Catalytic asymmetric [3,3]-rearrangements of allylic acetimidates†

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A streamlined synthetic access to enantiomerically pure allylic amines as advanced and valuable synthetic building blocks is important for pharmaceutical sciences. The rearrangement of allylic trihaloacetimidates is known as an attractive method to furnish branched chiral allylic trihaloacetamides with high levels of enantio- and regioselectivity. In the present article we report our studies on the catalytic asymmetric rearrangement of the corresponding non-halogenated acetimidates, which might provide economic advantages by avoiding CX₃ groups. The regioselective title reaction proceeds with high levels of enantioselectivity, provides high yields and requires only low catalyst loadings. In addition, the generated N-acetyl and N-phenacetyl functionalities offer the option of a subsequent mild enzymatic amide hydrolysis to get access to nearly enantiopure allylic amines.

Introduction

[3,3]-Rearrangements of allylic imidates provide a synthetic platform for a regioselective access of chiral branched allylic amines, which are masked as the corresponding amides.¹ The thermal sigmatropic [3,3]-rearrangement of allylic benzimidates was reported as early as 1937 by Mumm and Möller.² Allylic benzamides (4 in Scheme 1, R³ = aryl) are conveniently formed by this reaction type,² but are of restricted synthetic value, because the amide hydrolysis to release the corresponding allylic amines 5 has been reported as a difficult task.³ For that reason the rearrangement of allylic trichloroacetimidates 2 (Scheme 1, R³ = CCl₃) has been developed as a synthetically more attractive alternative, which is commonly known as Overman rearrangement. Overman reported in 1974 that this reaction type is significantly accelerated by catalytic amounts of soft Lewis acids.⁴ Based on these early studies enantioselective rearrangements of allylic trichloro-⁵ and trifluoroacetimidates⁶ (R³ = CF₃) were later advanced, enabling a 2-step transformation of achiral allylic alcohols 1 to enantioenriched branched allylic amides 4 catalysed by chiral Pd(II)-complexes (Scheme 1). Due to the strong inductive effect of the CCl₃ or CF₃ groups, the release of the unprotected allylic amines 5 from the rearrangement products is usually readily accomplished.

In the last few years our group has developed the most active catalysts for the asymmetric rearrangement of trifluoroacetimidates,⁷⁻⁹ allowing to reduce the catalyst loadings by 1–2 orders of magnitude. At the same time these catalysts enabled the highest levels of enantioselectivity achieved so far for a broad range of substrates. It became, e.g., possible to generate N-substituted quaternary stereocenters with very high levels of enantioselection⁷b,d or to create a divergent access towards secondary chiral allylic amines⁷c,d by variation of the N-residue R² in Scheme 1. On the other hand, the preparation of the trifluoroacetimidates 2 is relatively tedious, quite expensive, usually makes use of toxic CCl₄ and generates large amounts of PPh₃ based waste.¹⁰,¹¹ Moreover, isolation and storage of trifluoroacetimidates is often troubled by their sensitivity towards hydrolysis.

For these reasons our goal was to develop analogous methods offering a comparable efficiency, but in which the

Scheme 1 The allylic imidate rearrangement.
CX₃ groups would be avoided. A synthetically attractive alternative might be the rearrangement of simple acetimidates (R² = CH₃ in Scheme 1), because several efficient methods for the deprotection of acetamides have been reported – either chemically or by hydrolytically active enzymes. Depending on the enzymes used, the latter deprotection strategy might also allow for the formation of enantiomerically pure amines by an additional kinetic resolution. This would be appealing in those cases, where the achieved enantioselectivity would not fit to the demands for a certain application, e.g., as an active pharmaceutical ingredient. Moreover, the application of acetimidates would offer the advantage of an improved atom-economy.

The rearrangement of allylic non-halogenated acetimidates 2 (R¹ = alkyl) has only been scarcely reported. In 1992 Metz et al. reported the synthesis of racemic allylic propionylamides (R³ = Et) which proceeded in useful yields utilising (+)-phenyl acetamide could be prepared with high enantioselectivity (ee = 94%)⁷d In our subsequent studies (see below) we found that the used reaction conditions were not generally applicable for other substrates to provide very high enantioselectivity. Herein we now report a method which (1) allows for the catalytic asymmetric synthesis of a broad range of allylic acetamides, (2) proceeds in general with excellent enantioselectivity and (3) can be executed with low catalyst loads.

