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# Stereocontrolled and time-honored access to piperidine- and pyrrolidine-fused 3methylenetetrahydropyrans using lactam-tethered alkenols†

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Polycyclic oxygen-heterocycles bearing the 3-methylenetetrahydropyran (i.e., 3-MeTHP) motif are resident in bioactive molecules such as hodgsonox and iridoid. Meanwhile, the  $\delta$ - and  $\gamma$ -lactam topologies as well as their reduced variants (i.e., piperidines and pyrrolidines) are at the core of several pharmaceuticals and fragrances. A stereocontrolled, time-honored, and cost-effective strategy that merges a 3-MeTHP motif with the aforementioned azaheterocyclic scaffolds could exponentially expand the 3D-structural space for the discovery of new small molecules with medicinal value. In these studies, readily affordable lactam-tethered alkenols have been interrogated in two complementary cascade approaches, leading to the regioselective and stereocontrolled synthesis of lactam-fused 3-MeTHPs. The first approach hinges on regioselective 6-endo-tria bromoetherification of the alkenols and concomitant elimination to arrive at the desired 3-MeTHPs. The methylene portion of the 3-MeTHP is unveiled at a late stage, which is noteworthy since all existing approaches to 3-MeTHPs rely on early-stage introduction of the methylene group. The second strategy involves transition metal-catalyzed alkoxylation of the tethered alkenol followed by base-induced double bond isomerization. The lactam-fused 3-MeTHPs are obtained in high site- and diastereo-selectivities. Post-modification of the bicycles has led to the construction of 3-MeTHP-fused saturated piperidines and pyrrolidines as well as 3-MeTHPs bearing four contiguous stereocenters

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#### Introduction

The ever-increasing need for the development of expedient and efficient strategies for the construction and functionalization of privileged motifs (from the standpoint of drug discovery) such as the 3-methylenetetrahydropyran (3-MeTHP) motif is supported by their prevalence in several natural products and pharmaceuticals (see, antitumor agent A, hodgsonox, and iridoid; Fig. 1). Hippospongic acid A, which is a known inhibitor of gastrulation in starfish embryos, also harbors the 3-alkylidenetetrahydropyran topology.1ef Accordingly, several methodologies have emerged for the construction of diversely substituted 3-MeTHPs,2 including Claisen rearrangement,2e Nicatalyzed reductive coupling,2f palladium-catalyzed Umpolung cycloaddition,<sup>2g</sup> and intramolecular radical cycloaddition.<sup>2h</sup> Efforts to increase step/atom economy,3 reduce harmful environmental effects, and increase the overall efficiency of experimental sequences have led to the popularity of cascade4 or

of lactam-tethered alkenols of type 1 proceeds with 6-endo Hodgsonox Antitumor agent (A)

Me Me Me Йe (+)-Hippospongic acid A

domino reactions<sup>5</sup> in the organic synthesis community.<sup>6,7</sup> We

therefore surmised that a modular, stereocontrolled, and cascade strategy that merges a 3-MeTHP motif with the ever so

important lactam topology would likely expand the 3D-

structural space for the discovery of new small molecules with

Previously, we disclosed that the direct oxidative alkoxylation

Fig. 1 Examples of bioactive 3-methylenetetrahydropyrans.

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Iridoid

A: Our previous work: Enol etherification and dehydrative pentannulation

B1: Halocycloetherification and concomitant elimination (Approach #1)

B2: Oxidative alkoxylation and concomitant isomerization (Approach #2)

C: Previously reported approaches to 3-MeTHPs

Fig. 2 (A) Our prior cyclization efforts using lactam-tethered alkenol 1, (B1 and B2) our proposed plans for accessing lactam-fused 3-meth-ylenetetrahydropyrans from 1, (C) previously reported approaches to functionalized 3-MeTHPs.

