = 7.5 Hz), 2.53 (2H, td, J = 7.8, 1.2 Hz), 3.02 (2H, t, J = 7.8 Hz), 7.32 (1H, d, J = 8.4 Hz), 7.47 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.57 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.73 (1H, d, J = 8.3 Hz), 7.79 (1H, d, J = 8.4 Hz), 8.29 (1H, d, J = 8.1 Hz), 9.79 (1H, t, J = 1.5 Hz); ^{13}C NMR δ 202.2, 138.8, 133.2, 132.5, 128.0, 127.9, 127.7, 127.4, 127.2, 126.0, 123.8, 43.0, 36.3, 22.4; HRMS (EI) calcd for $C_{14}H_{13}BrO$ (M^+) 276.1050, found 276.1048.

1-Bromo-2-*N*-(phenylmethoxy)naphthalenepropanimine (6). 1-Bromonaphthalene-2-propanal (**4**) (0.033 g, 0.13 mmol) was dissolved in 3.5 mL of dichloromethane. After adding *O*-benzylhydroxylamine hydrochloride (0.022 g, 0.14 mmol) and pyridine (0.011 mL, 0.011 g, 0.14 mmol), the reaction mixture was allowed to stir at room temperature, until the aldehyde was no longer visible by TLC (8−9 h). The reaction mixture was then passed through a short silica gel column using a 2:1 mixture of hexanes/ethyl acetate. Purification of the crude product by radial chromatography with a 92:8 mixture of hexanes/ethyl acetate afforded 0.045 g (97%) of **6** as a 3:2 mixture of *E* and *Z* isomers: TLC R_f 0.49/0.53 (3:1 hexanes/ethyl acetate); IR (neat) ν 3063, 3032, 2926, 2868 cm^{-1}; ^{1}H NMR δ 2.62 (1.2H, m), 2.81 (0.8H, m), 3.19 (2H, m), 5.05 (1.2H, s), 5.13 (0.8H, s), 6.77 (0.4H, t, J = 5.4 Hz), 7.29−7.37 (6H, m), 7.50 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.56 (0.6H, t, J = 6.0 Hz), 7.59 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.72 (1H,

(15) General experimental techniques are described in ref 3.

d, J = 8.4 Hz), 7.80 (1H, d, J = 8.1 Hz), 8.33 (1H, d, J = 8.1 Hz); ^{13}C NMR δ 150.7, 150.1, 138.1, 138.1, 137.6, 133.3, 132.5, 128.3, 128.3, 128.2, 128.0, 127.9, 127.9, 127.8, 127.7, 127.7, 127.4, 127.2, 126.0, 123.8, 75.7, 75.6, 34.4, 33.6, 29.8, 26.1 (some signals of both isomers coincide); HRMS (EI) calcd for $C_{20}H_{18}BrNO$ (M^+) 367.0572, found 367.0574.

1-Bromo-*N*-(phenylmethoxy)naphthalene-2-butanimine (7). 1-Bromonaphthalene-2-butanal (**5**) (0.068 g, 0.25 mmol) was dissolved in 7 mL of dichloromethane. After adding *O*-benzylhydroxylamine hydrochloride (0.043 g, 0.27 mmol) and pyridine (0.021 mL, 0.021 g, 0.27 mmol), the reaction mixture was allowed to stir at room temperature, until the aldehyde was no longer visible by TLC (8–9 h). The reaction mixture was then passed through a short silica gel column using a 2:1 mixture of hexanes/ethyl acetate. Purification of the crude product by radial chromatography with a 92:8 mixture of hexanes/ethyl acetate afforded 0.086 g (92%) of **7** as a mixture of *E* and *Z* isomers: TLC R_f 0.48/0.52 (3:1 hexanes/ethyl acetate); IR (neat) ν 3063, 3032, 2928, 2864 cm^{-1}; ^{1}H NMR δ 1.88 (0.8H, quintet, J = 7.8 Hz), 1.89 (1.2H, quintet, J = 7.8 Hz), 2.30 (1.2H, m), 2.49 (0.8H, td, J = 7.5, 5.4 Hz), 3.00 (2H, t, J = 7.8 Hz), 5.07 (1.2H, s), 5.12 (0.8H, s), 6.77 (0.4H, t, J = 5.4 Hz), 7.27–7.37 (6H, m), 7.47 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.51 (0.6H, t, J = 6.0 Hz), 7.57 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.71 (1H, d, J = 8.4 Hz), 7.79 (1H, d, J = 8.4 Hz), 8.31 (1H, d, J = 8.7 Hz); ^{13}C NMR δ 151.8, 150.9, 139.1, 139.1, 138.0, 137.7, 133.2, 132.6, 128.4, 128.4, 128.2, 128.1, 127.9, 127.8, 127.7, 127.6, 127.6, 127.3, 127.2, 125.9, 123.7, 75.7, 75.5, 36.9, 36.6, 29.1, 26.9, 26.6, 25.6 (some signals of both isomers coincide); HRMS (EI) calcd for $C_{21}H_{20}BrNO$ (M^+) 381.0728, found 381.0746.

1-Bromo-2-naphthalenemethanol.[8] 1-Bromo-2-(bromomethyl)naphthalene (**2**) (4.287 g, 14.29 mmol) was dissolved in 100 mL of a 1:1 mixture of water and 1,4-dioxane. To this solution was added 7.183 g (71.77 mmol) of calcium carbonate, and the heterogeneous mixture was heated to reflux for 10 h. After that, the solvents were removed *in vacuo* and the residue acidified with 2 M hydrochloric acid. The clear solution was extracted three times with dichloromethane. The combined organic layers were washed twice with a saturated sodium bicarbonate solution and dried over magnesium sulfate. The crude product was purified by column chromatography with a 3:1 mixture of hexanes/diethyl ether to give 2.270 g (67%) of the alcohol as a colorless, crystalline solid: TLC R_f 0.31 (3:1 hexanes/ethyl acetate); IR (KBr) ν 3231 (br), 2955, 2924, 2855 cm^{-1}; ^{1}H NMR δ 2.21 (1H, t, J = 6.3 Hz), 4.95 (2H, d, J = 6.3 Hz), 7.50 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.58 (1H, m), 7.59 (2H, d, J = 8.2 Hz), 7.80 (2H, d, J = 8.2 Hz), 8.29 (1H, d, J = 8.5 Hz); ^{13}C NMR δ 137.7, 134.0, 132.1, 128.1, 127.9, 127.5, 126.9, 126.5, 125.9, 122.4, 65.8.

1-Bromonaphthalene-2-carboxaldehyde[8] **(8).** 1-Bromo-2-naphthalenemethanol (0.211 g, 0.89 mmol) was dissolved in 25 mL of dichloromethane. Then pyridinium chlorochromate (0.230 g, 1.07 mmol) was added portionwise and the reaction mixture was vigorously stirred for 1 h. After that, the mixture was passed through a short Florisil column with dichloromethane and the solvent removed *in vacuo*. Purification of the crude product was accomplished by radial chromatography with a 95:5 mixture of hexanes/ethyl acetate to afford 0.203 g (97%) of **8** as a colorless solid: TLC R_f 0.59 (3:1 hexanes/ethyl acetate); IR (KBr) ν 3059, 2866, 2741, 1686 cm^{-1}; ^{1}H NMR δ 7.65 (2H, m), 7.79–7.91 (3H, m), 8.42–8.49 (1H, m), 10.63 (1H, d, J = 0.7 Hz); ^{13}C NMR δ 192.8, 137.2, 132.0, 131.2, 131.1, 129.7, 128.4, 128.2, 128.2, 128.1, 124.0.