Results and discussion

Optimisation

Substrate preparation. The N-PMP (PMP = p-methoxyphenyl) protected acetamidine 9a (Scheme 2) was selected as the model substrate, because the PMP group is often used as a protecting group for amines. Two alternative ways towards 9a were developed and provided useful yields (Scheme 2). The first route is an optimisation of a previously reported method⁶d and starts from N-acetylated p-anisidine 6a. Generation of the iminochloride 7 and subsequent treatment with the lithiated allylic alcohol formed 9a in 65% yield over 2 steps after isolation by column chromatography. The other route used the imidoylbenzotriazole 8a as coupling partner for the lithium alkoxide of the allylic alcohol 1a.⁷,17 In contrast to iminochloride 7, 8a is stable and can be purified without significant decomposition, but the overall yield is lower in that case (39% over 2 steps starting from 6a) as compared to the method via the iminochloride 7.

Catalytic model reaction. At the starting point of this investigation the conditions of the above mentioned single example for a catalytic asymmetric rearrangement of a non-halogenated allylic acetimidate⁷d were used for the rearrangement of 9a. The chloride bridged dimeric pentaphenylferrocene oxazoline palladacycle [PPFOP-Cl]₂ (see Table 1) was used as precatalyst and activated by treatment with AgNO₃ according to the reported protocol.⁷d,18 Although a higher precatalyst loading of 1.0 mol% (rather than 0.2 mol% for the reported example) was used, the enantiomeric excess of 83% was not satisfactory for the rearrangement of this substrate (entry 1). With a reduced catalyst loading of 0.5 mol% the enantiomeric excess was further decreased to 78% ee (entry 2). The change from an N-phenyl to a more electron-rich N-PMP group thus had a negative impact on the reaction outcome indicating that the previously reported conditions⁷d are not generally useful for non-halogenated acetimidates. To find a more general solution, some alternative ferrocene based catalysts, which have recently been developed in our research group, were then examined under reaction conditions that have originally been optimised for the rearrangement of allylic N-PMP trifluoroacetimidates.⁷d,8b,9

The pentaphenylferrocene based imidazoline palladacycle [PPFIP-Cl]₂ (ref. 19 and 20) was thus activated by 4 equiv. (per precatalyst dimer) of AgO₂CCF₃.⁷d Earlier we have shown that 2 equiv. of a silver salt are responsible for an anion exchange of the strongly binding chloride bridges by a new anionic ligand. Another two equivalents oxidise the Pd-centers of PPFOP or PPFIP from Pd⁰ to Pdᴵ, leading to unique paramagnetic catalysts offering a significantly increased catalytic activity. Nevertheless, in the present case [PPFIP-Cl]₂ activated by AgO₂CCF₃ resulted in a low catalytic activity, yet promising enantioselectivity (entry 3).

For the bispalladacycle precatalyst [FBIP-Cl]₂ (ref. 8b and 21) and the mixed pallada-/platinacycle [FBIPP-Cl]₂ (ref. 9) an oxidation of the catalyst is usually not required for catalytic activity and activation by silver salts is just necessary for the chloride ligand exchange. In the present study the rearrangements could be done at room temperature providing high yields after reaction times of 3 days using precatalyst loadings of 1.0 or 2.0 mol% (entries 4 and 6). A reduced loading of 0.5 mol% also gave a high yield at a reaction temperature of 55 °C (entry 5). In all cases the enantioselectivity...
was somewhat lower than for the combination $\text{[PPFIP-Cl]}_2/\text{AgO}_2\text{CCF}_3$.

