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

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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. 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, has the most potent anti-proliferative activity in HL-60 cells (IC50 = 58 nM). 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. Altogether, the hibarimicins and hibarimicinone (2a) are challenging targets that have resisted total synthesis until earlier this year when Tatsuta et al. reported the first total synthesis of 2a. Herein, we report enantioselective 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).

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). 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 \((3a \rightarrow 2a)\) proceeds by breaking the \(C_2\)-symmetry of \(3a\) via oxidation of the \(B\)-, \(C\)-, 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 result in relay oxidation to the \(B\)- and \(D\)-rings. This could be achieved via (1) tautomeration of quinone \(4\) to \(C8'\)-ortho-quinone methide \(S\) 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.16

Results and Discussion

Scheme 2. Biosynthesis-Inspired Retrosynthesis Analysis of HMP-Y1 (3a), Hribarimicinone (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, \(C_2\)-symmetric octacycle 7 and pseudo-\(C_2\)-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 \(C_2\)-symmetry of 8 is perturbed by the presence of a benzylic 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 octacycle systems could be constructed in a single operation via a two-directional double annulation50 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.51 At the outset of our study, the configuration of the stereochemical axis about the \(C2'\)-\(C2'\) bond of hribarimicinone (2a) was ambiguous.52 Consequently, we elected to proceed with race-mic biaryl annulation donor 10 to prepare and characterize both atropisomers of HMP-Y1 (3a) and hribarimicinone (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.2 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 4-D-methyl-glucopyranoside by taking advantage of its latent \(C\)-symmetry. The \(AB\)/\(HG\)-enone synthesis commenced with AcOH-mediated deprotection of benzylidene acetal 11 followed by selective Wittig ionization 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 \(Hg(OCCOF_2)_2\).7 The resultant \(\beta\)-hydroxy-cyclohexanone was dehydrated to provide (+)-15. Following our previous procedures, (+)-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

\(^{\text{Conditions: (a) AcOH/H_2O, 80 °C; (b) PPh_3, I_2, \text{imidazole}, PhMe/CH_2Cl_2, RT → 45 °C, 76% (two steps); (c) TBSCI, imidazole, CH_2Cl_2, 0 °C → RT, 99%; (d) PivCl, 4-DMAP, CICH_2CH_2Cl, 50 °C, 94%; (e) DBU, MeCN, 80 °C, 75%; (f) 30 mol% \(Hg(OCCOF_2)_2\), MeCO/H_2O; (g) MsCl, Et_3N, CH_2Cl_2, 0 °C → RT, 74% (two steps); (d) LiHMDS, THF, 0 °C; then TMSOTf, 0 °C → RT, 99%.)\)
Our synthesis plan for HMP Y1 involves a symmetric two-directional double annulation to generate a cyclic octacyclonentase (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 annihilation 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).\(^\text{13}\) Our biaryl synthesis began with S-methylvanillin 21\(^\dagger\) (Scheme 5), which was converted to trisocytotoluene 22 in a three step process involving: (1) O-methylation, (2) Dakin oxidation followed by in situ formate methylation, and (3) MOM protection of the resultant phenol. Next, regioselective ortho-lithiation of 22 at C2’ and FeCl3-mediated oxidative dimerization of the resultant aryllithium species delivered biaryl (±)-23. Carbometoxy 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\(^\text{14}\) hinges on numerous factors. These include, but are not limited to: (1) the stability and nucleophilicity of the reacting carbaniion, (2) the stability of the electrophilic acceptor at 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 dianson underwent two-directional bis-Michael–Claisen reaction sequence with various 2-cyclohexenones, including the AB-/HG-ene ent-9. However, the slow rate of both the Michael and Claisen reactions\(^\text{17}\) of the sequence with sterically encumbered ent-9 versus simpler 2-cyclohexenones coupled with the finite lifetime of the dianson of (±)-24 led to very low yields (<10%) of the desired octacyclenic dihydronaphthalene 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. Benzyl sulfoxide and benzyl sulfone substituted ortho-toluates 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 benzyl fluoride Michael–Claisen reaction sequence to generate naphthalenes after subsequent dehydrohalogenation. Although there was no precedence for such a strategy, a benzyl fluoride annulation donor was attractive for several reasons: (1) the electrophilic nature of fluoride should stabilize the bifluoride dianion, (2) the small atomic radius of fluoride should provide minimal steric hinderance to the initial Michael reaction, (3) the strength of C–F bonds would disfavor a-elimination and S$_2$2 displacement of fluoride, and (4) despite the strength of C–F bonds, elimination of the benzyl fluoride under appropriate conditions could lead to C- and F-ring aromatization. The dianion of (+)-24 was brominated with (BrF)$_3$, to yield the bis-benzyl bromide, which upon heating with TBAT afforded bis-benzyl fluoride (+)-25. After significant experimentation, the desired protected HMP-Y1 derivatives (−)-27a and (+)-27b were accessed from (+)-9 and (−)-25 in a two-step procedure involving: (1) a bis-Michael–Claisen reaction sequence promoted by LiTMP and MgBr$_2$·OEt$_2$, to afford octacycles 26a and 26b and (2) the formal elimination of HF by heating the unpurified reaction product in 2,2,2-trifluoroethanol (TFE) to achieve aromatization of the C- and F-rings and provide atropisomers (−)-27a and (+)-27b, which were readily separated and carried forward independently. Several features of this sequence deserve comment. As we had hoped, the use of a bis-benzyl fluoride (±)-25 allowed for the initial bis-Michael addition to occur at −78 °C, thus minimizing decomposition of the dianion intermediate and of (+)-9. Addition of MgBr$_2$·OEt$_2$ to this annulation sequence was critical to promote the final intramolecular Claisen reactions and obviated 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 fluoride, and thus activate it for mild solvolysis. Indeed, use of ethanol in place of TFE only led to trace elimination. The employment of a benzyl fluoride annulation-elimination sequence to generate naphthalene derivatives is without precedence and may prove to be a general method for the synthesis of naphthols.