(*E*)-4-(1-Bromo-2-naphthalenyl)-3-buten-2-one. 1-Bromonaphthalene-2-carboxaldehyde (**8**) (0.651 g, 2.77 mmol) and acetonylidenetriphenylphosphorane (0.882 g, 2.77 mmol) were dissolved in 20 mL of toluene and heated to reflux, until the starting material was no longer visible by TLC (3–4 h). After that, the solvent was removed *in vacuo*. The residue was passed through a short silica gel column with dichloromethane and subjected to radial chromatography with a 95:5 mixture of hexanes/ethyl acetate to give 0.724 g (95%) of the enone as a pale yellow solid: TLC R_f 0.32/0.40 (3:1 hexanes/ethyl acetate) (both spots turned out to be mainly the *trans* isomer); IR (KBr) ν 3055, 2986, 1672, 1605 cm^{-1}; ^{1}H NMR δ 2.45 (3H, s), 6.70 (1H, d, J = 16.3 Hz), 7.51–7.62 (2H, m), 7.61 (1H, d, J = 8.6 Hz), 7.74–7.80 (2H, m), 8.19 (1H, d, J = 16.3 Hz), 8.35 (1H, dd, J = 8.2, 0.9 Hz); ^{13}C NMR δ 198.3, 142.9, 135.0, 132.5, 132.0, 130.2, 128.2 (2C), 128.2, 128.0, 127.8, 127.2, 123.7, 27.3; HRMS (EI) calcd for $C_{14}H_{11}BrO$ (M^+) 273.9993, found 273.9978.

4-(1-Bromo-2-naphthalenyl)-2-butanone (9). (*E*)-4-(1-Bromo-2-naphthalenyl)-3-buten-2-one (0.250, 0.91 mmol) was dissolved in 20 mL of ethyl acetate and the solution was transferred into a pressure tube. After the addition of 0.120 g of palladium (10% on carbon), the tube was sealed, evacuated, and subjected to a hydrogen pressure of 22 psi. The reaction mixture was stirred for 3 h. Then the solution was filtered and the solvent was removed *in vacuo*. The residue was separated by radial chromatography with a 94:6 mixture of hexanes/ethyl acetate to yield 0.161 g (64%) of **9** as a clear, colorless oil: TLC R_f 0.39 (3:1 hexanes/ethyl acetate); IR (neat) ν 3055, 3007, 2938, 1715 cm^{-1}; ^{1}H NMR δ 2.15 (3H, s), 2.82 (2H, t, J = 7.7 Hz), 3.22 (2H, t, J = 7.8 Hz), 7.34 (1H, d, J = 8.3 Hz), 7.46 (1H, ddd, J = 8.1, 6.8, 1.2 Hz), 7.56 (1H, ddd, J = 8.4, 6.8, 1.5 Hz), 7.70 (1H, d, J = 8.3 Hz), 7.77 (1H, d, J = 8.1 Hz), 8.28 (1H, d, J = 8.3 Hz); ^{13}C NMR δ 207.5, 138.5, 133.2, 132.4, 128.1, 128.0, 127.7, 127.3, 127.0, 126.0, 123.6, 43.4, 31.4, 29.9; HRMS (EI) calcd for $C_{14}H_{13}BrO$ (M^+) 276.0150, found 276.0118.

5-(1-Bromo-2-naphthalenyl)-2-pentanol. 1-Bromonaphthalene-2-butanal (**5**) (0.247 g, 0.89 mmol) was dissolved in 30 mL of diethyl ether and the solution cooled to 0 °C. Then a 1 M solution of methylmagnesium bromide (0.89 mL, 0.106 g, 0.89 mmol) was slowly added *via* syringe. After the addition was completed, the reaction mixture was allowed to stir at room temperature for 2 h, before a saturated ammonium chloride solution (2 mL) was added. The mixture was transferred into a separatory funnel, water (10 mL) was added, and the mixture extracted twice with diethyl ether (15 mL each). The combined organic layers were dried over magnesium sulfate. After filtration and concentration of the solution *in vacuo*, the crude product was purified by column chromatography with a 3:1 mixture of hexanes/diethyl ether to give 0.225 g (86%) of the alcohol as a colorless oil: TLC R_f 0.29 (2:1 hexanes/ethyl acetate); IR (neat) ν 3370 (br), 3052, 2965, 2932, 2865, 1622, 1597 cm^{-1}; ^{1}H NMR δ 1.19 (3H, d, J = 6.2 Hz), 1.50–1.60 (3H, m), 1.61–1.89 (2H, m), 2.98 (2H, m), 3.83 (1H, sextet, J = 6.2 Hz), 7.32 (1H, d, J = 8.4 Hz), 7.46 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.56 (1H, ddd, J = 8.4, 6.9, 1.4 Hz), 7.71 (1H, d, J = 8.4 Hz), 7.78 (1H, d, J = 8.1 Hz), 8.31 (1H, d, J = 8.5 Hz); ^{13}C NMR δ 139.8, 133.1, 132.6, 128.1, 128.0, 127.5, 127.3, 127.2, 125.8, 123.6, 67.9, 38.8, 37.1, 26.3, 23.5; HRMS (EI) calcd for $C_{15}H_{17}BrO$ (M^+) 292.0463, found 292.0456.

5-(1-Bromo-2-naphthalenyl)-2-pentanone (11). 5-(1-Bromo-2-naphthalenyl)-2-pentanol (0.154 g, 0.53 mmol) was dissolved in 30 mL of dichloromethane. To this solution was added pyridinium chlorochromate (0.136 g, 0.63 mmol) portionwise. The reaction mixture was stirred, until no starting material could be detected by TLC (1 h). The heterogeneous mixture was passed through a short Florisil column with dichloromethane and the crude product purified by radial chromatography with a 92:8 mixture of hexanes/ethyl acetate to afford 0.133 g (87%) of **11** as a colorless oil: TLC R_f 0.45 (2:1 hexanes/ethyl acetate); IR (neat) ν 3054, 2930, 2868, 1713 cm^{-1}; ^{1}H NMR δ 1.98 (2H, quintet, J = 7.5 Hz), 2.12 (3H, s), 2.50 (2H, t, J = 7.3 Hz), 2.98 (2H, t, J = 7.7 Hz), 7.32 (1H, d, J = 8.4 Hz), 7.46 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.56 (1H, ddd, J = 8.4, 6.9, 1.5 Hz), 7.72 (1H, d, J = 8.4 Hz), 7.78 (1H, d, J = 8.1 Hz), 8.30 (1H, d, J = 8.5 Hz); ^{13}C NMR δ 208.6, 139.1, 133.2, 132.6, 128.0 (2C), 127.6, 127.4, 127.3, 125.9, 123.8, 42.8, 36.2, 29.9, 24.0; HRMS (EI) calcd for $C_{15}H_{15}BrO$ (M^+) 290.0306, found 290.0314.

