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Palladium/Xu-Phos-catalyzed asymmetric carboamination towards isoxazolidines and pyrrolidines†

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An efficient palladium-catalyzed enantioselective carboamination reaction of *N*-Boc-*O*-homoallyl-hydroxylamines and *N*-Boc-pent-4-enylamines with aryl or alkenyl bromides was developed, delivering various substituted isoxazolidines and pyrrolidines in good yields with up to 97% ee. The reaction features mild conditions, general substrate scope and scalability. The obtained products can be transformed into chiral 1,3-aminoalcohol derivatives without erosion of chirality. The newly identified Xu-Phos ligand bearing an *ortho*-*O*ⁱPr group is responsible for the good yield and high enantioselectivity.

Introduction

Five-membered N-heterocyclic skeletons are commonly found in biological and pharmaceutical molecules (Fig. 1).¹ For example, pyrrolidine-based compounds can act as receptor antagonists, and their diverse activities are determined by the different configurations (eg 2 and 3).² Isoxazolidine is a versatile precursor for the synthesis of 1,3-amino alcohols, taking sitagliptin as a typical case (eg 5).³ Therefore, it is highly desirable to develop synthetic methods towards isoxazolidine and pyrrolidine compounds, especially for efficient construction of enantioenriched molecules.

Isoxazolidines could be furnished by 1,3-dipolar cycloaddition reactions or cyclization of unsaturated hydroxylamines proceeding through electrophilic or free radical pathways, Michael addition reactions *etc.*⁴ Transition metal catalyzed cyclization strategies have also been showcased in recent years using palladium or gold as common catalysts.⁵ In 2010, Toste^{6a} reported the Au(I)-catalyzed enantioselective synthesis of isoxazolidines from allenic hydroxylamines, which could be also extended for the preparation of pyrazolidines and tetrahydroxazines with high enantioselectivity (Scheme 1a). Recently, Gao and co-workers reported a tandem aza-Michael/hemiacetal

reaction between (*E*)-4-phenylbut-2-enal and *N*-Boc-hydroxylamine for the synthesis of 2-hydroxyl-isoxazolidines (Scheme 1b).³ The Wolfe group reported an elegant palladium-catalyzed carboamination of alkenes, which provides facile access to enantioenriched pyrrolidines (Scheme 1c).⁷ Recently, Zhang and co-workers⁸ also implemented an enantioselective radical cyclization approach by metalloradical C–H alkylation reactions (Scheme 1d).

Despite the above advances, the development of an efficient methodology for N-heterocyclic skeletons with high enantioselectivity is of great importance and still challenging, especially for the introduction of an alkenyl group. Based on our interests in the asymmetric synthesis of heterocyclic compounds,⁹ herein we wish to report our efforts in the development of palladium-catalyzed intermolecular carboamination of unsaturated hydroxylamines with aryl or alkenyl halides, in which the newly identified (*S*,*R*)-**Xu4** bearing an *ortho*-*O*ⁱPr group ligand showed a unique effect, leading to substituted isoxazolidines in relatively high yield and selectivity. Moreover, pyrrolidines could

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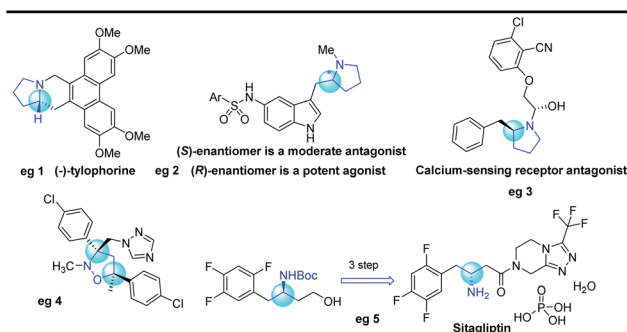
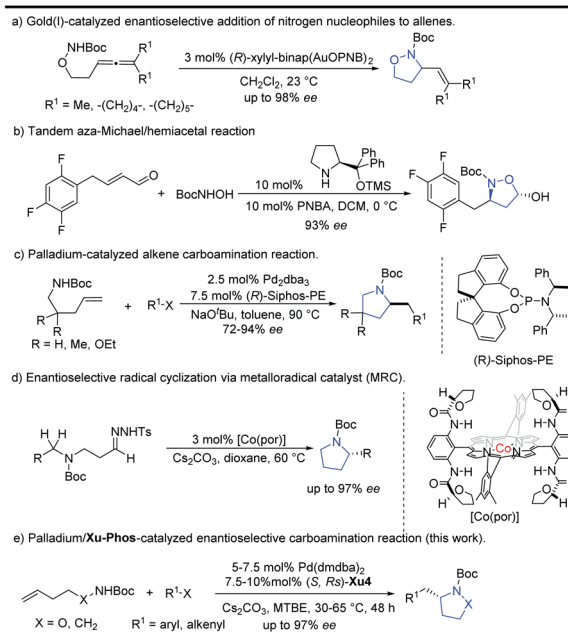