selectivity under Pd- or Cu-catalysis (Fig. 2A, see 2).8 Additionally, we showed that Fe- or Ru-catalyzed dehydrative coupling of 1 furnishes the C-C cross-coupling products (see 3).9 Desiring an efficient synthesis of lactam-fused 3-MeTHPs of type 4, we surmised that alkenol 1 offered a resplendent starting point. Two convergent and potentially complementary approaches to 4 were envisioned. The first would entail regioselective 6-endo halocycloetherification of 1 to afford intermediates such as 5 (Fig. 2B1), which could then undergo concomitant anti-Zaitsev dehydrohalogenation to furnish 4. The second envisioned approach to lactam-fused 3-MeTHPs involves dehydrogenative alkoxylation of 1 to arrive at fused dihydropyrans such as 2, which could then be isomerized to 4 under suitable contrathermodynamic conditions (Fig. 2B2). The first approach to lactam-fused 3-MeTHPs would proceed under transition metalfree conditions and would complement existing approaches to

3-MeTHPs, which are heavily reliant on transition metal catalysis (Fig. 2C).  $^{2fj}$ 

Another unique aspect of our design is the late-stage installation of the methylene portion of the 3-MeTHP given that all reported efforts depicted in Fig. 2C are predicated on early-stage introduction of the methylene group through one of the precursors. 2f-k Central to achieving the desired outcomes in this approach to 3-MeTHPs would be to properly control the site-selectivity of the haloetherification in favor of 6-endo-trig cyclization products anti-5 or syn-5 (Fig. 3) over the undesirable 5-exo bicycles (i.e., anti-15 or syn-16). Based on our experience with halolactonization of such substrates, we anticipate that reaction conditions would play a crucial role. We also recognized that it would be paramount to establish epimerizationfree elimination conditions that lead to the desired anti-Zaitsev product (4). This is all the more necessary since two of the three β-hydrogens resident in 5 are in innately more acidic and labile positions. One resides in the α-alkoxy and benzylic position, which could lead to the formation of enol ether 2. The other  $\beta$ -hydrogen is located in the  $\alpha$ -amino position and could generate bicyclic enamide 17. Another obstacle that we would have to overcome is that of double-bond isomerization, which could instead furnish the aforementioned thermodynamic products (i.e., 2 and 17). Detailed efforts toward the manifestation of our ideals are described herein.

### Results and discussion

Studies on the regioselective and stereocontrolled synthesis of lactam-fused 3-MeTHPs of type 4 commenced with the search

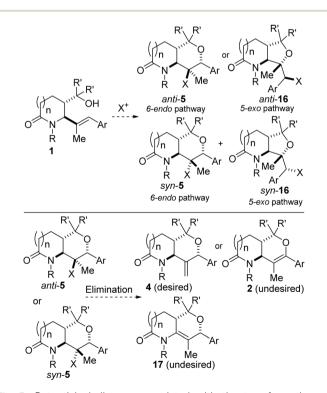


Fig. 3 Potential challenges associated with the transformation of lactam-tethered alkenol 1 to lactam-fused 3-MeTHP 4.

(X = Br),14 and being cognizant that the ICDA model is capable for appropriate conditions for efficient halocyclization of 1 and concomitant elimination (approach #1). It has previously been of delivering haloetherification products in less than an hour, reported that the combination of phthaloyl peroxide (PPO) and we sought to interrogate 1 in this potentially sagacious mode of X can generate Brønsted base covalently tethered carbonyl reactivity. hypohalites (BCTC).<sup>11</sup> Envisioning that BCTC could act as an in situ-generated electrophilic reagent for halocyclization reactions, the authors developed an Intramolecular Chaperone-

Table 1 Optimization of the bromoetherification of lactam-tethered alkenol 1a

assisted Dual-anchoring Activation (ICDA) model.12,13 Four

alkenols were engaged in a bromoetherification protocol and

they all furnished bromotetrahydrofurans.12 Having recently

found efficient but slow conditions for the conversion of 1 to 5

conditions A: PPO (1.1 equiv), TBAB (1.1 equiv) DCE (10 mL, 0.10 M), rt, 30 min. Yield of 5a = 95% diastereomeric ratio = 95:5 (anti:syn)

Entry	Deviation from conditions A	% Yiel of <b>5a</b>
2	BPO in place of PPO	12
3	DTBP in place of PPO	7
4	NBP in place of TBAB	11
5	NBS in place of TBAB	16
6	DBDMH in place of TBAB	14
7	NBA in place of TBAB	36
8	LiBr in place of TBAB	46
9	NaBr in place of TBAB	39
10	KBr in place of TBAB	18
11	CsBr in place of TBAB	11
12	DCM in place of DCE	90
13	THF in place of DCE	83
14	2-MeTHF in place of DCE	86
15	1,4-Dioxane in place of DCE	92
16	DMF in place of DCE	9
17	Diethylether in place of DCE	26

