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Enantioselective Synthesis of (+)-Cephalostatin 1

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Abstract: This Article describes an enantioselective synthesis of cephalostatin 1. Key steps of this synthesis are a unique methyl group selective allylic oxidation, directed C−H hydroxylation of a sterol at C12, Au(I)-catalyzed 5-endo-dig cyclization, and a kinetic spiroketalization.

Introduction

An important property of modern anticancer therapeutics is the selective killing of cancer cells over normal cells. One approach to achieve selectivity is "synthetic lethality,"[1] involving combination of a mutation, only present in cancer cells, and a small molecule, resulting in selective cell killing of the cells bearing the mutation. Because many genetic mutations have been identified in tumor cells, a challenge is to discover small molecules that selectively target cells harboring these mutations.

We have become interested in the therapeutic potential and cellular target of cephalostatin 1 (**1**), a natural product that may be synthetic lethal with the *p16* tumor suppressor gene. In a bioinformatics comparison of the cytotoxicity profiles of ∼43 000 small molecules with cell lines bearing altered *p16*, **1** emerged as the compound with the highest correlation, suggesting that it may be selectively cytotoxic to cells with altered *p16*.[2] The *p16* gene encodes cyclin-dependent kinase inhibitor 2A (CDKN2A or Ink4a), a tumor suppressor protein that blocks cell proliferation by binding to and inhibiting the kinase activity of cyclin-dependent kinase 4 (CDK4) and cyclin-dependent kinase 6 (CDK6).[2] In cells, both CDK4 and CDK6 each form active complexes with cyclin D that phosphorylate Rb (the retinoblastoma protein), allowing progression through the G1-S phase of the cell cycle. If CDKN2A is inactive due to a mutation or lack of expression, tumor cells can progress uncontrollably through the G1-S phase of the cell cycle.[3] Because *p16* is among the most frequently mutated genes in human tumor cells, **1** may be a uniquely selective anticancer therapeutic, and elucidation of its unknown cellular target may reveal new ways to achieve synthetic lethality with small molecules.

Cephalostatin 1 was first reported in 1988 as a potent growth inhibitory marine natural product.[4] The average GI_{50} of **1** against the NCI-60, a collection of 60 human cancer cell lines, is 1.8 nM.[5] Three other molecules, ritterazine B (**2**),[6] OSW-1 (**3**),[7] and schweinfurthin A (**4**),[8] have cytotoxicity patterns resembling

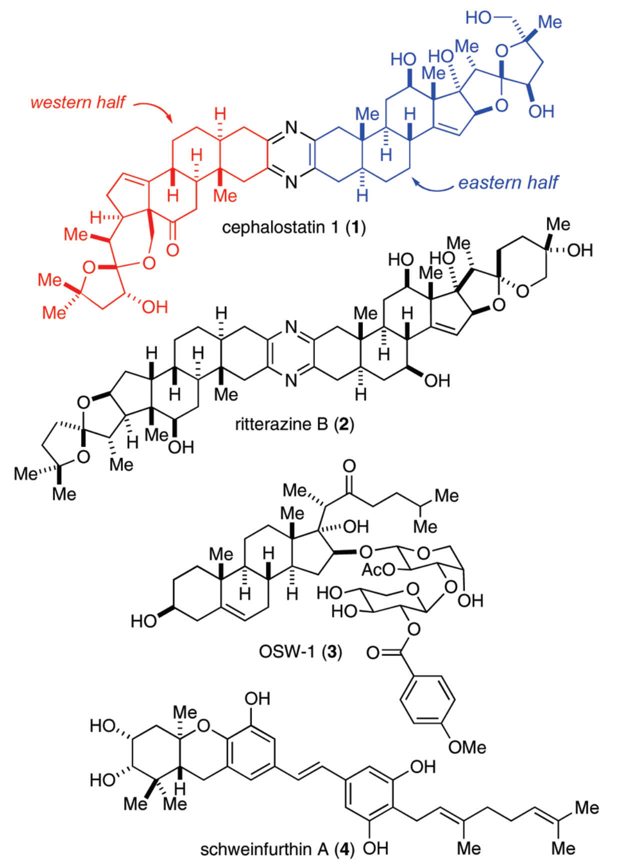

Figure 1. Cephalostatin 1, ritterazine B, OSW-1, and schweinfurthin A. Four antiproliferative natural products with similar cytotoxicity patterns.

