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Asymmetric Catalysis

Palladium-Catalyzed Enantioselective Decarboxylative Cycloaddition of Vinylethylene Carbonates with Isocyanates

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Abstract: An efficient method for the enantioselective construction of β-substituted β-vinylglycinol derivatives through palladium-catalyzed decarboxylative cycloaddition of vinylethylene carbonates with isocyanates was developed. By using a palladium complex generated in situ from $[Pd_2(dba)_3]\cdot CHCl_3$ (dba = dibenzylideneacetone) and (*S*)-Segphos as a catalyst under mild reaction conditions, the process provided 4-substituted-4-vinyloxazolidin-2-ones in high yields with a high level of enantioselectivity. The stereochemical outcome of the reaction was explained by DFT calculations and the synthetic utility of the process was demonstrated by the gram-scale transformation and formal synthesis of MK-0731 as a kinesin spindle protein inhibitor.

The development of enantioselective transformations that enable rapid access to multifunctional chiral molecules is a principal goal in asymmetric catalysis. Optically active β-substituted β-vinylglycinols are important chiral building blocks for a wide variety of medicinally relevant agents and natural products, such as the immunosuppressant myriocin,[1] manzacidins,[2] neurokinin receptor antagonist rolapitant,[3] and a kinesin spindle protein inhibitor MK-0731[4] as a potential drug for the treatment of taxane-refractory cancers (Figure 1). They are also highly useful precursors of biologically valuable quaternary amino acids, such as quaternary vinylglycines[5] and α-substituted serines.[6] In this context, various methods for the asymmetric synthesis of β-substituted β-vinylglycinol derivatives have been developed. However, most of them are based on the stoichiometric use of a chiral auxiliary, chiral pool, or stereospecific methods.[7] In contrast, the catalytic enantioselective routes to these compounds are largely unexplored.[8] Pd-catalyzed cycloaddition of vinyloxiranes with isocyanates[9] and intramolecular cycloaddition of 2-buten-1,4-diol carbamates,[10] pioneered by Trost and Hayashi, respectively, are efficient methods for the synthesis of vinylglycinols. However, the asymmetric variants of the reactions are mostly unsatisfactory.[11] The related asymmetric transformations, such as the cycloaddition of vinyloxiranes with carbodiimides[11c] and imines[12] as well as direct amination of vinyloxiranes,[13] which have also been developed for the synthesis of enantioenriched vinylglycinol derivatives. Nevertheless, limited progress has been accomplished for the construction of β-substituted β-vinylglycinol derivatives,[11c,12,13] and the substrate of which has been limited to isoprene oxide. Therefore, the development of an efficient method for the enantioselective construction of β-vinylglycinols with diverse β-substituents is highly appealing.

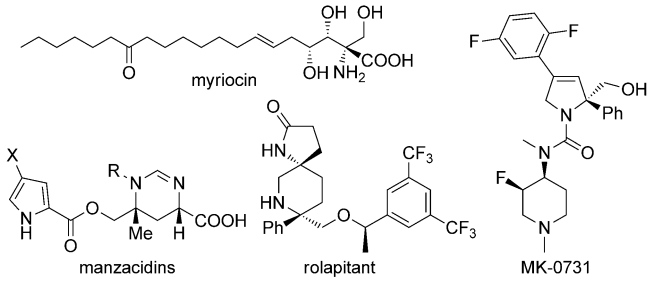

Figure 1. Representative medicinally relevant agents and natural products with β,β-disubstituted β-amino alcohols.

Transition-metal-catalyzed asymmetric interceptive decarboxylative allylations of allylic partners by unsaturated electrophiles are useful methods for the formation of multifunctionalized chiral building blocks.[14] Most recently, we disclosed a useful interceptive decarboxylative allylation processes using stable vinylethylene carbonates (VECs) as allylic donors and formaldehyde and activated Michael acceptors as interceptors.[15] The processes in the presence of chiral palladium–phosphoramidite complex as a catalyst afforded tertiary vinylglycols[15a] and multisubstituted tetrahydrofurans with vicinal all-carbon stereocenters[15b] in high yields with a high level of stereoselectivity. Based on these research results, we envisioned that β-substituted β-vinylglycinols could be constructed through the decarboxylative cycloaddition of VECs with isocyanates.[16] As illustrated in Scheme 1, the zwitterionic π-allylpalladium intermediate **A**, which is generated from VECs **1** through

