HHS Public Access

Author manuscript

Synthesis (Stuttg). Author manuscript; available in PMC 2017 September 01.

Published in final edited form as:

Synthesis (Stuttg). 2016 September ; 48(18): 3031–3041. doi:10.1055/s-0035-1562515.

Practical Synthetic Procedures for the Iron-Catalyzed Intermolecular Olefin Aminohydroxylation Using Functionalized Hydroxylamines

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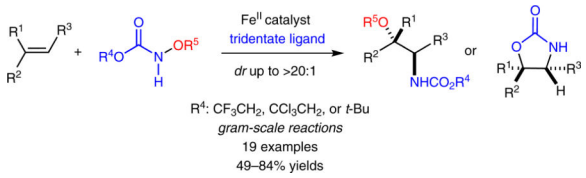
Abstract

A set of practical synthetic procedures for the iron-catalyzed intermolecular olefin aminohydroxylation reactions in gram scale is reported. In these transformations, a bench-stable functionalized hydroxylamine is applied as the amination reagent. This method is compatible with a broad range of synthetically valuable olefins including those that are incompatible with the existing aminohydroxylation methods. It also provides valuable amino alcohol building blocks with regio- and stereo-chemical arrays that are complementary to known methods.

Graphical abstract



Keywords

iron; alkenes; oxidation; amination; asymmetric catalysis

Introduction

A large number of pharmaceuticals and small-molecule biological probes contain at least one nitrogen atom and many of them are directly attached to stereogenic centers. Therefore, catalytic methods based on the direct nitrogen atom transfer to hydrocarbons are important tools for the synthesis of these valuable molecules. While selective C–H amination and olefin aziridination have been intensively studied, the direct olefin difunctionalization with nitrogen and a range of heteroatom-based functional groups are less developed, yet they are

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Supporting Information

Supporting information for this article is available online at http://dx.doi.org/10.1055/s-0035-1562515.

very important in organic synthesis. Among a range of difunctionalization reactions, the olefin aminohydroxylation has probably attracted the most research interests because vicinal amino alcohols are widely present in biologically active natural products and synthetic molecules. The pioneering osmium-based Sharpless aminohydroxylation has continued to be a powerful stereospecific method;[1] it also inspired extensive efforts for the development of alternative approaches to allow for a broader substrate scope and a better regioselectivity. In particular, nonprecious metal-catalyzed olefin aminohydroxylation reactions emerge with increasing interests.[2] Despite all these excellent tools, new nonprecious metal-catalyzed olefin aminohydroxylation methods, which are compatible with a broader range of substrates and can provide regio- and stereoselectivity complementary to existing methods, are still greatly desirable.

In 2013, we reported an iron(II)-catalyzed method for intramolecular olefin aminohydroxylation using a functionalized hydroxylamine (Scheme 1). The iron catalysts are capable of transferring both the N and O groups of the hydroxylamine to a variety of olefins.[3] Further mechanistic studies suggested that an iron-nitrenoid is a possible reactive intermediate in these stereo-convergent transformations and that the stereoselectivity can be modulated by nitrogen-based bidentate ligands. We further demonstrated that this new reactivity goes beyond unfunctionalized olefins and it can be adapted to achieve enantioselective indole aminohydroxylation,[3] which provides a unique approach for asymmetric de-aromatization reactions.

Our initial attempts to develop *intermolecular* olefin aminohydroxylation with the catalyst previously identified to be effective for the *intramolecular* reaction failed due to the lack of reactivity. We speculated that a delicate balance needs to be achieved between reactivity and stability of the iron-nitrenoid that is also possibly involved in an *intermolecular reaction*. Therefore, we explored a range of new amination reagents, iron catalysts, and ligands, and identified entirely new procedures for the intermolecular olefin aminohydroxylation (Scheme 2).[4]

This new method has a few unique features in complement to existing methods. First, it tolerates a variety of olefins including cyclopentadienes, cyclic enol ethers, and glycals, which are all incompatible with the existing aminohydroxylation methods. Next, it can effectively afford amino alcohol derivatives with regio- and stereochemical arrays complementary to known aminohydroxylation methods, especially osmium-based approaches. Herein, we provide a critical discussion of the scope and limitations of this new method and also wish to demonstrate the practicality of this method (Scheme 3).

Scope and Limitations

Styrene **1** was selected as a model substrate to study the structure–reactivity relationship of both catalysts and ami-nation reagents (Scheme 4). The reactions were set up with standard organic reaction techniques for air- and moisture-sensitive reactions outside of a glovebox. Freshly activated molecular sieves were used to remove deleterious moisture and facilitate the formation of iron–ligand complexes in situ. Our initial screening suggested that iron(II)–*N,N′*-bidentate ligand complexes are ineffective; however, nitrogen-based tridentate ligands,

including an achiral bisoxazoline PyBOX ligand **L1**, are uniquely effective for the intermolecular reaction. First, we observed that the styrene aminohydroxylation affords both an alkoxyoxazoline **3** and a protected amino alcohol **4** in good to excellent combined yields. Conveniently, both **3** and **4** can be easily converted to oxazolidinone **5** through a same hydrolytic procedure. Next, we discovered that a range of bench-stable acyloxy carbamates **2a–c** can be exploited as the amination reagents and that enhanced reactivity was observed with more electro-philic acyloxy carbamates **2b**, **2c** versus **2a** (Scheme 4, entries 1–3). Notably, both the ligands and the amination reagents can be easily prepared from readily available chemicals in large-scale and within short steps (Scheme 5).[5] Furthermore, we observed decreased reactivity with a less bulky $Fe(OTf)_2$–**L2** complex and essentially the same reactivity was identified with the $Fe(NTf_2)_2$–**L1** complex (entries 4–5).

Since this reaction affords a protected amino alcohol **5** with *inverse regioselectivity* observed using Sharpless method, we scaled it up using 3.81 g of acyloxy carbamate **2b** with *a decreased catalyst loading* (5 mol%) and observed that oxazolidinone **5** could be isolated in a good overall yield (Scheme 6; 75% yield over 2 steps).

In order to examine the substrate scope of this method, we explored a range of olefins with optimized catalysts (Scheme 7).

First, we observed that a 1,1-disubstituted α-methylstyrene is also an excellent substrate when the reaction was carried out at −40 °C (Scheme 7, entry 2, 75% yield). Subsequently, olefins that have been problematic for the existing aminohydroxylation or other iron-based amination methods were evaluated (entries 3–8). An allylsilane was first examined because it is a challenging substrate for the known iron-based amination approaches. We discovered that it can be efficiently amino-oxygenated using **2c** with an excellent regioselectivity (entry 3, 78%).

Next, a new procedure was developed using less oxidative **2a** and less bulky $Fe(OTf)_2$–**L2** complex for the amino-hydroxylation of cyclopentadiene, a substrate with labile C–H bonds and thereby has been incompatible with all the existing aminohydroxylation methods. Under these conditions, cyclopentadiene can be directly converted to an oxazolidinone in a decent yield and with excellent *dr* (Scheme 7, entry 4, *dr* >20:1). Additionally, cyclohexadiene can be smoothly converted to the corresponding oxazolidinone under the same conditions. Notably, an *inverse regioselectivity* was observed in the Sharpless aminohydroxylation of cyclohexadiene (entry 5).[1]

Although cyclic enol ethers have been challenging substrates for the known aminohydroxylation methods, they are excellent substrates for the iron-catalyzed *syn*-amino-hydroxylation, which delivers protected amino alcohols in good yields and *dr* (Scheme 7, entries 6, 7; yield up to 77% and *dr* up to >20:1). Most notably, a fully functionalized glycal can smoothly participate in the aminohydroxylation under modified conditions with **2a**, affording a 2-amino-α-sugar **13** in a decent yield and excellent *dr* (entry 8, 63% yield; *dr* >20:1 at both C1 and C2 positions).[6] Since 2-aminoglycosides are crucial building blocks for glycol-biology and catalytic methods for direct glycal aminohydroxylation have been underdeveloped, we further optimized the conditions such that this iron-catalyzed glycal

aminohydroxylation can be scaled up to gram scale without erosion of the yield and *dr* (Scheme 8).

Furthermore, we evaluated indene and discovered that indene can be efficiently amino-oxygenated under the standard conditions. Further experiments revealed that the gram-scale indene aminohydroxylation affords a protected *cis*-2-aminoindanol **14**, a valuable building block that is difficult to obtain directly with the known aminohydroxylation methods (Scheme 7, entry 9; and Scheme 9, 71% yield, *dr* >20:1).

The catalytic enantioselective indene aminohydroxylation has been a challenge in synthetic chemistry, and osmium-based protocols deliver a mixture of racemic 1-, and 2-aminoindanols.[7] In order to provide a solution for this synthetic challenge, the asymmetric induction was also explored for the indene aminohydroxylation with a range of iron–chiral ligand complexes. We discovered that a chiral 1-aminoindanol-derived PyBOX ligand **L3** is uniquely effective for the asymmetric induction and that a 2-aminoindanol derivative **14** was obtained with an excellent *dr* and significant *ee* (Scheme 10, 81% *ee*, *dr* >20:1). To our pleasure, this catalytic asymmetric reaction can be scaled up to gram scale with consistent stereo- and regioselectivity. Additionally, facile hydrolysis further converts **14** to 2-aminoindanol without erosion of its *ee* and *dr*.[8]

Moreover, conjugated ene-ynes and dienes were also evaluated (Scheme 7, entries 10–15). An ene-yne is an excellent substrate for the regioselective aminohydroxylation (entry 10, 62% overall yield). Conjugated styrenyl and aliphatic dienes can also be converted into protected vicinal amino alcohols with excellent regioselectivity and yield (entries 11–13). This method was also explored with more functionalized dienes, including a silyl dienol with a labile C–H bond and an electron-deficient dienoate and found they are both acceptable substrates to afford oxazolidinones regioselectively (entries 14, 15).

