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Exploration of a KI-catalyzed oxidation system for direct construction of bispyrrolidino[2,3b]indolines and the total synthesis of (+)-WIN 64821[†]

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A facile and environmentally benign KI(cat.)/NaBO₃·4H₂O oxidation system has been developed for the tandem oxidative aminocyclization/ coupling of tryptamines, affording a series of 3a,3a'-bispyrrolidino-[2,3-b]indolines with high efficiency (up to 94% yield). This reaction features an electrophilic "I⁺" mechanism, which is importantly quite different from and milder than the typical radical-involving process, and can be readily amplified for the total synthesis of (+)-WIN 64821.

Oxidation is one of the most important transformations for organisms to produce functional molecules. In vivo, the oxidation of tryptophan or tryptamine can result in a big family of structurally complex and biologically important $3a_3a'$ -bispyrrolidino-[2,3-b]indoline alkaloids (Fig. 1), which show antifungal, antiviral and cytostatic acivities.¹ Despite its significance for biological and medicinal chemistry, realizing this biotransformation by means of organic chemistry, especially with a catalytic amount of assistant oxidation reagent, is still rare and synthetically challenging.² To date, several groups have devoted much pioneering effort to this aspect.^{3,4} However, most of the current solutions require either equivalent amounts of transition metals or excess of strong acid or base. Furthermore, these methodologies generally give insufficient yields. Therefore, the development of a catalytic and transition-metal-free oxidative system for the efficient synthesis of 3a,3a'-bispyrrolidino[2,3-b]indolines under mild condition is in demand.

During the past fifteen years, the iodide-catalyzed oxidative reaction has received widespread attention because of its versatile reactivity and environmentally benign property.^{5,6} In general, however, these systems are mostly limited to the application of

synthesis of relatively simple organic compounds, and only a few can give access to sterically complex frameworks, such as those with the vicinal all-carbon quaternary centers.⁷ As indicated in Scheme 1, the oxidation systems mediated by a catalytic amount of iodide have not been expanded to effect the tandem coupling/ cyclizations of tryptamine or tryptophan to construct the more complex 3a,3a'-bispyrrolidino[2,3-*b*]indoline **6**, **8** and **11** with vicinal all-carbon quaternary centers. Instead, they are only applicable to mediate the simple cyclization to produce the monomer products **1–4** (Scheme 1(a)).⁸ Due to our continuing interest in the synthesis of 3a,3a'-bispyrrolidino[2,3-*b*]indoline alkaloids,⁹ we thus try to develop an alternative effective iodide-catalyzed oxidative system, which we expect will enable the coupling/cyclizations as shown in Scheme 1(b). Herein, we describe our research results.

To achieve the hypothesis above, our initial optimization started toward the oxidation of tryptamine **5a** with screening the oxidants and solvents using KI as a catalyst (Table 1). Fortunately, after testing H_2O_2 in several solvents, only TFE (trifluoroethanol) could generate the desired dimeric products (**6a** and **6a**') with a moderate 44% yield (entry 5), while the other solvents gave inferior results (entries 1–4). Subsequently, both organic (entries 6 and 7) and inorganic oxidants were screened (entries 8 and 9), among which, NaBO₃·4H₂O gave the best yield (64%, entry 9). In addition, other conditions which involved varying the iodide catalysts, additives, concentrations and component equivalents were widely investigated,¹⁰ with the conditions in entry 10 giving the best result (68% yield).



Fig. 1 Representative bispyrrolidino[2,3-b]indoline alkaloids.

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Scheme 1 (a) Previous I-catalyzed oxidation of tryptamine or tryptophan; (b) our design.

 Table 1
 Optimization of the conditions for the iodide-catalyzed oxidative dimerization of tryptamine^a



^{*a*} Unless otherwise noted, reactions were carried out with **5a** (0.2 mmol), KI (20 mol%) and oxidant (2.0 equiv.) in 2 mL solvent. The dr was 1.8:1 determined by ¹H NMR. ^{*b*} Determined by ¹H NMR. ^{*c*} 50 wt% in water. ^{*d*} No reaction was observed. ^{*e*} 5.5 M in decane. ^{*f*} Not detected. ^{*g*} 1 atm. ^{*h*} Reaction was carried out with **5a** (0.2 mmol), KI (10 mol%) and NaBO₃·4H₂O (1.2 equiv.) in 2 mL TFE.

With the optimal catalytic oxidative system in hand, we then expanded the tryptamine substrate scope by varying the substituents \mathbb{R}^6 and X– \mathbb{R}^7 (Table 2, **5a–m**). Initially, when X– \mathbb{R}^7 was selected as *N*-tosyl, varying the substituents \mathbb{R}^6 (**5b–d**) with the EDGs (electron-donating groups, *e.g.*, methyl, ethyl and allyl) generally led to excellent reaction results (**6b–d**, 91–93% yields, 1.4:1 to 2.9:1 dr), while the EWG (electron-withdrawing group, *e.g.*, Ac) substituted substrate (**5e**) remained inactive to give product **6e**. Subsequently, when the optimal methyl was selected as \mathbb{R}^6 (as indicated in **6f–l**), varying substitution of \mathbb{R}^7 (X = N) with the strong EWG sulfonyl (**5f–k**) and trifluoroacetyl (**5l**) could drive the reactions with satisfactory results (**6f–l**, 75–93% yields, 1.5:1 to 2.9:1 dr). Exceptionally, when a carbamate was introduced to tryptamine (**5m**, X– $\mathbb{R}^7 = N$ -CO₂Me), the reaction could not give the desired product **6m**, but gave a complex mixture





