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Cascade- and Orthoamide-Type Overman Rearrangements of Allylic Vicinal Diols

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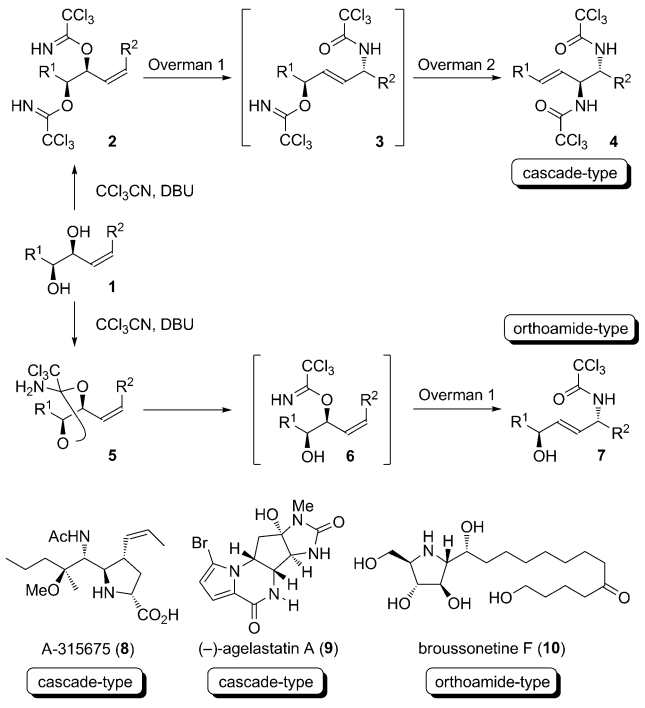
Abstract: This article describes the details of two new types of Overman rearrangement from allylic vicinal diols. Starting from identical diols, both bis(imidate)s and cyclic orthoamides were selectively synthesized by simply changing the reaction conditions. Whilst exposure of the bis(imidate)s to thermal conditions initiated the double Overman rearrangement to introduce two identical nitrogen groups in a single operation (the cascade-type Overman rearrangement), the reaction of cyclic orthoamides resulted in a single rearrangement (the orthoamide-type Overman rearrangement). The newly generated allylic alcohols from the orthoamide-type reaction can potentially undergo a variety of further transformations. For instance, we demonstrated an Overman/Claisen sequence in one pot. The most conspicuous feature of this method is that it offers precise control over the number of Overman rearrangements from the same allylic vicinal diols. This method also excludes the tedious protecting-group manipulations of the homoallylic alcohols, which are necessary in conventional Overman rearrangements. All of the performed rearrangements proceeded in a completely diastereoselective fashion through a chair-like transition state.

Keywords: allylic compounds · diastereoselectivity · diols · domino reactions · rearrangement

Introduction

The allylic trichloroacetimidate rearrangement (Overman rearrangement)[1] has been widely used as one of the most practical [3,3]-sigmatropic rearrangements[2] in organic synthesis. This reaction is extremely powerful and even proceeds with densely functionalized molecules. When imidates that are derived from chiral secondary or tertiary alcohols are employed, a chirality-transfer reaction[3] takes place through a well-defined chair-like transition state to provide enantiopure allylic amides.[1] The Overman rearrangement has been applied to a number of total syntheses of biologically active natural alkaloids.[4,5,6c,d] However, although most examples of the Overman rearrangement have been applied to allylic alcohols, the rearrangement of allylic vicinal diol **1** had been overlooked until our recent reports (Scheme 1).[5,6] Allylic vicinal diol **1** can give either a bis(imidate) (**2**) or a cyclic orthoamide (**5**) upon treatment with CCl_3CN and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU). Under thermal conditions, bis(imidate) **2** undergoes the first Overman rearrangement to provide compound **3**, which readily undergoes a second rearrangement in a single operation, thereby resulting in the formation of a doubly rearranged product (**4**, cascade-type Overman rearrangement).[5a,b,7] On the other hand, cyclic orthoamide **5** gives the singly rearranged product (**7**) through α-hydroxyimidate **6**.[5c,8] This method with



Scheme 1. Two types of Overman rearrangements of allylic vicinal diols (cascade-type and orthoamide-type) and their applications. DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene. Ac = acetyl.