Additionally, this method was applied to isolated olefins. The $Fe(ClO_4)_2$–**L1** complex catalyzes the amino-oxygenation of a 1,1-disubstituted olefin with **2a**, affording an oxazolidinone (Scheme 7, entry 16, 51% yield). We also observed that the $Fe(OTf)_2$–**L1** complex catalyzes the reaction of a monosubstituted olefin with **2b** to afford the oxazolidinone with a fair yield (entry 17, 49% yield). The iron catalysts discovered so far present low reactivity towards *cis*- and *trans*-disubstituted isolated olefins, which is the limitation of this method.

Our mechanistic studies suggested that an iron-nitrenoid and a subsequently generated carbo-radical species are possible reactive intermediates of the iron-catalyzed olefin aminohydroxylation. Since structural variations of an olefin will inevitably influence the reactivity and stability of the carbo-radical species, a set of iron catalyst/ligand combinations have been optimized for a variety of both unfunctionalized and highly functionalized olefins. Here are a few suggestions for practicality considerations: First, tridentate **L1** is most suitable for terminal olefins, cyclic enol ethers and glycals, while a sterically less hindered **L2** is uniquely effective for internal olefins as well as cyclic dienes. Next, commercially available $Fe(OTf)_2$ is a preferred iron catalyst for most reactions; however, $Fe(NTf_2)_2$ provides comparable, or sometimes enhanced, reactivity and more consistent results with

functionalized olefins because it has a few advantages over $Fe(OTf)_2$ and $Fe(ClO_4)_2$, including enhanced stability towards air and moisture, increased solubility in organic solvents, ease of preparation and handling, as well as minimal explosion hazard. Furthermore, since iron catalyst aggregation might attenuate the nitrogen atom transfer reactivity, we have prepared a preformed $Fe(NTf_2)_2$–**L1** complex that demonstrates comparable reactivity in the indene aminohydroxylation (Scheme 11). Therefore, either the preformed catalyst or the one formed in situ can be both suitable for the intermolecular olefin aminohydroxylation.

Since *cis*/*trans* β-methylstyrenes have been important mechanistic probes for nitrogen atom transfer reactions, we explored the new reactivity with these two isomeric olefins (Scheme 12).[9] Interestingly, although the $Fe(OTf)_2$–**L1** complex rapidly promotes undesirable C–H abstraction, we discovered that a less sterically hindered $Fe(OTf)_2$–**L2** complex catalyzes efficient amino-oxygenation of both β-methylstyrenes. Three observations should be noted. First, *trans*-β-methylstyrene is more reactive than its *cis* isomer, which is unique compared with known metal-catalyzed atom transfer reactions. Next, *trans*-β-methylstyrene undergoes a much more diastereoselective reaction compared to the *cis*-isomer. The aminohydroxylation is neither stereospecific nor fully stereoconvergent; yet it is partially stereoconvergent, favoring the *anti*-aminohydroxylation product. Additionally, this reaction is completely regioselective and therefore it complements the Sharpless method that is partially regioselective.[1]

Conclusion

In conclusion, we have described the scope and limitations of the iron-catalyzed method for intermolecular olefin aminohydroxylation. In this reaction, a bench-stable functionalized hydroxylamine is applied as the amination re-agent. This method is compatible with a range of synthetically valuable olefins including those that are incompatible with existing aminohydroxylation methods. We further reported 4 practical procedures for the iron-catalyzed gram-scale aminohydroxylation of styrene, glycals, and indene. These procedures have demonstrated the potential practicality of this new catalytic method.

All reactions were performed in flame-dried round-bottom flasks and vials. Stainless steel syringes and cannula were used to transfer airand moisture-sensitive liquids. Flash chromatography was performed using silica gel 60 (230–400 mesh) from Sigma–Aldrich. Reagents were purchased from Sigma–Aldrich, Fluka, EM Science, and Lancaster and used directly as received. All solvents were used after being freshly distilled. ^1H and ^{13}C NMR spectra were recorded on a Bruker UltraShield-400 (400 MHz) spectrometer. The mass spectroscopic data were obtained at the Georgia State University mass spectrometry facility using a Micromass Platform II single quadruple instrument. IR spectra were recorded on a PerkinElmer Spectrum 100 FT-IR spectrometer.

tert-Butyl (2,4-Dichlorobenzoyl)oxycarbamate (2a)

tert-Butyl *N*-hydroxycarbamate (**6a**) was prepared first according to a modified literature procedure. A suspension of $NH_2OH{\cdot}HCl$ (9.7 g, 140 mmol) and K_2CO_3 (9.7 g, 700 mmol) in Et_2O (60 mL) and H_2O (2 mL) was stirred for about 1 h at r.t. with evolution of CO_2 gas.

A solution of Boc_2O (20.0 g, 92 mmol) in Et_2O (40 mL) was then added dropwise at 0 °C and the suspension was stirred at r.t. for 12 h. The organic phase was decanted and the solid was washed with Et_2O (3 × 30 mL). The combined organic layers were concentrated and the residue was re-crystallized from cyclohexane/toluene to afford the desired product **6a** as a white solid; yield: 11.3 g (85 mmol, 92%); mp 57–58 °C. The characterization data is in accordance with the literature precedent.[10]

To a 250 mL oven-dried round-bottom flask equipped with a stir bar were added *N*-hydroxylcarbamate **6a** (2.66 g, 20 mmol), 2,4-dichlorobenzoic acid (4.01 g, 21 mmol), and anhydrous CH_2Cl_2 (80 mL). The flask was cooled to −15 °C. A solution of DCC (4.53 g, 22 mmol) in anhydrous CH_2Cl_2 (20 mL) was then added dropwise. The reaction mixture was stirred at the same temperature for an additional 30 min until the *N*-hydroxycarbamate **6a** was fully consumed (monitored by TLC). The white precipitate (*N*,*N*′-dicyclohexylurea) was removed by filtration and the filtrate was concentrated in vacuo and dissolved again in Et_2O (30 mL). The solution was stored at −20 °C for 2 h and filtered again to remove additional precipitate. The organic layer was then concentrated in vacuo and the residue was purified by column (hexanes/EtOAc from 100:1 to 10:1) to give the product **2a**, which can be further recrystallized from hexanes; yield: 4.47 g (14.6 mmol, 73%); mp 48–49 °C.

IR (ATR, neat): 3281 (w), 2977 (w), 1772 (m), 1732 (s), 1583 (m), 1469 cm^{-1} (m).

^1H NMR (400 MHz, $CDCl_3$): δ = 8.20 (s, 1 H), 7.95 (d, *J* = 8.4 Hz, 1 H), 7.53 (s, 1 H), 7.36 (d, *J* = 8.4 Hz, 1 H), 1.53 (s, 9 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.1, 155.4, 139.7, 135.6, 132.8, 131.2, 127.3, 125.1, 83.7, 28.0.

HRMS (ESI): *m*/*z* [M – H^+] calcd for $C_{12}H_{12}Cl_2NO_4^-$: 304.0149; found: 304.0148.

2,2,2-Trichloroethyl (2,4-Dichlorobenzoyl)oxycarbamate (2b)

$NH_2OH{\cdot}HCl$ (13.9 g, 200 mmol) was added to an aqueous solution of NaOH (1.5 M, 160 mL, 240 mmol). The solution was cooled to 0 °C and 2,2,2-trichloroethyl chloroformate (5.23 mL, 38 mmol) was added dropwise. Upon the completion of addition, the mixture was warmed up to r.t. and stirred for an additional 2 h. The reaction was then acid-ified with aq 6 M HCl to pH ~4.5. The mixture was extracted with Et_2O (3 × 200 mL) and the combined organic layers were washed with brine and dried (anhydrous Na_2SO_4). After removal of the solvent in vacuo, the *N*-hydroxycarbamate **6b** formed was used directly without further purification;[11] yield: 5.84 g (28 mmol, 73%).

To a 250 mL flame-dried round-bottom flask equipped with a stir bar were added *N*-hydroxycarbamate **6b** (4.17 g, 20 mmol), 2,4-dichlorobenzoic acid (4.01 g, 21 mmol), and anhydrous CH_2Cl_2 (80 mL). The flask was cooled to −15 °C. A solution of DCC (4.53 g, 22 mmol) in anhydrous CH_2Cl_2 (20 mL) was then added dropwise. The reaction mixture was stirred at the same temperature for an additional 30 min until the *N*-hydroxycarbamate **6b** was fully consumed (monitored by TLC). The white precipitate (*N*,*N*′-dicyclohexylurea) was removed by filtration and the filtrate was concentrated in vacuo and dissolved again in

Et_2O (30 mL). The solution was stored at −20 °C for 2 h and filtered again to remove additional precipitate. The organic layer was then concentrated in vacuo and the residue was recrystallized from hexanes and EtOAc (around 9:1) to afford the corresponding acyloxy carbamate **2b** as a white crystalline solid; yield: 5.80 g (15.2 mmol, 76%); mp 85–87 °C.

IR (ATR, neat): 3271 (m), 2957 (w), 1747 (s), 1583 (s), 1556 (w), 1469 cm^{-1} (m).

^1H NMR (400 MHz, $CDCl_3$): δ = 8.68 (br, 1 H), 7.97 (d, *J* = 8.5 Hz, 1 H), 7.55 (s, 1 H), 7.38 (d, *J* = 8.5 Hz, 1 H), 4.86 (s, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4, 154.5, 140.3, 136.0, 132.9, 131.4, 127.4, 124.3, 94.3, 75.3.

HRMS (ESI): *m*/*z* [M + Na^+] calcd for $C_{10}H_6Cl_5NO_4Na^+$: 401.8632; found: 401.8615.