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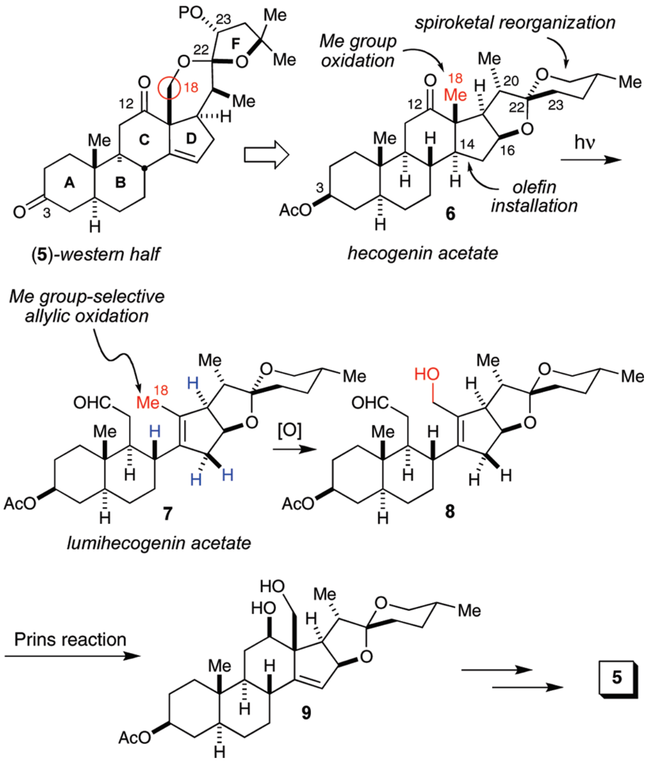
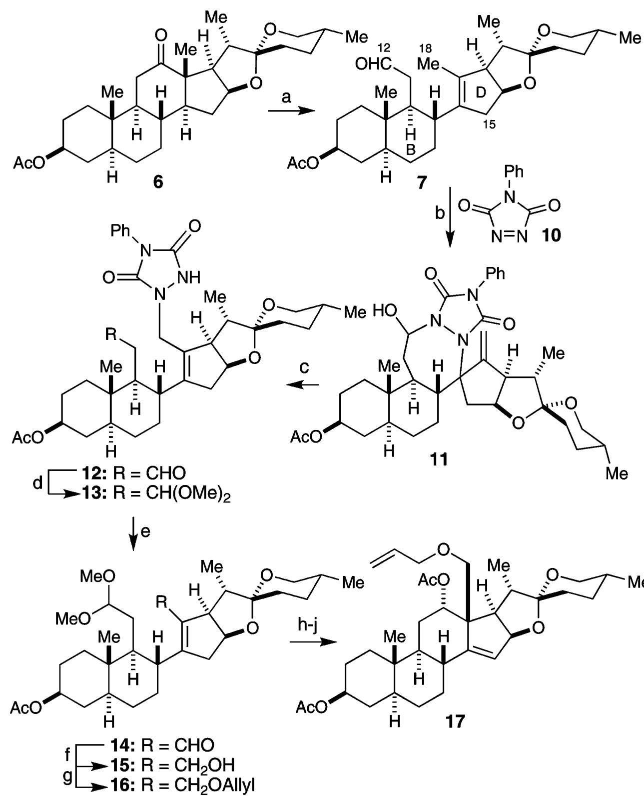
Scheme 1. Synthesis Plan for **5** Requiring a C18 Methyl Group-Selective Allylic Oxidation of **7**



Scheme 2. Selective C18 Methyl Group-Selective Allylic Oxidation Involving Ene Reaction, [2,3]-Sigmatropic Rearrangement, and Oxidation[a]



[a] Conditions: (a) *hν*, 1,4-dioxane, 25 °C; (b) 4-phenyl-1,2,4-triazoline-3,5-dione, dichloroethane, 25 °C, 61% two steps; (c) NaOAc, DMF, 100 °C, 69%; (d) $CH(OMe)_3$, TsOH·H_2O, MeOH, 25 °C; (e) $PhI(OAc)_2$, MeCN/H_2O, 0 °C, 64% two steps; (f) $NaBH_4$, MeOH, 0 °C, 88%; (g) NaH, DMF, 0 °C; allyl bromide, 25 °C, 93%; (h) PPTS, acetone, 25 °C; (i) BF_3·OEt_2, PhMe, 0 °C, 61% two steps; (j) Ac_2O, pyr., DMAP, 25 °C.

1, suggesting that all four compounds share similar mechanisms.[9] The cellular target and mechanism of **1** (or **2**−**4**) have not been elucidated, although an increasing amount of research is being focused on these issues.[10]

The unusually large and complex structure of **1** has been the target of many synthesis studies, with one synthesis reported by Fuchs.[11] Because of the small quantities of **1** available from natural sources, only through synthesis will sufficient amounts of **1** (and analogues) be available to address questions surrounding its potential synthetic lethality with *p16*, elucidate its cellular target and mechanism, and determine its efficacy in vivo for the treatment of cancer. This Article reports our synthesis of **1** (Figure 1), enabling us to answer the questions posed above surrounding its biological activity.

Synthesis of the Western Half of Cephalostatin 1 (5)

Our synthesis plan involved construction of the eastern and western portions of **1**, followed by unsymmetrical pyrazine formation following the reactions developed by Heathcock[12] and Fuchs.[11a,13] The C22 spiroketal of **5** (Scheme 1) is in a thermodynamically favorable configuration, meaning that its stereochemistry can be established by acid-catalyzed equilibration.[14] Hecogenin acetate (**6**), an inexpensive plant-derived steroid that is available in kilogram quantities,[15] is used as the starting material for our synthesis of the western half because it has handles for most of the functionality of **5**, especially oxygenation at C12. Compound **6** was also used by others for their synthesis studies on **1**. With **6** as a starting point for synthesis of **5**, we needed to rearrange the spiroketal, oxidize C23, deoxygenate C16, install a C14−C15 olefin, and, most challenging, oxidize the unactivated C18 angular methyl group (see Scheme 1). Our plan was to generate lumihecogenin acetate (**7**) by photolysis of **6**, a reaction first described by Bladon.[16] Selective oxidation of C18 of **7** to generate **8** followed by Prins cyclization would deliver **9**. Compound **9** would then be converted to **5**. We recognized that **7** is the only intermediate in our synthesis in which C18 is activated (allylic), and therefore we focused on methods to selectively oxidize the allylic methyl

