Check for updates

Advanced Synthesis & Catalysis

Accepted Article

Title: Borinic Acid-Catalyzed Regioselective Ring-Opening of 3,4- and 2,3-Epoxy Alcohols with Halides

Authors: Grace Wang and Mark Taylor

This manuscript has been accepted after peer review and appears as an Accepted Article online prior to editing, proofing, and formal publication of the final Version of Record (VoR). This work is currently citable by using the Digital Object Identifier (DOI) given below. The VoR will be published online in Early View as soon as possible and may be different to this Accepted Article as a result of editing. Readers should obtain the VoR from the journal website shown below when it is published to ensure accuracy of information. The authors are responsible for the content of this Accepted Article.

To be cited as: *Adv. Synth. Catal.* 10.1002/adsc.201901268

Link to VoR: http://dx.doi.org/10.1002/adsc.201901268

10.1002/adsc.201901268

FULL PAPER

DOI: 10.1002/adsc.201((will be filled in by the editorial staff))

Borinic Acid-Catalyzed Regioselective Ring-Opening of 3,4- and 2,3-Epoxy Alcohols with Halides

Grace Wang[a] and Mark S. Taylor[a]*

[a] Department of Chemistry, University of Toronto, 80 St. George St., Toronto ON M5S 3H6 CANADA
Phone: (+1) 416-946-0571. E-mail: mtaylor@chem.utoronto.ca

Received: ((will be filled in by the editorial staff))

Dedicated to Professor Eric N. Jacobsen on the occasion of his 60th birthday.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201######.

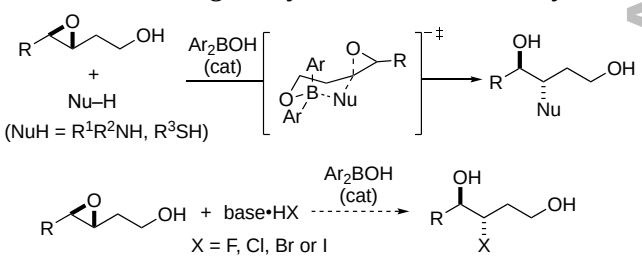
Abstract. Methods for the regioselective ring-opening of 3,4-epoxy alcohols and 2,3-epoxy alcohols with halide nucleophiles, using a diarylborinic acid catalyst, are disclosed. Ring-opening occurs at the position proximal to the OH group, an effect ascribed to a catalytic tethering mechanism whereby coordination to the substrate OH group positions the diarylborinic acid to deliver a coordinated halide nucleophile. These methods provide access to halohydrin substitution patterns that were not previously accessible through catalytic epoxide ring-opening reactions.

Keywords: boron; halides; homogeneous catalysis; regioselectivity.

Introduction

Regioselective ring-openings of epoxides are useful and versatile methods for the construction of functionalized, enantio- and/or diasteromerically enriched organic compounds.[1] Despite the synthetic utility of epoxide ring-opening reactions, protocols that provide reliable regioselectivity and broad scope of application are available for only a few substrate classes (*e.g.*, 2,3-epoxy alcohols,[2] 2,3-epoxypropionic acid derivatives,[3] glycal epoxides[4]). In recent years, important advances have been made in the development of catalytic protocols for epoxide ring-opening and their extension to new substrate classes. Yamamoto and co-workers have explored W(VI), Mo(VI), Ce(III), and Gd(III) complexes for enantioselective and/or regioselective ring-openings of 2,3-epoxy alcohols and 2,3-epoxy sulfonamides,[5] as well as Ni(II)-based catalysts for aminolysis of 3,4-epoxy alcohols.[6] These protocols give rise to outcomes consistent with chelation-based mechanisms (C3-selectivity for ring-openings of 2,3-epoxy alcohols and sulfonamides and C4-selectivity for 3,4-epoxy alcohols).[7] Similar patterns of regioselectivity have been obtained using the erbium(III) and lanthanum(III) trifluoromethanesulfonate-catalyzed methods developed by Iwabuchi and co-workers.[8],[9]

