Rapid synthesis of polyprenylated acylphloroglucinol analogs via dearomative conjunctive allyl...
Rapid Synthesis of Polyprenylated Acylphloroglucinol Analogs via Dearomative Conjunctive Allylic Annulation

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Supporting Information

ABSTRACT: Polyprenylated acylphloroglucinols (PPAPs) are structurally complex natural products with promising biological activities. Herein, we present a biosynthesis-inspired, diversity-oriented synthesis approach for rapid construction of PPAP analogs via double decarboxylative allylation (DcA) of acylphloroglucinol scaffolds to access allyl-desoxyhumulones followed by dearomative conjunctive allylic alkylation (DCAA).

INTRODUCTION

Polyprenylated acylphloroglucinol (PPAP) natural products including nemorosone, clusianone, and hyperforin are structurally complex molecules having promising chemotherapeutic properties (Figure 1).1,2 As such, their laboratory syntheses have received considerable attention.3 PPAPs are highly regarded for their biological activities1 which include anticancer,2b–e antiviral,2f and antibacterial2i properties. Bottlenecks toward their applications in disease treatment are stability issues,4 synthetic challenges,3 and promiscuous biological activity.1e Thus, medicinal chemistry and biological evaluation of novel analogs within the PPAP family are of high interest but have been underdeveloped.3m With these challenges in mind, we sought to develop a route that was both chemically efficient and applicable to diversity-oriented synthesis (DOS).6

Figure 1. Representative PPAP natural products.

As expertly penned by Mulzer in a recent review,7 there are numerous tactics to render a given synthesis efficient including biosynthetic considerations. By considering a biosynthetic hypothesis for a natural product, often innate reactivity can be exploited, ideally resulting in an efficient synthetic strategy. In the case of PPAPs, the molecules are presumed to be derived from three building blocks: a desoxyhumulone substrate such as 1 and two additional prenyl cation equivalents which react distinctly to assemble the bicyclo[3.3.1]nonane core via (a) dearomative prenylation and (b) alkene-intercepted prenylation (Scheme 1).1 Union of the prenyl fragments with the phloroglucinol at either the 2- and 4-positions or the 4- and 6-positions yields nemorosone (arbitrary absolute configuration shown) or clusianone, respectively. Generally speaking, this isomeric difference is referred to as “type A” and “type B” throughout this family. Thus, hyperforin is a “type A” PPAP through union of the phloroglucinol core to a geranyl fragment (dearomatization) and a prenyl cation (cascade bicyclo[3.3.1]nonane assembly). Although the biosynthesis is efficient and complexity generating, it has yet to be realized in a laboratory setting.3

We hypothesized that Pd-catalyzed dearomative conjunctive allylic annulation (DCAA) of desoxyhumulones 1 and 2-methylene-1,3-propanediol derivative 2 would serve as an efficient biosynthesis-inspired, diversity-oriented strategy to access a plethora of PPAP analogs possessing many of the essential structural features for bioactivity (Scheme 2).2 Such an approach to PPAP core structures would take advantage of biosynthetic, innate reactivity8,9 (phloroglucinol dearomatization, allylic alkylation) and utilize the predictably reactive reagent 2 which has been utilized extensively in conjunctive

Scheme 1. Biosynthetic Hypothesis for PPAP’s

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bond-forming processes. Herein, we report our initial discoveries enabling the rapid construction of diverse PPAP analogs for biological evaluation through this modular and step-economic sequence.

### Allyl-Desoxyhumulone Scaffold Synthesis via Double Decarboxylative Allylation

In order to realize a diversity-oriented approach to PPAP-type structures, it was necessary to establish a modular, scalable, and robust route to allyl-desoxyhumulone scaffolds. The synthesis of allyl desoxyhumulone, a common intermediate en route to the natural products plukenetione A, 7-epi-nemorosone, and (−)-clusianone (Scheme 3A), has been achieved by direct C-allylation of 2-acylphloroglucinol with allyl bromide in low yield due to overalkylation or by selective O-allylation then Claisen rearrangement requiring temperatures exceeding 200 °C (Scheme 3B).

Generally speaking, allylated phenols can be accessed through high-temperature (>200 °C) or Lewis acid promoted [3,3]-allyl phenyl ether Claisen rearrangements (Scheme 4). Due to the sensitivity of acylphloroglucinols and desoxyhumulones, we wondered if a relatively low-temperature and neutral formal allyl phenyl ether Claisen rearrangement could be achieved via Pd(0)-catalysis. As shown in Scheme 5, we envisioned access to desoxyhumulones via Pd-catalyzed decarboxylative allylation (DcA) which should controlably generate diallyl phenyl ether in accord with the specificity of the DcA process. The Pd-catalyst could then trigger a “formal” Claisen rearrangement under mild conditions via allyl phenyl ether ionization and concomitant C-allylation to provide product 1a (Scheme 5).

