Nickel(0)-catalyzed linear-selective hydroarylation of unactivated alkenes and styrenes with aryl boronic acids†

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Herein, we describe the first linear-selective hydroarylation reaction of unactivated alkenes and styrenes with aryl boronic acids, which was achieved by introducing a directing group on the alkenes. This efficient, scalable reaction serves as a method for modular assembly of structurally diverse alkyl arenes, including γ-aryl butyric acid derivatives, which are widely utilized as chemical building blocks for the synthesis of various drugs and other biologically active compounds.

Introduction

Transition-metal-catalyzed alkene hydroarylation involving metal hydrides (M–H)\(^1\) has become one of the most widely used strategies for the synthesis of alkyl arenes.\(^2\) To date, three types of aryl sources have been used for this purpose: (1) simple arenes, (2) aryl halides, and (3) aryl metals (i.e., aryl stannanes or boronic acids). The simple arenes are usually restricted to heteroarenes and arenes with a directing group because of the challenge of activating the inert C–H bonds of simple arenes.\(^3\) Aryl halides and aryl metals as the aryl sources require the use of \(\text{O}_2\) or an excess of a reductant (such as a silane or an alkyl halide), which limits the practicality of alkene hydroarylations with these two sources (Scheme 1a).\(^4,5\) A significant breakthrough was made by Zhou et al., who reported a highly selective Ni-catalyzed hydroarylation of styrenes and 1,3-dienes with aryl boron compounds under redox-neutral conditions (Scheme 1b).\(^6\) However, this method still suffers from some limitations: (1) the reaction is efficient only with styrene and 1,3-diene substrates, and (2) only branched products can be achieved.

Inspired by recent work on olefin functionalization reactions in which the reactivity and regioselectivity are controlled via the introduction of a coordinating group,\(^7,8\) we have developed the first method for directing-group-controlled linear-selective hydroarylation of unactivated alkenes and styrenes with aryl boronic acids under redox-neutral conditions (Scheme 1c). This efficient, scalable reaction serves as a method for modular assembly of structurally diverse alkyl arenes, including γ-aryl butyric acid derivatives, which are widely utilized as chemical building blocks for the synthesis of various drugs and other biologically active compounds (Scheme 1). γ-Aryl butyric acids are traditionally prepared by Friedel–Crafts reactions between arenes and butyrolactones,\(^9\) but this method suffers from disadvantages such as harsh reaction conditions, limited substrate scope (it is suitable only for electron-rich arenes), and poor regioselectivity.

Results and discussion

In a preliminary experiment, we found that treatment of 3-butenoic acid derivative 1a (0.2 mmol), which bears an 8-
various phosphine ligands were investigated (entries 9–12). Molar ratio to 1:2 increased the yield to 61% (entry 8). Finally, switching from PCy₃ to PPh₃ dramatically improved the yield (to 85%, entry 9). A control experiment confirmed that the reaction did not occur in the absence of Ni(COD)₂ (entry 13).

Next, we investigated the substrate scope with respect to the aryl boronic acid by carrying out reactions with 3-butenolic acid derivative 1a as the alkene (Scheme 2). To our delight, electron-rich, electron-poor, and sterically hindered aryl boronic acids all afforded the desired products in good to excellent yields (3a–3u). Heteroaryl boronic acids were also reactive (3v and 3w), as was an alkyl boronic acid, which selectively afforded (E)-6-phenylhexenoic acid derivative 3x under the optimized conditions. In addition, we found that a high yield of 3b could be obtained by hydroarylation of 1a with an aryl boroxine or an aryl boronic ester as the aryl source. It is important to stress that these reaction conditions were compatible with a remarkable variety of functional groups on the aryl boronic acids, including halogens (F, Cl, and Br) and acetyl, cyano, and methoxy groups, yielding products (3i–3s) that could be subjected to further synthetic transformations. In addition, the reaction could be carried out on gram scale without a decrease in the yield (1.5 g of 3b, 86%). The structure of 3b was confirmed by X-ray diffraction analysis of a single crystal.

We next evaluated the utility of this method for various unactivated alkenes (Scheme 3). Terminal alkenes bearing a single substituent at the α- or β-position reacted smoothly to afford the desired products in good to excellent yields (4a and 4b). A sterically congested α,α-disubstituted terminal alkene was also reactive, furnishing desired product 4c in moderate yield, although a higher temperature (125 °C) and a higher loading (10 mol%) of a different ligand, PhPMe₂, were required. Furthermore, internal alkenes bearing a variety of substituents at the γ-position could also be efficiently converted into the

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**Table 1** Optimization of directed hydroarylation of unactivated alkene 1a with 2-naphthylboronic acid 2a

| Entry | Ligand | Base | Solvent (H source) | Yield [%] |
|-------|--------|------|-------------------|----------|
| 1     | PCy₃   | —    | MeOH              | 21       |
| 2     | PCy₃   | —    | t-AmylOH          | 29       |
| 3     | PCy₃   | K₂CO₃| t-AmylOH          | 38       |
| 4     | PCy₃   | KHCO₃| t-AmylOH          | 23       |
| 5     | PCy₃   | K₃PO₄| t-AmylOH          | 43       |
| 6     | PCy₃   | NaOrBu| t-AmylOH         | NR       |
| 7     | PCy₃   | CsOPiv| t-AmylOH         | 53       |
| 8     | PCy₃   | CsOPiv| t-AmylOH         | 61       |
| 9     | PPh₃   | CsOPiv| t-AmylOH         | 86(85)   |
| 10    | CyPPh₂ | CsOPiv| t-AmylOH         | 77       |
| 11    | S-Phos | CsOPiv| t-AmylOH         | 33       |
| 12    | XantPhos| CsOPiv| t-AmylOH        | 59       |
| 13    | PPh₃   | CsOPiv| t-AmylOH         | NR       |