Our group has investigated diarylborinic acids as catalysts for regioselective ring-opening[10] and rearrangement reactions[11] of epoxy alcohols. In the case of 3,4-epoxy alcohols with amine or thiol nucleophiles, the use of diarylborinic acid catalysis resulted in C3-selective ring-opening, a complementary outcome to that achieved using the transition metal or lanthanide-based Lewis acids described above (Scheme 1).[12] We proposed that the regiochemical outcome arose from a catalytic tethering mechanism[13] in which the boron compound interacted simultaneously with the nucleophile and the electrophile (via the pendant hydroxyl group).[14] Related methods employing electron-deficient arylboronic acids as catalysts were reported by Wang and co-workers.[15] Considering the importance of halohydrin motifs in synthetic intermediates and bioactive natural products,[16] we sought to apply organoboron catalysis to ring-openings of 3,4-epoxy alcohols with halide nucleophiles. (In an earlier study of chloroacylations and chlorosulfonylations of 2,3-epoxy alcohols,[10a] we noted that the only 3,4-epoxy alcohol substrate examined gave an unexpected regiochemical outcome; it was this observation that motivated our efforts to explore such substrates for catalytic tethering using diarylborinic acids.) Here, we describe the development of protocols for the regioselective synthesis of chlorohydrins and bromohydrins by diarylborinic acid-catalyzed epoxide ring-opening. Consistent with our earlier work, and in contrast to existing catalytic methods for halohydrin



Scheme 1. Diarylborinic acid-catalyzed ring-opening of 3,4-epoxy alcohols with amine and thiol nucleophiles, and proposed extension to regioselective halohydrin formation.

This article is protected by copyright. All rights reserved.

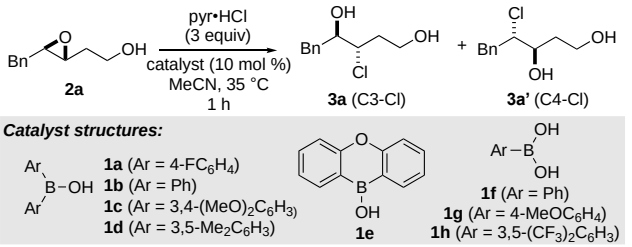
Accepted Manuscript

synthesis, these reactions result in C3-selective ring-opening of 3,4-epoxy alcohols. Extensions to C2-selective openings of 2,3-epoxy alcohols are also demonstrated, providing access to a regiochemical outcome complementing that of existing catalytic methods.[5c]

Results and Discussion

For ring-openings of 3,4-epoxy alcohols with amine and thiol nucleophiles, nucleophiles having pK_a values of roughly 5–6 gave rise to the highest reaction rates in the presence of the diarylborinic acid catalyst. While the mechanistic basis for this observation is not clear at this stage, we hoped to use it as a rough guideline for selecting appropriate nucleophilic partners. In the context of ring-openings by halide anions, this could be achieved by employing an acidic counterion. Consistent with this hypothesis, the reaction of epoxy alcohol **2a** with pyridinium chloride in the presence of 10 mol % of bis(4-fluorophenyl)borinic acid (**1a**) resulted in >19:1 regioselectivity for the formation of chlorohydrin diol **3a** (Table 1, entry 1). In the absence of catalyst, the ring-opened product was formed in quantitative yield (overnight reaction time), but as a 1.8:1 mixture of isomers. These results indicate that the diaryborinic acid-catalyzed process outcompetes a poorly selective background reaction and gives rise to the outcome consistent with a catalytic tethering mechanism. The use of La(III) trifluoromethanesulfonate ($La(OTf)_3$) or $Cu(OTf)_2$ in place of **1a** resulted in mixtures of regioisomers (entries 3 and 4). The parent diphenylborinic acid (**1b**) gave similar regioselectivity but slightly lower activity