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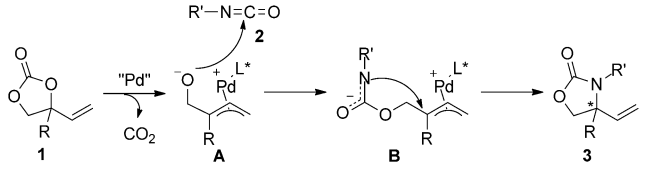


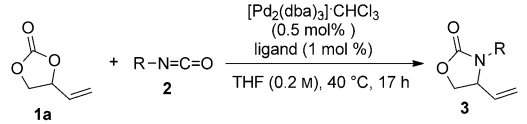
Scheme 1. Strategy for Pd-catalyzed decarboxylative cycloaddition of VECs **1** with isocyanates **2**.

a decarboxylative process, could attack isocyanates **2** to afford intermediate **B**. The subsequent cycloaddition could be feasible to form favored vinyloxazolidinones **3** as carbonyl-protected β-substituted β-vinylglycinols. Herein, we report the palladium-catalyzed asymmetric decarboxylative cycloaddition of VECs with isocyanates to construct 4-substituted-4-vinyloxazolidin-2-ones in high yields with a high level of enantioselectivity.

Initial studies focused on finding an effective chiral ligand for promoting the palladium-catalyzed decarboxylative cycloaddition. For this purpose, VEC **1a** and 2-methoxyphenylisocyanate (**2a**) were chosen as standard reaction partners because they are readily available commercial sources and the cycloadduct vinyloxazolidinone **3aa** is also a quite useful chiral building block.[11] Based on our previous research results,[15] we began our investigations by examining the cycloaddition of **1a** with **2a** by using phosphoramidite ligands (Table 1). To our delight, the reaction proceeded smoothly with phosphoramidite **L1** as a ligand to afford vinyloxazolidinone **3aa** in high yield with 94% *ee* (Table 1, entry 1). However, the diastereomeric phosphoramidite ligands **L2** and **L3** were less effective for the reaction (entries 2 and 3). Remarkably, the reaction could be further improved when using (*R*)-BINAP as a ligand, affording vinyloxazolidinone **3aa** in 97% yield with high enantioselectivity (95% *ee*, entry 4). By means of further screening of bisphosphine ligands (entries 5–9), we found that the reaction using (*R*)-Segphos as a ligand provided the best enantioselectivity (99% *ee*, entry 9). With the optimized conditions in hand, various phenylisocyanates containing different substituents was next examined. All of the reactions performed well, leading to the corresponding vinyloxazolidinones **3ab**–**ag** in good to excellent enantioselectivities (entries 10–15). Sterically demanding 2-substituted phenylisocyanates provided higher enantioselectivity than the 3- or 4-substituted analogues. However, low enantioselectivities were observed when the reactions were carried out with benzoylisocyanate **2h** and tosylisocyanate **2i** (entries 16 and 17).

With established 2-methoxyphenylisocyanate (**2a**) as the optimal electrophile, we subsequently turned our attention to the construction of vinyloxazolidinones bearing a quaternary stereocenter by the palladium-catalyzed decarboxylative cycloaddition of 4-substituted VECs with isocyanate **2a**. Gratifyingly, a wide range of 4-alkyl- and aryl-substituted VECs were tolerated in the reaction conditions affording the corresponding 4-substituted-4-vinyloxazolidin-2-ones **3** in acceptably high yields and enantioselectivities (Table 2). The reaction of 4-Me-VEC **1b** with **2a** by using a palladium complex generated in situ from $[Pd_2(dba)_3]$·$CHCl_3$ (dba = dibenzylideneacetone) and (*S*)-Segphos as a catalyst afforded cycloadduct **3ba** in 93% yield with 91% *ee*.[17] Interestingly, the absolute configuration of **3ba** is *S*-form which is an opposition configuration in comparison with the cycloaddition product **3aa** from VEC **1a**. The reactions of 4-alkyl substituted VECs **1c** and **1d** provided the corresponding vinyloxazolidinones **3ca** and **3da** in high yields with good enantioselectivities. Meaningfully, the cycloaddition reaction was also effective for more functionalized VECs bearing benzyl-protected hydroxymethyl **1e** and hydroxyethyl **1f**, as well as 3-butenyl **1g**, providing the corresponding highly functionalized vinyloxazolidinones **3ea**, **3fa**, and **3ga**, in which four different functional groups were located at one carbon stereogenic center. 4-Aryl VECs **1h**–**q** were also found to be suitable substrates, affording 4-aryl vinyloxazolidinones **3ha**–**qa** in good to excellent yields (61–95%) with high levels of enantio-