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 nitrated 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 acetonide 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.

**Scheme 6. Biomimetic Mono-Oxidation of Protected HMP-Y1.**

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)

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

*dConditions: (a) LiTMP, THF, -78 °C; then (BrCF$_3$)$_3$C, 82%; (b) Pr$_3$NEt, DMSO, 70 °C, 87%; (c) TFA, CH$_2$Cl$_2$, 0 °C → RT; (d) BCl$_3$, CH$_2$Cl$_2$, -78 °C → 0 °C; (e) Br$_2$, K$_2$CO$_3$, DMF, 0 → 60 °C, 94% (three steps); (f) Me$_2$C(OH)CN, Et$_3$N, CH$_2$Cl$_2$, 97%; (g) LiTMP, THF, -78 °C; then Ph(O)$_2$SSPh, 71%.

dideoxyglycosides of 1. The aforementioned reasons prompted us to investigate our alternative strategy for the synthesis of hibarimicinone (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 hibarimicins; cross-coupling technology to form such sterically hindered biaryls from electron-rich aromatics is limited. Therefore, in contrast, dimerization reactions to form hindered biaryls 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 benzyl bromides. However, we hypothesized that selective mono-deprotonation of (±)-24 would be feasible since the initial carbon would enable 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 (BrCF$_3$)$_3$C to give benzyl 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, 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 BCl$_3$, and (3) global reprotection with BnBr. Treatment of (±)-33 with a controlled source of hydrogen cyanide afforded a cyanothallate intermediate. Finally, double deprotonation of this intermediate with LiTMP followed by a short exposure to S-phenyl benzenethiosulfonate chemoselectively installed the phenyl sulfide moiety$^{22}$ 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 cyanothallate anion.

Completion of Hibarimicinone (2a) and atrop-Hibarimicinone (2b) via an Unsymmetrical Two-Directional Double Annulation. We anticipated that reaction of the lithiated cyanothallate 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 KHMS 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 KHMS was crucial to facilitate the final intramolecular Claisen reaction to construct the F-ring.6 At this stage, atropisomers (−)-35a and (+)-35b were separated and carried forward independently. Elimination of the C6-benzyl phenoxy sulfide 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,31 highlighting the difficulty to achieve naphthol annulations in the context of complex molecule synthesis. To the best of our knowledge, this is the first example of a benzyl sulfide 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 naphthalene 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 nonacyles (−)-37a and (+)-37b. This successful etherification of the benzyl protected naphthazarins, 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 acid-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, hibarimicine (2a) and atrop-hibarimicine (2b) were formed. All of the spectroscopic data for 2a and 2b match those reported18,20 and thereby confirmed the structure of 2b.

**Figure 2.** (A) Upon standing in acidic methanol (1 M HCl) at RT, hibarimicine (2a) and atrop-hibarimicine (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.16,22 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 arises 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
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 bicylic 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 ortho-quinone methide intermediate. The success of this reaction required an acid-stable protecting group on the C1'-phenol owing to suble 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-dideoxyxylglycosides prior to deprotection of the sensitive bisanhydro HMP ester functionality on 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.

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(5) The use of a benzyl group was a strategic concession to prevent 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.; Gauwan, 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-Methoxyvanillin (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 dihydroxynaphthalenes of simple BCD-ring model systems but proved unsuccessful on binaphthalenyl 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. Horii and Professor Y. Igarashi.

(27) (a) Preferential oxidation of the D-ring occurs in simpler BCD-ring model systems. (b) The 1H 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 carboxylates 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-g 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