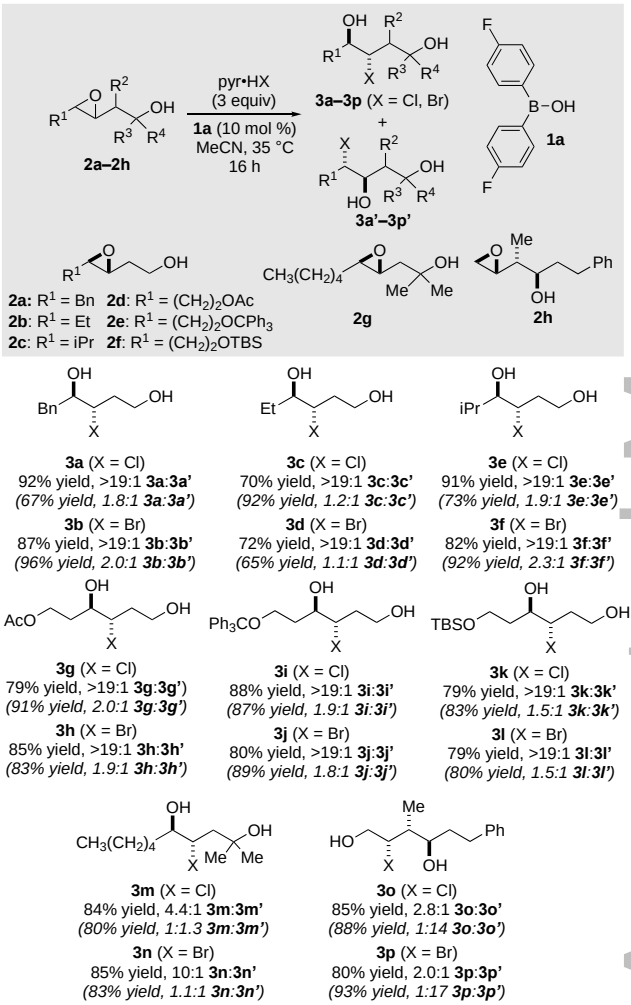
Table 1. Evaluation of catalysts for regioselective hydrochlorination of 3,4-epoxy alcohol **2a**.



entry	catalyst	yield[a]	**3a**:**3a'**[b]
1	**1a**	80%	>19:1
2	none	67%	1.8:1
3	$La(OTf)_3$	>95%	2.1:1
4	$Cu(OTf)_2$	>95%	2.2:1
5	**1b**	65%	>19:1
6	**1c**	86%	13:1
7	**1d**	80%	>19:1
8	**1e**	72%	2.4:1
9	**1f**	66%	1.7:1
10	**1g**	80%	2.0:1
11	**1h**	70%	2.5:1

[a] Yields (0.1 mmol scale) were determined by ^{1}H NMR spectroscopy using 1,3,5-trimethoxybenzene as a quantitative internal standard. [b] Regioselectivities were determined by ^{1}H NMR spectroscopy.

than catalyst **1a**, and roughly similar results were obtained using substituted diarylborinic acid catalysts **1c** and **1d**. In contrast, the less Lewis acidic oxaboraanthrancene **1e**[17] resulted in only a modest enhancement in C3:C4 regioselectivity relative to the uncatalyzed reaction. Low regioselectivities were also obtained using arylboronic acid catalysts **1f–1g**.[15b] Applications of **1a** to hydrochlorinations of other 3,4-epoxy alcohol substrates were investigated (Scheme 2). By using pyridinium bromide in place of the chloride salt, regioselective hydrobrominations were also achieved. The yields and C3:C4 ratios for reactions conducted in the absence of the organoboron catalyst are also shown for each substrate combination. Overall, the results show that diarylborinic acid catalysis enables C3-selective halohydrin formation from substituted epoxy alcohols that would otherwise lead to mixtures of regioisomers. Catalytic tethering was



Scheme 2. Diarylborinic acid-catalyzed hydrochlorinations and hydrobrominations of 3,4-epoxy alcohols. Combined yields of the two regioisomers (0.2 mmol scale) after purification by silica gel chromatography are reported. Regioselectivities were determined by ^{1}H NMR spectroscopy. Yields and regioselectivities for reactions carried out in the absence of catalyst (0.1 mmol scale, determined by ^{1}H NMR spectroscopy with 1,3,5-trimethoxybenzene as a quantitative internal standard) are shown in parentheses.

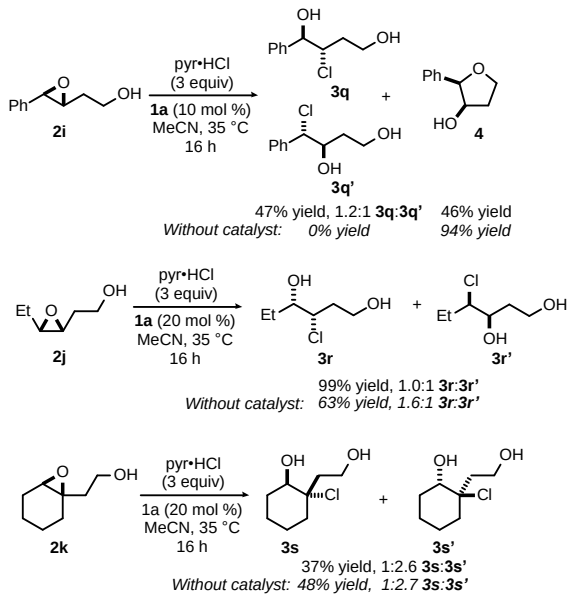
Accepted Manuscript

This article is protected by copyright. All rights reserved.