Since $\text{[PPFIP-Cl]}_2$ activated by $\text{AgO}_2\text{CCF}_3$ gave the highest enantioselectivity and the combination of $\text{[PPFOP-Cl]}_2/\text{AgNO}_3$ provided the highest activity, we studied the activation of $\text{[PPFIP-Cl]}_2$ with $\text{AgNO}_3$ as well. Gratifyingly, this combination provided the product with excellent enantioselectivity and an improved reactivity (entry 7). Either by a prolonged reaction time or at a reaction temperature of $70^\circ\text{C}$, $\text{10a}$ was finally formed in high yields and almost enantiomerically pure form (entries 8 and 9).

**Substrate scope**

Application of $\text{[PPFIP-Cl]}_2$ as precatalyst. Under the optimised conditions various substrate modifications were studied (Table 2). Substrates 9a–d in which $R_1$ either equals phenethyl, ethyl, $n$-propyl or $n$-pentyl all furnished the corresponding acetamides 10a–d in high yields and with high enantioselectivity (entries 1–4).

The electronic effect of substituents $R_3$ on the N-aryl residues is apparently negligible as a comparison of entries 3 and 5 shows. With both $p$-OMe as an example for a $\pi$-donor and $p$-NO$_2$ as an example for a strong $\pi$-acceptor very similar results in terms of product yields and enantioselectivity were obtained.

In addition to the parent acetimidate substrates with $R^2 = \text{H}$, we also examined substrates with $R^2 = \text{Ph}$. A phenylacetamide product might create additional opportunities for enzymatic deprotection by the penicillin-G-amidase (PGA). It was found that the imidate substrates 9 with $R^2 = \text{Ph}$ show a very similar behaviour (entries 6–12) compared to those with $R^2 = \text{H}$. Like before the electronic effect of the substituents $R_3$ on the N-aryl residues is of only minor importance and in each case ($R_3 = \text{NO}_2, \text{H}, \text{OMe}$) the products were generated in high yields and with high enantioselectivities (entries 6–8).

It was also possible to significantly reduce the catalyst loadings without a negative impact on the reaction outcome as has been demonstrated for substrate 9h. Various precatalyst loadings ranging from 1.0 mol% to as little as 0.05 mol% were studied and they all provided almost identical results (entries 8–10). Low catalyst loadings were also examined for the phenylacetimidates 9i and 9j carrying different alkyl residue $R^2$ and in both cases high product yields and enantioselectivities were determined (entries 11 & 12).

### Table 1 Investigation of different catalysts in the title reaction

| # | Precatalyst | $X$ | $\text{AgY}$ | Solvent | $T$ [°C] | $t$ [h] | Yield$^a$ [%] | ee$^b$ |
|---|-------------|-----|-------------|---------|---------|--------|-------------|------|
| 1 | $\text{[PPFOP-Cl]}_2$ | 1.0 | $\text{AgNO}_3$ | $\text{CH}_2\text{Cl}_2$ | 50 | 24 | 97 | 83 |
| 2 | $\text{[PPFOP-Cl]}_2$ | 0.5 | $\text{AgNO}_3$ | $\text{CH}_2\text{Cl}_2$ | 50 | 24 | 79 | 78 |
| 3 | $\text{[PPFIP-Cl]}_2$ | 1.0 | $\text{AgO}_2\text{CCF}_3$ | $\text{CH}_2\text{Cl}_2$ | 50 | 24 | 27 | 93 |
| 4 | $\text{[FBIP-Cl]}_2$ | 1.0 | $\text{AgOTs}$ | $\text{CHCl}_3$ | 25 | 72 | 93 | 89 |
| 5 | $\text{[FBIP-Cl]}_2$ | 0.5 | $\text{AgOTs}$ | $\text{CHCl}_3$ | 55 | 72 | 93 | 85 |
| 6 | $\text{[FBIPP-Cl]}_2$ | 2.0 | $\text{AgOTs}$ | $\text{CHCl}_3$ | 25 | 72 | 93 | 87 |
| 7 | $\text{[PPFIP-Cl]}_2$ | 1.0 | $\text{AgNO}_3$ | $\text{CH}_2\text{Cl}_2$ | 50 | 24 | 53 | 98 |
| 8 | $\text{[PPFIP-Cl]}_2$ | 1.0 | $\text{AgNO}_3$ | $\text{CH}_2\text{Cl}_2$ | 50 | 72 | 94 | 98 |
| 9 | $\text{[PPFIP-Cl]}_2$ | 1.0 | $\text{AgNO}_3$ | $\text{CHCl}_3$ | 70 | 24 | 93 | 98 |