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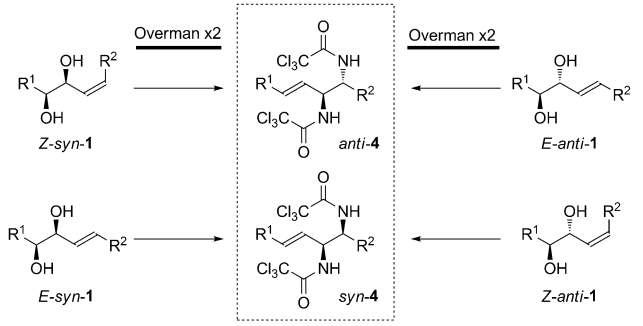
allylic vicinal diols has a number of salient synthetic features: First of all, enantiopure allylic vicinal diol **1** is readily available from naturally occurring polyols, such as carbohydrates, and Sharpless asymmetric dihydroxylation.[9] Second, the number of rearrangements can be precisely controlled by the selective formation of either bis(imidate) **2** or cyclic orthoamide **5**. The classical method for the synthesis of compounds **4** and **7** from allylic vicinal diol **1** requires the protection of the homoallylic alcohol group in compound **1** prior to the first rearrangement, with the second reaction performed after deprotection. However, our method can preclude extra protecting-group manipulations. One of the most practical advantages of this method is that it offers predictable stereochemical outcomes. That is, the stereochemistry can be engineered from considering the chair-like six-membered transition state and an appropriate combination of the stereochemistry of the two secondary alcohols and the geometry of the olefin. For example, as shown in Scheme 2, although the cascade-type Overman rearrangement of both (*Z*)-*syn*-**1** and (*E*)-*anti*-**1** would both give *anti*-**4**, the reactions of both (*E*)-*syn*-**1** and (*Z*)-*anti*-**1** would result in the formation of *syn*-**4**. This method is highly practical and has enabled the enantioselective total synthesis of various biologically active compounds: A-315675 (**8**)[5a] and (−)-agelastatin A (**9**)[5b] through cascade-type Overman rearrangements, and broussonetine F (**10**)[5c] through orthoamide-type Overman rearrangements. Herein, we now provide full details of our investigations on these new Overman rearrangements of allylic vicinal diols.

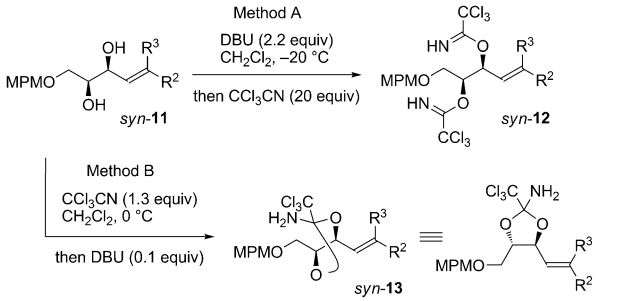


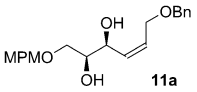
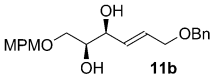
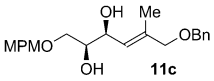
Scheme 2. The stereochemical relationship between the allylic vicinal diols (**1**) and the products (**4**) in the cascade-type Overman rearrangement.

Results and Discussion

Precise control over the number of Overman rearrangements from identical allylic vicinal diols requires flexible reaction conditions to form either bis(imidate)s or cyclic orthoamides. Our investigation to find such conditions commenced with optimization by using *syn*-diol **11**[10] (Table 1). Mechanistically, the treatment of *syn*-diol **11** with CCl_3CN in the presence of DBU initiates the formation of the α-hydroxyimidate, although we have no evidence for which alcohol reacts first. If the second intermolecular reaction with CCl_3CN is faster than the intramolecular cyclization reaction to form *syn*-cyclic orthoamide **13**, *syn*-bis(imidate) **12** can be selectively generated. Indeed, when excess CCl_3CN (20 equiv) was quickly added to a vigorously stirring solution of diols **11a**–**11c**, DBU (2.2 equiv), and CH_2Cl_2 (0.2 M) at −20 °C, bis(imidate)s **12a**–**12c** were selectively obtained in high yields, irrespective of the structure of the olefin (Table 1, method A, entries 1, 3, and 5). On the other hand, when the intramolecular cyclization of the α-hydroxyimidate dominates the second intermolecular reaction with CCl_3CN, *syn*-cyclic orthoamide **13** can be generated. The addition of a catalytic amount of DBU (10 mol %) to a solution of compounds **11a**–**11c**, CCl_3CN (1.3 equiv), and CH_2Cl_2 (0.05 M) at 0 °C resulted in the selective formation of cyclic orthoamides **13a**–**13c** as a 1:1 mixture of two diastereomers (Table 1, method B, entries 2, 4, and 6).

Table 1. Selective formation of bis(imidate)s (**12**) and cyclic orthoamides (**13**) from *syn*-vicinal diols (**11**).[a]

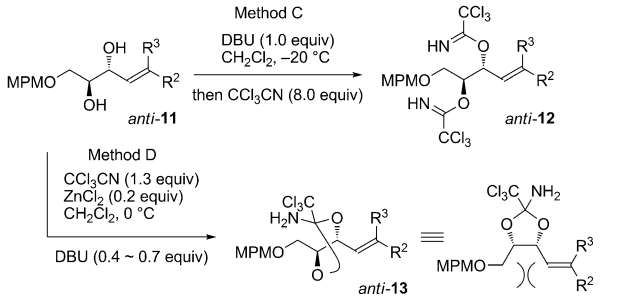


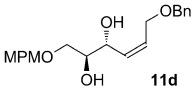
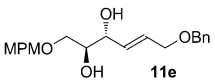
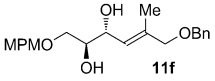
Entry	*syn*-**11**	Method	Yield [%][b]	d.r.[c]
1		A	82 (**12a**)	
2	**11a**	B	96 (**13a**)	1:1
3		A	84 (**12b**)	
4	**11b**	B	89 (**13b**)	1:1
5		A	86 (**12c**)	
6	**11c**	B	91 (**13c**)	1:1

[a] Method A: compound *syn*-**11** (100 μmol), DBU (2.2 equiv), CH_2Cl_2 (0.2 M), −20 °C, 15 min, then CCl_3CN (20 equiv), −20 °C, 1 h. Method B: compound *syn*-**11** (150 μmol), CCl_3CN (1.3 equiv), CH_2Cl_2 (0.05 M), 0 °C, 15 min, then DBU (0.1 equiv), 0 °C, 4 h. [b] Yield of isolated product after purification by column chromatography on silica gel. [c] Diastereomeric ratio was determined by ^1H NMR spectroscopy. Bn = benzyl, MPM = *p*-methoxybenzyl.

