**Pseudo-Enantiomeric Carbohydrate-Based N-Heterocyclic Carbenes as Promising Chiral Ligands for Enantiotopic Discrimination**

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The practical synthesis of carbohydrate-based NHC-Rh complexes bearing C1 or C3 sterically differentiated positions, accessed by glycosylation or S_{Ar} strategies, is reported. These catalysts exhibit pseudo-enantiomeric behaviour in the hydroboration of acetylene. We show that steric bulk at C1 gives preference for (S)-phenyl-1-ethanol, while bulk at C3 leads to the (R)-enantiomer. These results represent the first example of pseudo-enantiomeric carbohydrate-based NHC ligands leading to enantiotopic discrimination.

The search for stable and effective N-heterocyclic carbene (NHC) transition metal (TM) complexes is of great interest for catalytic applications. NHCs with tailored electronic and steric properties have become indispensable in many applications of transition metal and main group chemistry. For instance, the success of NHC ligands in non-stereoselective reactions, such as cross-coupling and olefin metathesis, has prompted the incorporation of homochiral units into NHC scaffolds and this offers exciting new opportunities in reaction development. Typical strategies to monodentate NHC ligands suitable for asymmetric TM-catalysis have employed commercially available enantioenriched amines, featured the resolution of racemic material and involved chiral pool substrates, such as amino acid and natural product derivatives. Enantiopure NHCs encompassing a diverse array of ligand architectures have been evaluated in a plethora of asymmetric reactions and, although highly effective examples exist, the search for increasingly more efficient systems is paramount. However, a limiting factor and general problem in the synthesis and assessment of novel NHC ligands is the ability to obtain readily modifiable building blocks, such as enantioenriched amines.

**Scheme 1.** Carbohydrate-based NHC complexes. $R_L = \text{large group}$; $R_S = \text{small group}$.

The abundance of inherently chiral, biologically derived saccharide material provides useful starting compounds with a range of stereochemistries for ligand syntheses. Indeed, the application of carbohydrates as the enantioinduction component in stereoselective catalysis is frequently encountered within the literature and a multitude of efficient ligands have been reported. Towards this end, our laboratory and others have described the use of carbohydrate-based NHCs for asymmetric catalysis in an effort to solve the issues highlighted above. Our initial report disclosed the expedient assembly of $C_3$-symmetric NHC ligands from per-alkylated $\beta$-
glucosamines.\textsuperscript{10a} Upon successful ligation to [Rh(cod)Cl]$_2$, the carbohydrate-based NHC complexes (e.g. 1, Scheme 1A, eqn. (1)) were evaluated in the asymmetric hydrosilylation of ketones (e.g. 2, Scheme 1A, eqn. (2)).\textsuperscript{1,2} Ultimately, catalyst 1, featuring permethylated $\beta$-glucoside residues attached to the NHC moiety, was most efficient and provided phenyl-1-ethanol (3) in modest er (81:19 R:S).\textsuperscript{10}

One of the advantages of carbohydrate chiral synths is the ability to chemoselectively incorporate functional groups at each of the different OH groups. We thus sought to achieve greater asymmetric induction from 1 by sterically differentiating the C1 and C3 positions which flank the connecting position (C2) between the carbohydrate and the imidazolylidene scaffold (4a-b, Scheme 1B). Practically, this can be realised in two different ways: (1) by employing a carbohydrate unit with a large group ($R_1$) at C1 and a small group ($R_2$) at C3, as depicted in 4a, or (2) vice versa as in 4b. We surmised that an aryl group would serve as an effective $R_1$ candidate as this motif is readily available. From a synthetic viewpoint, installation of an aryl residue (e.g. phenol or thiophenol) at C1 by stereoselective glycosylation is well known.\textsuperscript{12} Accessing a related C3-OH arylated carbohydrate derivative is conceptually more challenging, however, this could be achieved using $S_N$Ar-based methodology recently developed in our laboratory.\textsuperscript{13} Therefore, our aims were to synthesize sterically differentiated carbohydrate amines, access the corresponding C2-symmetric imidazolium salts, ligate to a Rh source and subsequently evaluate the complexes in the hydrosilylation of acetophenone (2).