$^a$ Yield of isolated product. $^b$ Determined by HPLC. $^c$ Reaction was performed in the absence of proton sponge (PS, 1,8-bis(dimethylamino)naphthalene).
Next the rearrangement of particularly challenging substrates was investigated, e.g. that of 9k possessing an iPr-group as R1. α-Branched alkyl residues are known to retard allylic imidate rearrangements.1,7 The α-branched alkyl residues are known to retard allylic imidate rearrangements.1,7 The results could be further improved by decreasing the reaction temperature to 50 °C using a prolonged reaction time of 48 h (96% yield, 95% ee, entry 14).

Similarly, the rearrangement of substrates carrying aromatic residues R1 required a lower reaction temperature for high enantioselectivities. Allylic imidate rearrangements of substrates of this type are in general inherently difficult, since the aryl residues accelerate a thermal background reaction.1,7 Nevertheless, at room temperature the products 10l and 10m were obtained in high yields and with high enantioselectivity after a reaction time of 3 days.

In addition, it is possible to form N-substituted quaternary stereocenters in excellent yield and with nearly perfect enantiocontrol as shown for substrate 9n. Obviously, the remote olefin functionality did not have a negative impact on the reaction outcome.

### Table 2: Investigation of different substrates in the PPFIP-catalysed title reaction

| # | 9/10 | R1 | R1’ | R2 | R3 | X | Yield[a] [%] | ee[b] |
|---|---|---|---|---|---|---|---|---|
| 1 | a | (CH3)2Ph | H | H | OMe | 1.0 | 93 | 98 |
| 2 | b | Et | H | H | OMe | 1.0 | 92 | 96 |
| 3 | c | nPr | H | H | OMe | 1.0 | 92 | 96 |
| 4 | d | nPent | H | H | OMe | 1.0 | 91 | 92 |
| 5 | e | nPr | H | H | NO2 | 1.0 | 94 | 94 |
| 6 | f | nPr | H | Ph | NO2 | 1.0 | 93 | 95 |
| 7 | g | nPr | H | Ph | H | 1.0 | 90 | 97 |
| 8 | h | nPr | H | Ph | OMe | 1.0 | 91 | 97 |
| 9 | h | nPr | H | Ph | OMe | 0.25 | 94 | 97 |
| 10 | h | nPr | H | Ph | OMe | 0.05 | 92 | 96 |
| 11 | i | nPent | H | Ph | OMe | 0.25 | 92 | 94 |
| 12 | j | Et | H | Ph | OMe | 0.1 | 93 | 96 |
| 13 | k | iPr | H | Ph | OMe | 1.0 | 84 | 91 |
| 14 | l | iPr | H | Ph | OMe | 1.0 | 96 | 95 |
| 15 | m | 4-NO2–C6H4 | H | Ph | OMe | 1.0 | 93 | 95 |
| 16 | n | (CH3)2C≡C(Me)2 | Me | Ph | OMe | 1.0 | 98 | 98 |

[a] Yield of isolated product. [b] Determined by HPLC.

### Table 3: Investigation of different substrates in the FBIP-catalysed title reaction

| # | 10 | R1 | R1’ | R2 | R3 | Yield[a] [%] | ee[b] |
|---|---|---|---|---|---|---|---|
| 1 | a | (CH3)2Ph | H | H | OMe | 93 | 89 |
| 2 | c | nPr | H | H | NO2 | 90 | 90 |
| 3 | (ent)-c | H | nPr | H | NO2 | 93 | 93 |
| 4 | h | nPr | H | Ph | OMe | 95 | 86 |
| 5 | (ent)-h | H | nPr | Ph | OMe | 97 | 89 |
| 6 | (ent)-f | H | nPr | Ph | NO2 | 96 | 95 |
| 7 | (ent)-o | H | nPr | CH3 | OMe | 84 | 92 |
| 8 | (ent)-p | H | nPr | CH3 | H | 85 | 90 |

[a] Yield of isolated product. [b] Determined by HPLC.
Application of [FBIP-Cl]₂ as precatalyst. In addition, the FBIP-catalysed reaction was applied to substrates differing in their electronic properties of the N-aryl group and in the C,C double bond configuration (Table 3).