Table 1. Palladium-catalyzed asymmetric decarboxylative cycloaddition of **1a** with **2**.[a]



2a, R = 2-$MeOC_6H_4$; **2b**, R = 4-$MeOC_6H_4$; **2c**, R = 2-MeC_6H_4; **2d**, R = 3-MeC_6H_4; **2e**, R = 2,4-di$MeOC_6H_3$; **2f**, R = 2-$CF_3C_6H_4$; **2g**: R = 2-ClC_6H_4; **2h**, R = Bz; **2i**, R = Ts

Entry	2	Ligand	3	Yield [%][b]	*ee* [%][c]
1	**2a**	**L1**	**3aa**	88	94 (*R*)
2	**2a**	**L2**	**3aa**	49	74 (*R*)
3	**2a**	**L3**	**3aa**	39	14 (*R*)
4	**2a**	(*R*)-BINAP	**3aa**	97	95 (*S*)
5	**2a**	(*S*)-Tol-BINAP	**3aa**	95	94 (*R*)
6	**2a**	(*S*)-xylyl-BINAP	**3aa**	95	87 (*R*)
7	**2a**	(*S*)-H_8-BINAP	**3aa**	93	85 (*R*)
8	**2a**	(*R*)-Cl-MeO-BIPHEP	**3aa**	99	92 (*S*)
9	**2a**	(*R*)-Segphos	**3aa**	95	99 (*S*)
10	**2b**	(*S*)-Segphos	**3ab**	92	74 (*R*)
11	**2c**	(*S*)-Segphos	**3ac**	93	92 (*R*)
12	**2d**	(*R*)-Segphos	**3ad**	93	84 (*S*)
13	**2e**	(*R*)-Segphos	**3ae**	95	92 (*S*)
14	**2f**	(*R*)-Segphos	**3af**	93	88 (*S*)
15	**2g**	(*R*)-Segphos	**3ag**	89	95 (*S*)
16	**2h**	(*S*)-Segphos	**3ah**	94	37 (*R*)
17	**2i**	(*S*)-Segphos	**3aj**	90	40 (*R*)

[a] Reaction conditions: $[Pd_2(dba)_3]$·$CHCl_3$ (0.5 mol%), ligand (1 mol% for bisphosphanes; 2 mol% for phosphoramidites), **1a** (0.2 mmol), **2** (0.2 mmol), THF (1.0 mL), 40 °C, 17 h. [b] Yields are of isolated materials. [c] Determined by HPLC analysis using a chiral stationary phase. The absolute configurations of **3aa**–**aj** were determined by comparison of the sign of optical rotation with that in the reported data,[11e,f] or surmised by analogy. BINAP = 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl; H_8-BINAP = 2,2′-bis(diphenylphosphino)-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl; Cl-MeO-BIPHEP = 5,5′-dichloro-6,6′-dimethoxy-2,2′-bis(diphenylphosphino)-1,1′-biphenyl; Segphos = 5,5′-bis(diphenylphosphino)-4,4′-bi-1,3-benzodioxole; dba = dibenzylideneacetone.