Fig. 1 Biologically active molecules with pyrrolidine and isoxazolidine motifs.



Scheme 1 Enantioselective synthesis of isoxazolidines and pyrrolidines.

also be synthesized efficiently starting from the corresponding carbamates.

Results and discussion

In our initial study, *N*-Boc-*O*-homoallyl-hydroxylamine **1a** and 4-bromobiphenyl were selected as the model substrates. A series of commercially available chiral ligands were investigated at first (Fig. 2). Although **L1** afforded the desired product **3a** with moderate enantioselectivity, other bisphosphine ligands **L2–L5** suppressed the reaction, with no or only a small amount of **3a**

detected. The desired product could be obtained in low yield with poor enantioselectivity when using chiral phosphoramidite ligand **L6**, but **L7** is not effective at all. Josiphos **L8** delivered the product **3a** with moderate yield but as a close to racemic mixture. The phosphos derivative **L9** is not effective for this reaction.

Inspired by the success of our developed Sadphos ligands in asymmetric catalysis, we turned our attention to evaluate their performance in the present carboamination reaction. Of note, the Sadphos kits are commercially available from Strem Inc. now. As an initial trial, Ming-Phos^{9h,10} (*S,Rs*)-**M1** with free NH was inactive, leaving the starting materials untouched. Surprisingly, when the amine moiety was protected by a methyl group (*S,Rs*)-**M2**, **3a** was obtained in 75% yield, albeit the enantioselectivity was unsatisfactory, indicating that the NH moiety of Ming-Phos might inhibit carboamination. The dicyclohexyl phosphine ligand Xu-Phos¹¹ showed a consistent trend, and (*S,Rs*)-**Xu2** bearing a *N*-methyl group resulted in higher yield and enantioselectivity. Inspired by these notable results, we investigated the modification of Xu-Phos ligand. (*S,Rs*)-**Xu3** bearing a 3,5-di-*tert*-butyl-4-methoxybenzyl group did not provide a better result. Amazingly, the introduction of *O*ⁱPr at the *ortho*-position of the phosphine moiety dramatically improved the enantioselectivity, delivering **3a** in 84% yield and 92% ee.¹³ These results unambiguously prove the subtleness and unique efficacy of the Xu-Phos ligands. We attribute this *ortho*-effect to the repulsion of the iso-propyl group with the cyclohexyl group on the P-atom, which would push the cyclohexyl group close to the catalytic center and affect the enantioselectivity.