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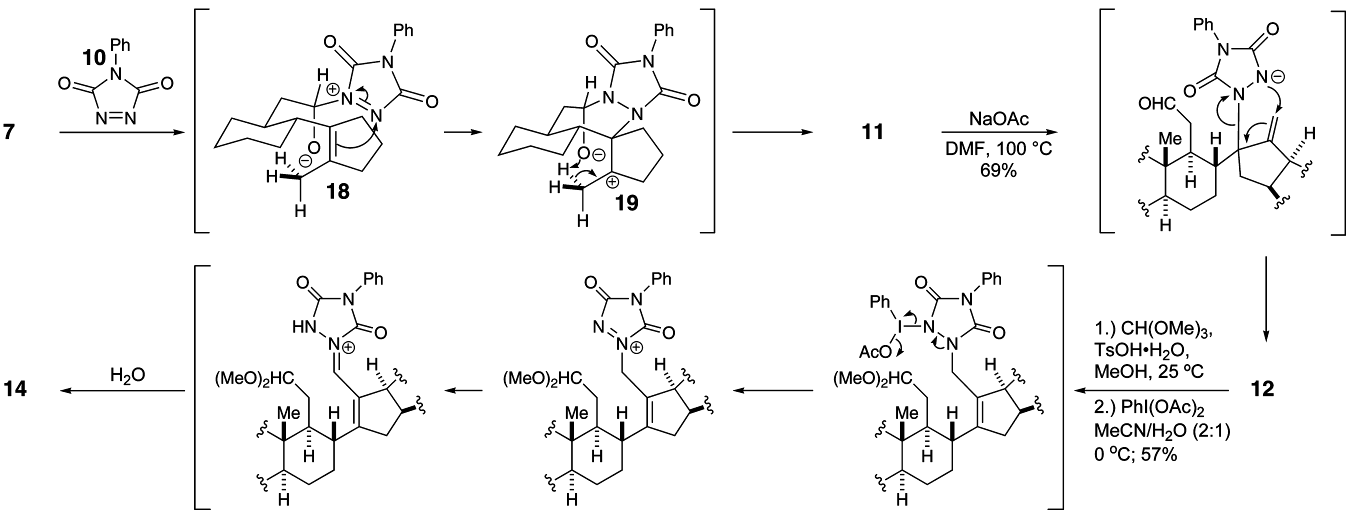
Scheme 3. Proposed Mechanism of the Selective Aza-Prins Reaction, [2,3]-Sigmatropic Rearrangement, and Urazole Oxidative Hydrolysis

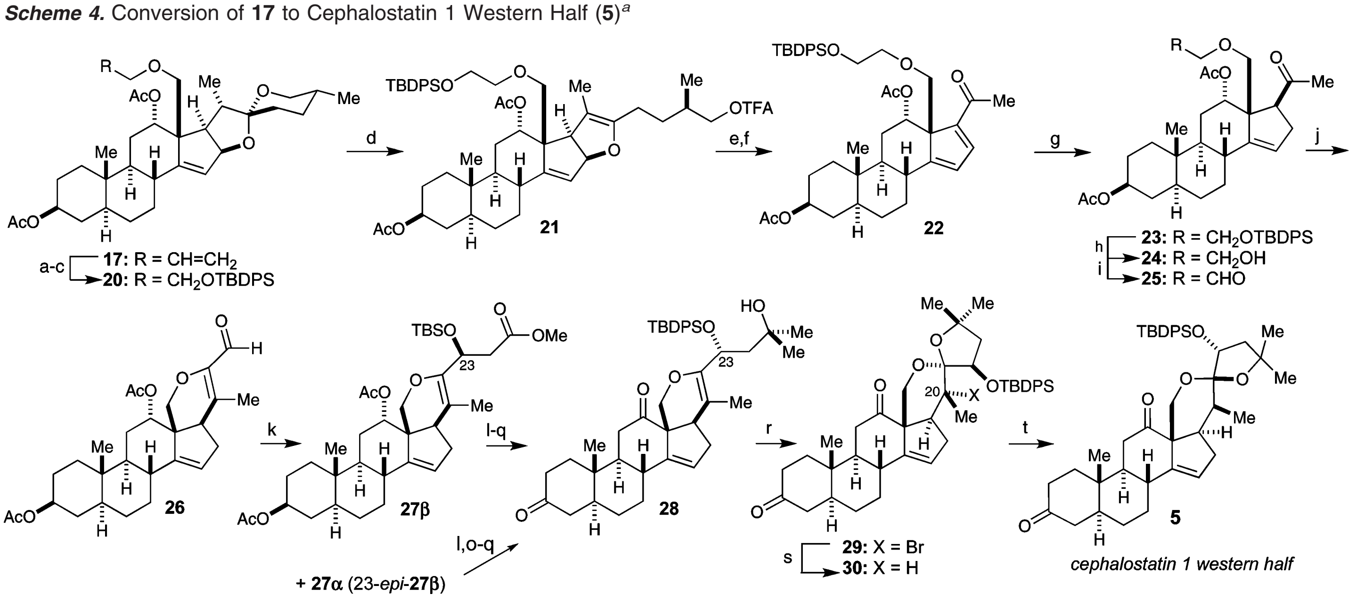


group. This is a significant challenge because the olefin of **7** is tetrasubstituted and there are four other allylic hydrogens (see blue H's), two methines, and one methylene. We required an oxidation that was selective for the C18 methyl group and tolerant of highly hindered double bonds, boundary conditions that exclude many of the known allylic oxidation reactions.

