Total Syntheses of HMP-Y1, Hibarimicinone, and HMP-P1

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Published Version</td>
<td>doi:10.1021/ja307207q</td>
</tr>
<tr>
<td>Citable link</td>
<td><a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:9639969">http://nrs.harvard.edu/urn-3:HUL.InstRepos:9639969</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Open Access Policy Articles, as set forth at <a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP">http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP</a></td>
</tr>
</tbody>
</table>
**Total Syntheses of HMP-Y1, Hibarimicinone, and HMP-P1**

Brian B. Liau, Benjamin C. Milgram, and Matthew D. Shair*

Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts 02138, United States

**ABSTRACT:** Total syntheses of HMP-Y1, atrop-HMP-Y1, hibarimicinone, atrop-hibarimicinone, and HMP-P1 are described using a two-directional synthesis strategy. A novel benzyl fluoride Michael–Claisen reaction sequence was developed to construct the complete carbon skeleton of HMP-Y1 and atrop-HMP-Y1 via a symmetrical, two-directional, double annulation. Through efforts to convert HMP-Y1 derivatives to hibarimicinone and HMP-P1, a biomimetic mono-oxidation to desymmetrize protected HMP-Y1 was realized. A two-directional unsymmetrical double annulation and biomimetic etherification were developed to construct the polycyclic and highly-oxidized skeleton of hibarimicinone, atrop-hibarimicinone, and HMP-P1. The use of a racemic biaryl precursor allowed for the synthesis of both hibarimicinone atropisomers and provides the first confirmation of the structure of atrop-hibarimicinone. Additionally, this work documents the first reported full characterization of atrop-hibarimicinone, HMP-Y1, atrop-HMP-Y1, and HMP-P1. Lastly, a pH-dependent rotational barrier about the C2–C2' bond of hibarimicinone was discovered, which provides valuable information necessary to achieve syntheses of the glycosylated congeners of hibarimicinone.

**INTRODUCTION**

**Background.** Hibarimicins A–G are complex pseudo-dimeric type-II polyketides isolated from the culture broth of the rare actinomycete *Microbispora rosea* subsp. *hibaria* TP-A0121.1 These metabolites inhibit proliferation and induce differentiation of numerous human cancer cell lines. In particular, hibarimicin B (1, Figure 1), which is identical to angelmicin B,2 has the most potent anti-proliferative activity in HL-60 cells (IC\(_{50}\) = 58 nM).3 The cellular target and biological mechanism of action of 1 remain undetermined. The hibarimicins are amongst the most complex and largest type-II polyketides known. Hibarimicins A–G share an unprecedented highly-oxidized aglycon, hibarimicinone (2a, Scheme 1). The C2'-symmetry of 2a is broken by oxidation of the B-, C-, and D-rings relative to the G-, F-, and E-rings, respectively. More specifically, the B-ring contains a cyclic ether bridging C8' and C13', the C-ring contains a hydroxyl group at C6', and the D-ring is a quinone. Furthermore, 2a exhibits axial chirality about its highly congested C2–C2' bond and is isolated as a single atropisomer.4–6 Altogether, the hibarimicins and hibarimicinone (2a) are challenging targets that have resisted total synthesis7 until earlier this year when Tatsuta et al. reported the first total synthesis of 2a.8,9 Herein, we report reantioselective total syntheses of hibarimicinone (2a) and atrop-hibarimicinone (2b), and the first total syntheses of the biosynthetically related natural product aglycons HMP-Y1 (3a), atrop-HMP-Y1 (3b) and HMP-P1 (6) (Scheme 1).

**Figure 1.** Structure of hibarimicin B (1).

**Scheme 1. Proposed Biosynthetic Conversion of HMP-Y1 (3a) to Hibarimicinone (2a) and HMP-P1 (6)**

**Biosynthesis Hypothesis.** Mutagenesis of *Microbispora rosea* subsp. *hibaria* TP-A0121 led to the identification of novel metabolites, including HMP-Y1 (3a), HMP-P1 (6), and their glycosylated derivatives (Scheme 1).10 Through 13C-acetate labeling studies, it was discovered that C2'-symmetric 3a is a precursor to 2a, which is subsequently glycosylated to yield hibarimicins A–G. Ostensibly,
this conversion (3a → 2a) proceeds by breaking the C₂-symmetry of 3a via oxidation of the B-, C₂, and D-rings and demethylation of the C₄'-OMe methyl group. We postulated that a single desymmetrizing oxidation of the C-ring of 3a to hypothetical quinone 4 would be sufficient to relay oxidation to the B- and D-rings. This could be achieved via (1) tautomerization of quinone 4 to C₈'-ortho-quinone methide 5 with subsequent oxy-Michael addition of the C₁₃'-OH to install the B-ring cyclic ether, (2) re-oxidation of the C-ring, and (3) transposition of the C-ring quinone to the D-ring with concomitant demethylation to give 2a. HMP-P1 (6) arises from 2a via cyclization of C₁-OH onto C₃' of the D-ring quinone and subsequent expulsion of methanol.²⁰