Table 1 Optimization of the reaction conditions^a

Entry	Pd sources	Base	Solvent	Yield ^b (%)	ee ^c (%)
1	PdCl ₂	Cs ₂ CO ₃	MTBE	55	85
2	Pd(OAc) ₂	Cs ₂ CO ₃	MTBE	64	80
3	Pd(MeCN) ₂ Cl ₂	Cs ₂ CO ₃	MTBE	24	91
4 ^f	[Pd(allyl)Cl] ₂	Cs ₂ CO ₃	MTBE	70	92
5 ^f	Pd ₂ (dba) ₃	Cs ₂ CO ₃	MTBE	82	92
6	Pd(dmdba) ₂	Cs ₂ CO ₃	MTBE	84	92
7	Pd(dmdba) ₂	Na ^t Bu	MTBE	49	90
8	Pd(dmdba) ₂	KO ^t Bu	MTBE	38	91
9	Pd(dmdba) ₂	K ₂ CO ₃	MTBE	40	91
10	Pd(dmdba) ₂	Cs ₂ CO ₃	Toluene	59	89
11	Pd(dmdba) ₂	Cs ₂ CO ₃	THF	78	90
12	Pd(dmdba) ₂	Cs ₂ CO ₃	DCM	79	88
13	Pd(dmdba) ₂	Cs ₂ CO ₃	MeCN	63	86
14	Pd(dmdba) ₂	Cs ₂ CO ₃	DMF	79	89
15 ^d	Pd(dmdba) ₂	Cs ₂ CO ₃	MTBE	82	93
16 ^e	Pd(dmdba) ₂	Cs ₂ CO ₃	MTBE	88	95

^a Reaction conditions: **1a** (0.2 mmol), 4-bromobiphenyl (0.4 mmol), Cs₂CO₃ (2 equiv.), 5 mol% Pd, and 7.5 mol% ligand in 2.0 mL MTBE at 75 °C under Ar for 24 h. ^b Isolated yield. ^c ee was determined by HPLC analysis. ^d 50 °C, 24 h. ^e 30 °C, 48 h. ^f 2.5 mol% Pd.

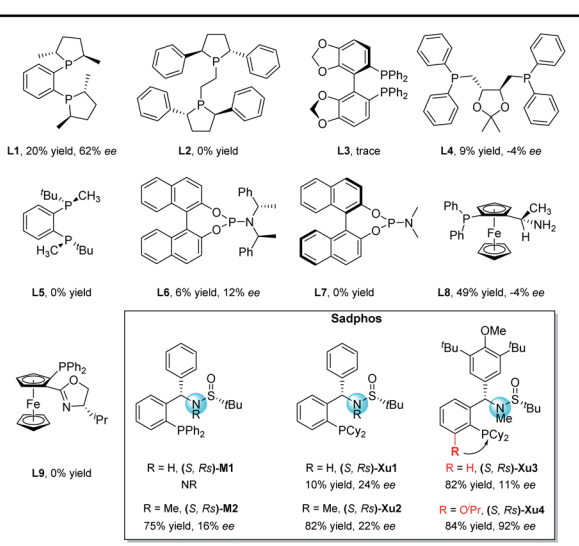


Fig. 2 Representative chiral ligands tested in this work.



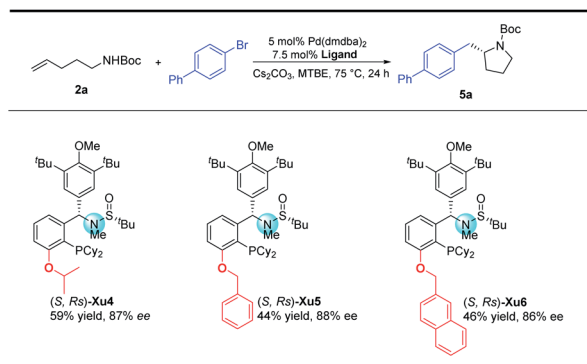
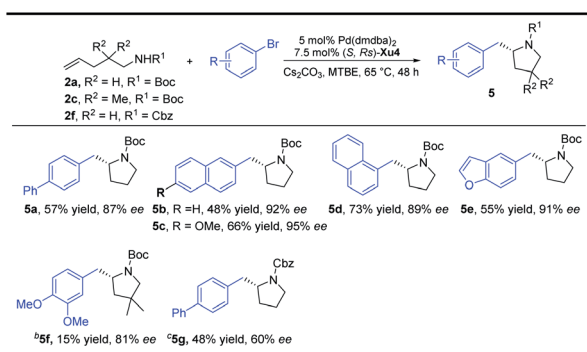


Fig. 3 Screening ligands in the synthesis of pyrrolidines.