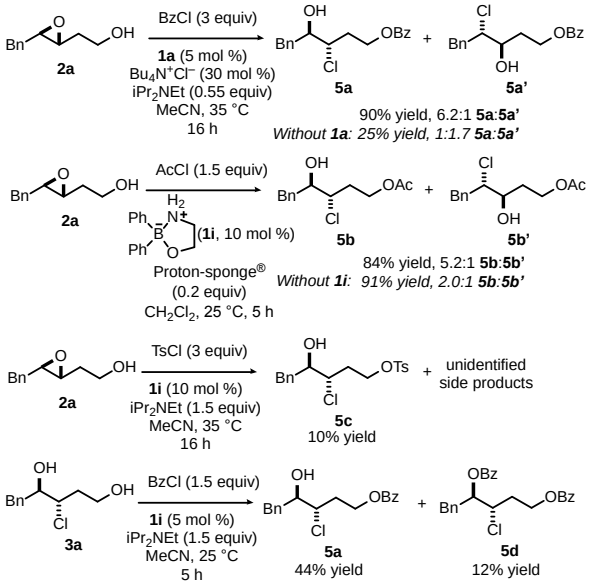
also possible in the case of a tertiary alcohol substrate (products **3m** and **3n**). The lower regioselectivies obtained in these cases presumably reflect impaired catalyst–substrate binding due to steric hindrance. Ring-opening of a terminal epoxide at the secondary carbon was also achieved (products **3o** and **3p**). In this instance, the organoboron catalyst was in competition with a background reaction that displayed high selectivity for opening at the less hindered, primary position. More generally, the relatively high rate of uncatalyzed hydrochlorination and hydrobromination of epoxides under the optimized conditions has presented a challenge for generating the products of 'contrasteric' ring-openings at the levels that were possible for our previously reported couplings with amine and thiol nucleophiles.[12]

Limitations of the organoboron-catalyzed halohydrin formation from 3,4-epoxy alcohols are depicted in Scheme 3. Styrene-derived epoxy alcohol **2i** underwent hydrochlorination with low regioselectivity, presumably due to the activated nature of the benzylic position. Competing cyclization to tetrahydropyran derivative **4** was also observed from this substrate; in the absence of catalyst, only the latter product was observed. A drop in regioselectivity was observed using *cis*-configured epoxy alcohol **2j** and trisubstituted **2k**. A similar dependence on epoxy alcohol configuration was observed previously for reactions with amine and thiol nucleophiles,[12] and was ascribed to unfavorable steric interactions in the chairlike transition state for boron-tethered ring-opening of the *cis*-isomer. Extension of the protocol to hydrofluorination of 3,4-epoxy alcohols was unsuccessful; ring-opening was not observed, and the addition of fluoride salts caused inhibition of the diarylborinic acid-catalyzed hydrochlorination reaction, perhaps due to the strong B–F interaction. Likewise, diarylborinic acid-catalyzed hydroiodination proved to be challenging, with no appreciable rate acceleration or change in regioselectivity relative to the background reaction. We speculate that the iodide affinity of the organoboron complex may be too low for efficient catalysis relative to the uncatalyzed ring-opening in this case.

As noted above, we documented a single example of C3-selective chloroacylation of a 3,4-epoxy alcohol while exploring the scope and limitations of the diarylborinic acid-catalyzed coupling of acid chlorides with 2,3-epoxy alcohol substrates.[10a] Consistent with this result, chlorobenzoylation of substrate **3a** was achieved in 90% yield (6.2:1 C3:C4-Cl regioselectivity) using a combination of **1a** and $Bu_4N^+Cl^-$ as co-catalysts (Scheme 4).[10b] In the absence of the organoboron catalyst, the yield and regioselectivity of chlorobenzoylation were considerably lower. Similarly chloroacetylation of **2a** was accomplished in 84% yield (5.2:1 **5b**:**5b'**) using diphenylborinic acid-derived pre-catalyst **1i**. The rate of the uncatalyzed reaction was higher in this case, but a significant difference in regioselectivity was again evident (2.0:1 **5b**:**5b'** in the absence of the organoboron catalyst). In contrast to the successful chloroacylations of **2a**, coupling with *para*-toluenesulfonyl chloride (TsCl) under the previously reported conditions for chlorosulfonylsulfonylation of 2,3-epoxy alcohols[10a] resulted in a low yield of **5c**, along with several unidentified side products. Whereas monoester **5a** was accessible via chlorobenzoylation



Scheme 3. Limitations of the diarylborinic acid-catalyzed hydrochlorination of 3,4-epoxy alcohols. Yields and regioselectivities were determined by ^{1}H NMR spectroscopy with 1,3,5-trimethoxybenzene as a quantitative internal standard, unless otherwise noted. [a]Yield after purification by silica gel chromatography.