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*Reactions were carried out with Ni(COD)₂ (5 mol%), ligand (10 mol%), base (0 or 1.5 equiv.), 1a (0.2 mmol), and 2-naphthylboronic acid (2a, 0.3 mmol) in solvent (1 mL) for 48 h at 25 °C under a N₂ atmosphere. Yields were determined by NMR spectroscopy with an internal standard. NR = no reaction. ² 2.0 equiv. of 2a was used. The isolated yield is given in parenthesis. ³ Reaction without Ni(COD)₂.
corresponding products (4d–4l); the steric and electronic effects of the substituents appeared to be negligible. Notably, the yields of 4e from trans- and cis-3-hexenoic acid were essentially the same. In addition, α,γ-disubstituted alkenes gave desired products 4i and 4j. Surprisingly, a γ,γ-disubstituted alkene could also be hydroarylated to produce compound 4l (88%), which has a quaternary carbon center.

We wondered whether the introduction of the AQ directing group at the ortho-position of styrene would result in linear selectivity rather than the branched selectivity reported by Sigman et al. and Zhou et al. for hydroarylation of styrenes with aryl metals. After extensive investigation, we found, to our delight, that reactions of styrene derivative 1m with various aryl boronic acids occurred smoothly with completely linear selectivity and in moderate yield by employment of PhPCy2 as the ligand and higher catalyst loading (10 mol% Ni(COD)2), higher temperature (125 °C), and longer reaction time (Scheme 4). This result clearly proved that the directing group controlled the regioselectivity of the hydroarylation.

The products obtained by the method described herein could provide access to structurally diverse synthetic building blocks by means of additional transformations (Scheme 5, upper panel). Specifically, removal of the AQ directing group of 3b smoothly provided 4-phenylbutanoic acid (5b) in 97% yield. Acid 5b could undergo intramolecular cyclization to yield tetralin-derivative 6a, or the carboxyl group could be replaced with an iodine atom (6b). Five-membered lactone 6c could be obtained by treatment of 5b with a hypervalent iodine reagent, and 5b readily underwent attack by CH3NO2 to afford corresponding ketone derivative 6d. To further demonstrate the synthetic usefulness of our method, we synthesized the drug Sensipar from 3s (Scheme 5, lower panel). First, free acid 5s was synthesized by removal of the AQ directing group, and then the acid was transformed into the corresponding alkyl iodide (6s) by treatment with NIS/I2 in DCE. Simple amination of 6s gave Sensipar in 97% yield.

To probe the reaction mechanism, we carried out a control experiment and a series of deuteration experiments (Scheme 6). We found that no reaction occurred when N-(naphthalenyl) butenamide 7 and 2-naphthalenylboronic acid (1a) were used as the substrates (eqn (1)). This result indicates that the presence of the AQ directing group on the unactivated alkene was indispensable. Treatment of PhB(OD)2 2b-D with alkene 1a in MeOH or treatment of (PhBO)3 with 1a in CD3OH gave undeutrated product 3b (eqn (2) and (3)). However, the use of MeOD as the solvent led to the formation of 3b that was only partially deuterated at both the α- and β-positions (eqn (4)), which reveals that the hydrogen atom of the Ni–H intermediate A (Scheme 7) came from the methanol O–H group and

![Scheme 4](image1)

**Scheme 4** Reactions of styrene derivative 1m with aryl boronic acids.

![Scheme 5](image2)

**Scheme 5** Transformations of hydroarylation products 3b and 3s.

![Scheme 6](image3)

**Scheme 6** Control experiment and deuteration experiments.

![Scheme 7](image4)

**Scheme 7** Proposed mechanism of the Ni(0)-catalyzed directing-group-controlled hydroarylation of unactivated alkenes with aryl boronic acids.
hydrometallation of Ni–H is irreversible in the presence of aryl boronic acid. Further experiments suggest that hydrometallation of starting material 1a via Ni–H species would also happen to form 5-membered nickelacycle and is irreversible in the absence of aryl boronic acid under our reaction conditions (eqn (5) and (6)). Additionally, the deuteriation of α-positions might be because of CsOPiv base.

On the basis of literature reports and our own mechanistic experiments, we propose two catalytic cycles that starts with the reversible formation of Ni–H species A (Scheme 7). For path A, coordination and subsequent hydrometallation of the C=C bond affords the six-membered nickelacyclic intermediate C, and then transmetalation of the aryl boronic acid generates intermediate D. Finally, reductive elimination gives the desired product and regenerates the Ni(0) catalyst. Alternatively, intermediate A could also undergo transmetalation first to form Aryl-Ni–H species C′, and then alkene insertion to form five-membered nickelacyclic intermediate D′, which would involve reductive elimination to yield the same linear product. Note, that we have detected the production of naphthalene under our reaction condition. It indicated that cycle B might be the real process. However, at this stage, we still can’t rule out cycle A.

Conclusions

In conclusion, we have described the first method for Ni(0)-catalyzed directing-group-controlled linear-selective hydroarylation of unactivated alkenes and styrenes with aryl boronic acids under redox-neutral conditions. Our efficient, scalable method provides a general route to structurally diverse alkyldiene derivatives, including γ-aryl butyric acid derivatives, which are widely utilized as chemical feedstocks for the preparation of drugs and other biologically active compounds.

Conflicts of interest

There are no conflicts to declare.

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