**Results and Discussion**

**Scheme 2. Biosynthesis-Inspired Retrosynthesis Analysis of HMP-Y1 (3a), Hibarimicinone (2a), and HMP-P1 (6)**

**Synthesis Plan.** Inspired by our proposed biosynthetic relay oxidation scheme, we envisioned that a similar set of biomimetic retrosynthetic disconnections could simplify 2a to two plausible precursors, C₂-symmetric octacycle 7 and pseudo-C₂-symmetric octacycle 8 (Scheme 2). Targeting 7 was attractive for two reasons: (1) global deprotection would yield HMP-Y1 (3a) and (2) it would allow direct assessment of the feasibility of a biomimetic monooxidation to access a quinone analogous to 4. In contrast to 7, the C₆'-symmetry of 8 is perturbed by the presence of a benzyl group³ and the C₆'-OH (both highlighted in red), the latter of which would facilitate chemoselective C-ring oxidation to a quinone. The most noteworthy feature shared by both 7 and 8 is the degeneracy of the AB- and HG-ring systems that result from the retrosynthetic excision of the B-ring cyclic ether bond. Next, it was envisioned that both octacyclic systems could be constructed in a single operation via a two-directional double annulation,⁴ where the diion of biaryl 10 would react with two equivalents of the AB-/HG-enone (+)-9. The use of a symmetric biaryl annulation donor would lead to 7 whereas the employment of an unsymmetrical variant, with additional oxidation at C₆', would result in 8. Both of these strategies are convergent and circumvent the need to construct the hindered C₂-C₂' bond at a late stage. Efforts by the Roush group to form the C₂-C₂' bond in simple model systems via cross-coupling were met with difficulty.⁵ At the outset of our study, the configuration of the stereocchemical axis about the C₂-C₂' bond of hibarimicinone (2a) was ambiguous.²¹ Consequently, we elected to proceed with racemic biaryl annulation donor 10 to prepare and characterize both atropisomers of HMP-Y1 (3a) and hibarimicinone (2a).

**Synthesis of the AB-/HG-Enone (+)-9.** We previously reported a gram-scale enantiospecific synthesis of the AB-/HG-ring system corresponding to the unnatural enantiomer of 2a. The AB-/HG-enone (+)-16 (Scheme 3), with stereochemistry corresponding to the natural enantiomer of 2a, was prepared from key intermediate cyclohexenone (+)-15 following an analogous series of diastereoselective transformations. Notably, both enantiomers of (+)-15 were accessed from a D-methyl-glucopyranoside by taking advantage of its latent C₂-symmetry. The AB-/HG-enone synthesis commenced with AcOH-mediated deprotection of benzylidene acetel 11 followed by selective Wittig iodination of the resultant primary hydroxyl group to provide diol (+)-12. Next, chemoselective monosilylation of (+)-12 with TBSCI was accomplished by exploiting a subtle steric difference between its two secondary hydroxyl groups. The remaining secondary hydroxyl group was then pivaloylated under forcing conditions to furnish differentially protected pyranose (+)-13. Exposure of (+)-13 to DBU promoted elimination of the primary iodide to generate exocyclic enol ether (+)-14, which underwent type-II Ferrier rearrangement upon treatment with catalytic Hg(OOC(F₃)C).⁷ The resultant β-hydroxy-cyclohexene was dehydrated to provide (+)-15. Following our previous procedures,⁶ (+)-15 was converted to (+)-16 and the tertiary C₁₄-OH was ultimately TMS-protected to give annulation acceptor (+)-9.

**Scheme 3. Synthesis of the AB-/HG-enone (+)-8**

*Conditions: (a) AcOH/H₂O, 80 °C; (b) PPh₃, I₂, imidazole, PhMe/CH₂Cl₂, RT → 45 °C, 76% (two steps); (c) TBSCI, imidazole, CH₂Cl₂, 0 °C → RT, 99%; (d) PivCl, 4-DMAP, CIH₂Cl₂, 50 °C, 94%; (e) DBU, MeCN, 80 °C, 75%; (f) 30 mol% Hg(OOC(F₃)C), MeCO/H₂O; (g) MscI, Et,N, CH₂Cl₂, 0 °C → RT, 74% (two steps); (d) LiHMDS, THF, 0 °C; then TMSOTf, 0 °C → RT, 99%.