Scheme 4. Reactions of 3,4-epoxy alcohol **1a** with BzCl, AcCl and TsCl, and attempted monoesterifications of diol **3a**. Yields after purification by silica gel chromatography, unless otherwise noted. Regioselectivities were determined by ^{1}H NMR spectroscopy. [a] Yields were determined by ^{1}H NMR spectroscopy with 1,3,5-trimethoxybenzene as a quantitative internal standard.

Accepted Manuscript

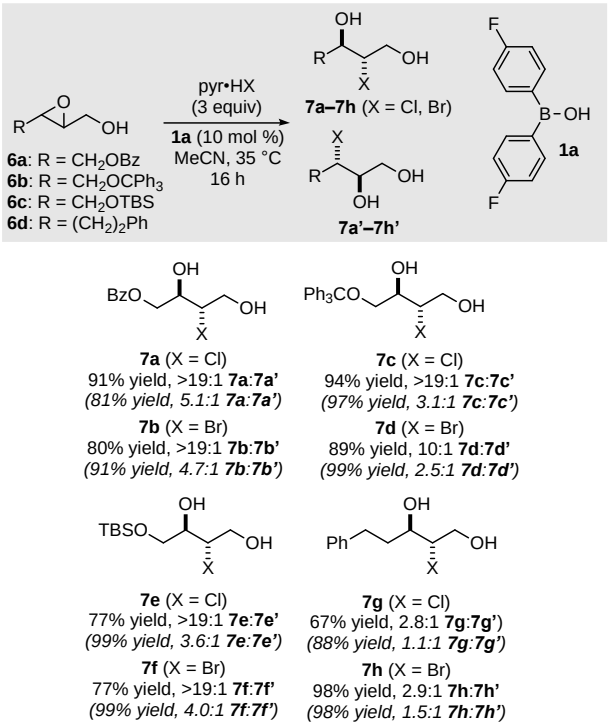
This article is protected by copyright. All rights reserved.

of **2a**, its synthesis by diarylborinic acid-catalyzed acylation of **3a**[18] was less successful, due to the competitive formation of dibenzoate **5d**. Considering that 1,2- and 1,3-diols have been employed successfully in such regioselective functionalizations, we propose that the affinity of the 1,4-diol group for the diarylborinic acid catalyst is not suffiently high to enable efficient activation of ring-opened products such as **3a**. It is noteworthy that the chloroacylation protocol provides accesso derivatives that are not readily available by sequential ring-opening/monofunctionalization.

Finally, diarylborinic acid-catalyzed hydrochlorinations and hydrobrominations of 2,3-epoxy alcohols[19] were also investigated. A variety of protocols for halohydrin formation from such substrates have been developed.[20] The majority of them give rise to C3-selectivity and require a stoichiometric amount of Lewis acid promoter, presumably because the 1,2-diol product can act as a chelating ligand. Transition metal-catalyzed, C3-selective openings of 2,3-epoxy alcohols and sulfonamides with chloride, bromide and iodide were developed by Yamamoto and Wang.[5c] Particularly relevant precedent was established by the group of Miyashita, who demonstrated that phenylboronic acid and trialkylborates act as stoichiometric promoters for C2-selective ring-openings of 2,3-epoxy alcohols with halide, azide, thiolate and cyanide nucleophiles.[21]

The authors proposed that an unusual *endo*-mode ring-opening of a boron chelate was responsible for the regiochemical outcome. Using diarylborinic acid catalyst **1a**, the reaction of 2,3-epoxy alcohol **6a** with pyridinium chloride resulted in C2-selective ring-opening in 91% yield and >19:1 regioselectivity (Scheme 5). Hydrochlorination and hydrobromination reactions of other *trans*-disubstituted 2,3-epoxy alcohols were accomplished using this protocol. For substrates **6a**–**6c**, the uncatalyzed ring-openings by pyridinium chloride and bromide took place with modest to good levels of C2-selectivity (results shown in parentheses in Scheme 3). In the case of substrate **6d**, the uncatalyzed hydrochlorination and hydrobromination reactions were unselective, while modest levels of C2-selectivity were achieved using catalyst **1a**.