The synthesis of **5** begins with the known conversion of **6** to **7** (Scheme 2).[16] Attempts to perform allylic oxidation of C18 on either aldehyde **7** or the protected alcohol at C18 were unsuccessful. As expected, SeO_2 led to hydroxylation of the C15 methylene. Radical halogenations were poorly regioselective, and the hindered double bond was inert to transition metal-catalyzed allylic oxidation reactions.

Ultimately, an unusual allylic oxidation of C18 was achieved. It was discovered that treatment of **7** with 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD, **10**), a potent eneophile, led directly to **11** achieving selective functionalization of the C18 methyl group via an apparent ene reaction, combined with formation of a seven-membered aminal. This transformation may in fact be directed by the C12 aldehyde because the corresponding C12 dimethyl acetal reacted to form a PTAD adduct with abstraction of a C15 proton. One explanation for the selective activation of C18 in this reaction involves initial formation of a zwitterionic adduct (**18**) between PTAD (**10**) and aldehyde **7** (Scheme 3). This species could participate in an intramolecular aza-Prins reaction via intermediate **19**. Close proximity between the C12 alkoxide and the C18 methyl group in **19** could explain the selective proton abstraction at C18. Alternatively, PTAD could add to the C12 aldehyde via its carbonyl and engage in an ene reaction, although inspection of molecular models appears to preclude this mechanism due to lack of required orbital overlap.

Scheme 4. Conversion of **17** to Cephalostatin 1 Western Half (**5**)[a]



[a] Conditions: (a) OsO_4, $NaIO_4$, 2,6-lutidine, 1,4-dioxane/H_2O, 25 °C; (b) $NaBH(OAc)_3$, PhH/AcOH, 0 °C; (c) TBDPSCl, Im., DMAP, CH_2Cl_2, 25 °C, 74% four steps; (d) trifluoroacetyl trifluoromethanesulfonate, 2,6-*tert*-butyl-4-methyl-pyridine, CH_2Cl_2, −78 °C, then PPTS, CH_2Cl_2, 40 °C; (e) PCC, CH_2Cl_2, 25 °C; (f) DBU, CH_2Cl_2, 43%three3 steps; (g) $(HMe_2Si)_2O$, H_2PtCl_6, PhMe, 25 °C; (h) TBAF, AcOH, THF, 25 °C, 51% two steps; (i) DMSO, *i*-Pr_2NEt, SO_3·pyr, CH_2Cl_2, 25 °C; (j) piperidine, AcOH, 25 °C, 75% two steps; (k) 1-methoxy-1-*tert*-butyldimethylsilyloxyethene, $LiClO_4$, CH_2Cl_2, ***27β***, 51%, **27α**, 18%; (l) TBAF, THF, 25 °C, 100%; (m) Ph_3P, DIAD, chloroacetic acid, THF, 25 °C, 69%; (n) HDTC, 2,6-lutidine, AcOH, 25 °C, 80%; (o) TBDPSCl, Im., DMAP, CH_2Cl_2, 25 °C, 93%; (p) MeMgBr, Et_2O, 25 °C; (q) TPAP, NMO, CH_2Cl_2, 25 °C, 69% two steps; (r) PhSeBr, pyridine, CH_2Cl_2, −78 to 0 °C, 92%; (s) AIBN, Bu_3SnH, toluene, 100 °C, 100%; (t) CSA, DCE, 83 °C, 78%.

Finally, an ene reaction may occur between **10** and **7** followed by hemiaminal formation.

Treatment of **11** with sodium acetate induced opening of the hemiaminal followed by apparent [2,3]-sigmatropic rearrangement, affording allylic N−Ph urazole **12** (Scheme 3). Protection of the C12 aldehyde as its dimethyl acetal was followed by oxygenation of C18 by treatment of **13** with $PhI(OAc)_2$, affording aldehyde **14**. In this reaction, the N−N bond is oxidized to N═N. Tautomerization, addition of water, and release of the urazole afforded **14**. Allylation of the primary hydroxyl group, followed by acid-catalyzed acetal hydrolysis, set the stage for C-ring closure, which was accomplished by treatment with $BF_3 \cdot OEt_2$ (Scheme 2). Finally, acetylation of the secondary alcohol provided **17**.

