Copper-catalyzed enantioselective 1,2-borylation of 1,3-dienes†

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A highly enantioselective Cu-catalyzed borylation of 2-substituted 1,3-dienes is reported. The use of a chiral phosphoramine ligand is essential in achieving high chemo-, regio-, diastereo- and enantioselectivity. It provides access to a variety of homoallylic boronates in consistently high yield and enantiomeric excess with 2-aryl and 2-heteroaryl 1,3-dienes as well as sterically demanding 2-alkyl 1,3-dienes. Preliminary investigations based on a non-linear effect study point to a mechanism involving more than one metal center.

Introduction

Conjugated 1,3-dienes represent a particularly attractive platform for selective functionalizations. They do occur in some natural products and have often been used as bifunctional building blocks for the synthesis of biologically active molecules as well as in several polymerization processes. From a selectivity standpoint, functionalization of 1,3-dienes represents a significant challenge due to the numerous coordination and insertion modes conceivable for a transition metal catalyst. To date, efforts to develop selective catalytic transformations have been essentially focused on linear 1,3-dienes (i.e. 4-substituted 1,3-dienes). Until recently, the limited synthetic accessibility of 2-substituted 1,3-dienes has hampered their use in the development of selective transformations. Moreover, most examples were focused on isoprene and myrcene, two readily available substrates of this subclass of conjugated dienes. Consequently, the effect of electronic and steric modifications has not been systematically investigated. For instance, the introduction of an aryl instead of an alkyl substituent at position 2- of a conjugated diene is likely to impart substantial changes in substrate polarity and/or in steric demand (Fig. 1A). Our laboratory recently reported a general procedure which streamlines access to 2-substituted 1,3-dienes and we decided to initiate a program on the selective functionalization of this underexplored scaffold. Among the approaches to functionalize 1,3-dienes, transition metal-catalyzed hydroborations and borylations have emerged as attractive strategies providing access to polyfunctionalized – potentially enantioenriched – structural motifs. For 2-substituted substrates, the selectivity challenge is highlighted by the fact that up to 6 different isomers can be generated upon exclusive mono-functionalization (Fig. 1B). Allylic boronates resulting from formal 1,4- or 4,1-hydroborations of 2-substituted 1,3-dienes have been reported by the groups of Suzuki and Ritter using highly chemo-, regio- and stereoselective Pd, Rh and Fe catalysts. Homoallylic boronates obtained by a 4,3-selective hydroboration are less common. Ito,
Fout and Chirik only described such products in studies where the focus was initially set on the hydroboration of cyclic 1,3-dienes and terminal alkenes. To our knowledge, methods to access products of 1,2-, 2,1- and 3,4-selective hydroboration are absent from the current literature (Fig. 1B). Cu/Pd-catalyzed cooperative carboration of alkenes represents another emerging class of transformation which involves the transient generation of copper-alkyl intermediates prior to transmetalation to a palladium catalyst. In this context, only few reports have placed emphasis on 1,3-dienes.\textsuperscript{9} Further optimization of the solvent, temperature, concentration and copper source led to a system which afforded homochiral boronate 2a as single regioisomer (2a : 3a : 4a)\textsuperscript{b} with 82% yield and 90% ee (Entry 10–15).

The scope of the process was first evaluated for 2-(hetero)aryl substituted 1,3-dienes. In most cases only products resulting from 1,2- and 4,3-borylation were detected. The selectivity was assessed by analysis of the crude reaction mixture after borylation and the yields and enantiomeric excess were measured after oxidation into the corresponding homoallylic alcohols (20 examples, Fig. 2). Overall, most conjugated 1,3-dienes containing electron-rich, electron-neutral and electron-deficient aromatic substituents participated well in the Cu-catalyzed borylation reaction, delivering the product in moderate to good yield, good to excellent regioselectivity and high enantioselectivity (2a–2f: 56–82% yield; chemoselectivity: 2.6 : 1 to > 20 : 1; 86–91% ee). Several functional groups (methoxy, fluoro, amino, trifluoromethyl, chloro) are tolerated. Whereas a homoallylic alcohol having a p-CN substituent (2g)\textsuperscript{a} was isolated in much reduced yield albeit in high ee, 2h which displayed an enantioenriched homoallylic boronate was generated in high yield, chemo- and enantioselectively. Reduced performances were observed in the borylation of heteroaromatic-containing 1,3-dienes although satisfactory enantioinduction were still measured for 2i and

