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BRIEF ARTICLE

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Improved Synthesis of Chiral Pyrrolidine Inhibitors and Their Binding Properties to Neuronal Nitric Oxide Synthase†

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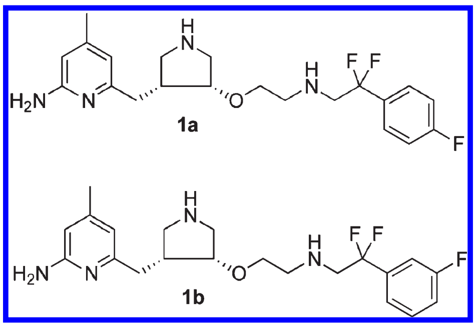
Supporting Information

ABSTRACT: We report an efficient synthetic route to chiral pyrrolidine inhibitors of neuronal nitric oxide synthase (nNOS) and crystal structures of the inhibitors bound to nNOS and to endothelial NOS. The new route enables versatile structure−activity relationship studies on the pyrrolidine-based scaffold, which can be beneficial for further development of nNOS inhibitors. The X-ray crystal structures of five new fluorine-containing inhibitors bound to nNOS provide insights into the effect of the fluorine atoms on binding.

INTRODUCTION

Selective inhibition of neuronal nitric oxide synthase (nNOS) over its closely related isozymes, inducible nitric oxide synthase (iNOS) and endothelial nitric oxide synthase (eNOS), has attracted tremendous drug discovery efforts for neurotoxicity and certain neurodegenerative conditions such as Parkinson's, Alzheimer's, and Huntington's diseases and cerebral palsy.[1−5] As part of our research program directed toward developing novel nNOS inhibitors, we recently disclosed a series of *gem*-difluorinated monocationic inhibitors including **1a** and **1b**, which are potent and highly selective inhibitors of nNOS.[6,7] Moreover, according to the results of detailed pharmacokinetic studies,[7,8] **1b** has demonstrated intriguing cell membrane permeability and oral bioavailability, which makes it a promising drug candidate for neurodegenerative diseases.



Although they possess desirable potency, selectivity, and pharmacokinetic properties, it is difficult to prepare gram-scale quantities of **1b** for a comprehensive preclinical study.[7,8] The previously reported route takes 16 steps starting from 4,6-dimethyl-2-aminopyridine. Several of the steps suffered from unsatisfactory yields, resulting in an overall yield of less than 1%.[7,8] In particular, the late stage benzyl deprotection step, employing a high temperature catalytic hydrogenation of an *N*-Boc-*N*-benzyl-protected intermediate, proceeded poorly. As a result, the utility of this route was dramatically compromised by the lack of scalability. More importantly, the strong reducing conditions used to remove the benzyl protecting group prohibited the possibility of incorporating reduction sensitive functional groups (e.g., nitriles, ketones, alkenes, cyclopropanes, and halophenyls) into the inhibitors, which significantly impaired structure−activity optimization based on this scaffold. For instance, attempts to remove the benzyl protecting group from a compound containing a chlorophenyl substituent led to dechlorination. Removal of the benzyl protecting group by catalytic hydrogenation from a compound containing a cyclopropane led to a partial reduction of the cyclopropyl ring.[9]

We report here a synthesis with improved overall yield and functional group compatibility. In the current method, the problematic benzyl protecting group in the previous synthesis is replaced by a Boc-protecting group. The new route not only produces **1b** in an enhanced overall yield but also provides a way to synthesize inhibitors with reduction-sensitive chlorophenyl groups.

CHEMISTRY

As shown in Scheme 1, the synthesis of key precursor **9** began with Boc-protected 4,6-dimethylaminopyridine **2**. Compound **2** was treated with 2 equiv of *n*-butyllithium (*n*-BuLi), and the resulting dianion was allowed to react with *tert*-butyl 6-oxa-3-azabicyclo[3.1.0]hexane-3-carboxylate[6] to generate the *trans*-alcohol (**3**) in modest yields. Attempts to convert **3** directly to **6** failed because the free hydroxyl group of **3** is more reactive toward $(Boc)_2O$ than the carbamate NH group, and the hydrolytic stability of the formed carbonate is very similar to that of the di-Boc-protected aminopyridine. Therefore, we had to use a