Reactions were performed under an air atmosphere PPO = phthaloyl peroxide; MPO = malonoyl peroxide BPO = benzoyl peroxide; DTBP = di-tert-butylperoxide TBAB = tetrabutylammonium bromide

NBP = N-bromophthalimide; NBS = N-bromosuccinimide DBDMH = 1,3-Dibromo-5,5-dimethylhydantoin NBA = N-bromoacetamide

Optimization studies were conducted using alkenol 1a and phthaloyl peroxide (PPO) out-competed other oxidants such as malonovl peroxide (MPO), benzovl peroxide (BPO), and di-tertbutyl peroxide (DTBP) (Table 1, entries 1-3). Other bromine sources did not perform as well as tetrabutylammonium bromide TBAB (entries 4-11). After screening several reaction media, DCE emerged as the optimum reaction medium with respect to the yield, regioselectivity and stereoselectivity (entries 12-17). Thus, after stirring a mixture of 1a (1 mmol) and TBAB (1.1 equiv.) in dichloroethane (10 mL, 0.1 M) for 30 minutes at room temperature, <sup>1</sup>H and <sup>13</sup>C NMR analyses of the crude mixture prior to extractive workup revealed the presence of 5a. The intramolecular bromoetherification performed well in 1,4dioxane. Desiring to develop a one-pot approach for the conversion of 1 to 4, we elected to go with 1,4-dioxane (entry 15) as the optimum reaction medium. Thus, a mixture of 1a (1 mmol) and TBAB (1.1 equiv.) in 1,4-dioxane (10 mL, 0.1 M) was stirred for 30 minutes at room temperature prior to heating to 100 °C for the desired length of time (Scheme 1). In the event, the structurally diverse lactam-fused 3-MeTHPs depicted in Scheme 1 were obtained. Differentially N-substituted lactams tend to display diverse reactivity and biological activity profiles.<sup>15</sup> We were pleased to see that γ-lactam-tethered alkenols harboring electronically diverse N-benzyl substituents underwent cyclization and concomitant site-selective dehydrobromination (see 4a-d). N-Alkyl lactam-alkenols are also competent substrates for the domino process (see 4e-i). These studies have revealed that y-lactams bearing halogenated arenes are well tolerated (see 4b-d, 4h, 4i, 4k-n, and 4p), which bodes well for late-stage diversification since the halogen group may be utilized as a requisite group for cross-coupling purposes. The results indicate that dehalogenation of the aryl halides does not occur during the second step of the one-pot process that is tailored toward dehydrobromination of the tertiary alkyl bromides. Innately more reactive γ-lactamtethered primary alkenols afford the lactam-fused 3-MeTHPs in synthetically attractive yields and selectivities when subjected to this bromoetherification-elimination protocol (see 40/p).

Polysubstituted and polycyclic 2-oxopiperidines (i.e., δvalerolactams) are increasingly attractive fragments for potential drug discovery since the strategic placement of substituents about this three-dimensional scaffold is ideally suited for structure-activity relationship studies.16 It was therefore gratifying to find that  $\delta$ -valerolactam-tethered alkenols also react regioselectively and diastereoselectively under the developed cascade protocol to afford the 2-piperidinone-fused 3-MeTHPs depicted in Scheme 1 (see 4q-4z8). A significant reactivity difference was observed with this one-carbon larger lactams. For example, whereas the second step of the one-pot, two-step sequence took about 36 h in the case of the γ-lactam-tethered alkenols, the homologous δ-lactam-tethered alkenols showed complete conversion in about 18 h. While these differences might not be surprising to practitioners of N-heterocyclic

Performed on 1.0 mmol scale using 10 mL 1,4-dioxane. Isolated yields are reported in all cases.

Reaction times for the elimination reaction ranged from 18 to 36 h.

Diastereomeric ratios were determined by GC-MS and <sup>1</sup>H NMR analyses of the crude product.