2-(1-Bromo-2-naphthalenyl)propenenitrile. Diethyl (cyanomethyl)phosphonate (0.620 mL, 0.678 g, 3.83 mmol) was dissolved in 40 mL of THF. To this solution was added potassium *tert*-butoxide (0.429 g, 3.83 mmol) and the reaction mixture was stirred at room temperature for 1 h. After that, a solution of 1-bromonaphthalene-2-carboxaldehyde (**8**) (0.600 g, 2.55 mmol) in 5 mL of THF was added *via* syringe and the reaction stirred for 15 min. The solvent was removed *in vacuo*

and the residue dissolved in 20 mL of dichloromethane. After adding 20 mL of water, the layers were separated and the aqueous phase was extracted twice with dichloromethane. The combined organic layers were dried over magnesium sulfate and the solvent removed *in vacuo*. Purification of the crude product by column chromatography with a 90:10 mixture of hexanes/ethyl acetate afforded 0.646 g (98%) of the nitrile as a colorless crystalline solid (*cis*/*trans* mixture, *trans* isomer constitutes major product): TLC R_f 0.46/0.53 (3:1 hexanes/ethyl acetate, both spots turned out to be a mixture of both isomers); IR (KBr) ν 3063, 2984, 2903, 2255, 1615 cm^{-1}; ^1H NMR (*trans* isomer) δ 5.92 (1H, d, J = 16.6 Hz), 7.51 (1H, d, J = 8.6 Hz), 7.55–7.66 (2H, m), 7.77–7.83 (2H, m), 8.11 (1H, d, J = 16.6 Hz), 8.36 (1H, m); ^{13}C NMR (*trans* isomer) δ 150.0, 135.2, 132.4, 131.0, 128.4 (2C), 128.4, 128.3, 128.2, 126.7, 122.5, 117.9, 99.3. Anal. Calcd for $C_{13}H_8BrN$: C, 60.49; H, 3.12; N, 5.43. Found: C, 60.23; H, 3.22; N, 5.31.

1-Bromo-2-naphthalenepropanenitrile (10). 2-(1-Bromo-2-naphthalenyl)propenenitrile (0.165 g, 0.64 mmol) and sodium borohydride (0.036 g, 0.96 mmol) were suspended in 10 mL of 2-propanol and the reaction mixture was heated to reflux for 36 h. After that, the solvent was removed *in vacuo* and the residue passed through a short silica gel column with ethyl acetate. Purification by radial chromatography with a 95:5 mixture of hexanes/ethyl acetate afforded 0.125 g (75%) of **10** as a colorless solid: TLC R_f 0.52 (3:1 hexanes/ethyl acetate); IR (neat) ν 3057, 2942, 2872, 2253 cm^{-1}; ^1H NMR δ 2.74 (2H, t, J = 7.5 Hz), 3.31 (2H, t, J = 7.5 Hz), 7.38 (1H, d, J = 8.3 Hz), 7.51 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.60 (1H, ddd, J = 8.3, 6.9, 1.5 Hz), 7.79 (1H, d, J = 8.1 Hz), 7.81 (1H, d, J = 8.3 Hz), 8.29 (1H, d, J = 8.5 Hz); ^{13}C NMR δ 135.3, 133.7, 132.4, 128.3, 128.1, 127.7, 127.6, 127.2, 126.6, 124.0, 118.8, 33.3, 17.6; HRMS (EI) calcd for $C_{13}H_{10}BrN$ (M^+) 258.9997, found 259.0006.

1-Bromo-2-naphthalenebutanenitrile (12). A solution of hydroxylamine hydrochloride (0.067 g, 0.97 mmol) in 0.22 mL of water and pyridine (0.078 mL, 0.076 g, 0.97 mmol) were added to 1-bromo-2-naphthalenebutanal (**5**) (0.255 g, 0.92 mmol) and the reaction mixture was stirred for 1 h at room temperature. After that, a solutiom of copper(II) sulfate pentahydrate (0.046 g, 0.18 mmol) and triethylamine (0.270 mL, 0.196 g, 1.94 mmol) in 0.4 mL of dichloromethane was added, upon which the solution turned green. Then a solution of 1,3-dicyclohexylcarbodiimide (0.228 g, 1.10 mmol) in 1.8 mL of dichloromethane was added and the mixture stirred for an additional 2 h. Formic acid (0.16 mL) was added and the reaction mixture subjected to column chromatography with dichloromethane to give 0.174 g (69%) of **12** as a clear colorless oil: TLC R_f 0.36 (3:1 hexanes/ethyl acetate); IR (neat) ν 3055, 2932, 2870, 2247 cm^{-1}; ^1H NMR δ 2.07 (2H, quintet, J = 7.3 Hz), 2.40 (2H, t, J = 7.2 Hz), 3.14 (2H, m), 7.33 (1H, d, J = 8.4 Hz), 7.49 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.58 (1H, ddd, J = 8.5, 6.9, 1.5 Hz), 7.76 (1H, d, J = 8.4 Hz), 7.80 (1H, d, J = 8.1 Hz), 8.30 (1H, d, J = 8.5 Hz); ^{13}C NMR δ 137.3, 133.4, 132.6, 128.1, 128.0, 127.8, 127.6, 127.3, 126.3, 124.0, 119.5, 36.0, 25.6, 16.7; HRMS (EI) calcd for $C_{14}H_{12}BrN$ (M^+) 273.0153, found 273.0158.

5-[2-[(Trimethylsilyl)ethynyl]phenyl]-4-pentynal. 5-[2-((Trimethylsilyl)ethynyl)phenyl]-4-pentyn-1-ol[3] (**15**) (0.310 g, 1.21 mmol) was dissolved in 50 mL of dichloromethane. Pyridinium chlorochromate (0.313 g, 1.45 mmol) was added portionwise and the reaction mixture stirred, until the starting material could no longer be detected by TLC (6–8 h). After that, the solvent was removed *in vacuo* and the residue passed through a short Florisil column with dichloromethane. Purification of the crude product by radial chromatography afforded 0.274 g (89%) of the aldehyde as a pale yellow oil: TLC R_f 0.50 (3:1 hexanes/ethyl acetate); IR (neat) ν 3063, 2961, 2901, 2828, 2728, 2236, 2158, 1728 cm^{-1}; ^1H NMR δ 0.27 (9H, s), 2.77 (4H, s), 7.21 (2H, m), 7.35–7.38 (1H, m), 7.42–7.45 (1H, m), 9.86 (1H, s); ^{13}C NMR δ 200.3, 132.1, 131.7, 128.1, 127.5, 126.1, 125.4, 103.6, 98.0, 91.9, 80.1, 42.5, 12.8, −0.1; HRMS (EI) calcd for $C_{16}H_{18}OSi$ (M^+) 254.1127, found 254.1123.

6-[2-[(Trimethylsilyl)ethynyl]phenyl]-5-hexyn-2-ol (19). 5-[2-((Trimethylsilyl)ethynyl)phenyl]-4-pentynal (0.240 g, 0.94 mmol) was dissolved in 20 mL of diethyl ether and the solution cooled to 0 °C. To this solution was added a 1 M solution of methylmagnesium bromide (1.038 mL, 0.124 g, 1.04 mmol) in diethyl ether. The reaction mixture was allowed to warm to room temperature and stir for 30 min. After that, 1 mL of an ammonium chloride solution was added and the mixture was stirred for an additional 10 min. The layers were separated and the aqueous layer extracted with diethyl ether (3 × 15 mL). The combined organic layers were dried over magnesium sulfate and filtered and the solvent was removed *in vacuo*. The crude product was subjected to radial chromatography with an 85:15 mixture of hexanes/diethyl ether to yield 0.214 g (84%) of **19** as a pale yellow oil: TLC R_f 0.29 (3:1 hexanes/ethyl acetate); IR (neat) ν 3376 (br), 3061, 2965, 2928, 2232, 2158 cm^{-1}; ^1H NMR δ 0.25 (9H, s), 1.23 (3H, d, J = 6.2 Hz), 1.68 (1H, s, br), 1.71–179 (2H, m), 2.55–2.60 (2H, m), 4.03 (1H, sextet, J = 6.2 Hz), 7.19 (2H, m), 7.34–7.37 (1H, m), 7.41–7.44 (1H, m); ^{13}C NMR δ 132.2, 131.7, 128.1, 127.2, 126.4, 125.3, 103.7, 97.9, 93.9, 79.7, 67.0, 37.6, 23.4, 16.2, −0.1; HRMS (EI) calcd for $C_{17}H_{22}OSi$ (M^+) 270.1440, found 270.1434.