The scope of the diarylborinic acid-catalyzed ring-opening of 2,3-epoxy alcohols with halides proved to be somewhat limited, with *cis*-disubstituted, trisubstituted and terminal epoxides giving rise to lower levels of regioselectivity. In this regard, the transformation is complementary to our previously reported chloroacylation of 2,3-epoxy alcohols, which favoured ring-opening at the C3-position and was most efficient for *cis*-configured epoxy alcohols.



Scheme 5. Diarylborinic acid-catalyzed hydrochlorinations and hydrobrominations of 2,3-epoxy alcohols. Combined yields of the two regioisomers (0.2 mmol scale) after purification by silica gel chromatography are reported. Regioselectivities were determined by ^{1}H NMR spectroscopy. Yields and regioselectivities for reactions carried out in the absence of catalyst (0.1 mmol scale, determined by ^{1}H NMR spectroscopy with 1,3,5-trimethoxybenzene as a quantitative internal standard) are shown in parentheses.

Conclusion

In conclusion, the catalytic tethering strategy based on interactions of diarylborinic acids with epoxy alcohols has been successfully extended to halides as nucleophiles. The method enables C3-selective ring-openings of 3,4-epoxy alcohols and C2-selective openings of *trans*-disubstituted 2,3-epoxy alcohols, using chloride and bromide as nucleophiles. For both epoxy alcohol substrate classes, catalytic protocols for halide ring-opening with this sense of regioselectivity had not been reported previously. Consistent with our previous work on ring-openings with amine and thiol nucleophiles, the presence of a mild Brønsted acid (in this case, the pyridinium counterion) was important for high catalytic reactivity. Detailed mechanistic studies of the ring-openings of epoxy alcohols, as well as extensions of the diarylborinic acid-based catalytic tethering approach to other transformations, are among our goals for future work.

Accepted Manuscript

This article is protected by copyright. All rights reserved.

Experimental Section

Typical Procedure for the Halide Ring-Opening of 3,4-Epoxy Alcohols

Under ambient atmosphere, a one dram vial equipped with a magnetic stirbar is charged with 3,4-epoxy alcohol (0.2 mmol, 1.0 equiv.), bis(*para*-fluorophenyl)borinic acid **1a** (10 mol %), and 0.80 mL acetonitrile. To the resulting homogeneous mixture, pyridinium halide (0.6 mmol, 3.0 equiv.) is added. The reaction vial is sealed with a screw cap, taped with PTFE and stirred at 35 °C for 16 hours. The reaction mixture is then concentrated *in vacuo* to remove solvent and then treated with aqueous $NaBO_3$ (0.05 M, 2.0 mL, 0.10 mmol)[4a] to facilitate subsequent product isolation by column chromatography by oxidative removal of the borinic acid catalyst **1a**. After 5 minutes of stirring, the mixture is diluted with saturated aqueous NH_4Cl and extracted three times with EtOAc. The combined organic layers are washed with brine, dried over anhydrous $MgSO_4$, filtered, and concentrated *in vacuo*. The crude residue is purified by flash chromatography on silica gel, eluting with a hexanes-EtOAc gradient system to afford the product as a mixture of regioisomers.

Typical Procedure for the Halide Ring-Opening of 2,3-Epoxy Alcohols

Under ambient atmosphere, a one dram vial equipped with a magnetic stirbar is charged with 2,3-epoxy alcohol (0.2 mmol, 1.0 equiv.), bis(*para*-fluorophenyl)borinic acid **1a** (10 mol %), and 0.80 mL acetonitrile. To the resulting homogeneous mixture, pyridinium halide (0.6 mmol, 3.0 equiv.) is added. The reaction vial is sealed with a screw cap, taped with PTFE and stirred at 35 °C for 16 hours before concentrating *in vacuo* to remove solvent. The crude residue is purified by flash chromatography on silica gel, eluting with a hexanes-EtOAc gradient system to afford the product as a mixture of regioisomers.