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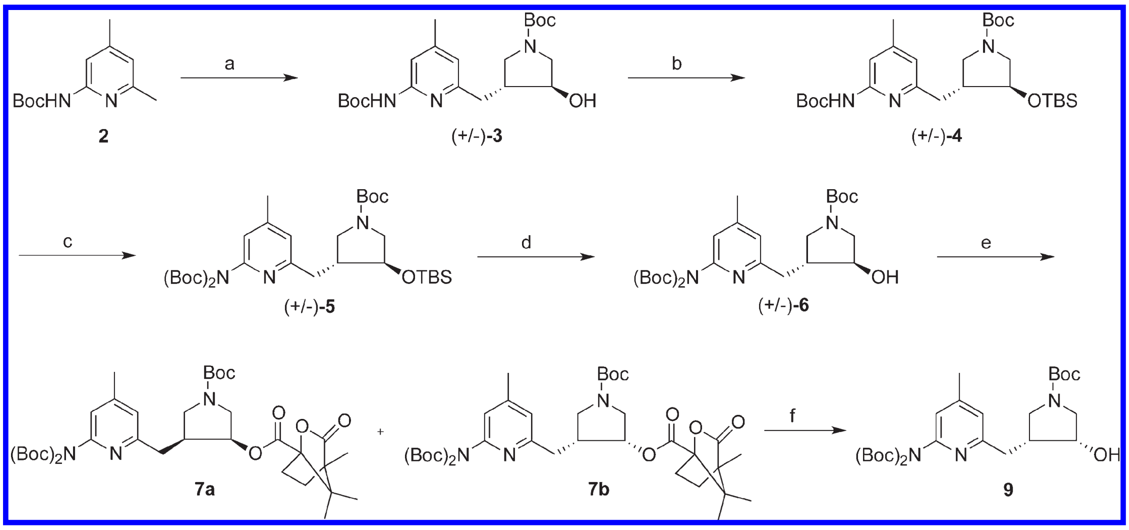
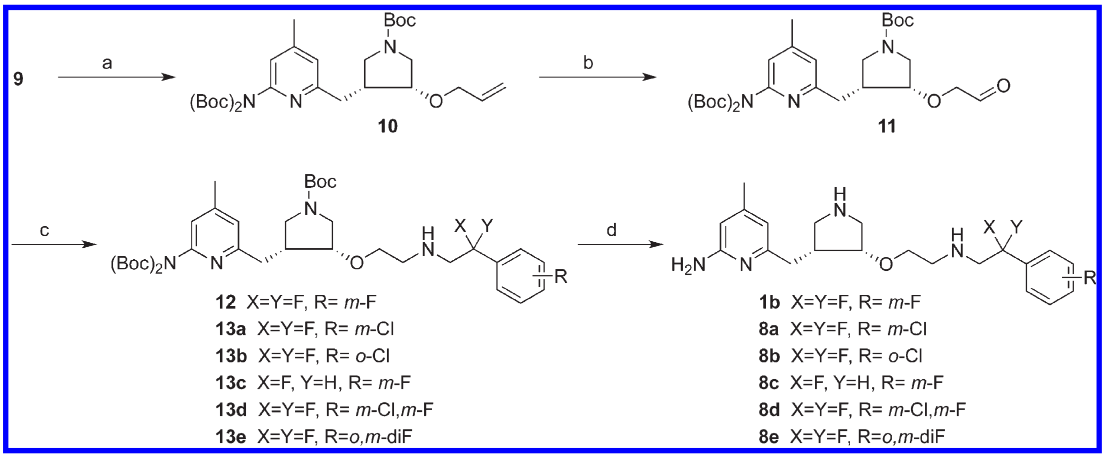
Scheme 1. Synthesis of 9[a]



[a] Reagents and conditions: (a) (i) *n*-BuLi (2 equiv), −78 °C to room temp, (ii) epoxide, −78 °C to room temp, 41%; (b) TBSCl, imidazole, DMF, room temp, 30 h, 93%; (c) $(Boc)_2O$, DMAP, room temp, 24 h, 95%; (d) TBAF, room temp, 15 min, 99%; (e) (*S*)-(−)-camphanic acid, DIAD, room temp, 16 h, 94%; (f) Na_2CO_3, H_2O/MeOH, 35 °C, 30 min, 97%.