Starting with compound **17**, allyl group-selective oxidative olefin cleavage, aldehyde reduction, and protection of the resulting primary hydroxyl afforded **20** (Scheme 4). Next, the atoms comprising the spiroketal were removed starting with application of a modified Marker degradation.[17] Treatment of **20** with trifluoroacetyl trifluoromethanesulfonate (TFAT) opened the F-ring, giving E-ring dihydrofuran **21**. Oxidative cleavage of the cyclic enol ether provided the corresponding ketoester, which was subjected to DBU-promoted elimination. The product, dienone **22**, underwent 1,4-reduction under platinum-catalyzed hydrosilylation conditions, affording the saturated methyl ketone **23** as a 4:1 mixture of β/α-methyl ketone stereoisomers. After removal of the TBDPS ether, and separation of the diastereomers, the undesired C17 α-methyl ketone was equilibrated in favor of the β-diastereomer. Oxidation of the C23 primary hydroxyl preceded an intramolecular aldol reaction to afford enal **26**.

Installation of the C24−C25 fragment of the incipient F-ring was accomplished by way of a Mukaiyama aldol reaction. Thus, treatment of aldehyde **26** with the enolsilane of methyl acetate in the presence of lithium perchlorate delivered a 3:1 mixture of diastereomers favoring the undesired 23-(*S*)-stereoisomer (**27*β***). Unfortunately, extensive efforts to override the substrate's inherent facial selectivity for aldol addition were met with failure. Attempts at Mukaiyama aldol addition with other catalysts, including chiral catalysts, afforded product mixtures favoring 23-(*S*)-configured products. Likewise, chiral auxiliary-based acetate equivalents reacted to give predominantly adducts with the undesired 23-(*S*) stereochemistry. Removal of the TBS group from **27*β***, Mitsunobu reaction with chloroacetic acid, hydrolysis of the chloroacetate, silylation of the C23 secondary carbinol, and addition of excess MeMgBr afforded **28** after oxidation with TPAP/NMO.

Because the spiroketal of **5** is known to be under thermodynamic control, we expected mild acid treatment of **28** would furnish the F-ring while establishing the desired (*S*)-stereochemistry at C20. However, in the presence of camphorsulfonic acid, **28** cyclized to give a spiroketal with the undesired 20-(*R*) stereochemistry. Surprisingly, the observed product results from protonation of the more hindered concave face of the dihydropyran E-ring. This result is in contrast to a similar reaction reported by Fuchs in which protonation of a compound closely related to **28** (except that the C14−C15 double bond was saturated) afforded the desired C20-(*S*) stereochemistry.[14]

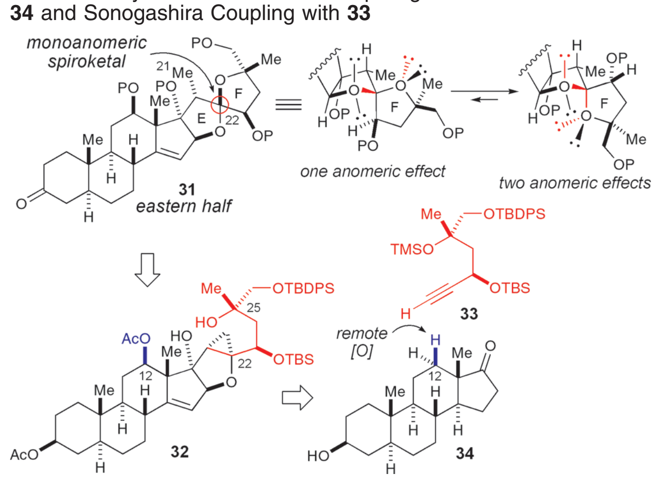
This outcome was corrected by a two-step bromoetherification/reductive debromination sequence. Bromoetherification of **28** with phenylselenyl bromide afforded **29**. Reductive dehalogenation of **29** delivered **30** as a single diastereomer with hydrogen atom addition occurring from the convex face. To complete the preparation of the cephalostatin western half **5**, C22 was epimerized by treatment of **30** with camphorsulfonic acid in refluxing dichloroethane.

Synthesis of the Cephalostatin 1 Eastern Half (31)

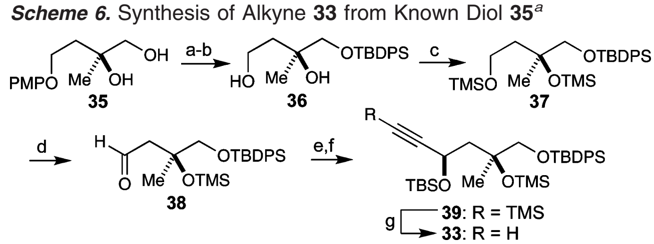
The E and F rings of the eastern half of cephalostatin 1 consist of a 5,5-spiroketal in a thermodynamically unfavorable configuration at C22, which require a kinetically controlled spiroketalization reaction (Scheme 5, **31**). The spiroketal in the natural C22-(*S*) configuration exhibits a single anomeric effect, while the unnatural C22-(*R*) configuration permits additional stabilization from a second anomeric effect. To form the 5,5-spiroketal, we planned to induce cyclopropane opening on **32** followed by irreversible attack by the C25 hydroxyl group on the less hindered β-face of the incipient oxonium ion, which would simultaneously give rise to the desired configurations of both the C22 spiroketal and the C21 methyl group. Rather than starting with hecogenin acetate (**6**) to make use of its C12 oxygenation as was done for the western half of **1**, we thought it would be more expedient to hydroxylate the C12 position of the steroid *trans*-androsterone (**34**) by a remote C−H oxidation process (see Scheme 5, **34**). To increase convergency of the synthesis of **32**, the remote oxidation of **34** would be followed by incorporation of alkyne **33**, which comprises seven of the eight carbons of the E,F-rings spiroketal.