Typical Procedure for the Chloroacylation of 3,4-Epoxy Alcohols

Chlorobenzoylation

Procedure was adapted from the reported chloroacylation protocol.[10a] Under ambient atmosphere, a one dram vial equipped with a magnetic stirbar is charged with 3,4-epoxy alcohol (0.2 mmol, 1.0 equiv.), bis(*para*-fluorophenyl)borinic acid **1a** (5 mol %), and 1.00 mL acetonitrile. To the resulting homogeneous mixture, benzoyl chloride (0.6 mmol, 3.0 equiv.), tetrabutylammonium chloride (0.06 mmol, 30 mol %) and *N,N*-diisopropylethylamine (0.11 mmol, 0.55 equiv.) are subsequently added. The reaction vial is sealed with a screw cap, taped with PTFE and stirred at 35 °C for 16 hours. The reaction mixture is then concentrated *in vacuo* to remove solvent and then purified by flash chromatography on silica gel, eluting with a hexanes-EtOAc gradient system to afford the product as a mixture of regioisomers.

Chloroacetylation

Procedure was adapted from the reported chloroacylation protocol.[10a] Under ambient atmosphere, a one dram vial equipped with a magnetic stirbar is charged with 3,4-epoxy alcohol (0.2 mmol, 1.0 equiv.), 2-aminoethyl diphenylborinate (10 mol %), and 1.00 mL dichloromethane. To the resulting homogeneous mixture, acetyl chloride (0.3 mmol, 1.5 equiv.), and proton sponge (0.04 mmol, 0.2 equiv.) are subsequently added. The reaction vial is sealed with a screw cap, taped with PTFE and stirred at 25 °C for 5 hours. The reaction mixture is then concentrated *in vacuo* to remove solvent and then purified by flash chromatography on silica gel, eluting with a hexanes-EtOAc gradient system to afford the product as a mixture of regioisomers.

Acknowledgements

This work was funded by NSERC, the Canada Foundation for Innovation (Projects #t17545 and #19119), the Province of Ontario and the McLean Foundation.

References

[1] a) A. K. Yudin, G. A. Molander, *Aziridines and Epoxides in Organic Synthesis*, Wiley−VCH, Weinheim, Germany, **2006**; b) E. N. Jacobsen, *Acc. Chem. Res.* **2000**, *33*, 421–431.

[2] a) M. Caron, K. B. Sharpless, *J. Org. Chem.* **1985**, *50*, 1557–1560; b) R. M. Hanson, *Chem. Rev.* **1991**, *91*, 437–475; c) P. C. A. R. Pena, S.M., *Curr. Org. Chem.* Vol. 7, Bentham Science Publishers **2003**; d) R. B. P. N. Guivisdalsky, *J. Am. Chem. Soc.* **1989**, *111*, 3077–3079; e) M. Chini, P. Crotti, L. A. Flippin, C. Gardelli, E. Giovani, F. Macchia, M. Pineschi, *J. Org. Chem.* **1993**, 58, 1221–1227.

[3] C. H. Behrens, K. B. Sharpless, *J. Org. Chem.* **1985**, *50*, 5696–5704.

[4] a) M. Tanaka, J. Nashida, D. Takahashi, K. Toshima, *Org. Lett.* **2016**, *18*, 2288–2291; b) D. Takahashi, M. Tanaka, N. Nishi, K. Toshima, *Carbohydr. Res.* **2017** *452*, 64–77.

[5] a) C. Wang, H. Yamamoto, *Angew. Chem. Int. Ed.* **2015**, *54*, 8760–8763; b) C. Wang, H. Yamamoto, *J. Am. Chem. Soc.* **2014**, *136*, 6888–6891; c) C. Wang, H. Yamamoto, *Org. Lett.* **2014**, *16*, 5937–5939; d) C. Wang, H. Yamamoto, *Angew. Chem. Int. Ed.* **2014**, *53*, 13920–13923.

[6] C. Wang, H. Yamamoto, *J. Am. Chem. Soc.* **2015**, *137*, 4308–4311.

[7] C. Wang, L. Luo, H. Yamamoto, *Acc. Chem. Res.* **2016**, *49*, 193–204.

This article is protected by copyright. All rights reserved.

Accepted Manuscript

[8] S.-i. Uesugi, T. Watanabe, T. Imaizumi, M. Shibuya, N. Kanoh, Y. Iwabuchi, *Org. Lett.* **2014**, *16*, 4408–4411.

[9] D. Nakamura, Y. Sasano, Y. Iwabuchi, *Org. Biomol. Chem.* **2019**, *17*, 3581–3589.