Scheme 2. Synthesis of 1b and 8a−e[a]



[a] Reagents and conditions: (a) allyl methyl carbonate, $Pd(PPh_3)_4$, 45 °C, 5 h, 66%; (b) O_3, −78 °C, 30 min, (ii) Me_2S, −78 °C to room temp, 2 h, 87%; (c) amine hydrochloride, triethylamine, $NaHB(OAc)_3$, room temp, 3 h, 86−91%; (d) 6 N HCl in MeOH (2:1), room temp, 12 h, 90−99%.

three-step procedure to convert **3** to **6**. Di-Boc protection of **2** also was fruitless because one of the Boc groups is transferred to the oxyanion of **3** upon condensation with diBoc **2** with *tert*-butyl 6-oxa-3-azabicyclo[3.1.0]hexane-3-carboxylate, as described earlier.[10] The hydroxyl group of **3** was first protected with *tert*-butyldimethylsilyl chloride (TBSCl) in the presence of imidazole to give the silyl ether (**4**) in excellent yields. Next, the NH of the carbamate group on the pyridine ring was further protected with another Boc protecting group using $(Boc)_2O$ in the presence of 4-dimethylaminopyridine (DMAP) to yield **5** in high yields. Then the silyl ether was cleaved using tetrabutylammonium fluoride (TBAF) to provide the tri-Boc protected alcohol (**6**) in very high yields. Finally, the two enantiomers of **6** were resolved through their camphanic ester derivatives (**7a** and **7b**) employing a Mitsunobu reaction using (*S*)-(−)-camphanic acid as the nucleophile. The ester linkage of **7b** was hydrolyzed carefully using Na_2CO_3 in MeOH/H_2O to provide chiral precursor **9** in excellent yields.

Allylation of chiral *cis*-alcohol **9** in the presence of allyl methyl carbonate using $Pd(PPh_3)_4$ as a catalyst provided **10** in good yields (Scheme 2).[10,11] Alkene **10** was treated with ozone, followed by dimethyl sulfide to generate **11** in excellent yields. Aldehyde **11** underwent a reductive amination reaction with the corresponding amines in the presence of $NaHB(OAc)_3$ to give **12, 13a−e** in high yields. Finally, the three Boc-protecting groups were removed simultaneously in HCl to provide the final inhibitors in excellent yields.

■ RESULTS AND DISCUSSION

We have determined the crystal structures of rat nNOS with inhibitors **8a−e** bound and that of bovine eNOS in complex with **8c**. The PDB codes are given in Supporting Information Table 1. As expected from the chirality of their pyrrolidine moiety, inhibitors **8a−e** adopt the same flipped binding mode as leads

1a,b (Figure 1).[7] The aminopyridine motif extends to the surface hydrophobic pocket (Tyr706, Leu337, and Met336) in nNOS, forming a charge−charge interaction with the heme propionate D and a $\pi-\pi$ stacking interaction with the aromatic side chain of Tyr706 in its newly adopted conformation. Substitution of the *m*-fluoro atom in the phenyl tail of **1b** with a larger chlorine atom slightly increases the potency (1.3-fold) of the inhibitor (**8a** vs **1b**, Table 1). A comparison between the structures of nNOS-**8a** (Figure 1A) and nNOS-**1b** provides some clues of why nNOS prefers the *m*-chloro over *m*-fluoro atom on the phenyl group. Similar to what was observed for nNOS-**1b**[7] the 2,2-difluoro-2-(*m*-chlorophenyl)ethyl moiety of **8a** has adopted two conformations, with the CF_2 group pointing away from (major) and toward (minor) the heme. Residual $F_o - F_c$ difference density is present especially around the fluorine atoms if only one conformation is modeled, clearly indicating two conformations. The two different conformations also result in two slightly different orientations of the chlorophenyl group, which is consistent with two conformations. However, because of the bulkier chlorine atom in **8a**, there is increased van der Waals contact and the phenyl ring has been pushed closer to the Glu592 side chain but is still well tolerated. The Glu592 side chain shows two rotamers in the nNOS-**8a** structure, which were seen in nNOS-**1b** as well. The new Glu592 rotamer forms a new hydrogen bond to the amino nitrogen of the inhibitor (Figure 1A). The active site of eNOS might also accommodate the *m*-chlorophenyl ring better; therefore, the selectivity of **8a** for nNOS over eNOS has dropped 6-fold, which makes this inhibitor comparable to inhibitor **1a**.