2,2,2-Trifluoroethyl (2,4-Dichlorobenzoyl)oxycarbamate (2c)

To an oven-dried 500 mL round-bottom flask equipped with a stir bar was added 1,1′-carbonyldiimidazole (17.8 g, 110 mmol) in anhydrous THF (200 mL). The flask was cooled to 0 °C and trifluoroethanol (7.3 mL, 100 mmol) was added dropwise. The mixture was stirred for an additional 1 h at r.t. and then $NH_2OH{\cdot}HCl$ (10.4 g, 150 mmol) and imidazole (8.2 g, 120 mmol) were added in one portion. The reaction was monitored by TLC, until the intermediate disappeared (about 1 h). Then the mixture was filtered and concentrated in vacuo. The residue was dissolved in EtOAc (200 mL) and washed with 1 M aq HCl (3 × 200 mL). The organic layer was dried (anhydrous Na_2SO_4) and concentrated to afford the crude product **6c** as a colorless oil, which was used directly without further purification; yield: 13.5 g (85 mmol, 85%).

6c

IR (ATR, neat): 3291 (m), 2982 (w), 1730 (s), 1487 (m), 1444 (m), 1252 (s), 1128 cm^{-1} (s).

^1H NMR (400 MHz, $CDCl_3$): δ = 7.44 (br s, 1 H), 6.18 (br s, 1 H), 4.56 (q, *J* = 8.3 Hz, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 157.3, 122.6 (q, *J* = 277.3 Hz), 61.5 (q, *J* = 37.1 Hz).

^{19}F NMR (376 MHz, $CDCl_3$): δ = −74.41 (t, *J* = 7.6 Hz).

HRMS (ESI): *m*/*z* [M – H^+] calcd for $C_3H_3F_3NO_3^-$: 158.0071; found: 158.0061.

To a 250 mL flame-dried round-bottom flask equipped with a stir bar were added *N*-hydroxycarbamate **6c** (3.18 g, 20 mmol), 2,4-dichlorobenzoic acid (4.01 g, 21 mmol), and anhydrous CH_2Cl_2 (80 mL). The flask was cooled to −15 °C. A solution of DCC (4.53 g, 22 mmol) in anhydrous CH_2Cl_2 (20 mL) was then added dropwise. The reaction mixture was stirred at the same temperature for an additional 30 min until the *N*-hydroxycarbamate was fully consumed (monitored by TLC). The white precipitate (*N*,*N*′-dicyclohexylurea) was removed by filtration and the filtrate was concentrated in vacuo and dissolved again in Et_2O (30 mL). The solution was stored at −20 °C for 2 h and filtered again to remove additional precipitate. The organic layer was then concentrated in vacuo and the residue was

recrystallized from hexanes and EtOAc (around 9:1) to afford the corresponding acyloxycarbamate **2c** as a white crystalline solid; yield: 4.91 g (14.9 mmol, 74%); mp 80–81 °C.

IR (ATR, neat): 3230 (m), 2972 (w), 1783 (m), 1735 (s), 1583 (m), 1497 cm^{-1} (m).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.52 (s, 1 H), 7.94 (d, *J* = 8.5 Hz, 1 H), 7.56 (d, *J* = 1.6 Hz, 1 H), 7.39 (d, *J* = 8.5, 1.9 Hz, 1 H), 4.61 (q, *J* = 8.2 Hz, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.4, 154.4, 140.3, 136.0, 132.8, 131.5, 127.4, 124.2, 122.4 (q, *J* = 277.5 Hz), 62.1 (q, *J* = 37.4 Hz).

^{19}F NMR (376 MHz, $CDCl_3$): δ = −74.10 (t, *J* = 8.2 Hz).

HRMS (ESI): *m*/*z* [M – H^+] calcd for $C_{10}H_5Cl_2F_3NO_4^-$: 329.9553; found: 329.9552.

2,6-Bis(4,4-dimethyl-4,5-dihydrooxazol-2-yl)pyridine (L1)

To a 100 mL flame-dried flask charged with a stir bar and a reflux condenser was added 2,6-pyridinedicarboxylic acid (3.34 g, 20 mmol). After the flask was evacuated and backfilled with N_2 twice, $SOCl_2$ (30 mL) and DMF (0.2 mL) were added. The reaction mixture was heated under reflux for 3 h and the excess of $SOCl_2$ was removed by distillation. Then the mixture was cooled to r.t. and further concentrated in vacuo to afford the 2,6-pyridinedicarbonyl dichloride as a white solid, which was used directly in the next step. Under N_2 atmosphere, to a solution of 2-amino-2-methylpropan-1-ol (6.23g, 70 mmol) and Et_3N (10.1g, 100 mmol) in CH_2Cl_2 (70 mL), were added 2,6-pyridinedicarbonyl dichloride in CH_2Cl_2 (30 mL) dropwise at 0 °C. After stirring the reaction mixture at r.t. for 16 h, it was poured into an ice-water mixture (60 mL), which was then extracted with CH_2Cl_2 (3 × 60 mL). The combined organic layers were washed with H_2O (20 mL) and brine (20 mL), dried (anhydrous Na_2SO_4), and concentrated in vacuo. The residue was purified through a silica gel flash column (hexanes/acetone: from 10:1 to 1:1) to afford the intermediate as a white solid (3.53 g, 57% yield for 2 steps), which is a known compound.[3]

The intermediate, which was obtained in the above step (3.09 g, 10 mmol) was dissolved in toluene (40 mL) in a 100 mL flame-dried flask equipped with a stir bar and a reflux condenser. $SOCl_2$ (7.14 g, 60 mmol) was added via a syringe and the mixture was heated under re-flux. The reaction was monitored by TLC. When the starting material had disappeared, the reaction was cooled to 0 °C and quenched with sat. aq $NaHCO_3$ (30 mL). The organic layer was separated from the aqueous one, which was then extracted with EtOAc (3 × 30 mL). The combined organic layers were dried (anhydrous Na_2SO_4) and concentrated in vacuo. The residue was filtered through a short silica gel pad with EtOAc as an eluent and concentrated again. The obtained oil was dissolved in anhydrous THF (50 mL) under N_2 atmosphere and cooled to 0 °C. NaH (2 g, 50 mmol, 60% in mineral oil) was added to the solution portionwise and the whole mixture was then warmed up to r.t. and the progress of the reaction was monitored by TLC until the starting material was fully consumed. The reaction mixture was filtered through a Celite pad, concentrated, and purified through a silica gel flash column (hexanes/acetone: from 20:1 to 2:1, buffered with 1%

NH_4OH) to provide the ligand **L1** as a white solid, which was further purified by recrystallization from a mixture of hexanes/EtOAc (9:1) as a colorless crystalline solid; yield: 2.02 g (7.4 mmol, 74% for the last two steps); mp 139–141 °C.

IR (ATR, neat): 3423 (w), 2967 (m), 2927 (w), 2896 (w), 1641 (s), 1573 (s), 1459 (s), 1365 (s), 1302 cm^{-1} (s).

^1H NMR (400 MHz, $CDCl_3$): δ = 8.22 (d, *J* = 7.9 Hz, 2 H), 7.87 (t, *J* = 7.9 Hz, 1 H), 4.24 (s, 4 H), 1.42 (s, 12 H).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 160.9, 147.0, 137.1, 125.7, 79.8, 68.0, 28.4.

HRMS (ESI): *m*/*z* [M + H^+] calcd for $C_{15}H_{20}N_3O_2^+$: 274.1550; found: 274.1554.

4,4-Dimethyl-2-(1,10-phenanthrolin-2-yl)-4,5-dihydrooxazole (L2)

2-Cyanophenanthroline (4.10 g, 20 mmol) was dissolved in anhydrous MeOH (60 mL) in a flame-dried flask equipped with a stir bar. NaOMe (108 mg, 2 mmol) was added to the solution. The reaction mixture was stirred at r.t. and the progress of the reaction was monitored by TLC until the starting material was fully consumed. The reaction was then quenched with AcOH (0.22 mL) and the mixture was filtered and concentrated in vacuo. The residue was dissolved in toluene (100 mL) together with of 2-amino-2-methylpropan-1-ol (1.87 g, 21 mmol) and *p*-TsOH·H_2O (380 mg, 2 mmol). The reaction mixture was then heated under reflux conditions with a Dean–Stark apparatus until the intermediate was consumed. After the reaction was cooled to r.t., the solvent was removed in vacuo and the residue was purified through a silica gel flash column (hexanes/acetone: from 2:1 to 1:2) to afford **L2** as a white solid. **L2** was further purified by recrystallization from a hexanes/EtOAc mixture as a white solid; yield: 3.6 g (12.9 mmol, 65%); mp 106–108 °C.[3]

IR (ATR, neat): 3385 (m), 3223 (m), 2966 (w), 1646 (s), 1493 (m), 1400 cm^{-1} (s).

^1H NMR (400 MHz, $CDCl_3$): δ = 9.25 (dd, *J* = 4.3, 1.3 Hz, 1 H), 8.43 (d, *J* = 8.3 Hz, 1 H), 8.34 (d, *J* = 8.3 Hz, 1 H), 8.29 (d, *J* = 6.9 Hz, 1 H), 7.86 (q, *J* = 8.8 Hz, 2 H), 7.68 (dd, *J* = 8.1, 4.4 Hz, 1 H), 4.34 (s, 2 H), 1.49 (s, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 161.7, 150.4, 146.4, 145.9, 145.5, 136.6, 136.2, 129.4, 128.9, 128.0, 126.1, 123.4, 122.7, 79.8, 68.1, 28.5.

HRMS (ESI): *m*/*z* [M + H^+] calcd for $C_{17}H_{16}N_3O^+$: 278.1288; found: 278.1289.