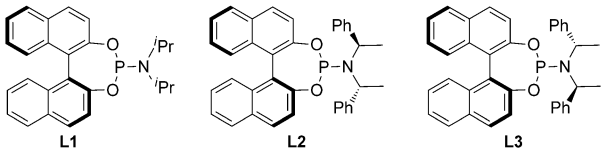
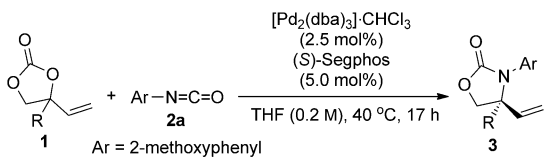
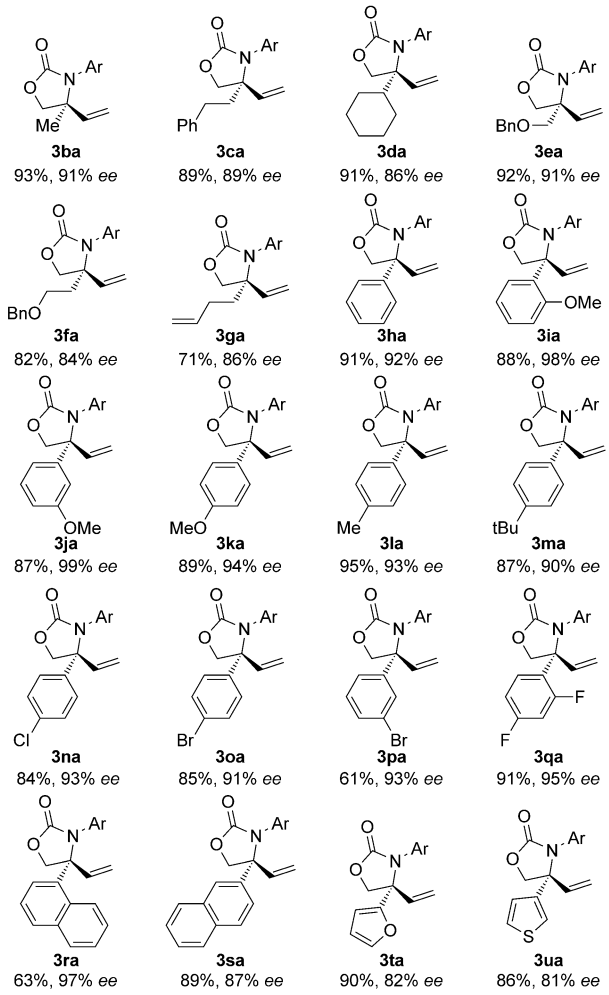


Table 2. Palladium-catalyzed asymmetric decarboxylative cycloaddition of 4-substituted VECs **1** with **2a**.[a]





[a] Reaction conditions: $[Pd_2(dba)_3]\cdot CHCl_3$ (2.5 mol%), (*S*)-Segphos (5 mol%), **1** (0.2 mmol), **2a** (0.2 mmol), THF (1.0 mL), 40 °C, 17 h. Yields are of isolated materials. Enantiomeric excesses were determined by HPLC analysis by using a chiral stationary phase. The determination of absolute configurations of **3ba** and **3ha** were described in the Supporting Information. Those of the other products were assigned by analogy. **1b**: R = Me, **1c**: R = $PhCH_2CH_2$, **1d**: R = cyclohexyl, **1e**: R = $BnOCH_2$, **1f**: R = $BnOCH_2CH_2$, **1g**: R = but-3-enyl, **1h**: R = Ph, **1i**: R = 2-$MeOC_6H_4$, **1j**: R = 3-$MeOC_6H_4$, **1k**: R = 4-$MeOC_6H_4$, **1l**: R = 4-MeC_6H_4, **1m**: R = 4-*t*BuC_6H_4, **1n**: R = 4-ClC_6H_4, **1o**: R = 4-BrC_6H_4, **1q**: R = 2,4-$diFC_{64}$, **1r**: R = 1-naphthyl, **1s**: R = 2-naphthyl, **1t**: R = 2-furanyl, **1u**: R = 3-thiophenyl.

selectivity (90–99% *ee*). The absolute configuration of **3ha** was determined as *R*-form, which indicated that it is formed through the same stereochemical mode with methyl-substituted **3ba** because of the change in priorities. The reaction of VECs with naphthyl group **1r** and **1s** were also effective to furnish the cycloadducts **3ra** and **3sa** in good yields with high enantioselectivities. In addition, the VECs with versatile furan **1t** and thiophene **1u** moieties were also suitable for the reaction conditions to afford the cycloadducts **3ta** and **3ua** in high yields with good enantioselectivities.

According to the proposed reaction pathway as revealed in Scheme 1, the final cycloaddition step might be the stereochemistry-determining step. To gain more information on the stereochemical outcome of the present process, DFT calculations were carried out by using the B3LYP/def2-TZVP method.[18] Considering that the cycloaddition products from 4-substituted VECs gave opposite stereochemistry with that obtained from H-VEC (**1a**), four plausible conformers of the π-allylpalladium-(*S*)-Segphos intermediate **B** from H-VEC (**1a**) (Figure 2) and that from Me-VEC (**1b**) (Figure 3) were chosen for the geometry optimizations (see the Supporting Information for details). In the case of H-VEC (**1a**), the π-allylpalladium intermediate $\mathbf{B}_{\text{H-VEC-}syn\text{-a}}$ bearing a *syn*-allylic unit (*syn* position between oxymethylene group and C2-proton of the allylic group) revealed much lower energy than the intermediate $\mathbf{B}_{\text{H-}}$