[10] a) K. Tanveer, K. Jarrah, M. S. Taylor, *Org. Lett.* **2015**, *17*, 3482–3485; b) G. E. Garrett, K. Tanveer, M. S. Taylor, *J. Org. Chem.* **2017**, *82*, 1085–1095.

[11] K. Tanveer, S.-J. Kim, M. S. Taylor, *Org. Lett.* **2018**, *20*, 5327–5331.

[12] G. Wang, G. E. Garrett, M. S. Taylor, *Org. Lett.* **2018**, *20*, 5375–5379.

[13] a) R. Pascal, *Eur. J. Org. Chem.* **2003**, 1813–1824; b) K. L. Tan, *ACS Catal.* **2011**, *1*, 877–886; c) B.-J. Li, C. Ei-Nachef, A. M. Beauchemin, *Chem. Commun.* **2017**, *53*, 13192–13204; d) G. Rousseau, B. Breit, *Angew. Chem. Int. Ed.* **2011**, *50*, 2450–2494.

[14] For other examples of organoboron reactivity for which tethering mechanisms have been proposed: a) R. L. D. Letsinger, S. Dandegaonker, W. J. Vullo, J. D. Morrison, *J. Am. Chem. Soc.* **1963**, *85*, 2223–2227; b) D. A. E. Evans, K. T. Chapman, E. M. Carreira, *J. Am. Chem. Soc.* **1988**, *110*, 3560–3578; c) D. R. Li, A. Murugan, J. R. Falck, *J. Am. Chem. Soc.* **2008**, *130*, 46–48; d) K. Scholl, J. Dillashaw, E. Timpy, Y.-h. Lam, L. DeRatt, T. R. Benton, J. P. Powell, K. N. Houk, J. B. Morgan, *J. Org. Chem.* **2018**, *83*, 5756–5765; e) D. G. Hall, Structure, properties and preparation of boronic acid derivatives: overview of their reactions and application. In *Boronic Acids*, 2nd Edition, Wiley-VCH, Weinheim, Germany, **2011**; f) E. Dimitrijević, M. S. Taylor, *ACS Catal.* **2013**, *3*, 945–962.

[15] a) H. Yao, J. Liu, C. Wang, *Org. Biomol. Chem.* **2019**, *17*, 1901–1905; b) J. Liu, H. Yao, C. Wang, *ACS Catal.* **2018**, *8*, 9376–9381.

[16] a) B.-G. Wang, J. B. Gloer, N.-Y. Ji, J.-C. Zhao, *Chem. Rev.* **2013**, *113*, 3632–3685; b) C. Nilewski, E. M. Carreira, *Eur. J. Org. Chem.* **2012**, *2012*, 1685–1698; c) W.-J. Chung, C. D. Vanderwal, *Acc. Chem. Res.* **2014**, *47*, 718–728.

[17] E. Dimitrijević, M. S. Taylor, *Chem. Sci.* **2013**, *4*, 3298–3303.

[18] D. Lee, M. S. Taylor, *J. Am. Chem. Soc.* **2011**, *133*, 3724–3727.

[19] T. Katsuki, K. B. Sharpless, *J. Am. Chem. Soc.* **1980**, *102*, 5974–5976.

[20] C. Bonini, G. Righi, *Synthesis* **1994**, *1994*, 225–238.

[21] a) H. Hayakawa, N. Okada, M. Miyazawa, M. Miyashita, *Tetrahedron Lett.* **1999**, *40*, 4589–4592; b) M. Sasaki, K. Tanino, A. Hirai, M. Miyashita, *Org. Lett.* **2003**, *5*, 1789–1791; c) Y. Tomata, M. Sasaki, K. Tanino, M. Miyashita, *Tetrahedron Lett.* **2003**, *44*, 8975–8977.

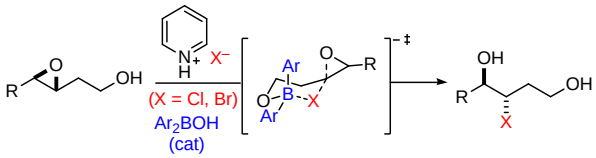
Accepted Manuscript

This article is protected by copyright. All rights reserved.

10.1002/adsc.201901268

COMMUNICATION

Borinic Acid-Catalyzed Regioselective Ring-Opening of 3,4- and 2,3-Epoxy Alcohols with Halides



Adv. Synth. Catal. **Year**, *Volume*, Page – Page

Grace Wang and Mark S. Taylor*

Accepted Manuscript

This article is protected by copyright. All rights reserved.