To examine the possibility for a mild Pd-catalyzed double decarboxylative allylation/Claisen rearrangement sequence yielding desoxyhumulones, we prepared the requisite starting material 6a in >95% yield from 2-benzoylphloroglucinol and allyl chloroformate. Excitingly, we found that a highly efficient reaction of 6a to the desired product 1a occurred using 1 mol % Pd(PPh3)4 in cyclohexane (CyH) at 75 °C for 2h (Table 1).

![Scheme 5. Double DcA/Formal Claisen Rearrangement](image)

| entry | solvent | temp (°C) | time (h) | product yield (%) |
|-------|---------|-----------|---------|------------------|
| 1     | CyH     | 75        | 2       | 87              |
| 2     | CyH     | 75        | 5 min   | 7a [100]        |
| 3     | CH2Cl2  | 40        | 1       | 7a [100]        |
| 4     | THF     | 66        | 1       | 7a [100]        |
| 5     | toluene | 110       | 1       | 1a 64           |

*Isolated yields after silica gel chromatography. Percent conversion as determined by 1H NMR analysis.

Due to the sensitivity of acylphloroglucinols and desoxyhumulones, we wondered if a relatively low-temperature and neutral formal allyl phenyl ether Claisen rearrangement could be achieved via Pd(0)-catalysis. As shown in Scheme 5, we envisioned access to desoxyhumulones via Pd-catalyzed decarboxylative allylation (DcA) which should controlably generate diallyl phenyl ether in accord with the site-
Regarding the scope of allyl-desoxyhumulone synthesis via double DcA/formal Claisen rearrangement, phloroglucinols with a variety of 2-acyl groups were found to be compatible coupling partners (Scheme 7A). For example, desoxyhumulones 1a−1d having 2-benzoyl-, acetyl-, isobutyryl-, and isovaleroyl groups were prepared. Internal allylic substitution proceeded as desired to afford products 1e and 1f; however, terminally substituted allylic coupling partners (e.g., cinnamyl and prenyl) afforded complex mixtures. 19 Excitingly, the reaction could be extended to related aromatic starting materials such as resorcinol 1g and orcinols 1h−1j.

Importantly, a variety of large-scale (gram−multigram scale) reactions were performed for each of the compatible scaffolds identified (phloroglucinols 1a/d, resorcinol 1g, and orcinol 1h). All multigram scale reactions were successful with reduced catalyst loading (0.25 mol % Pd(PPh₃)₄) at an increased concentration (0.5 M in cyclohexane). To broaden substrate scope and further enhance the diversity of PPAP analogs for our investigation, we also removed the O-methyl group on 1a, 1b, and 1d with BBr₃ to access the unprotected variants 1k−1m (Scheme 7B).

In addition to the synthesis of desoxyhumulones 1a−1m via DcA/formal Claisen rearrangement, we also investigated the synthesis of related scaffolds (Scheme 8). Interestingly, we found that the mono-allyl phenyl carbonate 8a only underwent DcA to provide allyl phenyl ether 8b under the optimized conditions and did not undergo formal allyl phenyl ether [3,3]-Claisen rearrangement regardless of the reaction duration (Scheme 8A). In addition, the double DcA/Claisen rearrangement was extended to the chrysin-derived flavone scaffold 9a under slightly modified conditions (Scheme 8B). From the commercially available flavone chrysin, we prepared 6,8-diallylchrysin20 1n without silica gel chromatography in 99% yield over the two-step sequence via intermediate 9a.

Scheme 7. Scope of Allyl-Desoxyhumulone Synthesis

Scheme 8. Related Scaffolds for Pd-Catalyzed DcA

BIOSYNTHESIS-INSPIRED, DIVERSITY-ORIENTED SYNTHESIS OF PPAP ANALOGS

With a variety of desoxyhumulone scaffolds 1a−1j in hand, many of which were prepared in multigram quantities, we next turned to the development of the key dearomative conjunctive allylic annulation (DCAA) to provide a diversified set of PPAP analogs. Using the model coupling reaction between 1a and 2, we began our quest for the optimal Pd catalyst, solvent, and reaction conditions (Table 2). Mono-methyl allyl desoxyhumulone 1a was chosen as an initial scaffold as it was thought, based on our previous studies, that the methyl ether would direct the annulation to the 2- and 4-positions of the substrate ("type A" annulation).