Iron-Catalyzed Gram-Scale Styrene Aminohydroxylation; 5-Phenyloxazolidin-2-one (5) (Scheme 6)

To a flame-dried sealable 25 mL round-bottom flask (flask **A**) equipped with a stir bar were added $Fe(OTf)_2$ (177 mg, 0.5 mmol) and **L1** (137 mg, 0.5 mmol). After the flask was evacuated and backfilled with N_2 three times, anhydrous CH_2Cl_2 (5.0 mL) and MeCN (1.0 mL) were added via syringes and the mixture was stirred at r.t. for 20 min. To another flame-dried round-bottom flask (flask **B**, 100 mL) equipped with a stir bar were added freshly activated 4Å molecular sieves (3.0 g) and acyloxy carbamate **2b** (3.82 g, 10 mmol). Flask **B**

was evacuated and backfilled with N_2 three times and then anhydrous CH_2Cl_2 (45 mL) was added. Both solutions were degassed with brief evacuation and backfilling with N_2 twice. Subsequently, freshly distilled styrene (1.26 mL, 11 mmol) was added to flask **B** and the catalyst solution was added through a syringe pump over 30 min to the flask at −15 °C. The reaction was kept at the temperature for an additional 1.5 h and quenched with sat. aq $NaHCO_3$ (30 mL). The organic layer was separated from the aqueous layer was extracted with CH_2Cl_2 (2 × 30 mL) and EtOAc (2 × 30 mL). The combined organic layers were concentrated in vacuo. The residue (a mixture of **3** and **4**) was dissolved in a mixture of THF/H_2O (3:1, 40 mL) and cooled to 4 °C. After the addition of *p*-TsOH·H_2O (1.9 g, 10 mol), the mixture was stirred at the same temperature and monitored by TCL until **3** was consumed (ca. 1 h). The reaction mixture was then concentrated in vacuo, treated with sat. aq $NaHCO_3$ (50 mL), and extracted with EtOAc (3 × 40 mL). The combined organic layers were concentrated in vacuo and the residue was dissolved again in THF/MeOH/H_2O mixture (2:2:1, 40 mL). After adding LiOH (0.6 g, 25 mmol), the mixture was stirred at r.t. for 3 h and then quenched by aq 1 M HCl (25 mL). After removal of THF and MeOH in vacuo, the aqueous phase was extracted with EtOAc (3 × 30 mL). The combined organic layers were dried (anhydrous Na_2SO_4) and concentrated. Product **5** was isolated through a silica gel flash column (hexanes/acetone: from 50:1 to 2:1), which is a known compound and the characterization is in accordance with the literature precedent;[12] yield: 1.22 g (7.47 mmol, 75% overall yield); white solid; mp 58–86 °C.

IR (ATR, neat): 3294 (br), 3031 (w), 1731 (s), 1454 (m), 1226 (m), 1027 cm^{-1} (m).

^1H NMR (400 MHz, $CDCl_3$): δ = 7.36–7.41 (m, 5 H), 6.62 (s, 1 H), 5.62 (t, *J* = 8.2 Hz, 1 H), 3.97 (t, *J* = 8.4 Hz, 1 H), 3.54 (t, *J* = 8.4 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 159.7, 138.5, 129.1, 125.7, 78.0, 48.4. HRMS (ESI): *m*/*z* [M + Na^+] calcd for $C_9H_9NO_2Na^+$: 186.0525; found: 186.0516.

Iron-Catalyzed Gram-Scale Glycal Aminohydroxylation; (4a*R*,6*R*,7*R*,8*R*,8a*R*)-7-[(*tert*-Butoxycarbonyl)amino]-2,2-dimethyl-8-[(triisopropylsilyl)oxy]hexahydropyrano[3,2-*d*][1,3]dioxin-6-yl 2,4-Dichlorobenzoate (13) (Scheme 8)

To a flame-dried sealable 25 mL round-bottom flask (flask **A**) equipped with a stir bar were added $Fe(NTf_2)_2$ (277 mg, 0.45 mmol) and **L1** (123 mg, 0.45 mmol). After flask **A** was evacuated and backfilled with N_2 three times, anhydrous CH_2Cl_2 (3.0 mL) and MeCN (1.0 mL) were added via syringes and the mixture was stirred at r.t. for 20 min. To another flame dried round-bottom flask (25 mL) equipped with a stir bar were added freshly activated 4Å molecular sieves (800 mg), functionalized glycal (1.03 g, 3.0 mmol), and **2a** (1.38 g, 4.5 mmol). The flask was also was evacuated and backfilled with N_2 three times and then anhydrous CH_2Cl_2 (6.0 mL) was added via a syringe. Both solutions were degassed with brief evacuation and backfilling with N_2 twice. Then the catalyst solution was added through a syringe pump over 30 min to the flask at −30 °C. The reaction was kept stirring at the same temperature for another 1.5 h. The reaction was quenched with sat. aq $NaHCO_3$ (6 mL) and stirred vigorously for an additional 10 min. The organic layer was separated and the aqueous phase was extracted with CH_2Cl_2 (2 × 6 mL) and EtOAc (2 × 6 mL). The combined organic layers were dried (anhydrous Na_2SO_4) and concentrated in vacuo. Product **13** was isolated

through a silica gel flash column as a colorless oil (hexanes/Et_2O: from 10:1 to 4:1); yield: 1.24 g (1.92 mmol, 64%); $[\alpha]_D^{20}$ +88.4 (*c* 1.0, CH_2Cl_2).

IR (ATR, neat): 2942 (m), 2866 (m), 1724 (s), 1585, 1499, 1368, 1269, 1130 (s), 982 cm^{-1} (s).

^1H NMR (400 MHz, C_6D_6): δ = 7.41 (d, *J* = 8.4 Hz, 1 H), 6.94 (d, *J* = 1.7 Hz, 1 H), 6.77 (br d, *J* = 2.5 Hz, 1 H), 6.55 (d, *J* = 8.4 Hz, 1 H), 4.87 (d, *J* = 8.7 Hz, 1 H), 4.38 (t, *J* = 8.2 Hz, 1 H), 4.18 (t, *J* = 9.4 Hz, 1 H), 3.88 (td, *J* = 10.1, 5.3 Hz, 1 H), 3.70 (dd, *J* = 10.6, 5.1 Hz, 1 H), 3.47 (t, *J* = 10.6 Hz, 1 H), 3.39 (t, *J* = 9.3 Hz, 1 H), 1.42 (s, 9 H), 1.36 (s, 3 H), 1.21 (d, *J* = 9.1 Hz, 21 H), 1.19 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.6, 155.0, 139.4, 134.5, 133.8, 131.3, 127.5, 99.7, 94.3, 80.0, 74.6, 71.3, 66.5, 62.0, 55.2, 28.9, 28.3, 18.8, 18.3, 18.2, 12.8.

HRMS (ESI): *m*/*z* [M – H^+] calcd for $C_{30}H_{46}Cl_2NO_8Si^-$: 646.2375; found: 646.2352.

Iron-Catalyzed Gram-Scale Indene Aminohydroxylation; 2-{[(2,2,2-Trichloroethoxy)carbonyl]amino}-2,3-dihydro-1*H*-inden-1-yl 2,4-Dichlorobenzoate (14) (Scheme 9)

To a flame-dried sealable 25 mL round-bottom flask (flask **A**) equipped with a stir bar were added $Fe(NTf_2)_2$ (615 mg, 1.0 mmol) and **L1** (273 mg, 1.0 mmol). After flask **A** was evacuated and backfilled with N_2 for three times, anhydrous CH_2Cl_2 (7.5 mL) and MeCN (2.5 mL) were added via syringes and the mixture was stirred at r.t. for 20 min. To another flame dried 100 mL round-bottom flask (flask **B**) equipped with a stir bar were added activated 4Å molecular sieves (3.0 g) and **2b** (3.82 g, 10 mmol). The flask was evacuated and back-filled with N_2 three times and then anhydrous CH_2Cl_2 (40 mL) was added. Both solutions were degassed with brief evacuation and backfilling with N_2 twice. Then freshly distilled indene (1.28 mL, 11 mmol) was added to the flask **B** followed by addition of the catalyst solution through a syringe pump over 30 min at −15 °C. The reaction was kept stirring at the same temperature for another 30 min. The reaction was quenched with sat. aq $NaHCO_3$ (30 mL) and stirred vigorously for an additional 10 min. The organic layer was separated and the aqueous phase was extracted with CH_2Cl_2 (2 × 30 mL) and EtOAc (2 × 30 mL). The combined organic layers were dried (anhydrous Na_2SO_4) and concentrated in vacuo. Product **14** was isolated as a white solid (*dr* >20:1) through a silica gel flash column (hexanes/acetone: from 50:1 to 10:1); yield: 3.54 g (7.10 mmol, 71%); mp 130–131 °C.

IR (ATR, neat): 3352 (w), 2952 (w), 1717 (w), 1853 (m), 1515 cm^{-1} (m).

^1H NMR (400 MHz, $CDCl_3$): δ = 7.78 (d, *J* = 8.5 Hz, 1 H), 7.64 (d, *J* = 7.4 Hz, 1 H), 7.48 (s, 1 H), 7.41–7.35 (m, 1 H), 7.31 (d, *J* = 9.8 Hz, 3 H), 6.35 (d, *J* = 5.5 Hz, 1 H), 5.66 (d, *J* = 8.6 Hz, 1 H), 4.93–4.66 (m, 3 H), 3.38 (dd, *J* = 15.4, 7.4 Hz, 1 H), 3.08 (dd, *J* = 15.5, 8.2 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.5, 154.2, 141.5, 138.7, 138.3, 134.3, 133.0, 131.0, 130.1, 128.4, 127.5, 127.2, 127.1, 125.0, 95.4, 77.9, 74.7, 53.8, 36.9.

HRMS (ESI): *m*/*z* [M + Cl^-] calcd for $C_{19}H_{14}Cl_6NO_4^-$: 529.9059; found: 529.9054.