Also with this bimetallic catalyst a π-donor (p-OMe) and a π-acceptor (p-NO₃) on the N-aryl residue were both well tolerated and very similar results were obtained for substrates carrying these substituents (entries 1 and 2). Also less reactive₁² (Z)-configured substrates 9 provided the corresponding products in high yields and with high enantioselectivity, irrespective of the use of an electron rich or deficient N-aryl residue (entries 3 & 5–8). Using the (Z)-configured substrates resulted in a switch of the absolute configuration of the generated stereogenic center (determined by HPLC using a chiral stationary phase). Like other Pd(II) catalysed allylic imidate rearrangements the reaction is thus stereospecific.¹

Amide cleavage

The release of the free amino functionality by cleavage of the amide moiety was investigated by chemical and enzymatic means.

Amide cleavage by chemical means. Treatment of allylic amide 10a with Li[Et₃BH] at 0–25 °C for 2 h proceeded smoothly and provided the PMP-protected amine 11 in high yield (Scheme 3).₁³ Comparison of the obtained product by HPLC using a chiral stationary phase with an authentic sample prepared by rearrangement of the corresponding trifluoroacetimide followed by cleavage of the generated trifluoroacetamide confirmed the expected (R)-configuration of 10a.⁷

Amide cleavage by enzymatic means. To allow deprotection under very mild conditions, an enzymatic amide hydrolysis was studied. For that purpose the phenylacetimide 9h was rearranged on a 250 mg scale (Scheme 4). After PMP-deprotection under standard conditions the phenylacetamide was applied to penicillin-G-amidase for 2 days at 38 °C. The purified samples were used to determine the ee value by HPLC.

General procedure for the catalytic asymmetric rearrangement of allylic imidates 9

A dry screw-cap vial was charged with the corresponding allylic imidate 9 (1.0 equiv.), then vacuum was applied and the vial was refilled with N₂ (3 times). A stock solution of proton sponge (1,8-bis-(N,N-dimethylamino)naphthalene, PS, 4× mol% [only used in the case of mono-palladacycles]) in the indicated solvent and a stock solution of the corresponding activated catalyst in the indicated solvent were added. The amount of solvent was reduced by a stream of N₂ if necessary (final concentration: 150 μL per 100 μmol of substrate). The vial was closed by a screw-cap and the mixture was stirred at the indicated temperature for the indicated time. Subsequently, the solvent was removed under reduced pressure and mesitylene (10 μL per each 50 μmol of substrate) was added to the crude product as an internal standard followed by CDCl₃ (1 mL) to determine conversion and yield by ¹H-NMR. The crude product was afterwards directly used for silica gel chromatography to isolate the corresponding allylic amide 10. The purified samples were used to determine the ee value by HPLC.

Enzymatic deprotection: (R)-hex-1-en-3-amine (13)

(R)-N-(Hex-1-en-3-yl)-2-phenylacetamide 12 (92.0 μmol, 20.0 mg) was suspended in sodium phosphate buffer (1.0 mL, pH = 7.5, 1 M) and PGA (penicillin-G-amidase from Escherichia coli, ammonium sulfate suspension, ≥10 units per mg protein, through CaH₂/celite (1:1) under N₂. The solvent was removed by a stream of N₂ and then high vacuum was applied. A stock solution was prepared by the addition of a defined amount of the corresponding solvent.

b) Activation of [FBIP-Cl]₂. To a solution of AgOTs (4.0 equiv.) in dry MeCN (0.5 mL per 5 mg [FBIP-Cl]₂) was added [FBIP-Cl]₂ (1.0 equiv.). The mixture was stirred at room temperature for 14 h and then filtered through CaH₂/celite (1:1) under N₂. The solvent was removed by a stream of N₂ and then high vacuum was applied. A stock solution was prepared by the addition of a defined amount of the corresponding solvent.