Table 1. K_i of Inhibitors for Rat nNOS, Bovine eNOS, and Murine iNOS[a]

compd	nNOS (μM)	eNOS (μM)	iNOS (μM)	selectivity[b] n/e	selectivity[b] n/i
1a	0.16	31	190	194	1188
1b[c]	0.11	130	25	1182	227
8a	0.086	16	78	186	907
8b	0.17	27	91	159	535
8c	0.026	19	26	731	1000
8d	0.077	17	17	221	221
8e	0.18	49	130	272	722

[a] The K_i values were calculated based on the directly measured IC_{50} values, which represent at least duplicate measurements with standard deviations of ±10%. There is high homology among these isozymes from different species.[5] [b] The ratio of K_i (eNOS or iNOS) to K_i (nNOS). [c] The K_i (nNOS) for inhibitor **1b** is different from that previously reported because of the use of a new high throughput assay improving both speed and reproducibility.

Inhibitor **8b**, the corresponding *o*-chloro isomer of **8a**, has 2-fold lower potency for rat nNOS (**8b** vs **8a**, Table 1). However, eNOS does not show a preference for inhibitors **8b** and **8a**. The structure of nNOS-**8b** (Figure 1B) reveals only one conformation for the inhibitor where the CF_2 group points toward the

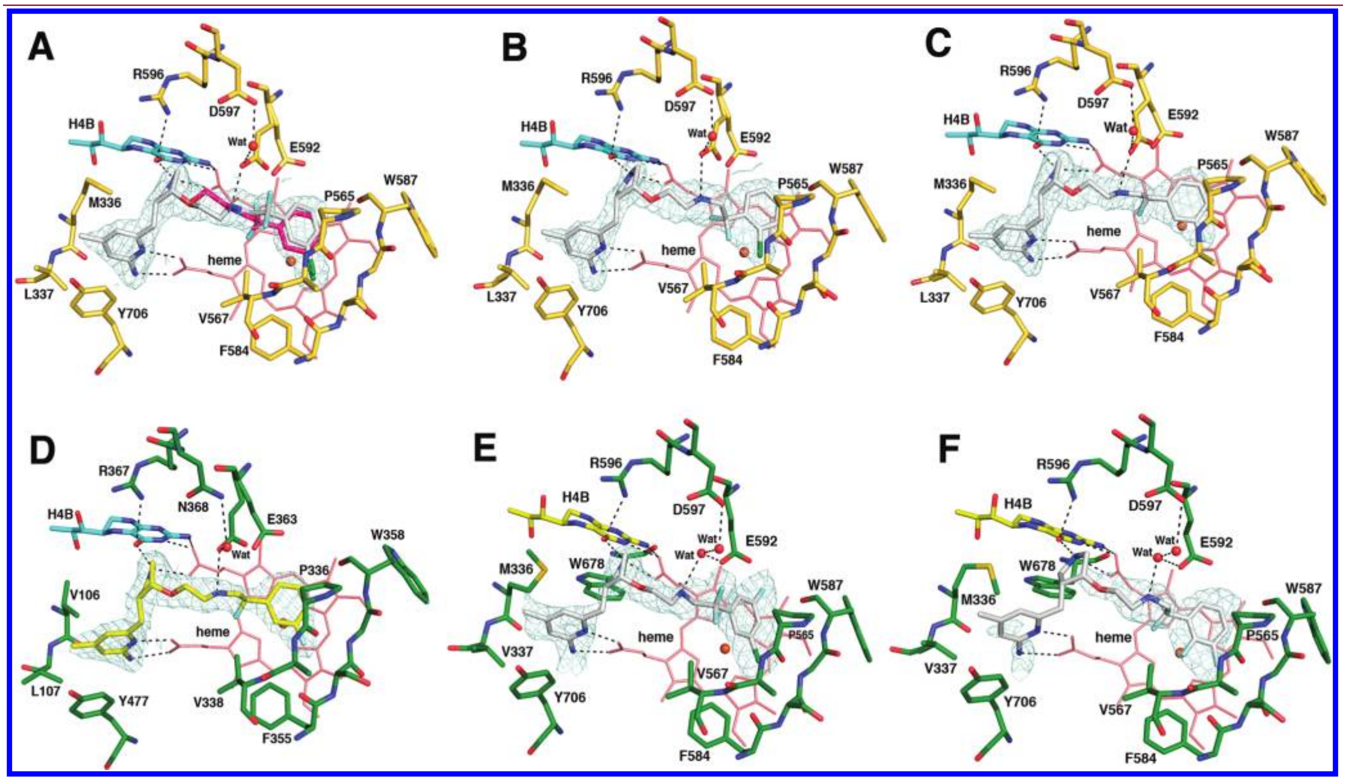


Figure 1. Active site structures in enzyme−inhibitor complexes: (A) nNOS-**8a**, (B) nNOS-**8b**, (C) nNOS-**8c**, (D) eNOS-**8c**, (E) nNOS-**8d**, and (F) nNOS-**8e**. The σ weighted $2F_o - F_c$ electron density map for each bound inhibitor at 1σ contour level is shown for parts A−D and the omit $F_o - F_c$ density map at 2.5σ contour level shown for parts E and F. Major hydrogen bonds are drawn with dashed lines. Alternative side chain rotamers are observed for Glu592 in nNOS or Glu363 in eNOS in parts A−D. The inhibitor **8a** also shows two conformations in its lipophilic tail (colored as gray and magenta in part A). The density for part of inhibitor **8e** is weak as shown, but the model presented in part F is supported by the $2F_o - F_c$ map at lowered contour level (0.5σ). Figures were prepared with PyMol (www.pymol.org). The PDB codes are as follows: nNOS-**8a**, 3PNE; nNOS-**8b**, 3PNF; nNOS-**8c**, 3PNG; eNOS-**8c**, 3PNH; nNOS-**8d**, 3SVP; nNOS-**8e**, 3SVQ.