6-(2-Ethynylphenyl)-5-hexyn-2-ol. 6-[2-((Trimethylsilyl)-ethynyl)phenyl]-5-hexyn-2-ol (**19**) (0.190 g, 0.70 mmol) was dissolved in 5 mL of methanol and a catalytic amount of potassium carbonate was added. The reaction mixture was stirred for 30 min at room temperature. Then 25 mL of diethyl ether was added, the heterogeneous mixture filtered and the solvents were removed *in vacuo*. The residue was passed through a short silica gel column and subjected to radial chromatography with an 85:15 mixture of hexanes/diethyl ether to afford 0.135 g (97%) of the product as a pale yellow oil: TLC R_f 0.17 (3:1 hexanes/ethyl acetate); IR (neat) ν 3370 (br), 3287, 3063, 2967, 2928, 2232, 2106 cm^{-1}; ^1H NMR δ 1.23 (3H, d, J = 6.3 Hz), 1.70–1.77 (2H, m), 1.99 (1H, s, br), 2.47–2.67 (2H, m), 3.28 (1H, s), 4.07 (1H, sextet, J = 6.2 Hz), 7.17–7.27 (2H, m), 7.36–7.39 (1H, m), 7.44–7.47 (1H, m); ^{13}C NMR δ 132.5, 131.8, 128.5, 127.4, 126.7, 124.3, 94.0, 82.4, 80.5, 79.6, 67.0, 37.4, 23.3, 16.2; HRMS (EI) calcd for $C_{14}H_{14}O$ (M^+) 198.1045, found 198.1042.

6-(2-Ethynylphenyl)-5-hexyn-2-one (21). 6-(2-Ethynylphenyl)-5-hexyn-2-ol (0.125 g, 0.63 mmol) was dissolved in 15 mL of dichloromethane. Then pyridinium chlorochromate (0.163 g, 0.76 mmol) was added and the mixture stirred for 2 h. The solution was passed through a short Florisil column with dichloromethane. The solvent was removed *in vacuo* and the crude product purified by radial chromatography with a 90:10 mixture of hexanes/ethyl acetate to give 0.111 g (90%) of **21** as a pale yellow oil: TLC R_f 0.43 (3:1 hexanes/ethyl acetate); IR (neat) ν 3283, 3063, 2917, 2236, 2106, 1713 cm^{-1}; ^1H NMR δ 2.21 (3H, s), 2.69–2.82 (4H, m), 3.28 (1H, s), 7.19–7.29 (2H, m), 7.37–7.40 (1H, m), 7.46–7.49 (1H, m); ^{13}C NMR δ 206.5, 132.5, 131.9, 128.4, 127.4, 126.5, 124.4, 93.0, 82.3, 80.5, 79.4, 42.4, 29.9, 14.2; HRMS (EI) calcd for $C_{14}H_{12}O$ (M^+) 196.0888, found 196.0880.

7-(2-Ethynylphenyl)-6-heptyn-2-ol. 6-(2-Ethynylphenyl)-5-hexynal (0.185 g, 0.94 mmol) was dissolved in 15 mL of diethyl ether and the solution cooled to 0 °C. To this solution was added a 1 M solution of methylmagnesium bromide (1.037 mL, 0.124 g, 1.04 mmol) in diethyl ether. The reaction mixture was allowed to warm to room temperature and stir for 30 min. After that, 1 mL of an ammonium chloride solution was added and the mixture was stirred for an additional 10 min. The layers were separated and the aqueous layer extracted with diethyl ether (3 × 15 mL). The combined organic layers were dried over magnesium sulfate and filtered and the solvent was removed *in vacuo*. The crude product was subjected to radial chromatography with an 85:15 mixture of hexanes/diethyl ether to yield 0.130 g (65%) of the alcohol as a pale yellow oil: TLC R_f 0.29 (3:1 hexanes/ethyl acetate); IR (neat) ν 3375 (br), 3287, 3061, 2967, 2930, 2866, 2230, 2106 cm^{-1}; ^1H NMR δ 1.18 (3H, d, J = 6.3 Hz), 1.59–1.68 (4H, m), 1.80 (1H, s, br), 2.47 (2H, m), 3.28 (1H, s), 3.83 (1H, sextet, J = 6.0 Hz), 7.20 (2H, m), 7.36–7.39 (1H, m), 7.43–7.46 (1H, m); ^{13}C NMR δ 132.4, 131.8, 128.4, 127.2, 126.9, 124.3, 94.5, 82.4, 80.5, 79.3, 67.6, 38.2, 29.2, 24.7, 23.5, 19.4; HRMS (EI) calcd for $C_{15}H_{16}O$ (M^+) 212.1201, found 212.1181.

7-(2-Ethynylphenyl)-6-heptyn-2-one (22). 7-(2-Ethynylphenyl)-6-heptyn-2-ol (0.110 g, 0.52 mmol) was dissolved in 15 mL of dichloromethane. Then pyridinium chlorochromate

(0.134 g, 0.62 mmol) was added and the mixture stirred for 2 h. The solution was passed through a short Florisil column with dichloromethane. The solvent was removed *in vacuo* and the crude product purified by radial chromatography with a 90:10 mixture of hexanes/ethyl acetate to give 0.102 g (94%) of **22** as a pale yellow oil: TLC R_f 0.36 (3:1 hexanes/ethyl acetate); IR (neat) ν 3283, 3063, 2955, 2234, 2106, 1713 cm^{-1}; ^{1}H NMR δ 1.87 (2H, quintet, J = 7.0 Hz), 2.15 (3H, s), 2.50 (2H, t, J = 6.7 Hz), 2.69 (2H, t, J = 7.2 Hz), 3.25 (1H, s), 7.18–7.28 (2H, m), 7.36–7.39 (1H, m), 7.44–7.47 (1H, m); ^{13}C NMR δ 208.4, 132.5, 131.8, 128.5, 127.4, 126.7, 124.4, 93.7, 82.5, 80.4, 79.9, 42.2, 30.1, 22.4, 18.8; HRMS (EI) calcd for $C_{15}H_{14}O$ (M^+) 210.1045, found 210.1052.

4-(2-Iodophenyl)-3-butyn-1-ol. *o*-Diiodobenzene (**13**) (0.396 mL, 1.000 g, 3.03 mmol) was dissolved in 30 mL of THF. After the addition of triethylamine (1.267 mL, 0.920 g, 9.09 mmol) and bis(triphenylphosphine)palladium(II) chloride (0.064 g, 0.09 mmol), the reaction mixture was stirred for 10 min. Then copper(I) iodide (0.058 g, 0.30 mmol) was added and the reaction mixture stirred for an additional 10 min, before 3-butynol (0.344 mL, 0.319 g, 4.55 mmol) was added in one portion *via* syringe. The reaction was allowed to stir at room temperature, until the starting material was consumed (TLC). The solvent was removed *in vacuo* and the residue filtered through silica gel using a 1:1 mixture of hexanes/diethyl ether. Purification by radial chromatography with an 85:15 mixture of hexanes/diethyl ether yielded 0.480 g (58%) of the product as a yellow oil: TLC R_f 0.14 (3:1 hexanes/ethyl acetate); IR (neat) ν 3356 (br), 3057, 2938, 2884, 2232 cm^{-1}; ^{1}H NMR δ 2.30 (1H, t, br), 2.71 (2H, t, J = 6.1 Hz), 3.83 (2H, q, br), 6.95 (1H, td, J = 7.5, 1.8 Hz), 7.25 (1H, td, J = 7.5, 1.2 Hz), 7.39 (1H, dd, J = 7.8, 1.5 Hz), 7.79 (1H, dd, J = 8.1, 1.5 Hz); ^{13}C NMR δ 138.4, 132.3, 129.7, 129.1, 127.8, 101.3, 90.9, 84.9, 60.9, 23.9; HRMS (EI) calcd for $C_{10}H_9IO$ (M^+) 271.9697, found 271.9698.