Scheme 2. Synthesis of a carbohydrate-based imidazolium salt with steric bulk at C1

Thioglycoside 5\textsuperscript{14}, synthesized in two steps from D-glucosamine HCl in 70% yield (see ESI for details), was chosen as it was a commonly used building block in carbohydrate synthesis and thus easily accessible, was globally deprotected by stirring with NaOMe in methanol to remove the ester groups, This was followed by addition of aq. NaOH at reflux to give amine intermediate 6\textsuperscript{15} (Scheme 2A). Cu-catalyzed azide formation from 6 with TfN$_3$ gave triol 7 in 78% yield over the three steps. Methylation of the remaining hydroxyl positions using MeI and NaH and subsequent azide hydrogenation (H$_2$, Pd/C) gave C1 sterically differentiated amine 8a in an 81% yield. It is pertinent to note that a methyl ether (OMe) was selected as the $R_2$ group based on our previous observations.\textsuperscript{10a}

Elaboration of 8a into imidazolium salt 9a was achieved in 41% yield by condensation with aq. glyoxal and then cyclization with MOMCl (Scheme 2B).

Scheme 3. Synthesis of a carbohydrate-based imidazolium salt with steric bulk at C3

With a C1 sterically differentiated carbohydrate-based NHCl salt in hand, our attention turned to the C3 analogue (Scheme 3A-B).\textsuperscript{16} The synthesis of carbohydrate-aryl ether 10 was accomplished by an $S_N$Ar reaction between the appropriate fluoro-arene and the corresponding OH-bearing carbohydrate.\textsuperscript{13} Next, under sonication, TsOH acid catalyzed deprotection of the benzyldiene acetel revealed the O4 and O6 hydroxyls, which were methylated as before to give 11 in 95% overall yield. Heterogeneous hydrogenation gave amine 8b and the corresponding imidazolium salt (9b) was accessed in 44% yield utilizing the same procedure outlined before.

\begin{equation}
9a + \overset{1}{BuONa} \rightarrow 12a \quad (1)
\end{equation}

\begin{equation}
9b + \overset{1}{BuOK} \rightarrow 12b \quad (2)
\end{equation}
Scheme 4. Ligation of 9a-b to [Rh(cod)Cl]₂

Imidazolylidene salt 9a was deprotonated by 'BuONa at rt and ligated to [Rh(cod)Cl]₂, which afforded complex 12a in usable yield (Scheme 4, (1)). NHC HCl 9b required the action of 'BuOK at 100 °C to effect ligation and this allowed isolation of 12b in 72% yield (Scheme 4, (2)). Unfortunately, neither complex was crystalline but HRMS confirmed product formation (see the Experimental Section) and the carbenc ¹³C NMR resonance was visible for 12b (δC: 189.2 ppm). The ¹H NMR data of 12a-b is similar to other β-glucoside-based NHC-Rh compounds and the spectra also featured significant peak broadening, which further supports metal conjugation. In 12b the backbone imidazolyldiene protons were not obscured and appeared at δH: 6.95 and 6.80 ppm respectably, indicating that the complex does not possess C₂ symmetry and, therefore, it is likely the pyranoside rings are each in unique environments. From this information we infer that our NHC ligands are dynamic in solution. Indeed, Grubbs and co-workers have observed rotation around C-Carbosaccharide-Imidazolylidene bonds in metathesis catalysts featuring carbohydrate-based NHC ligands.

### Table 1. Evaluation of 12a-b in the hydrosilylation of acetophenone

<table>
<thead>
<tr>
<th>Entry</th>
<th>Yield (%)</th>
<th>Er (R:S)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
<td>95</td>
</tr>
</tbody>
</table>

* Isolated yield. * Determined by chiral HPLC.

Next, complexes 12a-b were evaluated in the hydrosilylation of acetophenone as a model system and both were found to be catalytically competent (Table 1). Interestingly, although the enantiomer ratios (er) of the product were modest, 12a resulted in the isolation of 3 with a distinguishable preference for the S-enantiomer (30:70 R:S, entry 1), whereas 12b gave preference for the R-enantiomer (75:25 R:S, entry 2). Carbohydrates largely exist in nature in the D-configuration and this causes complications when employing them as ligands because sufficient quantities of the antipode are not normally available. Therefore, an asymmetric process must often rely on pseudo-enantiomeric ligands to give access to each enantiomer of the product. While pseudo-enantiomerism has been documented in carbohydrate-based ligands, such as phosphinites and phosphites, and carbohydrate-based organocatalysts, to the best of our knowledge this is the first example concerning a carbohydrate-based NHC ligand.