Iron-Catalyzed Gram-Scale Asymmetric Indene Aminohydroxylation; (1*R*,2*S*)-2-{[(2,2,2-Trichloroethoxy)carbonyl]amino}-2,3-di-hydro-1*H*-inden-1-yl 2,4-Dichlorobenzoate (14) (Scheme 10)

To a flame-dried sealable 25 mL round-bottom flask (flask **A**) equipped with a stir bar were added $Fe(NTf_2)_2$ (323 mg, 0.525 mmol) and ligand **L3** (207 mg, 0.525 mmol). After the vial was evacuated and backfilled with N_2 three times, anhydrous $CHCl_3$ (7.0 mL) and MeCN (1.0 mL) were added via syringes and the mixture was stirred at r.t. for 20 min. To another flame dried 100 mL round-bottom flask (flask **B**) equipped with a stir bar were added activated 4Å molecular sieves (900 mg) and **2b** (1.34 g, 3.5 mmol). The vial was also was evacuated and backfilled with N_2 for three times and then anhydrous $CHCl_3$ (10 mL) was added via a syringe. Both solutions were degassed with brief evacuation and backfilling with N_2 twice. Freshly distilled indene (612 μL, 5.25 mmol) was added to flask **B** and the catalyst solution (flask **A)** was added by a syringe pump over 30 min to flask **B** at −30 °C. The reaction was kept stirring at the same temperature for another 30 min. The reaction was quenched with sat. aq $NaHCO_3$ (20 mL) and stirred vigorously for additional 10 min. The organic layer was separated and the aqueous phase was extracted with CH_2Cl_2 (2 × 30 mL) and EtOAc (2 × 30 mL). The combined organic layers were dried (anhydrous Na_2SO_4) and concentrated in vacuo. Enatioenriched product **14** was isolated through a silica gel flash column (acetone/hexanes: from 2% to 10%) as a white solid; yield: 1.22 g (2.45 mmol, 70%, *dr* >20:1); mp 130–131 °C; $[\alpha]_D^{20}$ −60.1 (*c* 1.0, $CHCl_3$).

The *ee* was measured by Chiral HPLC analysis (Chiral *S.S.* Whelk, 1.0 mL/min, 254 nm, 5% EtOH in hexanes, t_R = 20.66 min (minor), 24.88 min (major), 81% *ee*).

Iron-Catalyzed Olefin Aminohydroxylation; General Procedure (Scheme 7)

To a flame-dried sealable 2-dram vial (vial **A**) equipped with a stir bar were added $Fe(NTf_2)_2$ (0.04 mmol) and a suitable ligand (see Scheme 7) (0.04 mmol). After the vial was evacuated and backfilled with N_2 for three times, anhydrous CH_2Cl_2 (1.0 mL) and MeCN (0.2 mL) were added via a syringe and the mixture was stirred at r.t. for 20 min. To another flame-dried 3-dram vial (vial **B**) equipped with a stir bar were added freshly activated 4Å molecular sieves (50 mg) and the corresponding acyloxy carbamate **2** (0.44 mmol). The vial was evacuated and backfilled with N_2 for three times and then anhydrous CH_2-Cl_2 (2.8 mL) was added. Both vials were degassed with brief evacuation and backfilling with N_2 twice. Subsequently, freshly distilled olefin (0.4 mmol) was added to vial **B** and the catalyst solution in vial **A** was added through a syringe pump over 15 min to vial **B** at −15 °C. The reaction was kept at this temperature for additional 45 min and quenched with sat. aq $NaHCO_3$ (2 mL). The organic layer was separated from the aqueous one, which was extracted with CH_2Cl_2 (2 × 2 mL) and EtOAc (2 × 2 mL). The combined organic layers were dried (anhydrous Na_2SO_4) and concentrated in vacuo. The residue was further purified through a silica gel flash column (hexanes/EtOAc as the eluent) to afford the aminohydroxylation products.

5-Methyl-5-phenyloxazolidin-2-one (7)

By following the general procedure under the conditions described in Scheme 7, compound **7** was isolated through a silica gel flash column (hexanes/acetone: from 10:1 to 2:1) as a white solid, which is a known compound;[13] yield: 53.2 mg (75%); mp 149–150 °C.

1-{[(2,2,2-Trifluoroethoxy)carbonyl]amino}-3-(triisopropylsilyl)propan-2-yl 2,4-Dichlorobenzoate (8)

By following the general procedure under the conditions described in Scheme 7, **8** was isolated through a silica gel flash column (hexanes/EtOAc: from 20:1 to 4:1) as a colorless oil; yield: 165.5 mg (78%).

IR (ATR, neat): 3367 (w), 2942 (m), 2867 (m), 1727 (s), 1589 (m), 1527 cm^{-1} (m).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.77 (d, *J* = 8.4 Hz, 1 H), 7.50 (d, *J* = 1.4 Hz, 1 H), 7.33 (dd, *J* = 8.4, 1.2 Hz, 1 H), 5.45 (qd, *J* = 7.4, 2.9 Hz, 1 H), 5.27 (br s, 1 H), 4.57–4.35 (m, 2 H), 3.67 (ddd, *J* = 14.3, 6.1, 3.0 Hz, 1 H), 3.43 (dt, *J* = 14.0, 6.9 Hz, 1 H), 1.28–1.23 (m, 1 H), 1.10–0.99 (m, 22 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.6, 154.6, 138.4, 134.5, 132.4, 131.0, 128.5, 127.1, 123.0 (q, *J* = 277.6 Hz), 73.7, 61.0 (q, *J* = 36.5 Hz), 47.0, 18.7, 18.7, 13.3, 11.3.

^{19}F NMR (377 MHz, $CDCl_3$): δ = −74.34 (t, *J* = 8.4 Hz).

HRMS (ESI): *m*/*z* [M + Cl^-] calcd for $C_{22}H_{32}Cl_3F_3NO_4Si^-$: 564.1124; found: 564.1112.

3,3a,4,6a-Tetrahydro-2*H*-cyclopenta[*d*]oxazol-2-one (9)

By following the general procedure under the conditions described in Scheme 7, **9** was isolated through a silica gel flash column (hexanes/EtOAc: from 4:1 to 1:1) as a white solid, which is a known compound;[14] yield: 30.5 mg (61%); mp 118–121 °C.

3a,4,5,7a-Tetrahydrobenzo[*d*]oxazol-2(3*H*)-one (10)

By following the general procedure under the conditions described in Scheme 7, **10** was isolated through a silica gel flash column (hexanes/EtOAc: from 4:1 to 1:1) as a white solid, which is a known compound;[15] yield: 34.5 mg (62%); mp 86–88 °C.

3-{[(2,2,2-Trifluoroethoxy)carbonyl]amino}tetrahydrofuran-2-yl 2,4-Dichlorobenzoate (11)

By following the general procedure under the conditions described in Scheme 7, **11** was isolated through a silica gel flash column (hexanes/EtOAc: from 20:1 to 4:1) as a white solid; yield: 115.8 mg (72%); mp 110–111 °C.

IR (ATR, neat): 3347 (w), 2972 (w), 2906 (w), 1724 (s), 1585 (m), 1530 cm^{-1} (m).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.85 (d, *J* = 8.4 Hz, 1 H), 7.51 (s, 1 H), 7.40–7.31 (m, 1 H), 6.44 (d, *J* = 4.3 Hz, 1 H), 5.36 (d, *J* = 8.9 Hz, 1 H), 4.59–4.35 (m, 3 H), 4.24 (td, *J* = 9.3, 2.5 Hz, 1 H), 4.07 (dd, *J* = 16.8, 8.7 Hz, 1 H), 2.52–2.40 (m, 1 H), 2.08–1.92 (m, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.2, 153.8, 139.0, 134.2, 133.2, 131.1, 128.1, 127.4, 122.9 (q, *J* = 277.5 Hz), 96.4, 67.5, 61.2 (q, *J* = 36.6 Hz), 53.5, 28.6.

^{19}F NMR (376 MHz, $CDCl_3$): δ = −74.25 (t, *J* = 8.4 Hz).

HRMS (ESI): *m*/*z* [M + Na^+] calcd for $C_{14}H_{12}Cl_2F_3NO_5Na^+$: 423.9937; found: 423.9941.

3-{[(2,2,2-Trifluoroethoxy)carbonyl]amino}tetrahydro-2*H*-pyran-2-yl 2,4-Dichlorobenzoate (12)

By following the general procedure under the conditions described in Scheme 7, **12** was isolated through a silica gel flash column (hexanes/EtOAc: from 20:1 to 4:1) as a colorless oil; yield: 128.2 mg (77%, *dr* = 10:1).

cis-Isomer

IR (ATR, neat): 3347 (s), 2947 (w), 1724 (s), 1585 (m), 1530 cm^{-1} (m).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.92 (d, *J* = 8.5 Hz, 1 H), 7.54 (d, *J* = 1.8 Hz, 1 H), 7.38 (dd, *J* = 8.4, 1.9 Hz, 1 H), 6.33 (d, *J* = 2.9 Hz, 1 H), 5.06 (br d, *J* = 9.1 Hz, 1 H), 4.59–4.34 (m, 2 H), 4.11–4.00 (m, 1 H), 3.89–3.73 (m, 2 H), 2.05–1.96 (m, 1 H), 1.94–1.76 (m, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.8, 153.7, 139.2, 134.5, 133.4, 131.2, 127.8, 127.4, 123.0 (q, *J* = 277.6 Hz), 93.2, 61.6, 60.9 (q, *J* = 36.6 Hz), 49.1, 25.3, 23.9.

^{19}F NMR (376 MHz, $CDCl_3$): δ = −74.25 (t, *J* = 8.5 Hz).