Compared with *syn*-diol **11**, the reaction of *anti*-diol **11**[10] was more prone to the formation of bis(imidate) **12** over cyclic orthoamide **13**, owing to steric repulsion between the two substituents in the five-membered cyclic orthoamide (**13**, Table 2). Therefore, the formation of *anti*-bis(imidate) **12** required less of the reagents (DBU (1.0 equiv) and CCl_3CN (8 equiv)) and afforded a higher yield than *syn*-bis(imidate) **12** (Table 2, method C, entries 1, 3, and 5). In contrast, the selective synthesis of *anti*-cyclic orthoamide **13** was

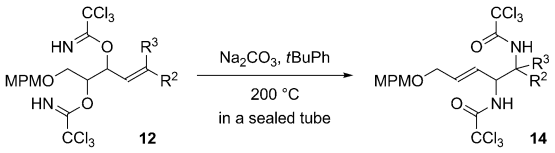
Table 2. Selective formation of bis(imidate)s (**12**) and cyclic orthoamides (**13**) from *anti*-vicinal diols (**11**).[a]

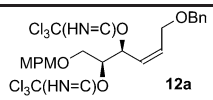
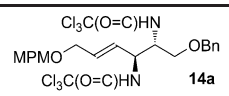
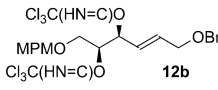
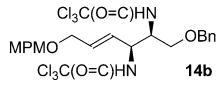
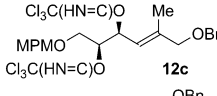
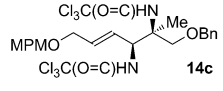
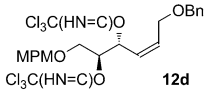
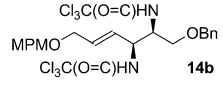
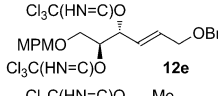
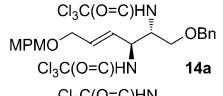
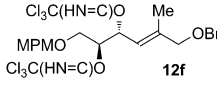
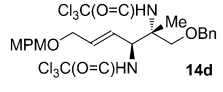


Entry	*anti*-**11**	Method	Yield [%][b]	d.r.
1	 **11d**	C	91 (**12d**)	
2		D	83 (**13d**)	single
3	 **11e**	C	90 (**12e**)	
4		D	84 (**13e**)	single
5	 **11f**	C	96 (**12f**)	
6		D	81 (**13f**)	single

[a] Method C: compound *anti*-**11** (100 μmol), DBU (1.0 equiv), CH_2Cl_2 (0.2 M), −20 °C, 15 min, then CCl_3CN (8.0 equiv), −20 °C, 30 min. Method D: compound *anti*-**11** (300 μmol), CCl_3CN (1.3 equiv), $ZnCl_2$ (0.2 equiv), CH_2Cl_2 (0.05 M), 0 °C, 15 min, then DBU (0.3–0.7 equiv), 0 °C, 4 days. [b] Yield of isolated product after purification by column chromatography on silica gel.

Table 3. Cascade-type Overman rearrangement.[a]



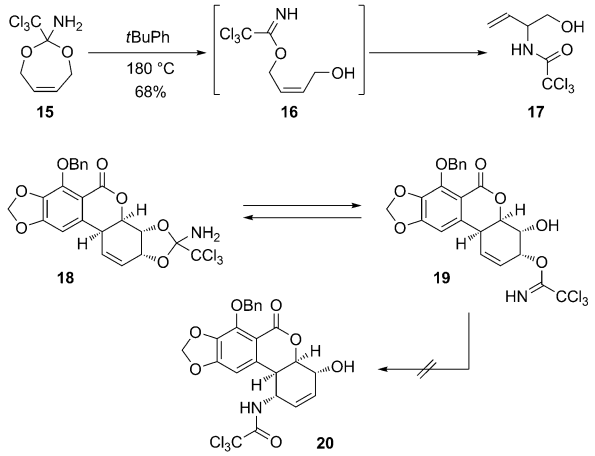
Entry	**12**	**14**	Yield [%][b]
1	 **12a**	 **14a**	95
2	 **12b**	 **14b**	89
3	 **12c**	 **14c**	90
4	 **12d**	 **14b**	73
5	 **12e**	 **14a**	95
6	 **12f**	 **14d**	81

[a] Compound **12** (60 μmol), Na_2CO_3 (0.4 equiv), *t*BuPh (0.03 M) in a sealed tube, 200 °C, 30–60 min. [b] Yield of isolated product after purification by column chromatography on silica gel.

not trivial. Application of method B, which was originally developed for *syn*-diol **11**, to *anti*-diol **11** resulted in the generation of a significant amount of undesired *anti*-bis(imidate) **12**. For example, the reaction of diol **11e** gave cyclic orthoamide **13e** in 45% yield, along with bis(imidate) **12e** in 44% yield. After extensive investigations, we found that the addition of a catalytic amount of $ZnCl_2$ (20 mol%) dramatically suppressed the formation of bis(imidate)s **12d**–**12f**, thus giving cyclic orthoamides **13d**–**13f** in high yields as single diastereomers (Table 2, method D, entries 2, 4, and 6).