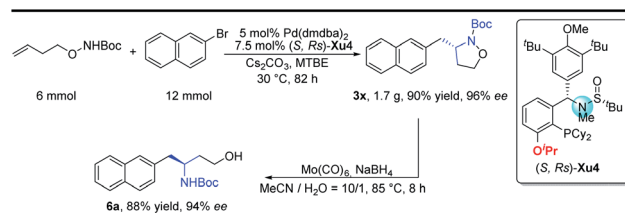
group (**5e**) could also be introduced into the final product easily. We next investigated the substituent effect on the alkyl chain and the corresponding product **5f** was produced in low yield (15%) and relatively lower enantioselectivity (81% ee). The amide moiety also affects the reaction significantly, for instance, the Cbz-derived **5g** was delivered in only 48% yield with 60% ee. The tosylated substrate produced the corresponding *N*-arylation product rather than the carboamination product, indicating that these two reaction pathways are competitive.

To demonstrate the practicability of our protocol, a 6 mmol scale reaction was carried out under standard conditions, delivering 1.7 g of naphthyl isoxazolidine **3x** in 90% yield with 96% ee. Further treatment with NaBH_4 furnished chiral aminoalcohol **9a** in 88% yield with 94% ee (Scheme 4).¹²

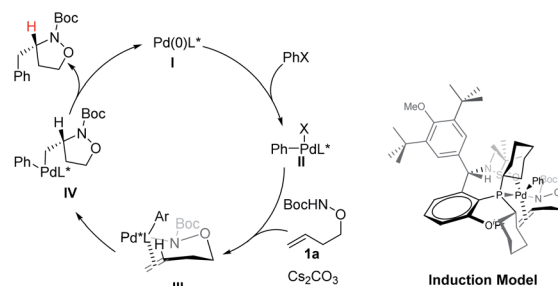
A catalytic cycle and asymmetric induction model were proposed in Scheme 5. The oxidative addition of aryl bromides to the $(S,Rs)\text{-Xu4}/\text{Pd}(0)$ complex would generate $\text{Pd}(\text{II})$ species **II**. In the presence of a base, species **II** would form a Pd-N bond to deliver the intermediate **III**, which undergoes insertion or aminopalladation of the alkene to produce the intermediate **IV**. The final product was obtained *via* reductive elimination, and the catalytic species were also regenerated. Xu-Phos and Pd



Scheme 3 Synthesis of substituted pyrrolidines. ^aUnless otherwise noted, all reactions were carried out with **2a** (0.4 mmol), aryl bromides (0.8 mmol), Cs_2CO_3 (2 equiv.), 5 mol% Pd(dmdba)_2 and 7.5 mol% ligand in 4.0 mL MTBE at 65°C under Ar for 48 h. ^b**2c** (0.2 mmol), 20 h. ^c**2f** (0.2 mmol), 24 h.



Scheme 4 Gram-scale synthesis and synthetic applications.



Scheme 5 Catalytic cycle and chirality induction model.

coordinate through P on the ligand and O on the sulfonamide to form the corresponding catalytic center. The cyclohexyl group is in the sensitive area of metal active species. The introduction of O^iPr as a side arm group may push the cyclohexyl group closer to the catalytic center and produce a key dynamic steric hindrance effect.

Conclusions

In summary, we have successfully developed a palladium-catalyzed asymmetric carboamination reaction of *N*-Boc-*O*-homallyl-hydroxylamine and *N*-Boc-pent-4-enylamine with either aryl or alkenyl bromides under mild reaction conditions, furnishing various substituted isoxazolidines and pyrrolidines in moderate to high yields with high enantioselectivity. The newly identified ligand of $(S,Rs)\text{-Xu4}$ with O^iPr at the *ortho*-position, which is easily prepared from commercially available starting materials, is responsible for the general substrate scope, good yield and high enantioselectivity. The application of this chiral ligand in other transition metal asymmetric reactions is ongoing in our lab.

Author contributions

Y. Wang, L. Wang, M. Chen and Tu did the experiments and collected the data. Y. Liu and J. Zhang directed the research. Y. Wang, Y. Liu and J. Zhang wrote the manuscript.

Conflicts of interest

There are no conflicts to declare.



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- CCDC: 2053552 (**3r**) and 2053557 (**(S,Rs)-Xu4**). Please find the detailed crystal data in the supporting information.†