4-[2-[(Trimethylsilyl)ethynyl]phenyl]-3-butyn-1-ol (14). 4-(2-Iodophenyl)-3-butyn-1-ol (0.408 g, 1.50 mmol) and triethylamine (0.627 mL, 0.455 g, 4.50 mmol) were dissolved in 20 mL of THF. After the addition of bis(triphenylphosphine)-palladium(II) chloride (0.032 g, 0.045 mmol), the reaction mixture was stirred for 10 min, before copper(I) iodide (0.029 g, 0.15 mmol) was added and the heterogeneous mixture stirred for an additional 10 min. After that, (trimethylsilyl)-acetylene (0.254 mL, 0.177 g, 1.80 mmol) was added in one portion *via* syringe. The reaction was allowed to stir for 30 min at room temperature. Then the solvent was removed *in vacuo* and the residue passed through a short silica gel column with a 1:1 mixture of hexanes/diethyl ether. The crude product was purified by radial chromatography with an 85:15 mixture of hexanes/diethyl ether to yield 0.348 g (96%) of **14** as a yellow oil: TLC R_f 0.42 (2:1 hexanes/ethyl acetate); IR (neat) ν 3376 (br), 3061, 2959, 2899, 2234, 2158 cm^{-1}; ^{1}H NMR δ 0.28 (9H, s), 2.23 (1H, s, br), 2.74 (2H, t, J = 6.1 Hz), 3.83 (2H, t, J = 6.1 Hz), 7.22–7.27 (2H, m), 7.39–7.42 (1H, m), 7.46–7.49 (1H, m); ^{13}C NMR δ 132.3, 131.5, 128.2, 127.6, 125.9, 125.6, 103.8, 98.2, 90.7, 81.5, 60.9, 24.1, −0.1; HRMS (EI) calcd for $C_{15}H_{18}$-OSi (M^+) 242.1127, found 242.1124.

4-(2-Ethynylphenyl)-3-butyn-1-ol. 4-[2-[(Trimethylsilyl)-ethynyl]phenyl]-3-butyn-1-ol (**14**) (0.242 g, 1.00 mmol) was dissolved in 5 mL of methanol. A catalytic amount of potassium carbonate was added and the reaction mixture stirred, until the starting material could no longer be detected by TLC (30–45 min). The solvent was then removed *in vacuo* and the residue passed through a short silica gel column with diethyl ether. The crude product was purified by radial chromatography with an 85:15 mixture of hexanes/diethyl ether to yield 0.165 g (97%) of the product as a clear yellow oil: TLC R_f 0.23 (2:1 hexanes/ethyl acetate); IR (neat) ν 3374 (br), 3285, 3063, 2944, 2888, 2234, 2106 cm^{-1}; ^{1}H NMR δ 2.39 (1H, s, br), 2.71 (2H, t, J = 6.0 Hz), 3.32 (1H, s), 3.80 (2H, t, J = 6.0 Hz), 7.19–7.29 (2H, m), 7.38–7.41 (1H, m), 7.45–7.48 (1H, m); ^{13}C NMR δ 132.4, 131.6, 128.5, 127.6, 126.2, 124.5, 91.0, 82.6, 81.2, 80.6, 60.9, 24.0; HRMS (EI) calcd for $C_{12}H_{10}O$ (M^+) 170.0732, found 170.0730.

4-(2-Ethynylphenyl)-3-butynyl 4-methylbenzenesulfonate. 4-(2-Ethynylphenyl)-3-butyn-1-ol (0.179 g, 1.05 mmol) and *p*-toluenesulfonyl chloride (0.221 g, 1.16 mmol) were dissolved in 3 mL of dichloromethane. After that, pyridine (0.094 mL, 0.092 g, 1.05 mmol) was added at 0 °C *via* syringe. The reaction mixture was allowed to warm to room temperature and stirred overnight. Then it was passed through a short silica gel column with dichloromethane. The crude mixture, which still contained some starting material, was separated by radial chromatography with a 95:5 mixture of hexanes/ethyl acetate to afford 0.276 g (81%) of the tosylate as a clear, pale yellow oil: TLC R_f 0.26 (3:1 hexanes/ethyl acetate); IR (neat) ν 3285, 3063, 2961, 2922, 2249, 2108, 1360, 1177 cm^{-1}; ^{1}H NMR δ 2.39 (3H, s), 2.82 (2H, t, J = 7.0 Hz), 3.25 (1H, s), 4.20 (2H, t, J = 7.0 Hz), 7.22–7.29 (2H, m), 7.28 (2H, d, J = 8.2 Hz), 7.31–7.34 (1H, m), 7.44–7.47 (1H, m), 7.81 (2H, d, J = 8.2 Hz); ^{13}C NMR δ 144.9, 132.8, 132.4, 131.9, 129.8, 128.4, 127.9, 127.8, 125.9, 124.6, 88.1, 82.0, 81.0, 81.0, 67.6, 21.5, 20.5; HRMS (EI) calcd for $C_{19}H_{16}O_3S$ (M^+) 324.0820, found 324.0818.

5-(2-Ethynylphenyl)-4-pentynenitrile (17). 4-(2-Ethynylphenyl)-3-butynyl 4-methylbenzenesulfonate (0.249 g, 0.77 mmol) was dissolved in 5 mL of dimethyl sulfoxide. After the addition of sodium cyanide (0.075 g, 1.54 mmol), the reaction mixture was stirred for 1 d at room temperature. After that, 25 mL of water was added and the resulting solution extracted with dichloromethane (4 × 10 mL). The combined organic layers were washed with water (2 × 10 mL) and dried over calcium chloride. After that, the solvent was removed *in vacuo* and the crude product mixture subjected to radial chromatography with a 90:10 mixture of hexanes/ethyl acetate to afford 0.106 g (77%) of **17** as a clear, pale yellow oil: TLC R_f 0.26 (3:1 hexanes/ethyl acetate); IR (neat) ν 3285, 3063, 2922, 2251, 2108 cm^{-1}; ^{1}H NMR δ 2.64 (2H, m), 2.81 (2H, m), 3.29 (1H, s), 7.20–7.28 (2H, m), 7.38–7.41 (1H, m), 7.44–7.47 (1H, m); ^{13}C NMR δ 132.5, 132.0, 128.5, 128.0, 125.6, 124.6, 118.2, 89.4, 81.9, 81.4, 81.1, 17.5, 16.8; HRMS (EI) calcd for $C_{13}H_9N$ (M^+) 179.0735, found 179.0737.

5-(2-Ethynylphenyl)-4-pentynyl 4-Methylbenzenesulfonate. 5-(2-Ethynylphenyl)-4-pentyn-1-ol (0.172 g, 0.93 mmol) and *p*-toluenesulfonyl chloride (0.196 g, 1.03 mmol) were dissolved in 3 mL of dichloromethane. After that, pyridine (0.083 mL, 0.081 g, 1.03 mmol) was added at 0 °C *via* syringe. The reaction mixture was allowed to warm to room temperature and stir overnight. Then it was passed through a short silica gel column with dichloromethane. The crude mixture, which still contained some starting material, was separated by radial chromatography with a 95:5 mixture of hexanes/ethyl acetate to afford 0.278 g (88%) of the tosylate as a clear, pale yellow oil: TLC R_f 0.34 (3:1 hexanes/ethyl acetate); IR (neat) ν 3293, 3059, 2984, 2232, 2108, 1362, 1177 cm^{-1}; ^{1}H NMR δ 1.97 (2H, quintet, J = 6.5 Hz), 2.36 (3H, s), 2.55 (2H, t, J = 6.8 Hz), 3.25 (1H, s), 4.30 (2H, t, J = 6.3 Hz), 7.22–7.34 (5H, m), 7.47–7.50 (1H, m), 7.82 (2H, d, J = 8.5 Hz); ^{13}C NMR δ 144.7, 132.7, 132.3, 131.6, 129.7, 128.3, 127.8, 127.4, 126.4, 124.4, 91.9, 82.2, 80.7, 80.1, 68.8, 27.7, 21.4, 15.6; HRMS (EI) calcd for $C_{20}H_{18}O_3S$ (M^+) 338.0977, found 338.0967.