With both *syn*- and *anti*-bis(imidate)s **12** in hand, we then investigated the cascade-type Overman rearrangement (Table 3). A solution of (*Z*)-*syn*-bis(imidate) **12a** and *tert*-butylbenzene in the presence of Na_2CO_3[11] was heated at 200 °C in a sealed tube, thus giving *anti*-bis(amide) **14a** in 95% yield (Table 3, entry 1). The reaction proceeded with complete diastereoselectivity. The reaction of (*E*)-*syn*-bis(imidate) **12b** also exhibited a high yield and high diastereoselectivity (Table 3, entry 2). Considering that both enantiomers of diols **12a** and **12b** are easily available,[10] all four possible stereoisomers of compound **14** can be synthesized as single diastereomers. The cascade reaction of trisubstituted olefin **12c** proceeded in 90% yield, thereby leading to the construction of two continuous stereocenters, including sterically hindered α-trisubstituted amines (Table 3, entry 3). These conditions were also applicable to *anti*-bis(imidate)s **12** (Table 3, entries 4–6).

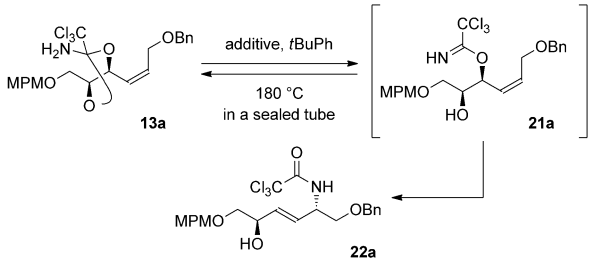
Having successfully developed the cascade-type reaction, we turned our attention to the more challenging orthoamide-type Overman rearrangement. When we started this program, only two reports relating to the orthoamide-type reaction had been documented, despite its synthetic utility (Scheme 3): Vyas et al. reported that the rearrangement of seven-membered cyclic orthoamide **15** gave compound **17** in 68% yield,[8a] whilst Danishefsky's group attempted the orthoamide-type Overman rearrangement of cyclic 1,2-diol **18**



Scheme 3. Precedents for the orthoamide-type Overman rearrangement.

in the total synthesis of (±)-pancratistatin.[8b] They reported that two diastereomers that were derived from the orthoamide group underwent equilibration upon thermolysis. However, no rearranged product (**20**) was produced. They proposed that one possible explanation for this result was that cyclic orthoamide **18** could open up to afford α-hydroxyimidate **19**, but that the rate of reclosure to afford compound **18** was much faster than the rearrangement step. We observed a similar phenomenon to Danishefsky's report (Table 4). A 1:1 diastereomeric mixture of cyclic orthoamide **13a** was separable by HPLC and an equilibrium was reached between two diastereomers in the same ratio after a few days at room temperature through α-hydroxyimidate **21a**. Indeed, the realization of the rearrangement was not trivial. After extensive investigation, we isolated rearranged product **22a** in only 17% yield after heating at 180°C in a sealed tube for 1 day. However, cyclic orthoamide **13a** had significantly decomposed, owing to the prolonged reaction time (Table 4, entry 1). Then, the effects of standard basic additives, such as K_2CO_3[12] and Na_2CO_3,[11] on the Overman rearrangement were investigated (Table 4, entries 2 and 3). Whilst the addition of K_2CO_3 led to a low yield, the less basic Na_2CO_3 had some positive effects in preventing the decomposition pathway. The addition of 500 wt.% 4 Å M.S. (molecular sieves) led to an increase in the yield (Table 4, entry 4). Finally, we found that BHT (2,6-di-*tert*-butylhydroxytoluene)[13,14] prevented the decomposition reaction to give compound **22a** in 19% yield, together with recovery of the starting material (**13a**) in 43% yield (Table 4, entry 5). Because large amounts of BHT suppressed the rate of the rearrangement itself, we found that the addition of 5 mol% BHT was the optimal amount, thus providing compound **22a** in 56% yield (77% yield based on recovered starting material; Table 4, entry 6).

Table 4. Optimization of the reaction conditions in the orthoamide-type Overman rearrangement.[a]

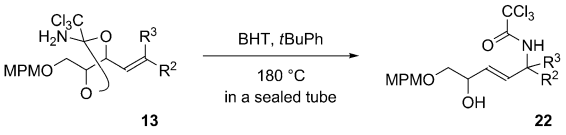


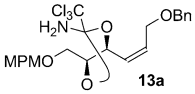
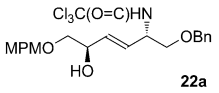
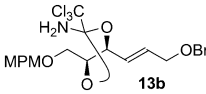
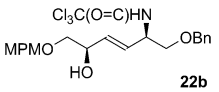
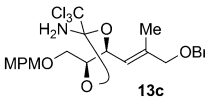
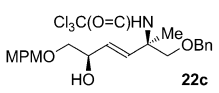
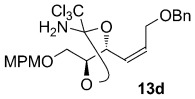
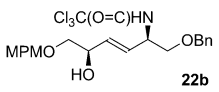
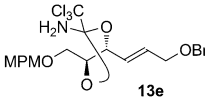
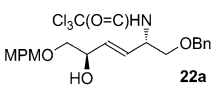
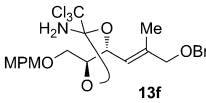
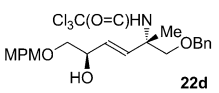
Entry	Additive	Yield [%][b]	
		22a	**13a**
1	none	17	0
2	K_2CO_3	8	54
3	Na_2CO_3	32	31
4	4 Å M.S.	48	28
5	BHT (100 mol%)	19	43
6	BHT (5 mol%)	56	27