HRMS (ESI): *m*/*z* [M + Na^+] calcd for $C_{15}H_{14}Cl_2F_3NO_5Na^+$: 438.0093; found: 438.0084.

trans-Isomer

IR (ATR, neat): 3347 (s), 2949 (w), 1722 (s), 1586 (m), 1531 cm^{-1} (m).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.91 (d, *J* = 8.6 Hz, 1 H), 7.53 (s, 1 H), 7.36 (d, *J* = 8.6 Hz, 1 H), 6.06 (s, 1 H), 5.38 (d, *J* = 9.1 Hz, 1 H), 4.56–4.40 (m, 2 H), 4.02 (t, *J* = 11.2 Hz, 1 H), 3.95 (s, 1 H), 3.79 (d, *J* = 11.0 Hz, 1 H), 2.22 (t, *J* = 11.9 Hz, 1 H), 1.93–1.74 (m, 2 H), 1.70–1.60 (m, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.0, 153.7, 139.1, 135.2, 133.2, 131.3, 127.4, 127.2, 123.0 (q, *J* = 277.3 Hz), 93.7, 62.8, 61.1 (q, *J* = 36.6 Hz), 48.0, 24.2, 20.6.

^{19}F NMR (377 MHz, $CDCl_3$): δ = −74.25 (t, *J* = 8.4 Hz).

HRMS (ESI): *m*/*z* [M + Na^+] calcd for $C_{15}H_{14}Cl_2F_3NO_5Na^+$: 438.0093; found: 438.0096.

5-(Phenylethynyl)oxazolidin-2-one (15)

By following the general procedure under the conditions described in Scheme 7, **15** was isolated through a silica gel flash column (hexanes/acetone: from 10:1 to 2:1) as a colorless oil; yield: 46.5 mg (62%).

IR (ATR, neat): 2324 (m), 1755 (s), 1540 (w), 1489 (s), 1343 cm^{-1} (w).

^1H NMR (400 MHz, $CDCl_3$): δ = 7.48 (d, *J* = 7.4 Hz, 2 H), 7.44–7.30 (m, 3 H), 6.26 (br s, 1 H), 5.49 (t, *J* = 7.7 Hz, 1 H), 3.94 (t, *J* = 8.6 Hz, 1 H), 3.74 (t, *J* = 7.7 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 159.1, 131.9, 129.3, 128.4, 121.3, 88.0, 84.1, 66.5, 47.3.

HRMS (ESI): *m*/*z* [M + H^+] calcd for $C_{11}H_{10}NO_2^+$: 188.0706; found: 188.0697.

(*E*)-4-Phenyl-1-{[(2,2,2-trichloroethoxy)carbonyl]amino}but-3-en-2-yl 2,4-Dichlorobenzoate (16)

By following the general procedure under the conditions described in Scheme 7, **16** was isolated through a silica gel flash column (hexanes/EtOAc: from 50:1 to 6:1) as a colorless oil; yield: 171.8 mg (84%).

IR (ATR, neat): 3347 (w), 3028 (w), 2952 (w), 1722 (s), 1583 (m), 1517 cm^{-1} (m).

^1H NMR (400 MHz, $CDCl_3$): δ = 7.86 (d, *J* = 8.4 Hz, 1 H), 7.51 (s, 1 H), 7.44–7.38 (m, 2 H), 7.38–7.27 (m, 4 H), 6.83 (d, *J* = 16.0 Hz, 1 H), 6.23 (dd, *J* = 15.9, 7.2 Hz, 1 H), 5.87–5.75 (m, 1 H), 5.36 (t, *J* = 5.9 Hz, 1 H), 4.79–4.69 (m, 2 H), 3.80–3.72 (m, 1 H), 3.71–3.62 (m, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 164.0, 154.8, 138.7, 135.6, 135.1, 134.8, 132.8, 131.1, 128.7, 128.5, 128.0, 127.2, 126.8, 123.3, 95.5, 75.0, 74.6, 44.5.

HRMS (ESI): *m*/*z* [M + Cl^-] calcd for $C_{20}H_{16}Cl_6NO_4^-$: 543.9216; found: 543.9213.

(*E*)-5-(Oct-1-en-1-yl)oxazolidin-2-one (17)

By following the general procedure under the conditions described in Scheme 7, **17** was isolated through a silica gel flash column (hexanes/EtOAc: from 4:1 to 1:1) as a white solid; yield: 48.2 mg (61%); mp 49–50 °C.

IR (ATR, neat): 3261 (m), 2916 (m), 2850 (m), 1719 (s), 1444 (w), 1373 (m), 1239 cm^{-1} (m).

^1H NMR (400 MHz, $CDCl_3$): δ = 6.10 (br s, 1 H), 5.93–5.80 (m, 1 H), 5.56 (dd, *J* = 15.3, 7.8 Hz, 1 H), 5.01 (q, *J* = 7.9 Hz, 1 H), 3.71 (t, *J* = 8.5 Hz, 1 H), 3.33 (t, *J* = 8.1 Hz, 1 H), 2.09 (q, *J* = 7.0 Hz, 2 H), 1.45–1.35 (m, 2 H), 1.35–1.22 (m, 6 H), 0.89 (t, *J* = 6.3 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 160.1, 137.4, 126.1, 77.9, 46.5, 32.1, 31.6, 28.8, 28.6, 22.6, 14.1.

HRMS (ESI): *m*/*z* [M + H^+] calcd for $C_{11}H_{20}NO_2^+$: 198.1489; found: 198.1482.

5-Methyl-5-(prop-1-en-2-yl)oxazolidin-2-one (18)

By following the general procedure under the conditions described in Scheme 7, **18** was isolated through a silica gel flash column (hexanes/EtOAc: from 4:1 to 1:1) as a colorless oil; yield: 42.9 mg (76%).

IR (ATR, neat): 3251 (m), 2977 (w), 1727 (s), 1648 (w), 1436 (m), 1269 cm^{-1} (s).

^1H NMR (400 MHz, $CDCl_3$): δ = 6.46 (br s, 1 H), 5.09 (s, 1 H), 4.92 (s, 1 H), 3.54 (d, *J* = 8.5 Hz, 1 H), 3.37 (d, *J* = 8.5 Hz, 1 H), 1.80 (s, 3 H), 1.57 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 159.6, 145.1, 111.2, 84.2, 51.0, 25.3, 18.2.

HRMS (ESI): *m*/*z* [M + H^+] calcd for $C_7H_{12}NO_2^+$: 142.0863; found: 142.0858.

(*E*)-5-{3-[(*tert*-Butyldimethylsilyl)oxy]prop-1-en-1-yl}oxazolidin-2-one (19)

By following the general procedure under the conditions described in Scheme 7, **19** was isolated through a silica gel flash column (hexanes/EtOAc: from 4:1 to 1:1) as a colorless oil; yield: 64.9 mg (63%).

IR (ATR, neat): 3286 (w), 2927 (m), 2856 (m), 1747 (s), 1472 (w), 1358 (w), 1249 cm^{-1} (m).

^1H NMR (400 MHz, $CDCl_3$): δ = 6.15 (br s, 1 H), 5.96 (dt, *J* = 15.3, 4.0 Hz, 1 H), 5.83 (dd, *J* = 15.3, 6.9 Hz, 1 H), 5.10 (q, *J* = 7.6 Hz, 1 H), 4.28–4.17 (m, 2 H), 3.74 (t, *J* = 8.6 Hz, 1 H), 3.36 (t, *J* = 8.1 Hz, 1 H), 0.92 (s, 9 H), 0.08 (s, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 160.1, 134.8, 125.4, 62.4, 46.4, 25.9, 18.4, −5.30, −5.33.

HRMS (ESI): *m*/*z* [M + Na^+] calcd for $C_{12}H_{23}NO_3SiNa^+$: 280.1339; found: 280.1329.

Ethyl (*E*)-3-(2-Oxooxazolidin-5-yl)acrylate (20)

By following the general procedure under the conditions described in Scheme 7, **20** was isolated through a silica gel flash column (hexanes/EtOAc: from 2:1 to 1:1) as a colorless oil; yield: 40.0 mg (54%).

IR (ATR, neat): 3281 (w), 2977 (w), 1742 (s), 1714 (s), 1664 (m), 1431 (w), 1368 (m), 1305 cm^{-1} (s).

^1H NMR (400 MHz, $CDCl_3$): δ = 6.91 (dd, *J* = 15.7, 5.2 Hz, 1 H), 6.31 (br s, 1 H), 6.18 (d, *J* = 15.7 Hz, 1 H), 5.23 (dd, *J* = 14.0, 6.8 Hz, 1 H), 4.23 (q, *J* = 7.1 Hz, 2 H), 3.85 (t, *J* = 8.9 Hz, 1 H), 3.42 (t, *J* = 7.6 Hz, 1 H), 1.31 (t, *J* = 7.1 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 165.5, 159.3, 141.9, 123.5, 74.5, 60.9, 45.5, 14.2.

HRMS (ESI): *m*/*z* [M + H^+] calcd for $C_8H_{12}NO_4^+$: 186.0761; found: 186.0753.

5-Heptyl-5-methyloxazolidin-2-one (21)

By following the general procedure under the conditions described in Scheme 7, **21** was isolated through a silica gel flash column (hexanes/EtOAc: from 4:1 to 1:1) as a colorless oil; yield: 40.7 mg (51%).

IR (ATR, neat): 3060 (w), 2927 (m), 2856 (w), 1737 (s), 1454 (w), 1378 (w), 1080 (m), 971 cm^{-1} (m).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 6.04 (br d, *J* = 9.2 Hz, 1 H), 3.40 (d, *J* = 8.4 Hz, 1 H), 3.28 (d, *J* = 8.4 Hz, 1 H), 1.73–1.65 (m, 2 H), 1.45 (s, 3 H), 1.43–1.20 (m, 10 H), 0.89 (t, *J* = 6.6 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 159.7, 83.3, 51.2, 40.3, 31.7, 29.7, 29.1, 25.5, 23.4, 22.6, 14.1.

HRMS (ESI): *m*/*z* [M + H^+] calcd for $C_{11}H_{22}NO_2^+$: 200.1645; found: 200.1636.