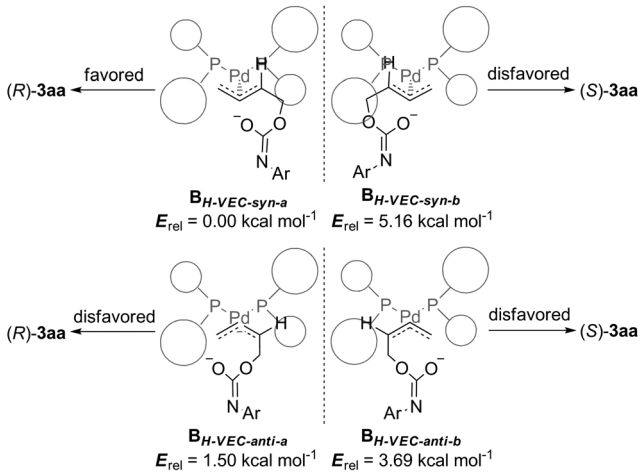


Figure 2. Stereochemical outcome by geometric optimization of plausible allylpalladium intermediates **B** from H-VEC (**1a**).

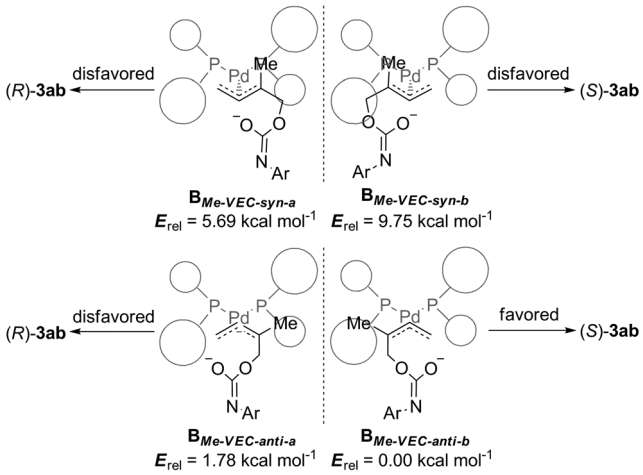
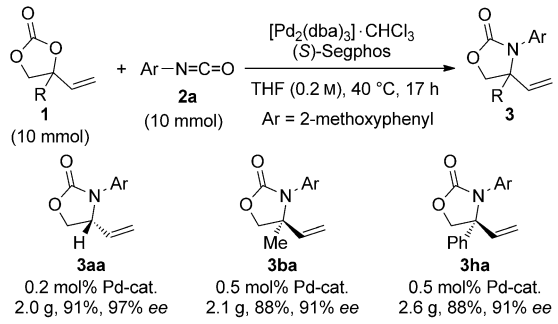


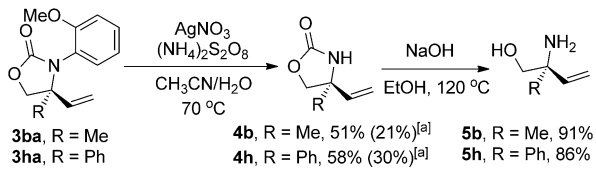
Figure 3. Stereochemical outcome by geometric optimization of plausible allylpalladium intermediates **B** from Me-VEC (**1b**).

$_{VEC\text{-}anti\text{-}b}$ bearing an *anti*-allyl unit (Figure 2). Thus, the reaction of **1a** with **2a** afforded (*R*)-**3aa** as the major enantiomer through a backside S_N2-type attack in the cycloaddition.[19] In contrast, for the π-allylpalladium intermediates from Me-VEC **1b**, the corresponding *syn* intermediates revealed much higher energy than the *anti* intermediates, and the *anti* intermediate $\mathbf{B}_{Me\text{-}VEC\text{-}anti\text{-}b}$ showed the lowest energy. Thus, affording (*S*)-**3ab** as the major enantiomer for the cycloaddition of Me-VEC (**1b**) is favorable. Although the true stereochemical outcome would be more complicated and the kinetic scenario of the reaction must be considered, opposite stereochemistry for the reaction of 4-substituted VECs in comparison with the reaction of H-VEC (**1a**) is convincing based on these DFT calculation results.[20]