heme. In this conformation one of the fluorine atoms makes an unfavorable intramolecular contact with the chlorine atom on the phenyl ring. However, there is no electron density indicating an altered orientation for the CF_2 group that avoids this unfavorable contact. This steric hindrance may partially account for the 2-fold drop in potency for **8b** compared to **8a**. When both meta positions of the phenyl ring are substituted (**8d**), the conformation of the phenyl ring is determined by the bulkier chlorine atom and the conformation is more like **8a** than **1b**. This ring is still well tolerated in the active site, and of the CF_2 analogues reported here (**1a**,**b**, **8a**,**b**, **8d**,**e**), **8d** is the most potent of the series. Interestingly, the side chain of **8d** shows only one conformation because the meta disubstituted ring is too large to be accommodated in the alternative conformation. Inhibitor **8e** is the least potent analogue of the series. Similar to **8b**, ortho substitution in **8e** leads to an intramolecular clash between fluorine of the ring and the CF_2 group, and again, only one side chain conformation is observed with CF_2 pointing downward to the heme (Figure 1B,F).

Inhibitor **8c**, a mixture of diastereomers, is the monofluoro methylene derivative of **1b** with a chiral pyrrolidine core. The mixture shows increased potency for rat nNOS (**8c** vs **1b**, Table 1). This may result from the higher basicity of the amino group in the lipophilic tail of **8c** compared to that of **1b**.[8] However, the nNOS selectivity of **8c** over eNOS is somewhat diminished compared with that for **1b** because of its relatively higher potency toward eNOS. The structures of **8c** bound to nNOS and eNOS were obtained (Figure 1C,D). In both structures, the same binding mode for **8c** is observed, with its single fluorine atom pointing down toward the heme. Apparently, despite being a mixture of diastereomers, the (*R*,*R*,*R*)-diastereomer has greater binding affinity to the isozymes than the (*R*,*R*,*S*)-diastereomer because the observed electron density for the fluorine atom only supports one position (*R*). This may be because there is no unfavorable contact between this fluorine atom and heme propionate A in contrast to the clashes observed for the CF_2 group in its "downward" conformation in the nNOS-**8a** structure (Figure 1A). The amino group in the lipophilic tail of the inhibitor lures Glu592 of nNOS (Glu363 of eNOS) into an alternative rotamer by hydrogen bonding.