5-Hexyloxazolidin-2-one (22)

By following the general procedure under the conditions described in Scheme 7, **22** was isolated through a silica gel flash column (hexanes/acetone: from 10:1 to 2:1) as a white foam; yield: 33.5 mg (49%).

IR (ATR, neat): 2927 (m), 2856 (w), 1745 (s), 1489 (w), 1264 (w), 1239 (m), 1077 cm^{-1} (m).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 6.04 (br s, 1 H), 4.73–4.56 (m, 1 H), 3.68 (dd, *J* = 11.2, 5.4 Hz, 1 H), 3.25 (t, *J* = 7.8 Hz, 1 H), 1.86–1.75 (m, 1 H), 1.72–1.59 (m, 1 H), 1.53–1.43 (m, 1 H), 1.42–1.24 (m, 7 H), 0.90 (t, *J* = 6.9 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 160.3, 77.2, 46.0, 34.9, 31.6, 28.9, 24.6, 22.5, 14.0.

HRMS (ESI): *m*/*z* [M + H^+] calcd for $C_9H_{18}NO_2^+$: 172.1332; found: 172.1324.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgment

This work was supported by the National Institutes of Health (GM110382) and Georgia State University. We also thank a referee for insightful comments and suggestions.

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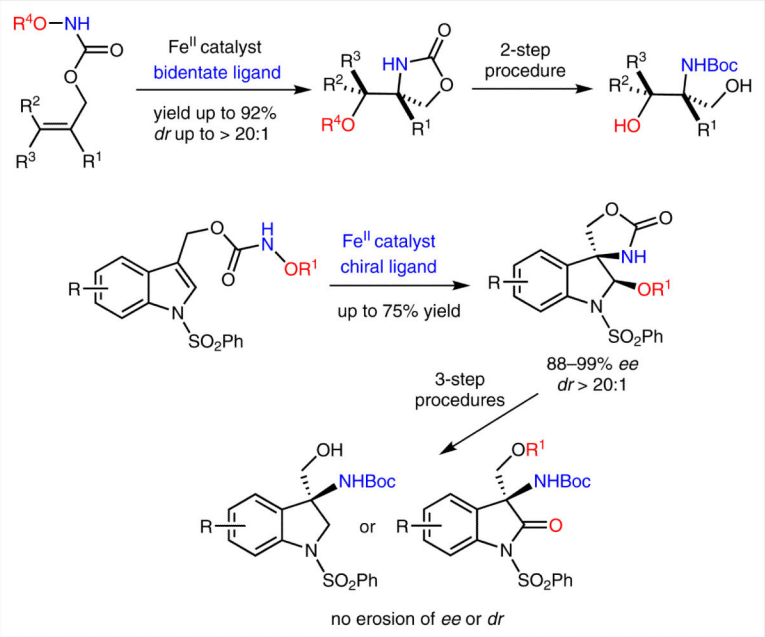
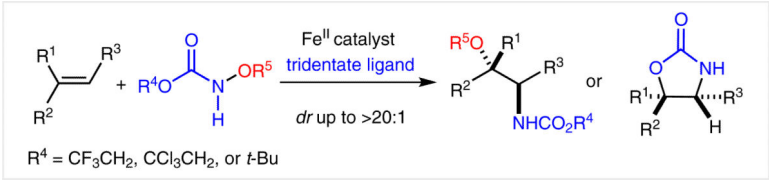


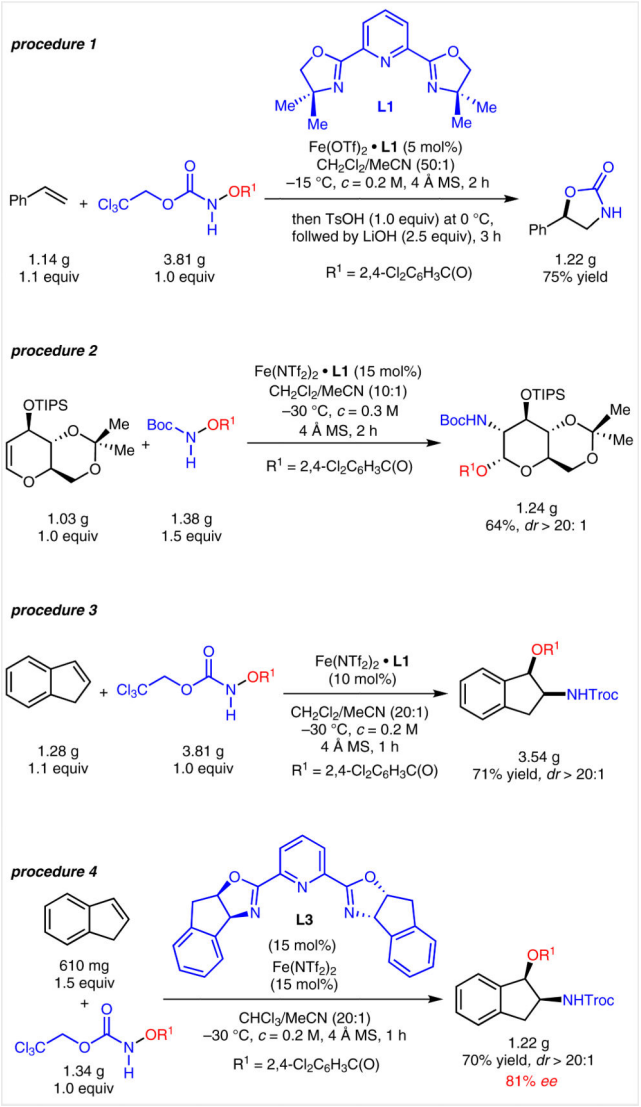
Scheme 1.

Iron-catalyzed stereoselective intramolecular aminohydroxylation of olefins and indoles



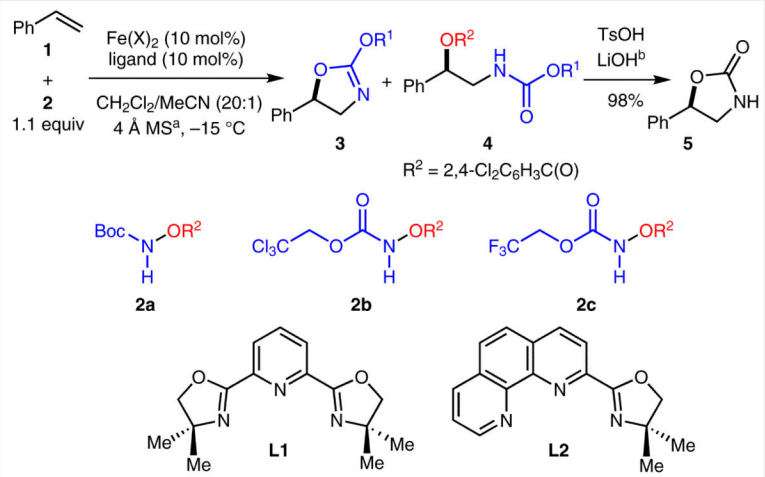
Scheme 2.

Iron-catalyzed intermolecular olefin aminohydroxylation using functionalized hydroxylamines



Scheme 3.

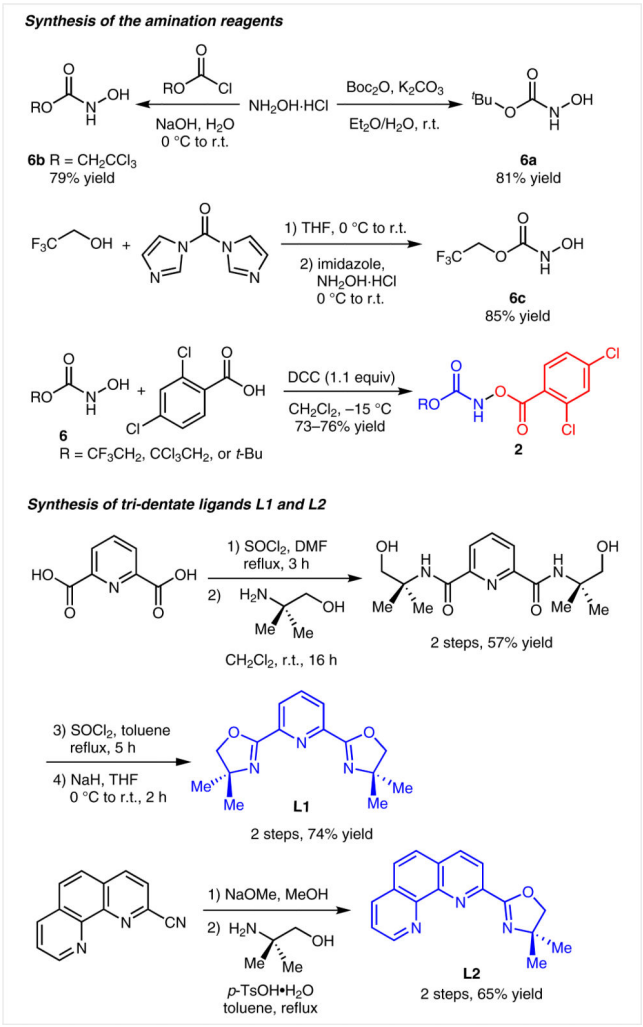
Practical synthetic procedures of the iron-catalyzed olefin aminohydroxylation using functionalized hydroxylamines



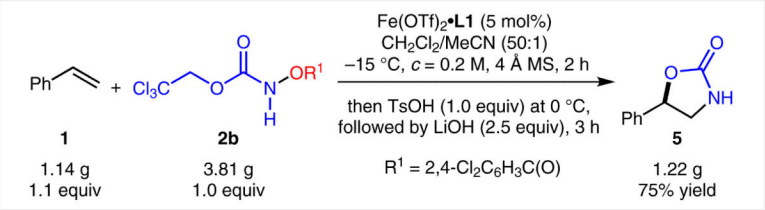
Entry[b]	$Fe(X)_2$	Ligand	2	Conversion[c]	Yield (3)[d]	Yield (4)[d]	Yield (5)[d]
1	$Fe(OTf)_2$	L1	2a	69%	<5%[e]	6%	48%[e]
2	$Fe(OTf)_2$	L1	2b	>95%	71%	12%	82%
3	$Fe(OTf)_2$	L1	2c	>95%	63%	10%	72%
4	$Fe(OTf)_2$	L2	2b	67%	44%	14%	57%
5	$Fe(NTf_2)_2$	L1	2b	>95%	62%	15%	76%

Scheme 4.