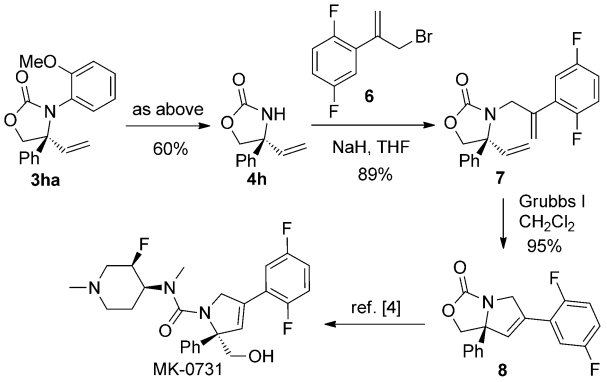
The synthetic versatility of the present protocol was demonstrated through the scale-up transformations, the conversion of cycloadducts into corresponding β-substituted β-vinylglycinols, and the formal synthesis of MK-0731 as a potential drug for the treatment of taxane-refractory cancers.[4] The present asymmetric decarboxylative cycloaddition reaction is quite scalable as demonstrated by the gram-scale syntheses of vinyloxazolidinones **3aa**, **3ba**, and **3ha** in high yields with high levels of enantioselectivity (Scheme 2). In the case of **3aa**, reducing the catalyst loading to 0.2 mol% still gave excellent efficiency. The vinyloxazolidinones **3** can be converted into the corresponding β-substituted β-vinylglycinols **5** through two-step deprotection processes (Scheme 3). The oxidative deprotection[21] of the *N*-aryl group of **3** was achieved with excess ammonium persulfate in the presence of a catalytic amount of $AgNO_3$ to afford vinyloxazolidinones **4** in moderate yields without deterioration of optical purity. Straightforward hydrolysis with NaOH in ethanol gave quaternary vinylglycinols **5** in high yields. More significantly, a short formal synthesis of MK-0731 was accomplished by using vinyloxazolidinone (*S*)-**3ha**, which was obtained from the cycloaddition of **1h** and **2a** with (*R*)-Segphos in 90% yield with 91% *ee*. As illustrated in Scheme 4, oxidative deprotection of (*S*)-**3ha** by using the above-mentioned method afforded (*S*)-**4h** in 60% yield, and subsequent *N*-alkylation with allylic bromide **6** furnished compound **7** in high yield. Straightforward ring-closing metathesis of **7** with the first generation of Grubbs catalyst provided bicyclic compound **8** in 95% yield. The compound **8** would be an advanced chiral intermediate in Merck's synthesis of MK-0731.[4]



Scheme 2. Scaled-up Pd-catalyzed asymmetric decarboxylative cycloaddition of VECs **1** with **2a**.



Scheme 3. Deprotection of **3** to β-substituted β-vinylglycinols **5**. [a] Yields of recovered starting materials within parenthesis.



Scheme 4. Formal synthesis of MK-0731.

In conclusion, we have developed an efficient method for the enantioselective construction of 4-substituted-4-vinyloxazolidin-2-ones as carbonyl-protected β-substituted β-vinylglycinols by Pd-catalyzed asymmetric decarboxylative cycloaddition of VECs with isocyanates. The reactions proceeded smoothly in the presence of $[Pd_2(dba)_3]\cdot CHCl_3$ and (*S*)-Segphos under the mild reaction conditions, providing vinyloxazolidinones **3** in high yields (up to 95%) with good to excellent enantioselectivities (81–99% *ee*). The stereochemical outcome of the process was explained by DFT calculations on the geometry optimizations of plausible reaction intermediates. In addition, the synthetic utility of the process was demonstrated by the gram-scale transformations, the deprotection of the cycloaddition products to β-substituted β-vinylglycinols, and the formal synthesis of MK-0731 as a potential drug for the treatment of taxane-refractory cancers. Further studies to extend the scope of the decarboxylative cycloaddition of VECs are currently underway and will be reported in due course.

Acknowledgements

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Keywords: amino alcohols · asymmetric catalysis · cycloaddition · palladium · substituted vinylglycinols

[1] a) T. Fujita, K. Inoue, S. Yamamoto, T. Ikumoto, S. Sasaki, R. Toyama, K. Chiba, Y. Hoshino, T. Okumoto, *J. Antibiot.* **1994**, *47*, 208 – 215; b) D. Kluepfel, J. Bagli, H. Baker, M.-P. Charest, A. Kudelski, S. N. Sehgal, C. Vezina, *J. Antibiot.* **1972**, *25*, 109 – 115.

[2] T. Hashimoto, K. Maruoka, *Org. Biomol. Chem.* **2008**, *6*, 829 – 835.

[3] R. A. Duffy, C. Morgan, R. Naylor, G. A. Higgins, G. B. Varty, J. E. Lachowicz, E. M. Parker, *Pharmacol. Biochem. Behav.* **2012**, *102*, 95 – 100.