**Demonstration of a Biomimetic Etherification on a Model ABCD-Ring System.** A key transformation in our synthesis plan is a late-stage biomimetic etherification that retrosynthetically symmetrizes hibarimicinone (2a) and HMP-P1 (6). Consequently, a model ABCD-ring system was first investigated to test the viability of this proposed reaction. Kraus annulation²² of cyanophalidide 17 with ent-AB-/HG-enone ent-9³ under rigorously oxygen-free conditions gave ABCD-tetracycle (−)-18 (Scheme 4). Deoxygenation was critical for the success of the annulation, as adventitious oxygen caused decomposition. (−)-18 was then oxidized with DDQ to the corresponding C-ring quinone, which upon exposure to anhydrous HCl led to clean formation of pentacyclic ether (−)-20. This transformation presumably occurs through the intermediary of ortho-quinone methide 19, which is trapped by the proximal acetone
Scheme 5. Synthesis of HMP-Y1 (3a) and atrop-HMP-Y1 (3b) via a Benzyl Fluoride Michael–Claisen Reaction Sequence

Conditions: (a) MeSO₃, K₂CO₃, Me₂CO, 98%; (b) tCPBA, NaHCO₃, CH₂Cl₂; then Na₂CO₃, MeOH; (c) NaH, MOMCl, DMF, 0 °C → RT, 91% (two steps); (d) BuLi, TMEDA, THF, –78 °C → 0 °C; then FeCl₃, 0 °C → RT, 76%; (e) Br₂, Py, CH₂Cl₂, 0 °C, 91%; (f) BuLi, THF, –78 °C; then CIC(O)OMe, –78 °C → RT, 89%; (g) LiTMP, THF, –78 °C; then BrCF₂, –78 °C, 62%; (h) TBAT, MeCN, 82 °C, 75%; (i) (+)-9, LiTMP, THF, –78 °C; then HMDMS, –78 °C → –35 °C; then MgBr₂·OEt₂, –35 °C; (j) CF₃CHO/CH₂OH/H₂O, NaHCO₃, 80 °C, 55% (two steps); (k) aq. HF, MeCN/THF, 50 °C; (l) H₂, Pd(OH)₂/C, THF; for 3a, 59% (two steps); for 3b, 62% (two steps).

Scheme 4. Synthesis of an ABCD-Pentacyclic Model System

Conditions: (a) LiHMDS, THF, –78 °C → 0 °C, 94%; (b) DDQ, CH₂Cl₂, –20 °C; (c) HCl, CH₂Cl₂, 0 °C, 69% (two steps).

Development of a Benzyl Fluoride Michael–Claisen Reaction Sequence to Achieve the First Total Synthesis of HMP-Y1 (3a) and atrop-HMP-Y1 (3b). Our synthesis plan for HMP-Y1 (3a) involved a symmetric two-directional double annulation to generate C₇-symmetric octacycle 7, which could potentially be desymmetrized through a biomimetic mono-oxidation to access hibarimicinone (2a) and HMP-P1 (6). Such an ambitious double annulation strategy required a flexible synthesis of symmetric biaryl annulation donors in which different substituents at C6/C6’ could be introduced, due to the lack of robust annulation sequences to generate naphthols (1-hydroxynaphthalenes rather than 1,4-dihydroxynaphthalenes, i.e., hydroquinones). Our biaryl synthesis began with 5-methylvanillin 21 (Scheme 5), which was converted to trialkylsilane 22 in a three step process involving: (1) O-methylation, (2) Dakin oxidation followed by in situ formate methanalysis, and (3) MOM protection of the resultant phenol. Next, regioselective ortho-lithiation of 22 at C2’ and FeCl₃-mediated oxidative dimethylation of the resultant aryllithium species delivered biaryl (±)-23. Carbomethoxy groups were then installed in a two-step sequence involving bromination and lithium–halogen exchange followed by acylation to afford bis-ortho-toluate (±)-24.