Experimental

Procedures for the activation of pre-catalysts

a) Activation of mono-palladacycles. The corresponding palladacycle (1.0 equiv.) and the corresponding silver salt (4.0 equiv.) were suspended in dry CH₂Cl₂ (0.5 mL per 5 mg palladacycle) and ultrasonificated for 10 min. The mixture was stirred at room temperature for 14 h and then filtered

\[
\text{PMP} \quad \begin{array}{c}
\text{N} \\
\text{CH₃}
\end{array}
\quad \begin{array}{c}
\text{Li[Et₃BH]} \\
\text{THF, 0 to 25 °C, 2 h}
\end{array}
\quad \begin{array}{c}
\text{PMP} \\
\text{N} \\
\text{Ph}
\end{array}
\]

Scheme 3 Reductive acetamide cleavage.

\[
\text{10a (ee = 98%)} \quad \begin{array}{c}
\text{0.5 mol% [PPFIP-Cl]₂} \\
\text{2 mol% AgNO₃} \\
\text{2 mol% PS, CHCl₃, 70 °C, 24 h}
\end{array}
\quad \begin{array}{c}
\text{R} \\
\text{N} \\
\text{Ph}
\end{array}
\quad \begin{array}{c}
\text{10h (R = PMP)} \\
\text{97%, ee = 96%}
\end{array}
\]

\[
\text{CAN, H₂O/MeCN, 0 °C-RT, 2.5 h}
\quad \begin{array}{c}
\text{R} \\
\text{N} \\
\text{Ph}
\end{array}
\quad \begin{array}{c}
\text{12 (R = H)} \\
\text{35%}
\end{array}
\]

Scheme 4 Synthesis of the highly enantioenriched primary amine 13 via enzymatic phenylacetamide hydrolysis using penicillin-G-amidase.
H2O (5 mL) and CH2Cl2 (5 mL) were added, the phases were separated and the aqueous phase was extracted with CH2Cl2 (2 × 5 mL). The combined organic phases were dried over Na2SO4 and the solvent removed under reduced pressure. Mesitylene (10 μL) was added to the crude product as an internal standard followed by CDCl3 (1 mL) to determine conversion and yield by 1H-NMR. The crude product was afterwards dissolved in CH2Cl2 (10 mL) and extracted with aqueous HCl (3 × 5 mL, 1 M). The pH value of the combined aqueous phases was adjusted to pH = 14 by addition of aqueous NaOH (2 M) and the combined aqueous phases were extracted by CH2Cl2 (3 × 10 mL). The combined organic phases were dried over Na2SO4 and the solvent was removed under reduced pressure to yield 13 as a colorless oil (88.7 μmol, 8.8 mg, 96%).

C6H5N2, MW: 99.18 g mol−1, 1H-NMR (300 MHz, CDCl3): δ = 3.58–3.65 (m, 6H, CH3), 1H, CH≡CH=CH2), 3.84–4.29 (m, 2H, CH<CH=CH2), 1.25 (bs, 2H, NH), 0.91 (t, J = 7.1, 3H, CH3CH2CH2NH). The analytical data are in accordance with the literature.22 The enantiomeric excess was determined by HPLC after tosyl protection of 13 (see the ESI†).

Conclusions

In conclusion, we have identified two catalytic systems, which are very efficient for the asymmetric rearrangement of allylic non-halogenated acetimidates. This rearrangement type can be conducted with a high level of generality and enantioselectivity. At elevated temperatures it is possible to perform the title reaction using very low catalyst loadings without a decrease of enantioselectivity or yield. Also difficult substrates were found to be tolerated with a high level of efficiency. This enabled, e.g., the formation of N-substituted quaternary sterocenters making use of a trisubstituted olefin moiety. Besides cleavage of the formed amide functions by known chemical methods, the products now also offer the option of enzymatic hydrolytic protocols for the access of almost enantiopure allylic amines.

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Chiral Ferrocenes in Asymmetric Catalysis

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