[4] C. D. Cox, P. J. Coleman, M. J. Breslin, D. B. Whitman, R. M. Garbaccio, M. E. Fraley, C. A. Buser, E. S. Walsh, K. Hamilton, M. D. Schaber, R. B. Lobell, W. Tao, J. P. Davide, R. E. Diehl, M. T. Abrams, V. J. South, H. E. Huber, M. Torrent, T. Prueksaritanont, C. Li, D. E. Slaughter, E. Mahan, C. Fernandez-Metzler, Y. Yan, L. C. Kuo, N. E. Kohl, G. D. Hartman, *J. Med. Chem.* **2008**, *51*, 4239 – 4252.

[5] Quaternary vinylglycines are potential inhibitors of pyridoxal phosphate-dependent decarboxylases or retroaldolases, see: a) D. B. Berkowitz, K. R. Karukurichi, R. de La Salud-Bea, G. Maiti, J. M. McFadden, M. L. Morris, *ACS Symp. Ser.* **2009**, *1009*, 288 – 303; b) K. R. Karukurichi, R. De La Salud-Bea, W. J. Jahng, D. B. Berkowitz, *J. Am. Chem. Soc.* **2007**, *129*, 258 – 259.

[6] a) C. Cativiela, M. D. Díaz-de-Villegas, *Tetrahedron: Asymmetry* **2007**, *18*, 569 – 623; b) S. H. Kang, S. Y. Kang, H.-S. Lee, A. J. Buglass, *Chem. Rev.* **2005**, *105*, 4537 – 4558; c) Y. Ohfune, T. Shinada, *Eur. J. Org. Chem.* **2005**, 5127 – 5143.

[7] For selected recent examples, see: a) A. Armstrong, D. P. G. Emmerson, *Org. Lett.* **2011**, *13*, 1040 – 1043; b) M. C. Jones, S. P. Marsden, *Org. Lett.* **2008**, *10*, 4125 – 4128; c) M. C. Jones, S. P. Marsden, D. M. Muñoz Subtil, *Org. Lett.* **2006**, *8*, 5509 – 5512; d) A. Armstrong, L. Challinor, R. S. Cooke, J. H. Moir, N. R. Treweeke, *J. Org. Chem.* **2006**, *71*, 4028 – 4030; e) J. Murga, R. Portolés, E. Falomir, M. Carda, J. A. Marcom, *Tetrahedron: Asymmetry* **2005**, *16*, 1807 – 1816; f) P. Wipf, C. R. J. Stephenson, *Org. Lett.* **2003**, *5*, 2449 – 2452; g) D. B. Berkowitz, E. Chisowa, J. M. McFadden, *Tetrahedron* **2001**, *57*, 6329 – 6343; h) D. Ma, W. Zhu, *J. Org. Chem.* **2001**, *66*, 348 – 350; i) D. B. Berkowitz, J. M. McFadden, E. Chisowa, C. L. Semerad, *J. Am. Chem. Soc.* **2000**, *122*, 11031 – 11032.

[8] a) J. S. Arnold, H. M. Nguyen, *J. Am. Chem. Soc.* **2012**, *134*, 8380 – 8383; b) G. Jiang, R. Halder, Y. Fang, B. List, *Angew. Chem. Int. Ed.* **2011**, *50*, 9752 – 9755; *Angew. Chem.* **2011**, *123*, 9926 – 9929; c) D. F. Fischer, Z.-Q. Xin, R. Peters, *Angew. Chem. Int. Ed.* **2007**, *46*, 7704 – 7707; *Angew. Chem.* **2007**, *119*, 7848 – 7851; d) S. Masumoto, H. Usuda, M. Suzuki, M. Kanai, M. Shibasaki, *J. Am. Chem. Soc.* **2003**, *125*, 5634 – 5635.

[9] a) B. M. Trost, A. R. Sudhakar, *J. Am. Chem. Soc.* **1988**, *110*, 7933 – 7935; b) B. M. Trost, A. R. Sudhakar, *J. Am. Chem. Soc.* **1987**, *109*, 3792 – 3794.

[10] T. Hayashi, A. Yamamoto, Y. Ito, *Tetrahedron Lett.* **1987**, *28*, 4837 – 4840.