^{*a*} Unless otherwise noted, all reactions were carried out with 5 (0.2 mmol), KI (10 mol%) and NaBO₃·4H₂O (1.2 equiv.) in 2 mL TFE and reacted for 1 h. Isolated yields and dr were determined by ¹H NMR. ^{*b*} Reacted for 2 h. ^{*c*} No reaction was observed after 24 h. ^{*d*} Reacted for 3 h. ^{*e*} Not detected.

accompanied by a partial starting material. It was also important that when tryptophol **5n** and 3-indolepropanol **5o** were separately subjected to the catalytic oxidative systems, interestingly, the former could react efficiently to give the tetrahydrofuran **6n** with an excellent yield of 94%, while the latter gave a mixture without hexahydropyran **6o** detected.

Next, a wide range of tryptamines with different substituents on the benzene rings were tested. As shown in Table 3, both EWG and EDG substituents at C₇, C₆ and C₅ of the benzene rings were effective for the expected oxidative dimerization reactions and generally gave satisfactory results (**8a–i**, 68–94% yield, 1.5:1 to 3.9:1 dr). The differences of these examples in the reaction time revealed that the EDG substituents were more favorable for reaction rates than the EWGs (**8f**, **8i** *vs.* **8a**, **8c**, **8j**, and **8k**). Notably, the C₄–F and C₄–Cl substituted tryptamines **7j** and **7k** could give **8j** and **8k** with excellent diastereoselectivities (11.7:1 and >20:1 dr)



Table 3 Investigation of benzene ring substituted tryptamines for oxidative dimerization $^{\rm a}$

^{*a*} Unless otherwise noted, all reactions were carried out with 5 (0.2 mmol), KI (10 mol%) and NaBO₃·4H₂O (1.2 equiv.) in 2 mL TFE and reacted for 1 h. Isolated yields and dr were determined by ¹H NMR.

and acceptable yields (72% and 46%), probably due to the steric interaction between F or Cl and C_{3a} or $C_{3a'}$.

In order to elucidate the mechanism of this catalytic oxidative coupling/cyclization reaction, we also conducted some additional control experiments (Scheme S1, ESI[†]).¹⁰ According to the experimental results, addition of the radical scavengers such as TEMPO (2,2,6,6-tetramethylpiperidinooxy) or DMPO (5,5-dimethyl-1-pyrroline *N*-oxide) was found to have little influence on the reaction, while use of the electrophilic iodide reagent NIS (*N*-iodosuccinimide) could efficiently promote the desired reaction with similar results (77% yield, 2.8 : 1 dr) compared to the standard reaction (Table 2, **6b**). Therefore, an electrophilic "T⁺" mechanism (Scheme 2) rather than the classical radical process was proposed.^{6*i*} As shown in Scheme 2, the reaction would begin with the oxidation of "I⁻"; thereafter, the resulting electrophilic "I⁺" species could readily interact with the nucleophilic tryptamine (5 or 7) to form a cyclic iodonium



Scheme 2 The plausible mechanism

ion intermediate $A^{3g,8b,11}$ Subsequently, the active intermediate A underwent an intramolecular cyclization to generate the 3-iodohexahydropyrroloindole compound B, which was then transferred to indolium C and released iodide for further catalytic cycles. Finally, the indolium C could couple with another tryptamine (5 or 7) through an electrophilic addition/cyclization process *via* either favorable model M-1 or a sterically hindered model M-2 to give the major product 6 or 8 and the minor one 6' or 8', respectively. It is worth noting that this stereo-control model was also consistent with the diastereoselectivities obtained from our reactions.¹⁰

To verify the utility of this methodology, the pharmacologically promising agent (+)-WIN 64821 was chosen as a synthetic target (Scheme 3).¹² The efficient construction of the 3a,3a'bispyrrolidino[2,3-*b*]indoline motif was the key to approach a concise total synthesis of (+)-WIN 64821. That could be conveniently realized by using our newly developed catalytic oxidative methodology. Initially, we synthesized the precursor **10** for the key reaction from commercially available (L)-tryptophan **9**. Then, compound **10** was successfully applied, at the gram-scale, to the KI-catalyzed oxidative coupling/cyclization reaction to give the 3a,3a'-bispyrrolidino[2,3-*b*]indoline **11** with satisfactory results (79% yield, 1.2 : 1 dr). Subsequent deprotections of *p*-nitrobenzene sulfonyl and allyl of **11** successively afforded the dimeric diamine **13**, which could be easily condensed with *N*-Cbz-L-phenylalanine over three steps^{4d,13} to finally give (+)-WIN 64821.

In conclusion, we have successfully established an iodidecatalyzed oxidative coupling/cyclization approach for the dimerization of tryptamine, tryptophol and tryptophan analogues. This protocol features a plausible catalytic cycle comprising iodide and hypoiodite catalyst states, the use of inexpensive and readily available as well as an environmentally benign system (KI and NaBO₃·4H₂O) and mild reaction conditions. Particularly, it provides a practical solution for the construction of synthetically challenging vicinal all-carbon quaternary motifs. Although it gives moderate diastereoselectivities in some cases, we have optimized it up to



>20:1 dr by adjusting the substituent at C₄ of the substrate. Furthermore, the synthetic utility of this methodology has been verified by the asymmetric total synthesis of bioactive natural product (+)-WIN 64821.

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Conflicts of interest

There are no conflicts to declare.

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