### Results and discussion

Our study commenced by evaluating several chiral ligands for the Cu-catalyzed borylation of 1a using prototypical reaction conditions favoring borylcupration (B₃h(pin)/MeOH; Table 1).\textsuperscript{8} With ligands L1–3, homoallylic boronate 3a was obtained predominantly along with trace amount of the desired 1,2-borylated product 2a (conv. = 67–86%; Entry 1–3). The commercially available bisphosphine (R)-BDPP afforded 2a and 3a in a nearly 1 : 1 ratio with a low but measurable enantioselectivity for the former (2a: 24% ee, Entry 4). Using either diastereoisomers of the well-established phosphoramidite ligands L5 and L6, 2a was obtained as major regioisomer albeit in mixture with both 3a and (E)-4a (a product of formal 1,4-borylation) and in low ee (Entry 5–6). The chiral heterotopic ligand (R)-Quinap L7, enabled to increase both the relative ratio in favor of 2a as well as its enantiomeric excess (2a: 43% ee; Entry 7). A slightly improved result was achieved with Simplephos L8 – a structure introduced by the Alexakis group which rapidly established itself as a ubiquitous ligand in numerous Cu-catalyzed enantioselective transformations.\textsuperscript{14} Given the higher modularity of L8 compared to L7, several members of the Simplephos family were evaluated next (See ESI† for details) and allowed for identification of L9 as the best congener for the borylation of 1a (Entry 9). Further optimization of the solvent, temperature, concentration, time and copper source led to a system which afforded homoallylic boronate 2a as a single regioisomer (2a : 3a > 20 : 1) in 82% yield and 90% ee (Entry 10–15).

| Entry | L | Solvent | Conv. (%) | 2a : 3a : 4a | ee 2a (%) |
|-------|---|---------|-----------|-------------|-----------|
| 1     | L1 | THF     | 86        | 1 : 15 : —  | nd        |
| 2     | L2 | THF     | 74        | 1 : 3 : —   | 5 (S)     |
| 3     | L3 | THF     | 67        | 1 : 7 : —   | 21 (R)    |
| 4     | L4 | THF     | 81        | 1 : 1.5 : — | 24 (R)    |
| 5     | L5 | THF     | 63        | 4.6 : 1 : 3 : 1 | 4 (R) |
| 6     | L6 | THF     | 80        | 4 : 1 : 1   | 20 (R)    |
| 7     | L7 | THF     | 74        | 6 : 1 : 2   | 43 (R)    |
| 8     | L8 | THF     | 87        | 8 : 2 : 1   | 48 (R)    |
| 9     | L9 | THF     | 91        | 27 : 2.7 : 1| 67 (R)    |
| 10    | L9 | Et₂O   | 51        | 12 : 1 : —  | 72 (R)    |
| 11    | L9 | Tol.   | 83        | 13 : 1 : —  | 70 (R)    |
| 12    | L9 | C₆H₅Cl | 85        | 12 : 1 : —  | 74 (R)    |
| 13    | L9 | C₆H₁₂ | 88        | 17 : 1 : —  | 70 (R)    |
| 14    | L9 | C₆H₁₂ | 77        | 20 : 1 : —  | 85 (R)    |
| 15    | L9 | C₆H₁₂ | 89 (82)  | 20 : 1 : —  | 90 (R)    |

*Reaction conditions: 1a (0.12 mmol), B₃h(pin) (0.10 mmol), 0.3 M HClO₄ (10 mol%), without base.*

\textsuperscript{a} Determined by \textsuperscript{1}H NMR using an internal standard. \textsuperscript{b} Determined by HPLC using a chiral stationary phase after oxidation to the corresponding alcohol 2a. \textsuperscript{c} 20 mol% of ligand. \textsuperscript{d} 0.1 M. \textsuperscript{e} 0.15 M. \textsuperscript{f} 40 °C, 4 h. \textsuperscript{g} CuO₄Bu (10 mol%), without base. \textsuperscript{i} Yield over 2 steps after oxidation to 2a and purification by column chromatography.
Finally, skipped dienes 2's-t which derived from the parent dendralenic 1,3-dienes were isolated as single regioisomers in good yield and high enantioselectivity.