We ultimately identified two standard conditions (A and B, Table 2, entries 1 and 2) that were utilized throughout our studies to construct PPAP analogs. With the methyl ether on the scaffold, we then investigated the effect of the substituent on the phenyl ring on Pd-catalyzed DCAA (Table 2, entries 3−5)
Standard conditions B (Pd/BINAP) appeared to be more tolerant to solvent choice, though reaction times were found to be significantly longer in lower boiling solvents such as cyclohexane and THF (Table 2, entries 6 and 7).

Interestingly, using either the methylated (1a−1f, Scheme 7A) or the nonmethylated (1k−1m, Scheme 7B) desoxyhumulone scaffolds, either “type A” or “type B” PPAP structures could be selectively prepared (Schemes 9 and 10, respectively). O-Methyldesoxyhumulones 1a−1f reacted under standard conditions A (Table 2, entry 1) to yield “type A” PPAP analogs 3a−3f in excellent yields (Scheme 9A). The reaction tolerated both allyl (3a−3d) and β-methylallyl (3e and 3f) substitution at C4 and C6. Pleasingly, the nonmethylated desoxyhumulones 1k−1m exclusively provided “type B” annulation adducts 3k−3m under modified conditions via regioselective cyclization at the more nucleophilic C4 and C6 positions (Scheme 10A). We discovered that increased reaction times, lower temperatures, and larger catalyst (Pd2dba3/BINAP) loadings were required for successful cyclization to the “type B” core as low yields were obtained using standard conditions A or B. As one possible explanation, the nucleophilic phenolate moiety at C5 may bind to binary palladium(0) more effectively than BINAP resulting in loss of catalytic activity. Pleasingly, our general purification procedure developed for dearomatized phloroglucinols and PPAP derivatives3p,18 allowed access to bicyclo[3.3.1]nonanes 3k−3m along with their potassium salts18,3p due to their enhanced stability and shelf life.4

We also found that alkyl substitution at C4 and C6 was important for success of the DCAA reaction (Scheme 11).

While the standard allyl-desoxyhumulone 1a underwent clean reaction under the optimized conditions to afford 3a, neither the proteo-(4a) or the chlorinated (10a) variants reacted with conjunctive reagent 2 under standard conditions A or B, likely due to a combination of steric and electronic influences.

From the successful studies on allyl-desoxyhumulones 1a−1f (Scheme 9) and 1k−1m (Scheme 10), we reasoned that other scaffolds bearing at least a resorcinol oxygenation pattern, an acyl group, and alkyl substituents at C4 and C6 should also undergo the desired DCAA process. We proceeded to test our hypothesis by further broadening our investigation to construct a diverse set of resorcinol- and orcinol-derived PPAP analogs via DCAA (Scheme 12). Excitingly, we discovered that resorcinol derivative 1g and orcinol derivatives 1h−1j yielded “type A” PPAP analogs 3g−3j lacking a vinylogous acid moiety (Scheme 12, eqs 1 and 2). Moreover, the structure of DCAA product 3h was unequivocally determined by X-ray crystallography (Figure 2). Diallyl-chrysin 1n exclusively afforded “type
pyranone heterocycle
likely resulting from enhanced nucleophilicity of the unprotected phenol moiety positioned para to the acyl group in 1n (cf. Scheme 10). DCAA adduct 3n is structurally similar to the anticancer PPAP natural products oblongifolins F and G. Next, starting from allylated methyl atratate (11a), available in 1-step from methyl atratate, an inexpensive flavoring molecule (∼$0.25/g), DCAA yielded two-separable products having “type A” (3o-major, 63% yield) and “type B” (3o-minor, 27% yield) fusion patterns. The mixture likely arises from the intermediate anion reacting through either major- or minor-contributing resonance structures, which can be reasoned by the fact that keto-stabilized allyl anions prefer to react at the most-stabilized position. Finally, lupulone derivative 12a yielded a PPAP analog bearing gem-diallyl substitution (Scheme 12, eq 5).

In conclusion, we have achieved a biosynthesis-inspired, diversity-oriented synthesis approach to both “type A and B” PPAP analogs. Through the use of two consecutive Pd-catalyzed reactions, double DcA/Claisen rearrangement and a DCAA, we can rapidly prepare PPAP molecules for biological evaluation. The reaction is applicable to a number of electron-rich aromatic substrates bearing a resorcinol or phloroglucinol substitution pattern. Further studies including construction of highly diverse PPAP-inspired chemical libraries for biological studies and development of asymmetric DCAA are currently in progress and will be reported in due course.

ASSOCIATED CONTENT

S Supporting Information
Experimental details and compound characterization. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
The authors declare no competing financial interest.

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