The reaction kinetics and ultimate success of Michael–Claisen reaction sequences hinges on numerous factors. These include, but are not limited to: (1) the stability and nucleophilicity of the reacting carbani, (2) the stability of the electrophilic acceptor to the base required to deprotonate the donor, and (3) the steric bulk of the donor (substituents at C6/C6’ and the ester side chain) and of the acceptor. Furthermore, the slow step of the tandem reaction sequence will change based on the particular donor and acceptor used. We found that (±)-24 could be deprotonated twice by LiTMP and that the corresponding dianion underwent two-directional bis-Michael–Claisen reaction sequence with various 2-cyclohexenones, including the AB-/HG-enone ent-9. However, the slow rate of both the Michael and Claisen reactions of the sequence with stERICALLY ent-9 versus simpler 2-cyclohexenones coupled with the finite lifetime of the dianion of (±)-24 led to very low yields (<10%) of the desired octacyclic dihydroxynaphthalene products. Attempts to facilitate the Claisen step
of the reaction sequence by utilizing activated ester analogues (i.e., phenyl and 2,2,2-trifluoroethyl) were particularly problematic since the sterically larger activated esters slowed the initial Michael reaction and the dians were more prone to decomposition. Most importantly, aromatization of the C-/F-rings of the octacyclic products was met with difficulty and led us to consider alternative approaches. Benzylic sulfoxide and benzylic sulfone substituted ortho-toluenes were also evaluated to achieve the desired naphthol annulation with (+)-9 or ent-9, but ultimately proved unsuccessful in the context of a two-directional double annulation (vide infra).

We next envisaged a benzylic fluoride Michael–Claisen reaction sequence to generate naphthalenes after subsequent dehydrohalogenation. Although there was no precedence for such a strategy, a benzylic fluoride annulation donor was attractive for several reasons: (1) the electronreceptive fluorine atom should stabilize the biaryl dianion, (2) the small atomic radius of fluorine should provide minimal steric hindrance to the initial Michael reaction, (3) the strength of C–F bonds would disfavor a-elimination and S2 displacement of fluoride, and (4) despite the strength of C–F bonds, elimination of the benzylic fluoride under appropriate conditions could lead to C- and F-ring aromatization. The dianion of (±)-24 was brominated with (BrCF3)2 to yield the bis-benzyl bromide, which upon heating with TBAT afforded bis-benzylic fluoride (±)-25. After significant experimentation, the desired protected HMP-Y1 derivatives (–)-27a and (+)-27b were accessed from (±)-9 and (±)-25 in a two-step process involving: (1) a bis-Michael–Claisen reaction sequence promoted by LiTMP and MgBr·OEt2 to afford octacycles 26a and 26b and (2) the formal elimination of HF by heating the unpurified reaction product in 2,2,2-trifluoroethanol (TFE) to achieve aromatization of the C- and F-rings and provide atropisomers (–)-27a and (+)-27b, which were readily separated and carried forward independently. Several features of this sequence deserve comment. As we had hoped, the use of a bis-benzylic fluoride (±)-25 allowed for the initial bis-Michael addition to occur at –78 °C, thus minimizing decomposition of the dianion intermediate and of (+)-9. Addition of MgBr·OEt2 to mid annulation sequence was critical to promote the final intramolecular Claisen reactions and obviate the need to use an activated ester analogue. This discovery should help expand the substrate scope of the Michael–Claisen reaction sequence. Finally, the unique ability of TFE to promote the desired elimination is presumably due to its ability to strongly hydrogen bond with fluorine, and thus activate it for mild solvolysis. Indeed, use of ethanol in place of TFE only led to trace elimination. The employment of a benzylic fluoride annulation-elimination sequence to generate naphthalene derivatives is without precedence and may prove to be a general method for the synthesis of naphthalins.

Global deprotection of (–)-27a and (+)-27b with aqueous HF followed by hydrogenolysis afforded HMP-Y1 (3a) and atrop-HMP-Y1 (3b), respectively. Heating 3a or 3b to 90 °C led to no detectable isomerization about the C2–C2′ bond. With no authentic CD-spectra for natural 3a available, synthetic 3a and 3b were designated based on comparison to the CD spectrum of the glycosylated derivative of 3a, HMP-Y6. The axial stereochemistry of HMP-Y1 (3a) has not been rigorously determined, although model studies and the CD-spectra of HMP-Y6 and hibarimicinone (2a) suggest 3a possesses the αR configuration by the CD exciton chirality method. Additionally, 3a, 2a, and hibarimicin A–G are all isolated as single atropisomers. We show that the axial stereochemistry of 3a and 2a are not the result of thermodynamic equilibration (vide infra), and thus their biosynthetic relationship also argues that they possess the same relative configuration about the C2′–C2 bond. Therefore, since the axial chirality of 2a was unambiguously determined, 3a can be assigned the αR configuration.