[a] Compound **13a** (50 mmol), additive, *t*BuPh (0.03 M) in a sealed tube, 180°C, 1 d. [b] Yield of isolated product after purification by column chromatography on silica gel. BHT = 2,6-di-*tert*-butylhydroxytoluene.

With optimized conditions in hand, we investigated the scope of the reaction with a range of substrates (Table 5). In contrast to the cascade-type reaction, the yield of the orthoamide-type rearrangement depended on the structure of the substrates. The *E* olefins showed slightly higher yields than the *Z* olefins (Table 5, entry 1 vs. entry 2, and entry 4 vs. entry 5). The *anti*-cyclic orthoamides **13d** and **13e** exhibited better results than *syn*-orthoamides **13a** and **13b**, probably because *anti*-orthoamides **13d** and **13e** were prone to open up into the α-hydroxyimidates, as shown in Table 2 (Table 5, entry 1 vs. entry 4, and entry 2 vs. entry 5). Disappointingly, the reaction of trisubstituted olefins resulted in a significant decrease in yield because of the large degree of steric hindrance (Table 5, entries 3 and 6). Notably, all of the orthoamides that were tested (**13**) provided their corresponding stereoisomers (**22**) as a single product.

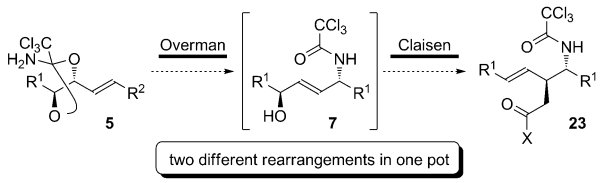
Table 5. Substrate scope in the orthoamide-type Overman rearrangement.[a]



Entry	**13**	**22**	Yield [%][b]
1	 **13a**	 **22a**	56
2	 **13b**	 **22b**	67
3	 **13c**	 **22c**	34
4	 **13d**	 **22b**	63
5	 **13e**	 **22a**	72
6	 **13f**	 **22d**	27

[a] Compound **13** (50 mmol), BHT (5 mol%), *t*BuPh (0.03 M) in a sealed tube, 180°C. [b] Yield of isolated product after purification by column chromatography on silica gel.

The orthoamide-type Overman rearrangement of compound **5** can lead to the construction of a carbon–nitrogen bond, along with the generation of a new allylic alcohol, which has the potential to undergo another [3,3]-sigmatropic rearrangement, such as the Claisen rearrangement (Scheme 4).[15] Namely, the orthoamide-type reaction would

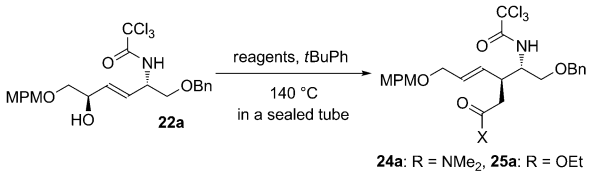


Scheme 4. One-pot sequential Overman/Claisen rearrangement.

enable us to perform two different rearrangements in one pot. If the Overman/Claisen sequence were successful, highly useful chiral building blocks **23** could be obtained from simple cyclic orthoamide **5**.

Although our final goal was the execution of two different rearrangements in a one-pot process, we first surveyed optimal conditions for the second Claisen rearrangement from allylic alcohol **22a** (Table 6). The reaction was performed

Table 6. Optimization of the reaction conditions in the Claisen rearrangement.



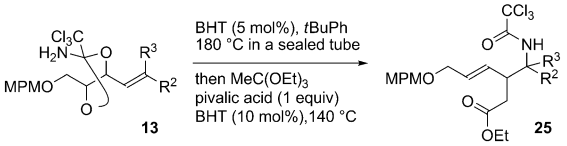
Entry	Reagents	Yield [%]
1	$MeC(OMe)_2NMe_2$	44 (**24a**)
2	$MeC(OEt)_3$, 2-nitrophenol	69 (**25a**)
3	$MeC(OEt)_3$, propionic acid	53 (**25a**)
4	$MeC(OEt)_3$, pivalic acid	71 (**25a**)
5	$MeC(OEt)_3$, pivalic acid, BHT (10 mol%)	77 (**25a**)