Structure–reactivity relationship of catalysts and amination reagents. [a] Molecular sieves were used to remove deleterious moisture. [b] Reactions were carried out under N_2 in 1 h and then quenched with saturated aqueous $NaHCO_3$ solution, unless stated otherwise. The crude mixture was first subjected to acidic conditions with TsOH (1.0 equiv) and then to basic conditions with LiOH (2.5 equiv) to afford **5**. [c] Conversion was measured by GC. [d] Isolated yield. [e] An oxazolidinone was isolated directly without the additional step.

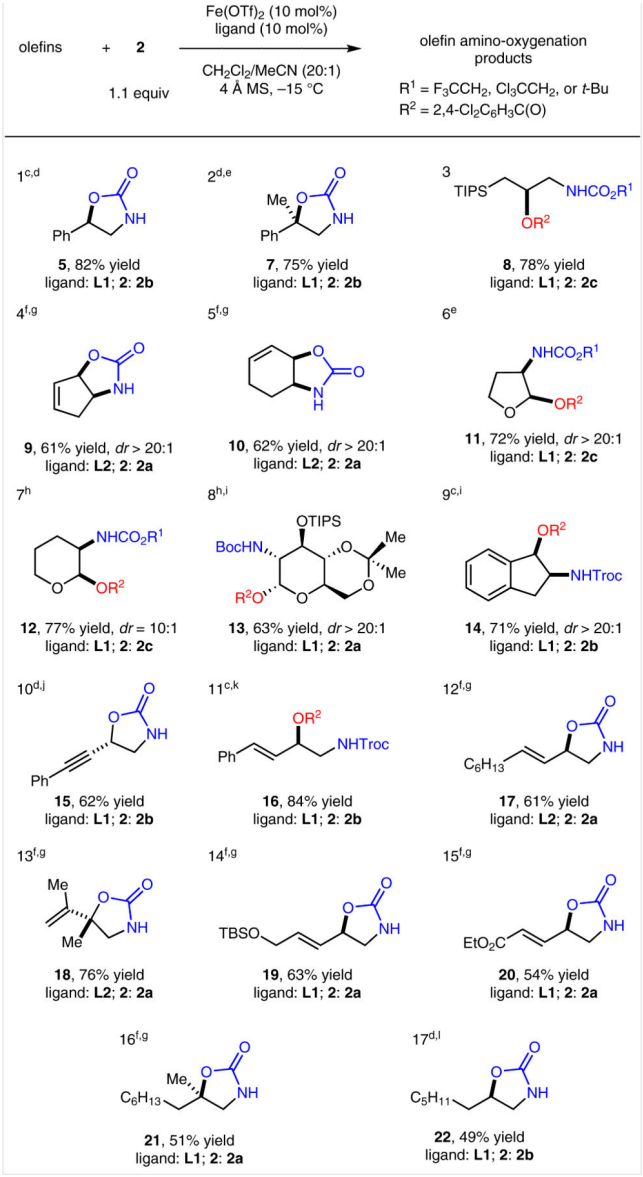


Scheme 5.
Synthesis of the amination reagents and the ligands



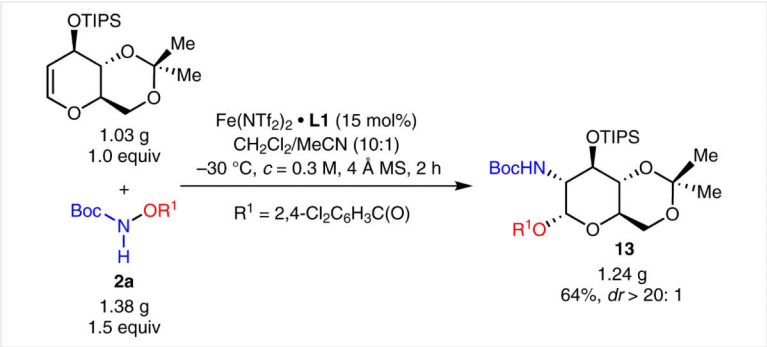
Scheme 6.

A practical synthetic procedure of the iron-catalyzed styrene aminohydroxylation



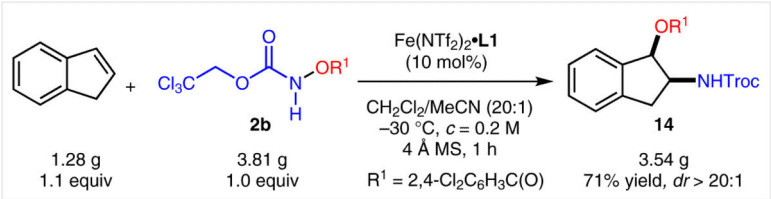
Scheme 7.

Substrate scope for the iron-catalyzed olefin aminohydroxylation. [a] Reactions were carried out under N_2 for 2 h, unless stated otherwise. [b] Isolated yield. [c] Reaction time: 1 h. [d] The crude mixture was treated with TsOH and then LiOH. [e] Reaction temperature: −40 °C. [f] Catalyst loading: 20 mol%; reaction temperature: 0 °C. [g] Reaction time: 12 h. [h] Reaction temperature: −30 °C. [i] $Fe(NTf_2)_2$ (15 mol%), **L1** (15 mol%). [j] Catalyst loading: 15 mol%. [k] $Fe(OTf)_2$ (2.5 mol%) and $FeCl_2$ (2.5 mol%) were used. [l] Catalyst loading: 30 mol%; reaction temperature: 0 °C; reaction time: 24 h.



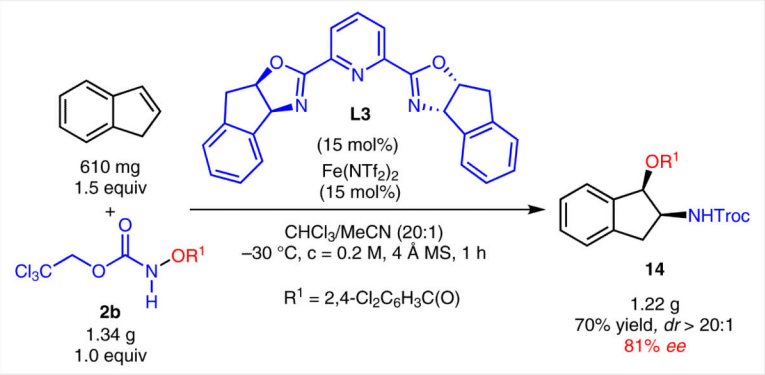
Scheme 8.

A practical synthetic procedure of the iron-catalyzed glycal aminohydroxylation



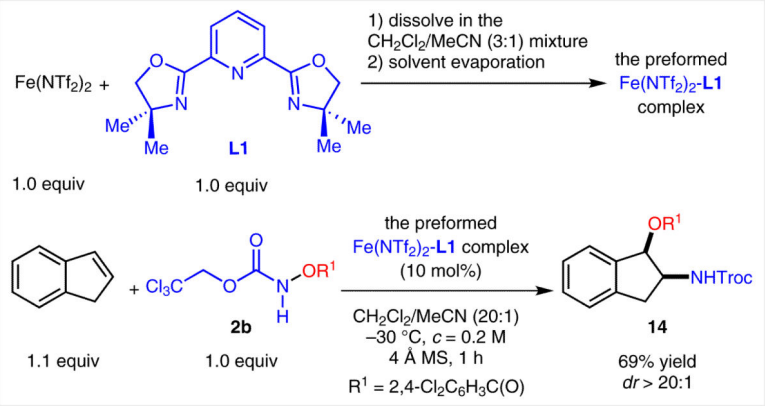
Scheme 9.

A practical procedure of the iron-catalyzed indene amino-hydroxylation



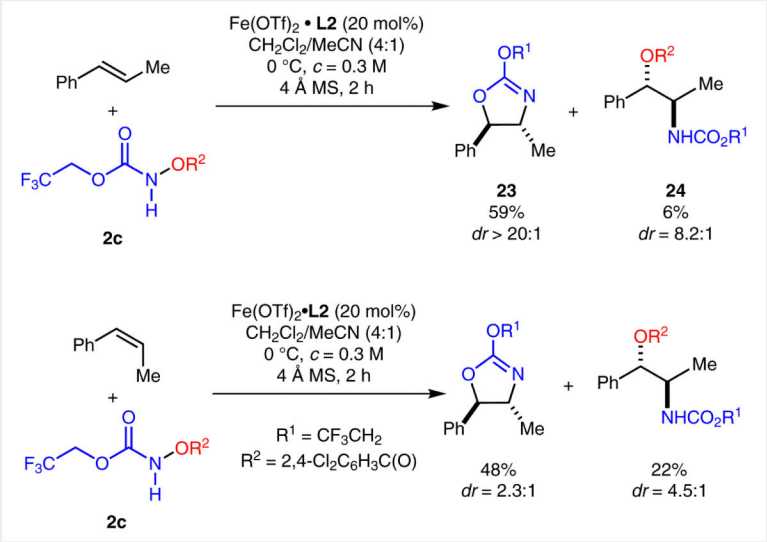
Scheme 10.

A practical procedure of the iron-catalyzed asymmetric indene aminohydroxylation



Scheme 11.

Catalytic indene aminohydroxylation using the preformed iron catalyst



Scheme 12.

Iron-catalyzed aminohydroxylation of isomeric β-methylstyrenes