Our synthesis of alkyne **33** began with the known diol **35** (two steps from 3-methyl-3-buten-1-ol, 89% yield, 96% ee).[18]

Scheme 5. Synthesis Plan for **31** Requiring a Remote Oxidation of **34** and Sonogashira Coupling with **33**



Scheme 6. Synthesis of Alkyne **33** from Known Diol **35**[a]



[a] Conditions: (a) TBDPSCl, imidazole, DMF; (b) CAN, CH_3CN, H_2O, 0 °C; (c) TMSCl, imidazole, DMF, 80% three steps; (d) oxalyl chloride, DMSO, Et_3N, CH_2Cl_2, −78 °C; (e) $Zn(OTf)_2$, (+)-*N*-methylephedrine, Et_3N, ethynyltrimethylsilane, toluene, 40 °C, 57% two steps; (f) TBSCl, imidazole, DMAP, CH_2Cl_2; (g) $AgNO_3$, THF, H_2O, EtOH, 2,6-lutidine, 93% two steps.

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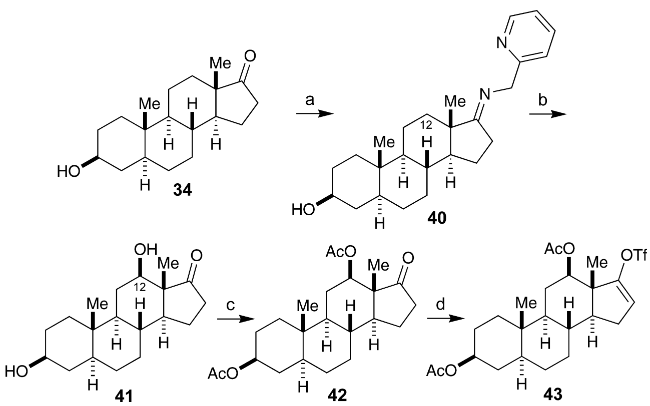
Scheme 7. Synthesis of Vinyl Triflate **43** from Commercially Available *trans*-Androsterone **34** by Remote Oxidation at C12^a



^{a} Conditions: (a) 2-aminomethylpyridine, TsOH, toluene, 110 °C, 89%; (b) $Cu(OTf)_2$; benzoin, Et_3N, acetone, O_2, HCl, NH_4OH, 25%; (c) Ac_2O, pyridine, 97%; (d) $PhN(Tf)_2$, KHMDS, THF, −78 to 25 °C, 91%.

We protected the primary hydroxyl as a TBDPS ether, removed the PMP group by CAN oxidation, and protected both hydroxyl groups of the resulting 1,3-diol as TMS ethers to afford **37** in 80% yield over three steps (Scheme 6). The Swern reagent chemoselectively converted the TMS ether of the primary carbinol directly into aldehyde **38**. Carreira alkynylation[19] with ethynyltrimethylsilane favored the desired (**4R**)-propargyl alcohol by 32:1 and provided it in 57% yield from **37**. The secondary carbinol was protected as a TBS ether to deliver **39**, and the alkynyl TMS was removed with $AgNO_3$ and 2,6-lutidine,[20] affording alkyne **33**.

Synthesis of the steroid-derived Sonogashira coupling partner began with the commercially available steroid *trans*-androsterone **34** (Scheme 7). Utilizing the procedure of Schönecker for the hydroxylation of unactivated C−H bonds,[21] we treated the steroid with 2-(aminomethyl)pyridine and catalytic TsOH to form imine **40** in 89% yield. Treatment of **40** with $Cu(OTf)_2$, benzoin, and Et_3N in acetone to generate Cu(I), followed by the addition of molecular oxygen, resulted in hydroxylation at the unactivated C12 position. Hydrolytic workup provided diol **41** as a single diastereomer in 25% yield. Acetylation with Ac_2O/pyridine and treatment with $PhN(Tf)_2$/KHMDS led to vinyl triflate **43** in 88% yield.