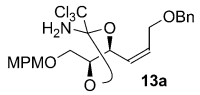
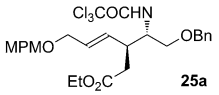
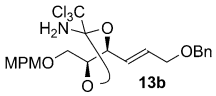
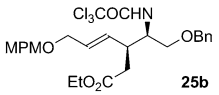
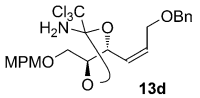
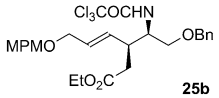
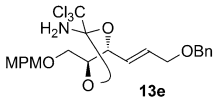
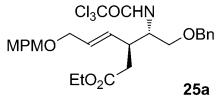
[a] Compound **22a** (30 mmol), $MeC(OMe)_2NMe_2$ or $MeC(OEt)_3$ (16 equiv), acid (1.0 equiv), *t*BuPh (0.03 M) in a sealed tube, 140 °C. [b] Yield of isolated product after purification by column chromatography on silica gel.

with identical solvent and reaction vessels as for the orthoamide-type Overman rearrangement. The use of Eschenmoser's conditions resulted in a low yield of the product (Table 6, entry 1) and so Johnson's conditions were employed in the presence of a variety of Brønsted acids,[16] thus revealing that pivalic acid was the best choice (Table 6, entries 2–4). A combination of pivalic acid and 10 mol% BHT, which was used in the orthoamide-type Overman rearrangement, resulted in a slight improvement in yield (Table 6, entry 5).

With the reaction conditions for the Claisen rearrangement established, we then implemented two different rearrangements in one pot (Table 7). After the completion of the first Overman rearrangement of cyclic orthoamides **13a**–**13e** at 180 °C, the reaction mixture was cooled to 140 °C and $MeC(OEt)_3$, pivalic acid, and 10 mol% BHT were added. Gratifyingly, the one-pot sequential reaction of

Table 7. Sequential one-pot Overman/Claisen rearrangement.

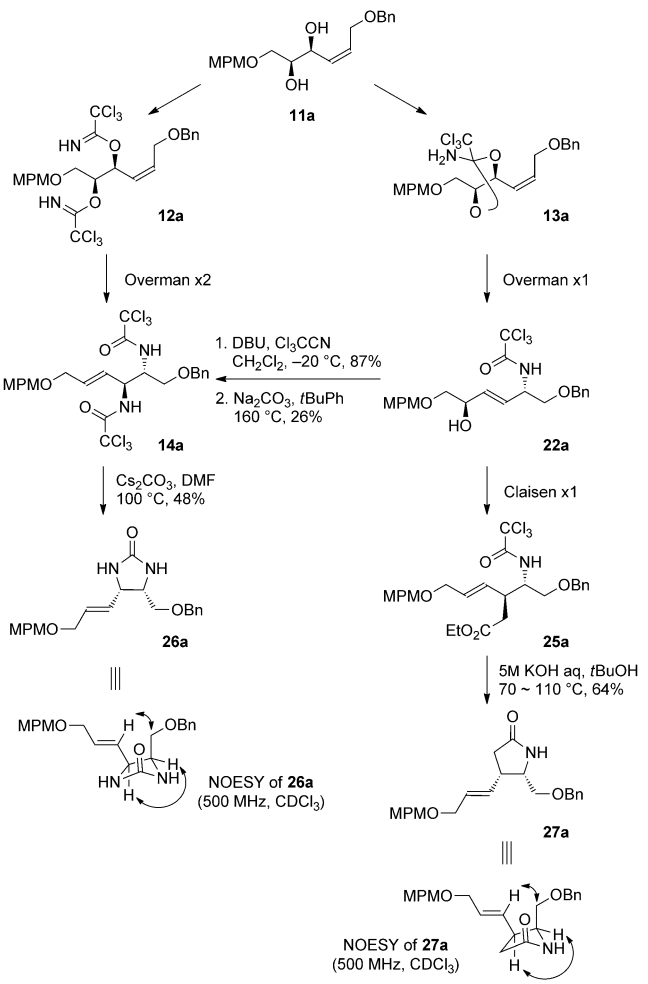


Entry	**13**	**25**	Yield [%]
1	 **13a**	 **25a**	45
2	 **13b**	 **25b**	54
3	 **13d**	 **25b**	54
4	 **13e**	 **25a**	55

[a] Compound **13** (50 mmol), BHT (5 mol%), *t*BuPh (0.03 M) in a sealed tube, 180 °C, 1–2 d, then $MeC(OEt)_3$ (16 equiv), pivalic acid (1.0 equiv), BHT (10 mol%), *t*BuPh (0.03 M) in a sealed tube, 140 °C. [b] Yield of isolated product after purification by column chromatography on silica gel.

orthoamides **13a**–**13e** smoothly took place, irrespective of the structure of the orthoamides (Table 7, entries 1–4). Here again, all of the products were obtained as single diastereomers. Thus, we accomplished the sequential stereoselective installation of carbon–nitrogen and carbon–carbon bonds in a one-pot reaction.

The stereochemistries of the newly generated carbon centers were unambiguously determined through their conversion into cyclic compounds. An example that was derived from (*Z*)-allylic *syn*-diol **11a** is shown in Scheme 5. The *anti*-bis(amide) **14a**, which was produced by the cascade-type Overman rearrangement of compound **12a**, was treated with Cs_2CO_3 in DMF at 100 °C[17] to afford cyclic urea **26a** in 48% yield. The stereochemistry of the resulting urea (**26a**) was convincingly confirmed by a NOESY experiment, which showed that the cascade-type Overman rearrangement indeed proceeded through a six-membered chair-like transition state. Singly rearranged product **22a** from cyclic orthoamide **13a** was converted into *anti*-bis(amide) **14a** upon exposure to the reaction conditions of the conventional Overman rearrangement. On the other hand, compound **25a**, which was synthesized by the sequential Overman/Claisen rearrangement of compound **13a**, was converted into γ-lactam **27a**. The treatment of compound **25a** with a 5 M aqueous solution of KOH and *t*BuOH at 70–110 °C gave 64% yield of γ-lactam **27a**, the NOESY spectrum of which clearly indicated that the rearrangement took place in a highly stereoselective manner, as expected.