Structure−activity relationship (SAR) studies demonstrate the key role of the meta substituent in **1b**, **8c**, and **8d** for retaining high inhibitory activity for rat nNOS. A bulkier *m*-chloro group in **8a** increases potency relative to the *m*-fluoro substituent but leads to a loss in selectivity over the other two isoforms. Although *m*-chloro and *m*-fluoro disubstitution (**8d**) achieves another small boost in potency, it also results in an additional drop in selectivity. The *o*-chloro group in **8b** or *o*-fluoro group in **8e** leads to tight intramolecular contacts with its CF_2 group, which is accompanied by an unfavorable side chain conformation and a drop in potency. The *p*-fluoro in **1a** forces its CF_2 group into a downward conformation, weakening the hydrogen bond from the amino group to the Glu592 side chain. It seems then that only meta substituents place the phenyl ring in the right position to optimize van der Waals contact with the hydrophobic pocket surrounded by Val567 and Phe584 in nNOS,[7] and *m*-fluoro inhibitor **1b** achieves the optimum balance between potency and selectivity.

CONCLUSION

An improved synthesis of chiral pyrrolidine inhibitors of nNOS has been developed. Compared with the reported synthesis, it is three steps shorter with an overall yield of ∼10% (>10-fold larger). It also enables expanded SAR studies on the pyrrolidine-based scaffold, which can be beneficial for further development of nNOS inhibitors.

EXPERIMENTAL SECTION

The purity of the final compounds was determined by HPLC analysis to be ≥95%. For experimental details, see the Supporting Information.

6-(((3*R*,4*R*)-4-(2-((2,2-Difluoro-2-(3-fluorophenyl)ethyl)-amino)ethoxy)pyrrolidin-3-yl)methyl)-4-methylpyridin-2-amine (1b). To a solution of **12a** (60 mg, 85 umol) in MeOH (2 mL) was added 6 N HCl (4 mL) at room temperature. The mixture was stirred for 12 h and then concentrated. The crude product was purified by recrystallization (EtOH/H_2O) to give inhibitor **1b** (40 mg, 99%) as a tri-HCl salt; $[\alpha]^{20}$ +6.25 (*c* 4, MeOH).

6-(((3*R*,4*R*)-4-(2-((2,2-Difluoro-2-(3-chlorophenyl)ethyl)-amino)ethoxy)pyrrolidin-3-yl)methyl)-4-methylpyridin-2-amine (8a). To a solution of **12b** (70 mg, 0.10 mmol) in MeOH (2 mL) was added 6 N HCl (4 mL) at room temperature. The mixture was stirred for 12 h and then concentrated. The crude product was purified by recrystallization (EtOH/H_2O) to give inhibitor **8a** (50 mg, 95%) as a tri-HCl salt: ^1H NMR (500 MHz, D_2O) δ 2.19 (s, 3H), 2.60−2.75 (m, 1H), 2.85−2.95 (m, 1H), 3.00−3.10 (m, 2H), 3.20−3.30 (m, 1H), 3.30−3.45 (m, 3H), 3.55−3.60 (d, *J* = 13.0 Hz, 1H), 3.65−3.70 (m, 1H), 3.75−3.90 (m, 3H), 4.15 (d, *J* = 3.0 Hz, 1H), 6.41 (s, 1H), 6.55 (s, 1H), 7.30−7.45 (m, 3H), 7.52 (s, 1H); ^{13}C NMR (125 MHz, D_2O) δ 20.0, 29.2, 41.3, 41.4, 47.0, 47.4, 49.1, 51.7, 63.6, 78.3, 110.4, 114.0, 118.2, 123.39, 123.42, 123.47, 125.07, 125.12, 130.7, 131.5, 133.9, 134.4, 145.4, 153.9, 158.1; LC-TOF (M + H^+) calcd for $C_{21}H_{28}ClF_2N_4O$ 425.1920, found 425.1919.