Biomimetic Mono-Oxidation of Protected HMP-Y1. With a route to HMP-Y1 (3a) and atrop-HMP-Y1 (3b) established, we next attempted the biomimetic mono-oxidation of protected HMP-Y1 derivatives. We discovered that the desired oxidation of ent-27a to the C-ring quinone (–)-29 could be achieved in low yield with CAN (Scheme 6), demonstrating the plausibility of our proposed biomimetic desymmetrizing oxidation. We speculate that the congested biaryl may sterically occlude the approach of oxidants to the otherwise easily oxidized D-/E-ring system, allowing oxidation of the more electron-deficient C-/F-rings. Despite this initial success, our attempts to optimize the CAN oxidation were met with difficulty due to bis-oxidation and formation of nitrate byproducts. A survey of other oxidants also proved fruitless.

Nevertheless, with naphthazarin (–)-29 in hand we next investigated the desired biomimetic etherification reaction. Unfortunately, exposure of (–)-29 to the optimized conditions developed on our model system led to no observable etherification but rather only rapid MOM group cleavage. A screen of various acids and conditions also proved unsuccessful. The resistance of (–)-29 to undergo the desired etherification in contrast to the C-ring quinone derivative of (–)-18 was surprising. Since the major difference between the two systems is the lability of the MOM groups of (–)-29 relative to the methyl group of (–)-18, we postulated that a free phenol at C1′ might disfavor either acetone decomposition or formation of the necessary ortho-quinone methide intermediate. This prompted us to replace the MOM group with a more acid-stable protecting group.


Additionally, our current biomimetic strategy would inevitably require a late-stage demethylation of the C4′-OMe methyl group. Ideally, one would remove the C4′-OMe methyl group as late in an eventual synthesis of hibarimicin B (1) as possible to protect the sensitive and stereochemically labile binaphthyl core (vide infra). However, the acidic conditions necessary to effect demethylation would be incompatible with the sensitive 2-deoxy- and 2,3-
Scheme 8. Completion of Hibarimicinone (2a), atrop-Hibarimicinone (2b), and HMP-P1 (6)

Conditions: (a) LiHMDS, THF, -78 °C; then KHMDMS, 0 °C → RT, 50–59%; (b) DMTSF, DTBMP, MeCN, 0 °C → RT; for (-)-35a, 75%; for (+)-35b, 89%; (c) for (-)-35a: DDQ, PhMe, 0 °C; for (+)-35b: DDQ, PhMe, 0 °C → RT; (d) HCl, CHCl₃, CH₂Cl₂, 5 °C; for (-)-37a, 77% (two steps); for (+)-37b, 86% (two steps); (e) aq. HF, MeCN/THF; (f) H₂, Pd(OH)₃/C, EtOAc; then HCl, MeOH, air; for 2a, 81% (two steps); for 2b, 60% (two steps); (g) aq. pH 7.5 NaH₂PO₄/NaOH buffer, MeOH, RT; for 2a, 84%; from 2b, 84%.

Scheme 7. Synthesis of Unsymmetrical Biaryl (±)-34 via a Selective Mono-Deprotonation of (±)-24

Conditions: (a) LiTMP, THF, -78 °C; then (BrCF₃)₂, 82%; (b) Pr₃NEt, DMSO, 70 °C, 87%; (c) TFA, CH₂Cl₂, 0 °C → RT; (d) BCl₃, CH₂Cl₂, -78 °C → 0 °C; (e) BuBr, K₂CO₃, DME, 0 → 60 °C, 94% (three steps); (f) Me₃C(OH)CN, Et₃N, CH₂Cl₂, 97%; (g) LiTMP, THF, -78 °C; then Ph(O)₂SSPh, 71%.

dideoxyglycosides of 1. The aforementioned reasons prompted us to investigate our alternative strategy for the synthesis of hibariminone (2a) and HMP-P1 (6) utilizing an unsymmetrical two-directional annihilation reaction with biaryl (±)-34 (Scheme 7).