[11] a) M. Raghunath, X. Zhang, *Tetrahedron Lett.* **2005**, *46*, 8213 – 8216; b) B. M. Trost, R. C. Bunt, R. C. Lemoine, T. L. Calkins, *J. Am. Chem. Soc.* **2000**, *122*, 5968 – 5976; c) C. Larksarp, H. Alper, *J. Am. Chem. Soc.* **1997**, *119*, 3709 – 3715; d) S. F. Kirsch, L. E. Overman, *J. Org. Chem.* **2005**, *70*, 2859 – 2861; e) L. E. Overman, T. P. Remarchuk, *J. Am. Chem. Soc.* **2002**, *124*, 12 – 13; f) D. B. Berkowitz, G. Maiti, *Org. Lett.* **2004**, *6*, 2661 – 2664; g) T. Hayashi, A. Yamamoto, Y. Ito, *Tetrahedron Lett.* **1988**, *29*, 99 – 102.

[12] M. B. Shaghafi, R. E. Grote, E. R. Jarvo, *Org. Lett.* **2011**, *13*, 5188 – 5191.

[13] a) B. M. Trost, C. Jiang, K. Hammer, *Synthesis* **2005**, 3335 – 3345; b) ref. 11b.

[14] a) For reviews, see: J. D. Weaver, A. Recio, III, A. J. Grenning, J. A. Tunge, *Chem. Rev.* **2011**, *111*, 1846 – 1913. For examples, see: b) J. Streuff, D. E. White, S. C. Virgil, B. M. Stoltz, *Nat. Chem.* **2010**, *2*, 192 – 196; c) R. Shintani, M. Murakami, T. Tsuji, H. Tanno, T. Hayashi, *Org. Lett.* **2009**, *11*, 5642 – 5645; d) R. Shintani, S.-y. Hayashi, M. Murakami, M. Takeda, T. Hayashi, *Org. Lett.* **2009**, *11*, 3754 – 3756; e) R. Shintani, M. Murakami, T. Hayashi, *Pure Appl. Chem.* **2008**, *80*, 1135 – 1140; f) R. Shintani, S. Park, F. Shirozu, M. Murakami, T. Hayashi, *J. Am. Chem. Soc.* **2008**, *130*, 16174 – 16175; g) C. Wang, J. A. Tunge, *J. Am. Chem. Soc.* **2008**, *130*, 8118 – 8119; h) R. Shintani, M. Murakami, T. Hayashi, *J. Am. Chem. Soc.* **2007**, *129*, 12356 – 12357.

[15] a) A. Khan, R. Zheng, Y. Kan, J. Ye, J. Xing, Y. J. Zhang, *Angew. Chem. Int. Ed.* **2014**, *53*, 6439 – 6442; *Angew. Chem.* **2014**, *126*, 6557 – 6560; b) A. Khan, L. Yang, J. Xu, L. Y. Jin, Y. J. Zhang, *Angew. Chem. Int. Ed.* **2014**, *53*, 11257 – 11260; *Angew. Chem.* **2014**, *126*, 11439 – 11442.

[16] Tamaru and co-workers reported Pd-catalyzed nonasymmetric decarboxylative cycloaddition of six-membered cyclic carbonates with isocyanates, see: T. Bando, H. Harayama, Y. Fukazawa, M. Shiro, K. Fugami, S. Tanaka, Y. Tamaru, *J. Org. Chem.* **1994**, *59*, 1465 – 1474.

[17] For further screening of different ligands and solvents for the cycloaddition of **1b** and **2a** see the Supporting Information.

[18] a) A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648 – 5652; b) C. T. Lee, W. T. Yang, R. G. Parr, *Phys. Rev. B* **1988**, *37*, 785 – 789; c) P. J. Stephens, F. J. Devlin, C. F. Chabalowski, M. J. Frisch, *J. Phys. Chem.* **1994**, *98*, 11623 – 11627.

[19] a) B. M. Trost, D. R. Fandrick, *Aldrichimica Acta* **2007**, *40*, 59 – 72; b) B. M. Trost, M. L. Crawley, *Chem. Rev.* **2003**, *103*, 2921 – 2944; c) A. Pfaltz, M. Lautens, in *Comprehensive Asymmetric Catalysis Vol. II*; (Eds: E. N. Jacobsen, A. Pfaltz, H. Yamamoto), Springer, Berlin, **1999**, pp. 833 – 884.

[20] B. M. Trost, M. R. Machacek, A. Aponick, *Acc. Chem. Res.* **2006**, *39*, 747 – 760.

[21] K. Bhattarai, G. Cainelli, M. Panunzio, *Synlett* **1990**, 229 – 230.

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