6-(((3*R*,4*R*)-4-(2-((2,2-Difluoro-2-(2-chlorophenyl)ethyl)-amino)ethoxy)pyrrolidin-3-yl)methyl)-4-methylpyridin-2-amine (8b). Inhibitor **8b** was synthesized using a procedure similar to that for **8a** (50 mg, 95%) as a tri-HCl salt: ^1H NMR (500 MHz, D_2O) δ 2.19 (s, 3H), 2.60−2.75 (m, 1H), 2.85−2.95 (m, 1H), 3.03−3.08 (t, *J* = 11.5 Hz, 1H), 3.19 (s, 1H), 3.21−3.25 (dd, *J* = 3.0, 13.0 Hz, 1H), 3.35−3.42 (m, 3H), 3.52−3.58 (d, *J* = 13.0 Hz, 1H), 3.63−3.66 (m, 1H), 3.82−3.88 (m, 1H), 3.90−4.00 (m, 2H), 4.14−4.16 (t, *J* = 3.5 Hz, 1H), 6.42 (s, 1H), 6.54 (s, 1H), 7.30−7.35 (m, 1H), 7.40−7.45 (m, 2H), 7.55−7.60 (m, 1H); ^{13}C NMR (125 MHz, D_2O) δ 21.0, 29.0, 41.2, 47.0, 47.4, 48.8, 49.2, 50.3, 50.5, 63.4, 78.2, 110.4, 113.9, 118.1, 127.57, 127.63, 127.70, 129.1, 130.8, 131.4, 131.5, 133.1, 145.5, 153.9, 158.1; LC-TOF (M + H^+) calcd for $C_{21}H_{28}ClF_2N_4O$ 425.1920, found 425.1919.

6-(((3*R*,4*R*)-4-(2-((2-Fluoro-2-(3-fluorophenyl)ethyl)amino)-ethoxy)pyrrolidin-3-yl)methyl)-4-methylpyridin-2-amine (8c). Inhibitor **8c** was synthesized as a mixture of two diastereomers using a procedure similar to that for **8a** (32 mg, 90%) as a tri-HCl salt: ^1H NMR (500 MHz, D_2O) δ 2.19 (s, 3H), 2.65−2.75 (m, 1H), 2.85−2.95 (m, 1H), 3.03−3.11 (m, 1H), 3.20 (s, 1H), 3.21−3.25 (dd, *J* = 3.0, 13.0 Hz, 1H), 3.30−3.45 (m, 4H), 3.50−3.58 (m, 2H), 3.60−3.66 (m, 1H), 3.80−3.85 (m, 1H), 4.14−4.16 (m, 1H), 5.80−6.00 (m, 1H), 6.46 (s, 1H), 6.50−6.55 (m, 1H), 7.00−7.15 (m, 3H), 7.30−7.41 (m, 1H); ^{13}C NMR (125 MHz, D_2O) δ 21.0, 29.0, 29.1, 41.3, 41.4, 43.7, 43.9, 47.0, 47.1, 47.3, 48.7, 49.2, 49.3, 51.3, 51.5, 51.7, 51.8, 63.6, 63.9, 78.2, 88.4, 89.8, 110.4, 112.48, 112.54, 112.56, 112.61, 112.69, 112.72, 112.74, 114.0, 114.1, 116.3, 116.5, 116.6, 121.35, 121.40, 121.46, 121.49, 121.51, 130.85, 130.92, 131.0, 136.8, 136.99, 137.02, 145.60, 145.64, 153.85, 153.86, 158.11, 158.12, 161.6, 163.5; LC-TOF (M + H^+) calcd for $C_{21}H_{29}F_2N_4O$ 391.2309, found 391.2288.