Scheme 5. An example of the stereochemical determination of the rearranged products that were derived from (*Z*)-allylic *syn*-diol **11a**.

Conclusion

We have developed two new types of Overman rearrangements of allylic vicinal diols. Both bis(imidate)s and cyclic orthoamides were selectively synthesized from common allylic vicinal diols; the resulting intermediates underwent either cascade-type or orthoamide-type Overman rearrangements, respectively. Whereas the rearrangement of the bis(imidate)s established two contiguous carbon–nitrogen bonds in a single operation, the orthoamide-type rearrangement gave the singly rearranged products. The conspicuous features of our method are: 1) the ease of preparation of the chiral allylic vicinal diols; 2) precise control over the number of rearrangements from the same starting diols; 3) complete diastereoselectivity and predictable stereochemical outcomes; and 4) exclusion of the need for protecting-group manipulations on the homoallylic alcohol, which is a requisite in conventional Overman rearrangements. Furthermore, the newly generated allylic alcohols by the orthoamide-type rearrangements can undergo versatile transformations. As an example, we demonstrated the sequential Overman/Claisen rearrangement of cyclic orthoamides in one pot. The second Claisen rearrangement proceeded without isolation of the product of the first orthoamide-type Overman rearrangement, thus affording the installation of two different functional groups (Scheme 5).

Acknowledgements

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[1] a) L. E. Overman, *J. Am. Chem. Soc.* **1974**, *96*, 597–599. For a review on Overman rearrangements, see: b) L. E. Overman, N. E. Carpenter, in *Organic Reactions, Vol. 66* (Ed.: L. E. Overman), Wiley, New York, **2005**, pp. 1–107.

[2] For selected recent reviews on cascade, tandem, and domino reactions, including sigmatropic rearrangements, see: a) K. C. Nicolaou, D. J. Edmonds, P. G. Bulger, *Angew. Chem.* **2006**, *118*, 7292–7344; *Angew. Chem. Int. Ed.* **2006**, *45*, 7134–7186; b) H. Pellissier, *Tetrahedron* **2006**, *62*, 1619–1665; c) A. Padwa, S. K. Bur, *Tetrahedron* **2007**, *63*, 5341–5378; d) J. Poulin, C. M. Grisé-Bard, L. Barriault, *Chem. Soc. Rev.* **2009**, *38*, 3092–3101; e) E. A. Ilardi, C. E. Stivala, A. Zakarian, *Chem. Soc. Rev.* **2009**, *38*, 3133–3148.

[3] For selected reviews on chirality transfer through sigmatropic rearrangements, see: a) D. Enders, M. Knopp, R. Schiffers, *Tetrahedron: Asymmetry* **1996**, *7*, 1847–1882; b) U. Nubbemeyer, *Synthesis* **2003**, 961–1008.

[4] For selected recent reports on the synthesis of natural products and related compounds that utilize Overman rearrangements, see: a) T. Nishikawa, M. Asai, N. Ohyabu, N. Yamamoto, Y. Fukuda, M. Isobe, *Tetrahedron* **2001**, *57*, 3875–3883; b) T. Tsujimoto, T. Nishikawa, D. Urabe, M. Isobe, *Synlett* **2005**, 433–436; c) N. Ohyabu, T. Nishikawa, M. Isobe, *J. Am. Chem. Soc.* **2003**, *125*, 8798–8805; d) T. Nishikawa, D. Urabe, K. Yoshida, T. Iwabuchi, M. Asai, M. Isobe, *Chem. Eur. J.* **2004**, *10*, 452–462; e) H. Sato, T. Maeba, R. Yanase, A. Yamaji-Hasegawa, T. Kobayashi, N. Chida, *J. Antibiot.* **2005**, *58*, 37–49; f) A. E. Håkansson, A. Palmelund, H. Holm, R. Madsen, *Chem. Eur. J.* **2006**, *12*, 3243–3253; g) M. Matveenko, O. J. Kokas, M. G. Banwell, A. C. Willis, *Org. Lett.* **2007**, *9*, 3683–3685; h) H. Sato, K. Sato, M. Iida, H. Yamanaka, T. Oishi, N. Chida, *Tetrahedron Lett.* **2008**, *49*, 1943–1947; i) D. P. Dickson, D. J. Wardrop, *Org. Lett.* **2009**, *11*, 1341–1344; j) T. Momose, Y. Kaiya, J. Hasegawa, T. Sato, N. Chida, *Synthesis* **2009**, 2983–2991; k) H. Yamanaka, K. Sato, H. Sato, M. Iida, T. Oishi, N. Chida, *Tetrahedron* **2009**, *65*, 9188–9201; l) T. Imaoka, O. Iwamoto, K. Noguchi, K. Nagasawa, *Angew. Chem.* **2009**, *121*, 3857–3859; *Angew. Chem. Int. Ed.* **2009**, *48*, 3799–3801; m) T. Imaoka, T. Akimoto, O. Iwamoto, K. Nagasawa, *Chem. Asian J.* **2010**, *5*, 1810–1816; n) Y. Kaiya, J. Hasegawa, T. Momose, T. Sato, N. Chida, *Chem. Asian J.* **2011**, *6*, 209–219; o) N. D. Collett, R. G. Carter, *Org. Lett.* **2011**, *13*, 4144–4147; p) A. M. Zaed, A. Sutherland, *Org. Biomol. Chem.* **2011**, *9*, 8030–8037; q) K. Takahashi, D. Yamaguchi, J. Ishihara, S. Hatakeyama, *Org. Lett.* **2012**, *14*, 1644–1647.