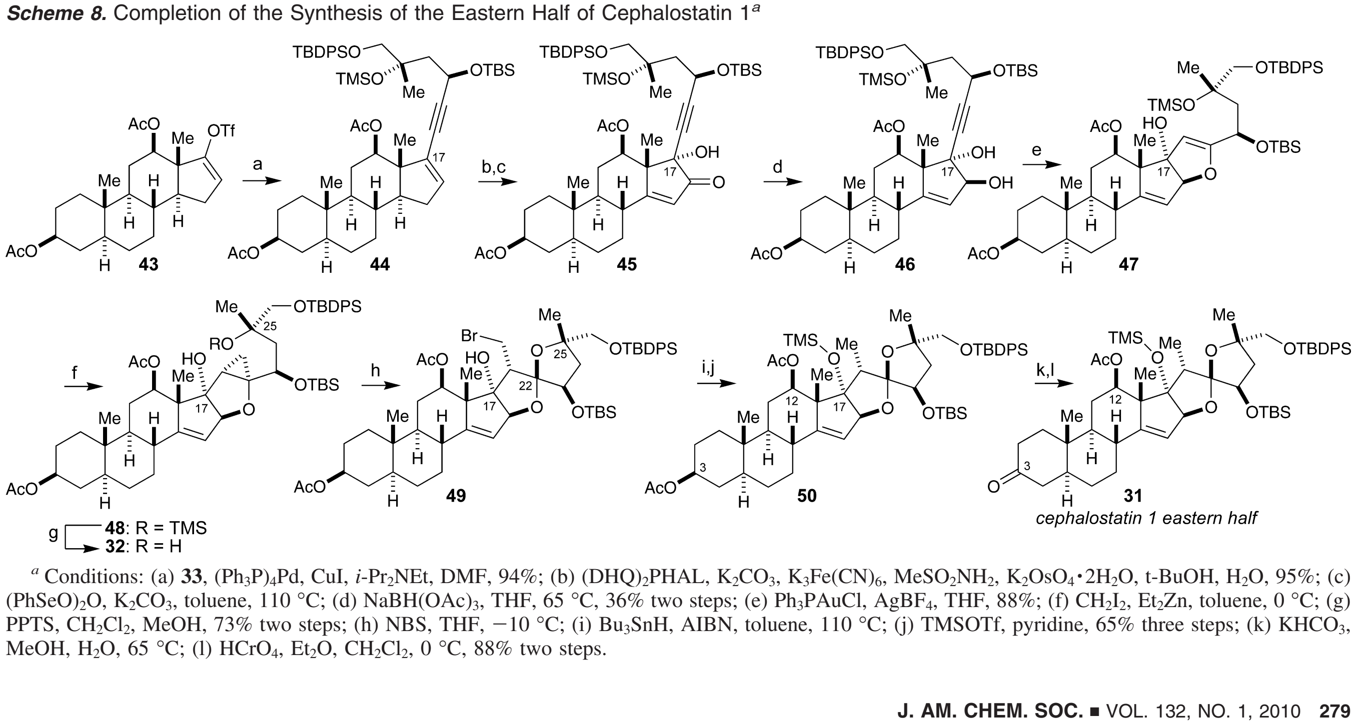
Pd-catalyzed Sonogashira coupling of vinyl triflate **43** and alkyne **33** provided enyne **44** in 94% yield (Scheme 8). Sharpless dihydroxylation of the enyne proceeded with complete stereocontrol to install the α-hydroxyl at C17. Further oxidation with benzeneseleninic anhydride[22] converted the *cis*-diol into unstable α-hydroxy cyclopentenone **45** in fairly low yield despite extensive efforts toward optimization.

Treatment of the enone **45** with $NaBH(OAc)_3$ resulted in C17 hydroxyl-directed reduction to *trans*-diol **46**. Diol **46** underwent Au(I)-catalyzed 5-endo-dig cyclization[23] to provide dihydrofuran **47** in 88% yield. It is worth noting the ease with which the Au(I)-catalyzed cyclization takes place on what is a highly hindered internal alkyne. Again, using the C17 hydroxyl as a directing group, Simmons−Smith conditions stereoselectively converted the dihydrofuran **47** to cyclopropane **48**. Deprotection of the C25 hydroxyl with PPTS delivered spiroketalization substrate **32** as a single diastereomer in 73% yield from **47**. Treatment of **32** with Zeise's dimer $[\{(\eta^2\text{-}C_2H_4)PtCl_2\}_2]$ resulted in quantitative spiroketalization;[24] however, the undesired C22-(*R*) spiroketal stereoisomer was favored by a 13:1 ratio. This may be due to HCl generated during the reaction, and attempts to buffer the reaction with nitrogenous bases inhibited spiroketalization. We later discovered that oxidative spiroketalization using NBS in THF furnished a separable mixture of bromomethylene spiroketals favoring the desired C22-(*S*) isomer **49** by a 5:1 ratio. Lack of equilibration in this reaction is due to the neutral reaction conditions. Debromination of **49** by Bu_3SnH/AIBN followed by silylation of the extremely hindered C17 hydroxyl using neat pyridine/TMSOTf delivered **50** in 65% yield from **49**. Selective hydrolysis of the C3 acetate (the C12 acetate is shielded by the C17 OTMS group) followed by Brown-modified Jones oxidation[25] provided **31**, the eastern half of cephalostatin 1, in 88% yield over two steps.