6-(2-Ethynylphenyl)-5-hexynenitrile (18). 5-(2-Ethynylphenyl)-4-pentynyl 4-methylbenzenesulfonate (0.148 g, 0.44 mmol) was dissolved in 5 mL of dimethyl sulfoxide. After the addition of sodium cyanide (0.043 g, 0.87 mmol), the reaction mixture was stirred for 1 d at room temperature. After that, 25 mL of water was added and the resulting solution extracted with dichloromethane (4 × 10 mL). The combined organic layers were washed with water (2 × 10 mL) and dried over calcium chloride. After that, the solvent was removed *in vacuo* and the crude product mixture subjected to radial chromatography with a 90:10 mixture of hexanes/ethyl acetate to afford 0.077 g (91%) of **18** as a clear, pale yellow oil: TLC R_f 0.29 (3:1 hexanes/ethyl acetate); IR (neat) ν 3283, 3063, 2944, 2909, 2249, 2106 cm^{-1}; ^{1}H NMR δ 1.95 (2H, quintet, J = 6.9 Hz), 2.62 (4H, m), 3.29 (1H, s), 7.19–7.29 (2H, m), 7.36–7.39 (1H, m), 7.45–7.48 (1H, m); ^{13}C NMR δ 132.5, 131.7, 128.5, 127.7, 126.1, 124.5, 119.2, 91.3, 80.9, 80.7, 80.5, 24.5, 18.6, 16.0; HRMS (EI) calcd for $C_{14}H_{11}N$ (M^+) 193.0892, found 193.0891.

General Procedure for the Tributyltin Hydride-Mediated Radical Cyclization of Aldehydes 4 and 5 as well as Oxime Ethers 6 and 7. A solution of the respective aldehyde or oxime ether (**4**–**7**) (0.40 mmol), tributyltin hydride

(0.129 mL, 0.140 g, 0.48 mmol), and 2,2'-azobis(2-methylpropanenitrile) (0.007 g, 0.04 mmol) in 2 mL of benzene was degassed and heated to reflux under nitrogen for 1 h. The solvent was then removed *in vacuo* and the residue passed through a short silica gel column with a 2:1 mixture of hexanes/ethyl acetate. The crude product mixture was dissolved in hexanes and extracted with acetonitrile. The solvent was removed *in vacuo* and the products were separated by radial chromatography starting to elute with a 98:2 mixture of hexanes/ethyl acetate and slowly increasing the polarity by adding ethyl acetate.

Tributyltin Hydride-Mediated Radical Cyclization of Aldehyde 4. 2-Naphthalenepropanal[3] (27): pale yellow oil (0.021 g, 29%); IR (neat) ν 3054, 1722 cm^{-1}; ^1H NMR δ 2.86 (2H, t, J = 7.5 Hz), 3.11 (2H, t, J = 8.4 Hz), 7.31 (1H, d, J = 8.4 Hz), 7.43 (2H, m), 7.62 (1H, s), 7.77 (3H, m), 9.85 (1H, s); ^{13}C NMR δ 201.6, 137.8, 133.6, 132.1, 128.3, 127.6, 127.5, 126.9, 126.5, 126.1, 125.5, 45.2, 28.2; HRMS (EI) calcd for $C_{13}H_{12}O$ (M^+) 184.0888, found 184.0888.

2-Ethylnaphthalene[3] (25): colorless oil (0.0125 g, 20%); ^1H NMR δ 1.31 (3H, t, J = 7.5 Hz), 2.80 (2H, q, J = 7.5 Hz), 7.34 (1H, dd, J = 8.7, 1.8 Hz), 7.41 (2H, m), 7.61 (1H, s), 7.77 (3H, m); ^{13}C NMR δ 141.8, 133.7, 131.9, 127.8, 127.6, 127.4, 127.1, 125.8, 125.5, 125.0, 29.0, 15.5; HRMS (EI) calcd for $C_{12}H_{12}$ (M^+) 156.0939, found 156.0939.

2,3-Dihydro-1*H*-benz[*e*]inden-1-ol (24)/2-Ethyl-1-naphthalenemethanol (23): colorless oil (0.031 g combined, 42% combined); ^1H NMR δ 1.28 (3H, t, J = 7.5 Hz), 1.62 (2H, s, br), 2.13–2.22 (1H, m), 2.59 (1H, m), 2.92 (2H, q, J = 7.5 Hz), 2.97 (1H, ddd, J = 16.5, 9.3, 3.6 Hz), 3.29 (1H, m), 5.17 (2H, s), 5.78 (1H, dd, J = 7.1, 2.9 Hz), 7.29 (1H, d, J = 8.4 Hz), 7.38 (1H, d, J = 8.4 Hz), 7.44 (2H, m), 7.53 (2H, m), 7.76 (1H, d, J = 8.1 Hz), 7.77 (1H, d, J = 8.7 Hz), 7.81 (1H, d, J = 7.5 Hz), 7.86 (1H, d, J = 7.8 Hz), 8.15 (1H, d, J = 7.8 Hz), 8.21 (1H, d, J = 8.3 Hz); HRMS (EI) calcd for $C_{13}H_{12}O$ (**24**) (M^+) 184.0888, found 184.0878; HRMS (EI) calcd for $C_{13}H_{14}O$ (**23**) (M^+) 186.1045, found 186.1048.

Tributyltin Hydride-Mediated Radical Cyclization of Aldehyde 5. 2-Naphthalenebutanal[3] (28): pale yellow oil (0.040 g, 51%); IR (neat) ν 3054, 1721 cm^{-1}; ^1H NMR δ 2.04 (2H, quintet, J = 7.5 Hz), 2.47 (2H, td, J = 7.5, 1.5 Hz), 2.81 (2H, t, J = 7.5 Hz), 7.30 (1H, dd, J = 8.4, 1.8 Hz), 7.43 (2H, m), 7.59 (1H, s), 7.77 (3H, m), 9.76 (1H, t, J = 1.5 Hz); ^{13}C NMR δ 202.3, 138.7, 133.6, 132.1, 128.1, 127.6, 127.4, 127.1, 126.6, 126.0, 125.3, 43.1, 35.1, 23.4; HRMS (EI) calcd for $C_{14}H_{14}O$ (M^+) 198.1045, found 198.1055.

1,2,3,4-Tetrahydrophenanthren-1-ol (29): colorless crystalline solid (0.027 g, 34%); IR (KBr) ν 3428 (br), 2990, 2940, 2872 cm^{-1}; ^1H NMR δ 1.71 (1H, s, br), 1.83–2.08 (3H, m), 2.23–2.30 (1H, m), 2.86–2.93 (2H, m), 5.45 (1H, s), 7.20 (1H, d, J = 8.5 Hz), 7.43 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.53 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.69 (1H, d, J = 8.5 Hz), 7.79 (1H, d, J = 7.9 Hz), 8.24 (1H, d, J = 8.5 Hz); ^{13}C NMR δ 135.3, 132.6, 132.3, 132.0, 128.5, 128.2, 128.0, 126.6, 125.1, 123.3, 63.5, 31.6, 30.3, 17.2; HRMS (EI) calcd for $C_{14}H_{14}O$ (M^+) 198.1045, found 198.1050.