[5] Part of this work was published as a preliminary account; see: a) T. Momose, N. Hama, C. Higashino, H. Sato, N. Chida, *Tetrahedron Lett.* **2008**, *49*, 1376–1379; b) N. Hama, T. Matsuda, T. Sato, N. Chida, *Org. Lett.* **2009**, *11*, 2687–2690; c) N. Hama, T. Aoki, S. Miwa, M. Yamazaki, T. Sato, N. Chida, *Org. Lett.* **2011**, *13*, 616–619.

[6] We have reported the cascade-type Claisen rearrangement of allylic vicinal diols in the total synthesis of (–)-morphine, see: a) H. Tanimoto, R. Saito, N. Chida, *Tetrahedron Lett.* **2008**, *49*, 358–362; b) M. Ichiki, H. Tanimoto, S. Miwa, R. Saito, T. Sato, N. Chida, *Chem. Eur. J.* **2013**, *19*, 264–269. We have also documented the developments in the orthoamide-type Claisen rearrangement and its application to the total synthesis of (–)-kainic acid; see: c) K. Kitamoto,

M. Sampei, Y. Nakayama, T. Sato, N. Chida, *Org. Lett.* **2010**, *12*, 5756–5759; d) K. Kitamoto, Y. Nakayama, M. Sampei, M. Ichiki, N. Furuya, T. Sato, N. Chida, *Eur. J. Org. Chem.* **2012**, 4217–4231. For a selected example of Claisen/Claisen rearrangements from other groups, see: e) D. P. Curran, Y.-G. Suh, *Carbohydr. Res.* **1987**, *171*, 161–191.

[7] For selected examples of sequential reactions that include Overman rearrangements from other groups, see: a) D. Villemin, M. Hachemi, *Synth. Commun.* **1996**, *26*, 1329–1334; b) K. Banert, W. Fendel, J. Schlott, *Angew. Chem.* **1998**, *110*, 3488–3491; *Angew. Chem. Int. Ed.* **1998**, *37*, 3289–3292; c) S. Demay, A. Kotschy, P. Knochel, *Synthesis* **2001**, 863–866; d) O. V. Singh, H. Han, *Org. Lett.* **2004**, *6*, 3067–3070.

[8] For pioneering works on the orthoamide-type Overman rearrangement of allylic diols, see: a) D. M. Vyas, Y. Chiang, T. W. Doyle, *J. Org. Chem.* **1984**, *49*, 2037–2039; b) S. Danishefsky, J. Y. Lee, *J. Am. Chem. Soc.* **1989**, *111*, 4829–4837.

[9] H. Becker, M. A. Soler, K. B. Sharpless, *Tetrahedron* **1995**, *51*, 1345–1376.

[10] For the synthesis of *syn*- and *anti*-allylic vicinal diols, see refs. [6c,d].

[11] C.-G. Cho, Y.-K. Lim, K.-S. Lee, I.-H. Jung, M.-Y. Yoon, *Synth. Commun.* **2000**, *30*, 1643–1650.

[12] T. Nishikawa, M. Asai, N. Ohyabu, M. Isobe, *J. Org. Chem.* **1998**, *63*, 188–192.

[13] J. Ammenn, K.-H. Altmann, D. Belluš, *Helv. Chim. Acta* **1997**, *80*, 1589–1606.

[14] We believe that BHT might suppress the decomposition pathway through a radical species.

[15] For selected reviews on Claisen rearrangements, see: a) A. M. M. Castro, *Chem. Rev.* **2004**, *104*, 2939–3002; b) K. C. Majumdar, S. Alam, B. Chattopadhyay, *Tetrahedron* **2008**, *64*, 597–643.

[16] We previously reported that the use of 2-nitrophenol improved the yield of the Claisen rearrangement; see: a) M. Bohno, K. Sugie, H. Imase, Y. B. Yusof, T. Oishi, N. Chida, *Tetrahedron* **2007**, *63*, 6977–6989; b) H. Tanimoto, T. Kato, N. Chida, *Tetrahedron Lett.* **2007**, *48*, 6267–6270; c) T. Kato, H. Tanimoto, H. Yamada, N. Chida, *Heterocycles* **2010**, *82*, 563–579.

[17] a) N. Yamamoto, M. Isobe, *Chem. Lett.* **1994**, 2299–2302; b) T. Nishikawa, N. Ohyabu, N. Yamamoto, M. Isobe, *Tetrahedron* **1999**, *55*, 4325–4340.

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