Relative configurations were established through chemical shift, coupling constant, 1D and 2D NOE analyses

Scheme 1 Scope of bromocycloetherification and concomitant dehydrobromination of lactam-tethered tertiary trisubstituted alkenols.

chemistry, they further highlight why extending reactivity trends from one class of a nitrogen heterocycle to another requires special consideration. Presumably, this pronounced disparity in reactivity is due to conformational differences. As a testament to the generality of the transformation, when the phenyl group on the styrenyl unit resident in alkenol 1 is replaced by an electron-deficient aryl group (see 4z4) or an electron-rich aryl substituent (see 4z5), the efficacy of the

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Scheme 2 Construction of lactam-fused 3-MeTHPs by transition metal-catalyzed dehydrogenative coupling and base-assisted isomerization

transformation is not compromised. Since the methyl-bearing styrenyl motif resident in alkenol 1 is derived from alphamethyl cinnamaldehydes,17 a current limitation of these studies is our inability to install  $\pi$ -excessive or  $\pi$ -deficient heteroaromatic groups (e.g., thiophenes and pyridines, respectively) at site of cyclization.

These studies have revealed that lactam-fused 3-MeTHPs can also be assembled using the second postulated approach, which features catalytic intramolecular dehydrogenative enol etherification of 1 and concomitant base-assisted contrathermodynamic isomerization (Scheme 2).

Scheme 3 Synthesis of piperidine- and pyrrolidine-fused 3-MeTHPs.

Catalytic hydrogenation of lactam-fused 3-MeTHPs

A potentially beneficial aspect of these studies is the scalable nature of the reactions given that several of the products (e.g., 4a/h/l) have been prepared in over 5 mmol scale, with little to no compromise in efficiency. This has set the stage for postdiversification studies.

There are high incentives for the construction of saturated azaheterocyclic scaffolds, especially the piperidine and pyrrolidine motifs, which are common structural motifs in agrochemicals, fragrances, and pharmaceuticals. 18,19 Recognizing that some of the most potent 2-oxopyrrolidines and 2-oxopiperidines have the lactam portion reduced to the corresponding saturated cyclic amine, and seeking to demonstrate the versatility of our synthetic methodology, we decided to subject some of the lactam-fused 3-MeTHPs to complete reduction. In the event, we found that the lithium aluminium hydride-assisted reduction of selected examples of 4 affords the bicyclic amines depicted in Scheme 3 (see 18a-d). No erosion in the diastereoselectivity was observed during the reduction process. The bicyclic tertiary amines are unsurprisingly less stable than their lactam counterparts and require special handling.

We have found that catalytic hydrogenation of the exocyclic alkene present in 4 proceeds diastereoselectively and furnishes lactam-fused tetrahydropyrans of type 19, which bear four contiguous stereocenters (Scheme 4). The diastereomeric ratios were determined using GC-MS analysis of the crude products. In the case of **19c**, <sup>19</sup>F NMR analysis was also employed. The ascribed relative configuration was established based on 1D and 2D NOE analyses.

### Conclusions

In summary, we have leveraged the synthetic versatility of lactam-tethered alkenols, which are readily obtainable through the 1,3-azadiene-anhydride annulation reaction, to develop two step-economical approaches to lactam-fused 3-MeTHPs. The first strategy takes advantage of the spatially confined noncovalent orientation and proximity effect for the direct generation of heteroatom-centered radicals from O-H bonds, leading to rapid regioselective bromocycloetherification and concomitant elimination. This approach to bicyclic 3-MeTHPs proceeds

under transition metal-free conditions and nicely complements existing approaches to 3-MeTHPs, which utilize transition metal catalysis. The late-stage introduction of the methylene portion of the 3-MeTHP through a thermally induced elimination or base-induced isomerization event is a unique feature of these studies. These novel cascade approaches to highly customized bicyclic 3-MeTHPs have set the stage for future post-diversification and structure–activity relationship studies. We anticipate that the scalable as well as operationally simple nature of these protocols would endear them to the organic and medicinal chemistry communities.

### Data availability

The data supporting this article have been included as part of the ESI.†

### **Author contributions**

T. K. B. – conceptualization, project administration, supervision, investigation, data curation, methodology, writing – original draft, internal funding acquisition; I. S. A. – investigation, data curation, methodology; J. K. – investigation, data curation, methodology.

### Conflicts of interest

There are no conflicts of interest to declare.

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