3,4-Dihydro-1(2*H*)-phenanthrenone (26): pale yellow oil (0.003 g, 4%); IR (neat) ν 3052, 2940, 2870, 1667 cm^{-1}; ^1H NMR δ 2.18 (2H, quintet, J = 6.6 Hz), 2.77 (2H, t, J = 6.6 Hz), 3.11 (2H, t, J = 6.1 Hz), 7.31 (1H, d, J = 8.4 Hz), 7.47 (1H, ddd, J = 8.1, 6.9, 1.2 Hz), 7.61 (1H, ddd, J = 8.7, 6.9, 1.6 Hz), 7.79 (1H, m), 7.91 (1H, d, J = 8.4 Hz), 9.39 (1H, d, J = 8.8 Hz); ^{13}C NMR δ 200.6, 146.8, 134.2, 132.8, 131.4, 128.8, 128.3, 127.3, 127.0, 126.7, 125.8, 41.1, 31.6, 23.0; HRMS (EI) calcd for $C_{14}H_{12}O$ (M^+) 196.0888, found 196.0895.

Tributyltin Hydride-Mediated Radical Cyclization of Oxime Ether 6. *N*-(phenylmethoxy)-2,3-dihydro-1*H*-benz[*e*]inden-1-amine[3] (35): yellow oil (0.083 g, 72%); IR (neat) ν 3248, 3053, 1445 cm^{-1}; ^1H NMR δ 2.27–2.48 (2H, m), 2.95 (1H, ddd, J = 16.5, 9.0, 2.4 Hz), 3.26 (1H, dt, J = 16.5, 8.1 Hz), 4.66 (2H, s), 5.08 (1H, d, J = 6.6 Hz), 5.63 (1H, s, br), 7.27–7.48 (8H, m), 7.74 (1H, d, J = 8.4 Hz), 7.83 (1H, d, J = 8.4 Hz), 7.95 (1H, d, J = 8.4 Hz); ^{13}C NMR δ 143.1, 138.0, 135.8, 132.8, 130.6, 129.0, 128.6, 128.4, 128.3, 127.8, 126.3, 124.8, 124.1, 123.4, 76.6, 65.2, 31.4, 30.4; HRMS (EI) calcd for $C_{20}H_{17}NO$ ($M^+ - 2$) 287.1310, found 287.1302.

Tributyltin Hydride-Mediated Radical Cyclization of Oxime Ether 7. *N*-(phenylmethoxy)-1,2,3,4-tetrahydrophenanthren-1-amine[3] (37): yellow oil (0.025 g, 21%); ^1H NMR δ 1.68 (1H, tt, J = 13.8, 3.4 Hz), 1.76–1.85 (1H, m), 2.05–2.21 (1H, m), 2.49–2.57 (1H, m), 2.86–2.91 (2H, m), 4.77 (1H, d, A of AB, J = 11.5 Hz), 4.81 (1H, hidden by AB q), 4.85 (1H, d, B of AB, J = 11.5 Hz), 5.73 (1H, s, br), 7.16 (1H, d, J = 8.5 Hz), 7.29–7.48 (7H, m), 7.64 (1H, d, J = 8.5 Hz), 7.73 (1H, dd, J = 8.4, 1.4 Hz), 8.00 (1H, d, J = 8.0 Hz); ^{13}C NMR δ 138.2, 136.9, 132.4, 132.4, 128.7, 128.6, 128.4, 128.0, 128.0, 127.9, 126.6, 124.8, 122.5, 76.9, 54.2, 30.2, 25.3, 16.9 (one carbon not detected); HRMS (EI) calcd for $C_{21}H_{21}NO$ (M^+) 303.1623, found 303.1617.

(*Z*)-*N*-(Phenylmethoxy)-2-naphthalenebutanimine[3] (36a): yellow oil (0.029 g, 24%); IR (neat) ν 3055, 3032, 2928, 1632, 1601 cm^{-1}; ^1H NMR δ 1.89 (2H, quintet, J = 7.8 Hz), 2.44 (2H, td, J = 7.5, 5.6 Hz), 2.80 (2H, t, J = 7.6 Hz), 5.10 (2H, s), 6.72 (1H, t, J = 5.6 Hz), 7.30 (1H, dd, J = 8.5, 1.7 Hz), 7.32–7.35 (5H, m), 7.41–7.45 (2H, m), 7.60 (1H, s), 7.74–7.81 (3H, m); ^{13}C NMR δ 151.9, 139.1, 138.1, 133.6, 132.0, 128.4, 128.0, 127.9, 127.7, 127.6, 127.4, 127.2, 126.5, 125.9, 125.2, 75.7, 35.6, 27.7, 25.4; HRMS (EI) calcd for $C_{21}H_{21}NO$ (M^+) 303.1623, found 303.1611.

(*E*)-*N*-(Phenylmethoxy)-2-naphthalenebutanimine[3] (36b): yellow oil (0.045 g, 37%); IR (neat) ν 3055, 3032, 2928, 1632, 1601 cm^{-1}; ^1H NMR δ 1.90 (2H, quintet, J = 7.5 Hz), 2.22–2.29 (2H, m), 2.79 (2H, t, J = 7.5 Hz), 5.07 (2H, s), 7.30 (1H, dd, J = 8.5, 1.7 Hz), 7.35–7.38 (5H, m), 7.41–7.45 (2H, m), 7.48 (1H, t, J = 6.1 Hz), 7.58 (1H, s), 7.75–7.81 (3H, m); ^{13}C NMR δ 151.0, 139.1, 137.7, 133.6, 132.0, 128.4, 128.2, 127.9, 127.8, 127.6, 127.4, 127.2, 126.6, 125.9, 125.2, 75.5, 35.2, 29.0, 28.1; HRMS (EI) calcd for $C_{21}H_{21}NO$ (M^+) 303.1623, found 303.1614.

General Procedure for the Tandem Enediyne-Radical Cyclization of Ketones 21 and 22 as well as Nitriles 17 and 18. The starting enediyne (**17**, **18**, **21**, or **22**) (0.50 mmol) was dissolved in 7.5 mL of chlorobenzene and transferred into a tube with Teflon screw cap. The solution was purged with nitrogen for 30 min, before 1,4-cyclohexadiene (0.355 mL, 0.301 g, 3.75 mmol) was added *via* syringe. The vial was sealed, slowly heated to 190 °C, and kept at this temperature for 8 h. After that, the reaction solution was allowed to cool to room temperature. The solvent was removed *in vacuo* and the residue passed through a short silica gel column with a 3:1 mixture of ethyl acetate/hexanes. The products were separated by radial chromatography starting to elute with pentane and slowly increasing the polarity by adding ethyl acetate.

Tandem Enediyne-Radical Cyclization of Ketone 21. 4-(2-Naphthalenyl)-2-butanone (40): colorless oil (0.078 g, 79%); ^1H NMR δ 2.15 (3H, s), 2.83 (2H, t, J = 7.7 Hz), 3.05 (2H, t, J = 7.6 Hz), 7.30 (1H, dd, J = 8.5, 1.6 Hz), 7.42 (2H, m), 7.60 (1H, s), 7.77 (3H, m); ^{13}C NMR δ 208.0, 138.5, 133.6, 132.0, 128.1, 127.6, 127.4, 127.0, 126.4, 126.0, 125.3, 45.1, 30.1, 29.8; HRMS (EI) calcd for $C_{14}H_{14}O$ (M^+) 198.1045, found 198.1045.

