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A chelating tetrapeptide rhodium complex comprised of a histidylidene residue: biochemical tailoring of a NHC-Rh hydrosilylation catalyst

Angèle Monney and Martin Albrecht*

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Coupling of histidinium salt with a MetAlaAla amino acid sequence followed by metallation with [RhCl(cod)]₂ yields a rhodium(I) NHC complex with a pending peptide residue. Methionine chelation, induced by chloride abstraction from the metal coordination sphere, affords an efficient hydrosilylation catalyst precursor comprised of a peptidic macrocyclic chelate backbone.

The combination of organometallic entities and peptides offers attractive opportunities in bioorganometallic chemistry. Peptides provide a biocompatible scaffold, and they induce structural conformations that impact the organometallic site. This approach has furnished, for example, peptide-decorated organometallic complexes and enantioselective organometallic catalysts from achiral complexes deeply buried in enzymatic pockets, and it spurred the development of artificial (organometallic) amino acids for de-novo peptide synthesis.

Based on earlier work by Erker, we have recently disclosed a route to modify histidine stereospecifically to access C-bound histidine metal complexes. These histidylidene complexes combine the fields of N-heterocyclic carbene (NHC) and peptide chemistry, thus providing new opportunities for catalysis. We have become particularly interested in functionalising the amino acid moiety to tailor the catalytic activity of the histidylidene-bound metal centre. Here we have introduced methionine (Met) as potentially chelating amino acid. Chelation through C,S-bidentate bonding was anticipated in a +3 arrangement with Met separated by two amino acids from histidylidine. Alanine (Ala) residues were selected as spacers as they promote α-helix formation, thus positioning the two metal-binding amino acids on the same side of two adjacent loops.

The histidinium-containing tetrapeptide was synthesised from the corresponding N- and C-protected histidinium salt Boc-His*-OMe and the Met-Ala-Ala tripeptide (Scheme 1). Histidine methylation before coupling to the oligopeptide circumvented potential complications arising from partial methylation of the thioether in methionine. The Boc protecting group in the N₈N₆-dimethyalted histidinium salt Boc-His*-OMe (Scheme 1) was removed in excellent yield using a solution of HCl in 1,4-dioxane followed by an ion exchange. Subsequent coupling to Boc-Met-Ala-Ala-OMe was achieved by O-(7-Azabenzotriazol-1-yl)-N,N',N''-tetramethyluronium hexafluorophosphate (HATU) activation in THF. The histidinium-containing tetrapeptide Boc-Met-Ala-Ala-His*-OMe was isolated as a highly hygroscopic solid. Successful coupling was indicated by the expected high-resolution mass for the cationic portion, and by the presence of four distinct carbonyl signals in the ¹³C NMR spectrum for the three different amid functionalities and the terminal ester in the 171–176 ppm range. The C₇-bound proton appeared at δH 8.86 ppm. Subsequent carbene formation and installation of rhodium(I) was accomplished under mild conditions using a transmetallation protocol. The use of freshly prepared Ag₂O and the addition of a source of iodide was essential for the formation of the silver carbene intermediate, which was then transmetallated with [RhCl(cod)]₂ to yield 1a.‡ The NMR spectra of 1a revealed the disappearance of the signal due to the C₇-bound proton and a characteristic 0.1–0.15 ppm downfield shift of the methyl wingtip groups of the NHC ligand. Two sets of signals were observed, which was attributed to the formation of two rotamers (e.g. δH 4.01, 3.97, 3.96, 3.92 ppm for the NMe groups). The carbene resonance was poorly resolved and was only detectable indirectly through long-range C–H correlation spectroscopy as a broad resonance at δC 182 ppm (δC₁₀, not resolved), indicative for

Scheme 1 Synthesis of the rhodium tetrapeptides. Reagents: i) HCl, dioxane; then Boc-Met-Ala-Ala-OMe, HATU, NEt₃Ph, THF; ii) [NEt₃Me]I, Ag₂O, CH₂Cl₂, then [RhCl(cod)]₂; iii) KPF₆, CH₂Cl₂/H₂O.

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rhodium bonding at the C_{α} position. No epimerization at C_{α} was observed provided the reaction with Ag_{2}O was carried out at room temperature and for short time only (1 h).