Synthesis of the Unsymmetrical Biaryl Annulation Donor (±)-34. The unsymmetrical fully substituted biaryl (±)-34 presents unique synthesis challenges that are shared with the hibarimincines; cross-coupling technology to form such sterically hindered biaryl from electron-rich aromatics is limited. 24 In contrast, dimerization reactions to form hindered biaryl are robust and reliable (e.g., 22 → (±)-23). Thus we imagined that a practical synthesis approach to (±)-34 would necessitate the desymmetrization of (±)-24. A strategy to mono-functionalize (±)-24 involving radical bromination would inevitably result in an inefficient statistical mixture of benzylic bromides. However, we hypothesized that selective mono-deprotonation of (±)-24 would be feasible since the initial carbanion would enolate the pKa of the remaining ortho-toluate due to a field effect. Indeed, we found that selective mono-deprotonation of (±)-24 at C6’ could be achieved with 1.25 equiv of LiTMP (Scheme 7). The resultant anion (±)-30 was then brominated with (BrCF₃)₂ to give benzylic bromide (±)-31 in 82% yield (Scheme 7). This single element of asymmetry was sufficient to introduce the remaining differential functionality of (±)-34. (±)-31 was oxidized to aldehyde (±)-32, 28 which was then converted to tri-benzyl-protected biaryl (±)-33 by 1 (acid-promoted removal of the MOM groups, 2) chemoselective cleavage of the C4’-OMe methyl group with BCl₃, and 3) global reprotection with BnBr. Treatment of (±)-33 with a controlled source of hydrogen cyanide afforded a cyanophthalde intermediate. 29 Finally, double deprotonation of this intermediate with LiTMP followed by a short exposure to S-phenyl benzenethiosulfonate chemoselectively installed the phenyl sulfide moiety 32 at C6 to provide biaryl (±)-34. The observed chemoselectivity in this reaction is a result of the much higher reactivity of the ortho-toluate anion relative to the cyanophthalde anion.

Completion of Hibarimicinone (2a) and atrop-Hibarimicinone (2b) via an Unsymmetrical Two-Directional Double Annulation. We anticipated that reaction of the lithiated cyanophthalde of (±)-34 with (+)-9 would directly construct the C-ring hydroquinone via a Kraus annulation, and reaction of the lithiated benzyl phenyl sulfide of (±)-34 with a second equivalent of (+)-9 would lead to the F-ring via a Michael–Claisen reaction sequence. We found that the desired transformations could be
achieved by treating a mixture of (±)-34 and (+)-9 with LiHMDS followed by subsequent addition of KHMDMS mid annulation sequence under rigorously oxygen-free conditions to yield octacycle (−)-35a and (+)-35b as a ~1.3:1 mixture of atropisomers (Scheme 8). The addition of KHMDMS was crucial to facilitate the final intramolecular Claisen reaction to construct the F-ring. At this stage, atropisomers (−)-35a and (+)-35b were separated and carried forward independently. Elimination of the C6-benzyl phenyl sulfoxide was accomplished with dimethyl(methylthio)sulphonium tetrafluoroborate (DMTSF) to yield binaphthalenes (−)-36a and (+)-36b. It is worth reiterating at this point that the corresponding C6-benzyl sulfoxide and sulfone derivatives of (±)-34 ultimately proved unsuccessful in a two-directional annulation, highlighting the difficulty to achieve naphthaline annulations in the context of complex molecule synthesis. To the best of our knowledge, this is the first example of a benzyl sulfoxide Michael–Claisen reaction sequence to generate naphthalenes, and together with the benzyl fluoride Michael–Claisen reaction sequence reported offer two new alternatives to approach challenging naphthaline annulations.

Oxidation of (−)-36a and (+)-36b with DDQ produced the corresponding C-ring quinones. Exposure of the respective quinones to anhydrous HCl promoted the desired biomimetic etherification to yield nonacyle (−)-37a and (+)-37b. This successful etherification of the benzyl protected napthazarins, in contrast to MOM-protected (−)-29, confirmed our suspicion that the nature of the C1'-phenol has far-reaching stereoelectronic effects on this system. With the complete skeletons of 2a and 2b in hand, all that remained to complete the syntheses was global deprotection and oxidation of the D-ring. Deprotection of the acetyl labile protecting groups was accomplished upon exposure to HF. Finally, the benzyl groups were removed via hydrogenolysis, and after addition of acidic methanol, filtering, and exposure to air, hibarimicinone (2a) and atrop-hibarimicinone (2b) were formed. All of the spectroscopic data for 2a and 2b match those reported18,26 and thereby confirmed the structure of 2b.

**Figure 2.** (A) Upon standing in acidic methanol (1 M HCl) at RT, hibarimicinone (2a) and atrop-hibarimicinone (2b) undergo minor interconversion and minimal conversion to HMP-P1 (6) (orange HPLC traces). (B) Exposure of 2a to pH 7.5 aqueous phosphate buffer at RT (blue HPLC traces) or (C) acidic methanol (1 M HCl) at 60 °C (red HPLC traces) resulted in isomerization to 2b and eventual formation of 6. See SI for HPLC timecourses for 2b.

**Figure 3.** A proposed model to explain the pH-dependent rotational barrier about the C2–C2' bond of 2a and 2b. Only the CDEF-ring system is depicted for brevity.