Completion of a Synthesis of Cephalostatin 1

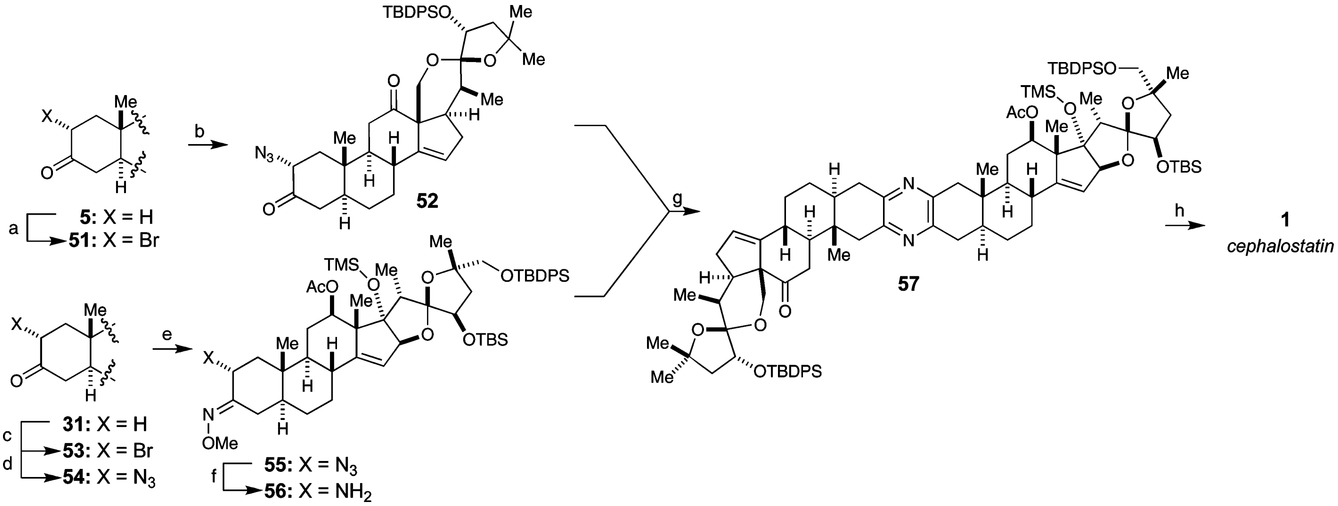
To prepare the A rings of western half **5** and eastern half **31** for pyrazine coupling, we used a sequence of reactions

Scheme 8. Completion of the Synthesis of the Eastern Half of Cephalostatin 1^a



^{a} Conditions: (a) **33**, $(Ph_3P)_4Pd$, CuI, *i*-Pr_2NEt, DMF, 94%; (b) $(DHQ)_2PHAL$, K_2CO_3, $K_3Fe(CN)_6$, $MeSO_2NH_2$, $K_2OsO_4\cdot 2H_2O$, t-BuOH, H_2O, 95%; (c) $(PhSeO)_2O$, K_2CO_3, toluene, 110 °C; (d) $NaBH(OAc)_3$, THF, 65 °C, 36% two steps; (e) Ph_3PAuCl, $AgBF_4$, THF, 88%; (f) CH_2I_2, Et_2Zn, toluene, 0 °C; (g) PPTS, CH_2Cl_2, MeOH, 73% two steps; (h) NBS, THF, −10 °C; (i) Bu_3SnH, AIBN, toluene, 110 °C; (j) TMSOTf, pyridine, 65% three steps; (k) $KHCO_3$, MeOH, H_2O, 65 °C; (l) $HCrO_4$, Et_2O, CH_2Cl_2, 0 °C, 88% two steps.

Scheme 9. Pyrazine Coupling and Completion of the Synthesis of Cephalostatin 1[a]



[a] Conditions: (a) $PhMe_3NBr_3$, THF, 0 °C; (b) tetramethylguanidinium azide, $EtNO_2$, 83% two steps; (c) $PhMe_3NBr_3$, THF, 0 °C; (d) tetramethylguanidinium azide, $EtNO_2$, 78% two steps; (e) $NH_2OMe{\cdot}HCl$, pyridine/CH_2Cl_2; (f) PPh_3, THF/H_2O, 0 to 25 °C, 77% two steps; (g) polyvinylpyridine, Bu_2SnCl_2, benzene, 80 °C; (h) TBAF, THF, 47% two steps.

developed by Fuchs[11b] (Scheme 9). Bromination α to the C3 ketone and azidation with tetramethylguanidinium azide in $EtNO_2$ provided **52** from **5** and **54** from **31**. The C3 ketone of **54** was converted to methoxime **55**, and Staudinger reduction of the azide to an amine gave pyrazine coupling partner **56**. **52** and **56** were treated with polyvinylpyridine and Bu_2SnCl_2 in refluxing benzene to provide protected cephalostatin 1 (**57**) along with a trace of recovered **56**. Global deprotection of the silyl groups and the C12 acetate was affected by TBAF in refluxing THF to afford cephalostatin 1 in 47% yield from **52**.

Conclusion

In conclusion, an enantioselective synthesis of cephalostatin 1 has been achieved. In the course of our synthesis of the western half, a unique methyl group-selective allylic oxidation was developed. PTAD underwent selective functionalization of the C18 methyl group, apparently directed by a proximal aldehyde. Subsequent [2,3]-sigmatropic rearrangement and oxidative hydrolysis of the resulting urazole led to a C18 aldehyde that could not be produced using other methods. This allylic functionalization sequence may be useful in other systems where conventional methods fail. Key steps in the eastern half synthesis include a remote C−H hydroxylation of C12, Sonogashira coupling between a steroid-derived vinyl triflate and an alkyne containing most of the atoms of the E and F rings, a Au(I)-catalyzed 5-endo-dig cyclization, and a kinetic spiroketalization by cyclopropane ring-opening. Our goal is to uncover the cellular target of cephalostatin 1 and explore its therapeutic potential. This synthesis is a first step toward achieving these goals.

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Supporting Information Available: Experimental procedures and spectral data for new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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