Comparison of the NMR data of 1a with those of the monopeptide histidylidene complexes 3a and 4a (Scheme 2) indicated no spontaneous chelation of the methionine. However, KPF_{6}-mediated chloride abstraction induced the formation of the macrocyclic cationic complex 2a.\textsuperscript{9} Sulfur coordination was most diagnostically indicated by the characteristic shift of the signals due to the cod ligand. Specifically the olefinic C_{α}H resonances moved from δ_{H} 4.9 and 3.3 ppm in the neutral complex 1a to 4.7 and 4.0 ppm in 2a. Similar behaviour was observed upon exchange of Cl in 3a for a neutral SME_{2} in 4a. The chemical shift of the S–CH_{3} protons provides a further—though less diagnostic—probe for sulfur bonding, as the corresponding signal undergoes a small highfield shift from 2.09 in 1a to 2.05 ppm in 2a.

Further confirmation of sulfur coordination was obtained when displacing the cod ligand with CO. In both caticonic thioether complexes 2b and 4b, the asymmetric stretch vibration appears at approximately 30 cm\textsuperscript{-1} higher energy than in the corresponding neutral precursors 1b and 3b, respectively, as expected for the transformation of a formally neutral rhodium center into a cationic residue (Fig. 1).\textsuperscript{13} Methionine binding was also supported by NMR spectroscopy, which was facilitated by using isotopically labeled \textsuperscript{13}CO for cod displacement. In the chelate 2b, \textsuperscript{13}C NMR spectroscopy showed two doublets for the rhodium-bound carbonyl groups located at 188.8 and 187.5 ppm (\textit{\textit{J}}_{\text{RhC}} = 84 and 79 Hz, respectively). These signals are at distinctly lower field than in the monodentate carbene tetraptpeptide 1b (δ_{C} 187.2 and 183.8 ppm, \textit{\textit{J}}_{\text{RhC}} = 53 and 75 Hz, respectively). Both the downfield shift of the resonances as well as the increased coupling constants\textsuperscript{14} reflect the lower electron density at rhodium in the cationic complex 2b due to bonding of a neutral methionine as opposed to the anionic chloride in 1b.

Chelation was supported by ESI MS, which indicates a monomeric structure, and spectroscopically by the broad NMR resonances of 2a, which were much poorer resolved compared to 1a and which suggest conformational flexibility. Preliminary CD spectroscopy does not reveal a pronounced α-helical peptide conformation, despite the propensity of alanines to stabilise such secondary structural motifs. Molecular modeling studies (mm2 geometry optimisation)\textsuperscript{15} also support a macrocyclic structure as depicted in Scheme 1.

The rhodium complexes 1a–4a were evaluated as catalyst precursors for the hydrosilylation of ketones.\textsuperscript{9} Para-fluorocacetophenone was chosen as substrate since conversion is readily detectable by \textsuperscript{1}H and \textsuperscript{19}F NMR spectroscopy. Hydrosilylation with diphenylsilane in the presence of 1 mol% of rhodium tetrapeptide 1a produced about 80% of the silyl tether 1I together with minor quantities of the disilylenol ether 1I and gaseous H_{2} within 2 h (entry 1, Table 1).\textsuperscript{15} Under the same conditions, the histidylidene rhodium complex 3a showed substantially higher activity and selectivity (entry 3). With this precursor, the same level of conversion was achieved within 5 min with high selectivity towards 1I, even though the first coordination sphere around rhodium is identical in 1a and 3a. The strong influence of the peptide backbone in 1a supposedly originates from a limited diffusion of the oligopeptide-thethered catalyst and suggests a remote tunability of these carbene metal complexes.\textsuperscript{9} In addition, coordination of the dangling thioether of methionine to the catalytically active species may compete in occupying one of the coordination sites available for substrate coordination after cod dissociation, thus leading to severe deactivation. A similar effect was observed when catalytic runs with 3a were carried out in the presence of SME_{2} (1 equiv), resulting in a mere 59% conversion after 30 min. In contrast, the C,S-bidentate chelating tetrapeptide rhodium complex 2a exhibits very high catalytic activity and induced full conversion within less than 10 min (entry 2). This performance corresponds to a turnover frequency at 50% conversion TOF\textsubscript{50} ~ 1200 h\textsuperscript{-1}. The selectivity is slightly improved when compared with the neutral complexes, and it is also higher than when using the SME\textsubscript{2}-containing monodentate histidylidene complex 4a, the most active complex in this series (TOF\textsubscript{50} ~ 3200 h\textsuperscript{-1}, entry 4). The thioether group has thus an ambivalent role: it is a catalytic poison when coordinating to the neutral [RhCl(carbene)] fragment as in 1a and 3a, yet a strong promotor when coordinating to the cationic [Rh(carbene)]\textsuperscript{+} unit (cf. activity of 2a and 4a).