These findings are particularly interesting owing to prior observations that heating 2a in neutral methanol at 60 °C leads to nearly complete interconversion to 2b in 30 minutes and ultimately complete cyclization to yield 6 after 90 minutes. However, we found that heating either 2a or 2b to 60 °C in acidic methanol (1 M HCl) led to only partial interconversion between 2a and 2b and minor conversion to 6 after 90 minutes (Figure 2C). This suggests that the observed rapid rotation at 60 °C in neutral methanol has less to do with providing the necessary thermal energy to surpass the intrinsic activation barrier about C2–C2' in the uncharged forms of 2a/2b (38a/38b in Figure 3), but rather enables access to the deprotonated form of 2a and 2b (39a/39b in Figure 3) via inter- or intramolecular proton transfer. Rapid interconversion between 37a and 37b can then follow through a transition state that is stabilized by π-electron overlap19,33 as depicted in cross-conjugated resonance structures 40a and 40b. Consequently, variables that affect the equilibrium between 38a and 39a, and 38b and 39b will affect the rate of isomerization. The addition of acid to the
media inhibits access to species 39a and 39b by driving the equilibrium toward 38a and 38b, and thus disfavors isomerization. In contrast, heat (60 °C) should promote equilibration between the protonation states and thus facilitate isomerization. Our discovery of the pH-dependent barrier demonstrates the delicate nature of the C2–C2′ which must be accommodated in an eventual synthesis of hibarimicin B (1).32

**Conclusion**

Enantioselective syntheses of hibarimicinone (2a) and atrop-hibarimicinone (2b), and the first total syntheses of HMP-Y1 (3a), atrop-HMP-Y1 (3b), and HMP-P1 (6) have been accomplished. The complete carbon skeleton of each natural product was assembled via a convergent two-directional annulation strategy. The use of a racemic biaryl in conjunction with the two-directional annulation strategy enabled both atropisomers of the natural products to be separately constructed and fully characterized, thus providing the first reported full characterization of 2b, 3a, 3b, and 6. Additionally during the pursuit of this annulation strategy, we encountered numerous challenges when conducting naphthol annulation reactions. Consequently, we developed two valuable Michael–Claisen reaction sequences to construct complex naphthols that might find use as general methods. The mild conditions needed to dehydrohalogenate the benzyl fluoride intermediates are particularly noteworthy given the strength of C–F bonds.

The plausibility of our proposed biosynthesis was also validated by the demonstration that a desymmetrizing mono-oxidation of the C-ring can be conducted on protected HMP-Y1 derivatives. Oxidation to the bis-C-/F-ring quinone was also observed, but natural products corresponding to such a double oxidation have not been isolated in nature or during mutagenesis studies. This perhaps suggests that an enzyme mediates this key biosynthetic transformation, but how 3a is only mono-oxidized remains unclear.

After the key two-directional annihilations, only three and five steps were needed to complete HMP-Y1 (3a) and hibarimicinone (2a), respectively. In the case of 2a, these steps include a biomimetic etherification to install the B-ring cyclic ether via an orthoquinone methide intermediate. The success of this reaction required an acid-stable protecting group on the C1′-phenol owing to subtle yet far-reaching stereoelectronic effects imparted by the naphthazarin-naphthalene system. The peculiarities and sensitivity of this system are also highlighted by our discovery of the pH-dependent rotational barrier about the C2–C2′ bond. These particular observations provide crucial information that will facilitate an eventual synthesis of hibarimicin B (1).

Lastly, the intermediate (−)-37a will be highly useful in an eventual total synthesis of 1; it is suitably protected with orthogonal protecting groups to allow for the sequential installation of the 2-deoxy- and 2,3-dideoxyglycosides prior to deprotection of the sensitive binaphthyl core of the molecule. Future studies toward the total synthesis of 1 will be reported in due course.

**ASSOCIATED CONTENT**

**Supporting Information.** Experimental procedures, spectroscopic data, and copies of CD, UV–vis, 1H and 13C NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

**AUTHOR INFORMATION**

**Corresponding Author**

shair@chemistry.harvard.edu

**Funding Sources**

No competing financial interests have been declared. We acknowledge financial support from NIH (RO1GM090068). B.B.L. acknowledges a NSF Predoctoral Fellowship and Bristol-Myers Squibb. B.C.M. acknowledges Eli Lilly and AstraZeneca.

**ACKNOWLEDGMENT**

We thank Prof.’s Y. Igarashi, H. Hori, and G. Sulikowski for communication regarding atropisomerism and for providing authentic spectroscopic data. B.B.L. acknowledges Amy S. Lee for helpful discussions.