Encouraged by the results, we envisaged optimizing the asymmetric induction potential of the carbohydrate-based NHC ligands by altering the size and substitution pattern of the C₃ aryl group. Commercially available fluoroarylariyls were introduced using S₄Ar, expeditiously delivering a small library of carbohydratearyl ethers (13a-e) as previously described. The ethers were then transformed into the required amines (15a-e) by benzylidene acetal cleavage, methylation of the OHs (14a-e) and reduction of the azide functionality as before (Scheme 5).

### Scheme 5. Synthesis of S₄Ar modified amines 15a-e

The S₄Ar modified amines were swiftly elaborated into the corresponding imidazolylidene salts (16a-e) by treatment with aq. glyoxal and then MOMCl (Scheme 6). Deprotonation with 'BuOK and ligation to Rh was performed in THF at reflux to give complexes 17a-e in 40-99% yields. While the yields for both of these steps were predominantly good, the example featuring Ar₁ (bearing ortho-orthoaryl substitution, e.g. 13a-17a) was consistently low yielding despite our best efforts and this was attributed to the level of steric bulk present in the system.

### Table 2. Evaluation of 17a-e in the hydrosilylation of acetophenone

<table>
<thead>
<tr>
<th>Entry</th>
<th>Yield (%)</th>
<th>Er (R:S)</th>
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<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>72</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
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<tr>
<td>5</td>
<td>e</td>
<td>73</td>
</tr>
</tbody>
</table>

* Isolated yield. * Determined by chiral HPLC.
Complexes 17a-e were then evaluated in the hydroxylation of 2 and the results are displayed in Table 2. Catalysts 17a-b, featuring an ortho-CF$_3$ substituted aryl group (Ar$_1$,2), gave negligible stereoinduction in 3 (entries 1-2). However, 17c (entry 3) resulted in the isolation of 3 in high yield and with the greatest ee to date (86:14). Both 17d and 17e (entries 4-5) afforded 3 with detectable ee’s but were ultimately less efficient systems.

Conclusions

In summary, a series of pseudo-enantiomeric carbohydrate-based NHC-ligands featuring sterically differentiated groups at positions C1 or C3 of the carbohydrate were synthesized by simple glycosylation or $S_i$Ar strategies and evaluated in the Rh-catalyzed hydroxylation of acetophenone. We show that ligands bearing a bulky group at C1 lead to a preference for (S)-phenyl-1-ethanol, while the presence of large groups at C3 afforded preferentially the (R)-enantiomer. Our results suggest this effect is achieved by the steric differentiation of the carbohydrate’s C1 and C3 positions which flank the attachment to the imidazolylidene scaffold. This “pseudoenantiomeric” design feature is shown in Figure 1.22

Figure 1. Pseudo-stereochemical ligands 12a and 17c.

While our efforts to achieve a high level of asymmetric induction in the benchmark hydroxylation reaction 11-12 have been less successful, we have surpassed our previous results and shown, for the first time to the best of our knowledge, that the judicious functionalization of carbohydrate synthons can lead to pseudo-enantiomeric NHC-ligands for asymmetric catalysis.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

ASH thanks EPSRC Bristol Chemical Synthesis CDT EP/G036764/1, JFB thanks Royal Society for a University Research Fellowship and MCG thanks the ERC (COG: 648239) and EPSRC CAF EP/L001926/1 and EPSRC EP/J002542/1 for funding.

Notes and references

16. The use of an identical aryl group for the C1 and C3 sterically differentiated NHC ligands would have been ideal, however, for proof of principle aryls compatible with the respective glycosylation and SNAr methodologies were initially used.


21. It is pertinent to note that given the pseudo-enantiomeric relationship between the C1 and C3 positions, a promising aryl moiety at C3 could also be mirrored at C1 by glycosylation with the appropriate phenol or thiol.

22. Sulfur-containing molecules can act as ligands outright, however, we have no evidence for a Rh-S interaction in complex 12a. For a review on sulfur-containing ligands in asymmetric catalysis see: H. Pellissier, Tetrahedron 2007, 63, 1297