Subsequently, conjugated 2-alkyl-1,3-dienes were investigated (Fig. 3). Counter-intuitively – perhaps – the reactivity, the chemoselectivity and the enantioselectivity were all found to increase drastically when going from primary (1u-v), to secondary (1w) and finally tertiary alkyl substituents (1x). While primary and secondary alkyl favored 4,3-borylation, a sterically demanding 1-adamantyl group restored preferential 1,2-borylation (7 : 1) generating 2x in good yield and excellent enantioselectivity. At first sight, these data suggest that enantiodifferentiation may preferentially occur during 1,4-protodecupration from intermediate C rather than during 1,2-borocupration as a particularly congested quaternary Cu-α-allyl species B would be formed in the case of 2x. The situation is likely to be more subtle and complex. Indeed, non-linear-effect studies revealed a substantial deviation from linearity – a signature for catalyst aggregation as is apparent from Fig. 4.15

2'. Fig. 2 Sequential borylation/oxidation of 2-(hetero)aryl substituted 1,3-dienes. Reaction conditions: 1a (0.36 mmol), B2(pin)2 (0.30 mmol). Chemoselectivity assessed by 1H NMR after borylation. Yields of isolated alcohols 2'. Enantioselectivity determined after oxidation by HPLC, GC or SFC using a chiral stationary phase. a The minor isomer is 4'n. b Isolated as a 5 : 1 mixture.

Fig. 3 Sequential borylation/oxidation of 2-alkyl substituted 1,3-dienes. Reaction conditions: 1u-x (0.18–0.36 mmol), B2(pin)2 (0.15–0.30 mmol). Chemoselectivity assessed by 1H NMR after borylation. Isolated yields for alcohols 2v-x. Enantioselectivity determined after oxidation by HPLC, GC, SFC using a chiral stationary phase. a Conversion of non-separable isomers determined by 1H NMR (2'u + 3'u). b At 0 °C for 24 h.

Fig. 4 Non-linear effect study. Reaction conditions: 1a (0.12 mmol), B2(pin)2 (0.10 mmol). Chemoselectivity > 20 : 1 in all cases as assessed by 1H NMR. Enantioselectivity determined after oxidation by HPLC using a chiral stationary phase. Average of two experiments.
Catalyst-controlled diastereoselective transformations where a chiral catalyst can install one (or several) new stereocenter(s) independently of the stereochemical complexity of the substrate have gained a certain momentum recently.\(^\text{16,17}\) Hence, the innate bias imposed by \((S)\)-1y on the Cu-catalyzed borylation was assessed using DREWPhos (L10) leading to a \(2 : 1\) diastereomeric ratio in favor of \((S,S)\)-2y (Fig. 5).\(^\text{18}\) Diastereoselective borylation reactions were performed with both enantiomers of the chiral ligand. In the match situation \((S,S)\)-2y was isolated in \(86\%\) yield and \(>20 : 1\ dr\) with \((R,R)\)-L9. In the mismatch situation, the enantiomeric ligand \((S,S)\)-L9 proved able to substantially override the substrate bias, generating \((R,S)\)-2y preferentially (\(85\%\) yield; \(1 : 7\ dr\)). In addition to serving as a prototype for further developments, this example highlights the high chemoselectivity of our protocol as only one of the four olefinic functionalities present in \((S)\)-1y underwent borylation.

Finally, double borylation of bis-diene 1z led preferentially to the formation of \((S,S)\)-2z (\(>99\%\) ee) over the \(meso\) isomer \((R,S)\)-2z (\(8 : 1\ dr\)) (Fig. 6). This approach is based on the Horeau duplication principle and demonstrates that the catalyst can induce high levels of selectivity of each diene moiety independently of the other leading to an overall amplification.\(^\text{19,20}\)

**Conclusions**

In conclusion, we have developed a highly chemo-, regio- and enantioselective Cu-catalyzed borylation of 2-aryl and 2-alkyl substituted 1,3-dienes using a chiral phosphanamine ligand. The method is compatible with a broad range of functional groups and provides rapid access to synthetically relevant homoallylic boronates/alcohols and is amenable to a catalyst-controlled diastereoselective process. Further mechanistic investigations into the origin of the selectivity of this catalytic reaction are underway.

**Conflicts of interest**

There are no conflicts to declare.

**Acknowledgements**

This work was supported by the University of Geneva. S. Rosset is acknowledged for technical assistance.

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20 When 1,3-dienes with other substitutions patterns (2,3-disubstituted, linear, cyclic…) were investigated with our optimized conditions, unsatisfactory levels of selectivity were observed. See ESL†