**REFERENCES**


(5) The use of a benzyl group was a strategic concession to protect the sensitive core of 1 up until the last step of an eventual synthesis of 1.

(6) For other examples of two-directional double annulation reactions, see: (a) Hauser, F. M.; Gauvin, P. J. Org. Lett. 1999, 1, 671–672. (b) Ref. 2. (c) Ref. 4. and references therein.


(8) See SI for full details.


(13) 5-Methylvanillin (515) was prepared from vanillin in two steps on multigram scale following a literature procedure: Sinhababu, A. K.; Borchardt, R. T. Syn. Comm. 1983, 13, 677–683.

(14) (a) For other uses of Michael–Claisen reaction sequences to construct naphthalene derivatives, see: Sun, C.; Wang, Q.; Brubaker, J. D.; Wright, P. M.; Lerner, C. D.; Noson, K.; Charest, M.; Siegel, D. R.; Wang, Y.-M.; Myers, A. G. J. Am. Chem. Soc. 2008, 130, 17913–17927, and references therein. (b) For a related approach to 3a, see ref. 2.

(15) (a) ortho-Toluate and related carbanions will suffer from competitive bimolecular self-condensation reactions with the ester moiety if the Michael addition is not fast enough. For an interesting discussion on the stability of ortho-toluate and related carbanions, see Brubaker, J. D. Ph.D. Thesis, Harvard University, 2007 and references therein. (b) In the case of a single annulation process, the instability of the deprotonated annulation donor can often be partially circumvented through the use of excess donor. However, due to the inherent stoichiometry of the two-directional double annulation, the biaryl donor is used as the limiting reactant and thus the stability of its dianion is critical to the success of the reaction.

(16) We observed that ent-9 is stable to LiTMP and LDA at –78 °C, and LiHMDS at 0 °C in THF. At higher respective temperatures for prolonged reaction times, significant decomposition occurred.

(17) Simple 2-cyclohexenones will undergo the Michael addition within seconds at –78 °C and eventual Claisen reaction at –10 °C with the ortho-toluate carbanion corresponding to the D-/E-ring. In contrast, ent-9 underwent Michael addition after approximately 1 hour and the Claisen reaction was never driven to completion with the dianion of (+)-24.

(18) DDQ or PhSeCl with pyridine could successfully be employed to aromatize dihydroanaphalenes of simple BCD-ring model systems but proved unsuccessful on binaphthyl systems.


(21) Benzyl phenylsulfide substituted ortho-toluates were concurrently found to be useful partners for naphthol annulations and were ultimately employed in our synthesis of 2a and 6 due to the inability to incorporate a benzyl fluoride at C6 of (+)-34.


(24) (a) For brevity, each atropisomer is depicted as a single structure lacking stereochemistry about the C2-C2' bond. See SI for full details. (b) The regioisomer of the enolized 1,3-diketone is arbitrarily depicted.

(25) No NMR or CD spectra for 3a and 6 have been previously recorded according to ref. 26. See SI for full details.

(26) Described in a personal communication with Professor H. Hori and Professor Y. Igarashi.

(27) (a) Preferential oxidation of the D-ring occurs in simpler BCD-ring model systems. (b) The 'H NMR signal of the methoxymethyl groups of ent-27a and ent-27b are shifted over 0.6 ppm up-field relative to the corresponding monomer, suggesting that they are positioned over the naphthyl ring systems and subject to anisotropic magnetic field effects.


(31) The small coupling constant between the C6' and C7' hydrogen atoms of (−)-35a and (+)-35b suggest a syn relationship of the hydrogen atoms with respect to the ring system. This relative stereochemistry would preclude syn-elimination to aromatize the F-ring. Indeed, one diastereomer of the corresponding sulfoxide of (+)-34 underwent two-directional annulation but failed to eliminate to aromatize the F-ring.

(32) The carbohydrates of the hibarimicin natural products are cleaved with acidic methanol (1 M HCl, 30 °C). These conditions are similar to those we employ during the benzyl deprotection and oxidation of (−)-37a and (+)-37b. However, milder acidic conditions (i.e.,aq pH 3.5 phosphate buffer) in methanol may potentially be substituted during the analogous deprotection and oxidation of 1 since these conditions are employed in the HPLC purification of 1 and hibarimicin related natural products. See ref 1f for the conditions used for carbohydrate cleavage and purification of the hibarimicin natural products.

Two-Directional Annulation Strategy

Hibarimicin Aglycons: HMP-Y1, Hibarimicinone, and HMP-P1