2,3-Dihydro-1*H*-benz[*e*]inden-1-one (42): colorless oil (0.005 g, 5%); IR (neat) ν 3055, 3030, 2924, 2861, 1692 cm^{-1}; ^1H NMR δ 2.80 (2H, m), 3.21 (2H, m), 7.51 (1H, d, J = 8.5 Hz), 7.54 (1H, ddd, J = 8.1, 6.9, 1.3 Hz), 7.65 (1H, ddd, J = 8.3, 6.9, 1.3 Hz), 7.88 (1H, d, J = 8.4 Hz), 8.03 (1H, d, J = 8.4 Hz), 9.16 (1H, d, J = 8.5 Hz); ^{13}C NMR δ 207.6, 158.5, 135.7, 132.5, 131.0, 129.4, 128.9, 128.1, 126.6, 124.1, 124.0, 36.9, 26.2; HRMS (EI) calcd for $C_{13}H_{10}O$ (M^+) 182.0732, found 182.0739.

Tandem Enediyne-Radical Cyclization of Ketone 22. 5-(2-naphthalenyl)-2-pentanone (41): colorless oil (0.075 g, 71%); IR (neat) ν 3054, 3023, 2938, 2868, 1711 cm^{-1}; ^1H NMR δ 1.98 (2H, quintet, J = 7.5 Hz), 2.10 (3H, s), 2.45 (2H, t, J = 7.4 Hz), 2.77 (2H, t, J = 7.5 Hz), 7.31 (1H, dd, J = 8.4, 1.7 Hz), 7.42 (2H, m), 7.59 (1H, s), 7.78 (3H, m); ^{13}C NMR δ 208.8, 139.1, 133.6, 132.1, 128.0, 127.6, 127.4, 127.2, 126.5, 126.0, 125.2, 42.7, 35.1, 30.0, 24.9; HRMS (EI) calcd for $C_{15}H_{16}O$ (M^+) 212.1201, found 212.1209.

Tandem Enediyne-Radical Cyclization of Nitrile 17. 2-Naphthalenepropanenitrile (46): pale yellow oil (0.035 g, 39%); IR (neat) ν 3055, 3027, 2937, 2859, 2247 cm^{-1}; ^1H NMR δ 2.70 (2H, t, J = 7.4 Hz), 3.11 (2H, t, J = 7.4 Hz), 7.33

(1H, dd, J = 8.4, 1.7 Hz), 7.46 (2H, m), 7.67 (1H, s), 7.78–7.83 (3H, m); ^{13}C NMR δ 19.3, 31.7, 119.1, 125.9, 126.3, 126.4, 126.9, 127.6, 127.7, 128.7, 132.5, 133.5, 135.5; HRMS (EI) calcd for $C_{13}H_{11}N$ (M^+) 181.0892, found 181.0891.

1*H*-Benz[*e*]indene/3*H*-benz[*e*]indene[3] (32): colorless oil (0.010 g, 12%); 1:1 mixture: ^{1}H NMR δ 3.56 (1H, dd, J = 1.8, 1.8 Hz), 3.71 (1H, dd, J = 1.8, 1.8 Hz), 6.65 (0.5H, dt, J = 5.4, 1.8 Hz), 6.73 (0.5H, td, J = 5.4, 1.8 Hz), 6.99 (0.5H, td, J = 5.4, 1.8 Hz), 7.34–8.21 (6.5H, m); HRMS (EI) calcd for $C_{13}H_{10}$ (M^+) 166.0783, found 166.0799 for 1*H*-benz[*e*]indene, 166.0787 for 3*H*-benz[*e*]indene.

2,3-Dihydro-1*H*-benz[*e*]inden-1-one (42): colorless oil (0.030 g, 33%).

Tandem Enediyne-Radical Cyclization of Nitrile 18. 2-Naphthalenebutanenitrile (47): pale yellow oil (0.050 g, 51%); IR (neat) ν 3054, 3027, 2940, 2868, 2249 cm^{-1}; ^{1}H NMR δ 2.06 (2H, quintet, J = 7.2 Hz), 2.32 (2H, t, J = 6.8 Hz), 2.93 (2H, t, J = 7.3 Hz), 7.30 (1H, dd, J = 8.4, 1.8 Hz), 7.45 (2H, m), 7.63 (1H, s), 7.77–7.82 (3H, m); ^{13}C NMR δ 137.1, 133.5, 132.2, 128.4, 127.6, 127.5, 126.9, 126.8, 126.2, 125.6, 119.5, 34.4, 26.7, 16.3; HRMS (EI) calcd for $C_{14}H_{13}N$ (M^+) 195.1048, found 195.1048.

3,4-Dihydro-1(2*H*)-phenanthrenone (26): pale yellow oil (0.033 g, 34%).

General Procedure for the Tributyltin Hydride-Mediated Radical Cyclization of Ketones 9 and 11. A degassed solution of bromide **9** or **11**, respectively (0.30 mmol), in 15 mL of benzene was heated to reflux. To this solution was added a degassed solution of tributyltin hydride (0.968 mL, 0.105 g, 0.36 mmol) and 2,2′-azobis(2-methylpropanenitrile) (0.007 g, 0.04 mmol) in 50 mL of benzene *via* syringe pump over a period of 5 h. After that, the reaction mixture was allowed to cool to room temperature and the solvent was removed *in vacuo*. The residue was passed through a short silica gel column and subjected to radial chromatography with a 96:4 mixture of hexanes/ethyl acetate.

Tributyltin Hydride-Mediated Radical Cyclization of Ketone 9. 4-(2-naphthalenyl)-2-butanone (40): colorless oil (0.031 g, 52%).

2,3-Dihydro-1*H*-benz[*e*]inden-1-one (42): colorless oil (0.022 g, 40%).

Tributyltin Hydride-Mediated Radical Cyclization of Ketone 11. 5-(2-naphthalenyl)-2-pentanone (41): colorless oil (0.0634 g, 100%).

General Procedure for the Tributyltin Hydride-Mediated Radical Cyclization of Nitriles 10 and 12. A degassed solution of bromide **10** or **12**, respectively (0.30 mmol), in 15 mL of benzene was heated to reflux. To this solution was added a degassed solution of tributyltin hydride (0.968 mL, 0.105 g, 0.36 mmol) and 2,2′-azobis(2-methylpropanenitrile) (0.007 g, 0.04 mmol) in 50 mL of benzene *via* syringe pump over a period of 5 h. After that, the reaction mixture was allowed to cool to room temperature and the solvent was removed *in vacuo*. The residue was dissolved in 25 mL of diethyl ether and 3 mL of acetic acid (80% in water) was added. This mixture was stirred for 1 h. The layers were separated and the aqueous phase extracted with diethyl ether (2 × 10 mL). The combined organic layers were washed with a saturated sodium bicarbonate solution and dried over magnesium sulfate. After filtration and removal of the solvent *in vacuo* the residue was subjected to radial chromatography with a 96:4 mixture of hexanes/ethyl acetate.

Tributyltin Hydride-Mediated Radical Cyclization of Nitrile 10. 2,3-Dihydro-1*H*-benz [*e*]inden-1-one (42): colorless oil (0.050 g, 91%).

Tributyltin Hydride-Mediated Radical Cyclization of Nitrile 12. 2-Naphthalenebutanenitrile (47): pale yellow oil (0.038 g, 65%).

3,4-Dihydro-1(2*H*)-phenanthrenone (26): pale yellow oil (0.019 g, 32%).

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Supplementary Material Available: ^{1}H NMR or ^{13}C NMR spectra of most compounds (37 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of this journal, and can be ordered from the ACS; see any current masthead page for ordering information.