Lowering the catalyst loading to 0.1 mol% decelerated the reaction significantly and allowed for a better comparison of the catalytic activity of caticonic complexes 2a and 4a. The monopeptide complex 4a is moderately better performing than the chelating tetrapeptidic catalyst derived from 2a, reaching TOF\textsubscript{50} values of 910 h\textsuperscript{-1} vs 610 h\textsuperscript{-1} under these conditions (entries 5, 6).\textsuperscript{16} It is worth noting that a lower catalyst loading
reduced the product selectivity of 2a and afforded a 3:1 ratio of silyl ether and silylenol ether (cf 9:1 ratio at 1 mol% 2a). In contrast, the selectivity of the histididyldiene complex 4a is consistently about 70%, independent of the catalyst loading.

Despite the α-helical backbone of the catalyst precursors, no asymmetric induction was observed when analysing the hydroxysilylated silyl ether by chiral HPLC. The bidentate coordination mode apparently fails to induce stereoselective binding of prochiral substrates, even in catalytic reactions carried out at −18 °C, possibly because the chirality of the peptidic macrocycle is too remote from the active metal centre. Better stereo-discrimination may become accessible through biochemical optimisation, e.g. by further modification of the tetrapeptide backbone particularly at the C-terminus.

In conclusion, we disclosed a convergent de-novo synthesis of a metalloenzyme analogue featuring a C-bound histididyldiene amino acid and a chelating methionine residue. Chelation substantially enhanced the catalytic competence of the bound rhodium centre, affording highly active hydroxylation catalysts. Biochemical strategies such as peptide modifications provide interesting routes to further optimise the activity of the organometallic entity, thus providing new organometallic peptide hybrid systems with vast opportunities in catalysis and for novel active site models of metalloenzymes.

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Notes and references

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† Dedicated to Gerard van Koten on the occasion of his 70th birthday and in admiration of his ground-breaking work in many areas of organometallic chemistry, including bioorganometallics.

‡ Electronic Supplementary Information (ESI) available: Synthetic and catalytic procedures and model of 2b. See DOI: 10.1039/b000000x/

Table 1

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<th>10 min</th>
<th>30 min</th>
<th>2 h</th>
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<td>80 (67)</td>
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<tr>
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<td>2a</td>
<td>56 (83)</td>
<td>100 (82)</td>
<td>100 (80)</td>
<td>100 (79)</td>
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<tr>
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<td>3a</td>
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<td>n.d.</td>
<td>90 (97)</td>
<td>100 (92)</td>
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<tr>
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<td>100 (75)</td>
<td>100 (71)</td>
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<tr>
<td>5</td>
<td>2a</td>
<td>n.d.</td>
<td>n.d.</td>
<td>16 (68)</td>
<td>59 (53)</td>
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<tr>
<td>6</td>
<td>4a</td>
<td>n.d.</td>
<td>n.d.</td>
<td>23 (69)</td>
<td>77 (65)</td>
</tr>
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General conditions: ketone (1 mmol), silane (2 mmol), catalyst precursor (1 mol%) in CDCl₃ (1 mL) at rt.

Conversion (selectivity towards II in parentheses) determined by 1H and 19F NMR spectroscopy; n.d. = not determined.

0.1 mol% catalyst precursor.


13. The lower energy of the symmetric stretch vibration in the methionine-containing complexes 1b and 2b compared to the model analogues, as well as weak asymmetric vibration band may be tentatively attributed to stereoelectronic effects rather than to a difference in electronic properties of the histididyldiene fragment, which is identical in both cases.


16. First order kinetics of product formation was observed for both catalytic reactions with 0.1 mol% catalyst loading; the relative rate constants were 1.0 and 1.3 for 2a and 4a respectively (R² > 0.998), with a reproducible induction time of 16 min for both reactions.