6-(((3*R*,4*R*)-4-(2-((2,2-Difluoro-2-(3-chloro-5-fluorophenyl)-ethyl)amino)ethoxy)pyrrolidin-3-yl)methyl)-4-methylpyridin-2-amine (8d). Inhibitor **8d** was synthesized as a mixture of two diastereomers using a procedure similar to that for **8a** (7 mg, 80%) as a tri-HCl salt: ^1H NMR (500 MHz, MeOD) δ 2.35 (s, 3H), 2.80−2.87 (m, 1H), 2.93−2.98 (m, 1H), 3.07−3.13 (m, 1H), 3.23−3.27 (m, 1H), 3.38−3.45 (m, 1H), 3.51−3.56 (m, 2H), 3.50−3.58 (m, 2H), 3.65−3.68 (d, *J* = 13.0 Hz, 1H), 3.73−3.79 (m, 2H), 3.94−3.99 (m, 1H), 4.00−4.07 (m, 1H), 4.19−4.21 (m, 1H), 6.66 (s, 1H), 6.67 (s, 1H), 7.42−7.46 (m, 2H), 7.56 (s, 1H); ^{13}C NMR (125 MHz, MeOD) δ 22.0, 30.4, 43.5, 52.5, 52.7, 64.9, 80.0, 111.5, 112.8, 112.9, 115.1, 120.2, 120.4, 123.1, 137.47, 137.48, 147.95, 156.0, 159.2, 163.2, 165.2; LC-TOF (M + H$^+$) calcd for $C_{21}H_{26}ClF_3N_4O$ 443.1747, found 443.3306.

6-(((3*R*,4*R*)-4-(2-((2,2-Difluoro-2-(2,3-difluorophenyl)ethyl)-amino)ethoxy)pyrrolidin-3-yl)methyl)-4-methylpyridin-2-amine (8e). Inhibitor **8e** was synthesized as a mixture of two diastereomers using a procedure similar to that for **8a** (12 mg, 75%) as a tri-HCl salt: ^{1}H NMR (500 MHz, MeOD) δ 2.35 (s, 3H), 2.82−2.88 (m, 1H), 2.95−3.00 (m, 1H), 3.08−3.14 (m, 1H), 3.23−3.30 (m, 1H), 3.40−3.44 (m, 1H), 3.53−3.55 (m, 2H), 3.60 (d, *J* = 13 Hz, 1H), 3.77−3.79 (m, 1H), 3.95−3.97 (m, 1H), 4.04−4.10 (m, 2H), 4.19−4.20 (m, 1H), 6.66 (s, 1H), 6.67 (s, 1H), 7.32−7.55 (m, 3H); ^{13}C NMR (125 MHz, MeOD) δ 22.0, 30.35, 30.40, 43.5, 49.9, 50.4, 52.5, 65.0, 79.9, 111.5, 115.1, 122.2, 122.3, 123.5, 126.7, 137.47, 137.48, 147.9, 148.0, 156.0, 159.2; LC-TOF (M + H$^+$) calcd for $C_{21}H_{26}F_4N_4O$ 427.2043, found 427.4021.

ASSOCIATED CONTENT

Supporting Information. Procedure for the syntheses of **4**, **5**, **6**, **7a**−**b**, **9**, **10**, **11**, **12**, and **13a**−**e**, enzyme assays of **8a**−**e**, and crystal structures of **8a**−**e** in the active site of enzyme and crystallographic statistics table. This material is available free of charge via the Internet at http://pubs.acs.org.

Accession Codes

[†]The PDB codes for compounds in Figure 1 are as follows: nNOS-**8a**, 3PNE; nNOS-**8b**, 3PNF; nNOS-**8c**, 3PNG; eNOS-**8c**, 3PNH; nNOS-**8d**, 3SVP; nNOS-**8e**, 3SVQ.

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ABBREVIATIONS USED

nNOS, neuronal nitric oxide synthase; NO, nitric oxide; eNOS, endothelial nitric oxide synthase; iNOS, inducible nitric oxide synthase; *n*-BuLi, *n*-butyllithium; TBSCl, *tert*-butyldimethylsilyl chloride; DMAP, 4-dimethylaminopyridine; TBAF, tetrabutylammonium fluoride; SAR, structure−activity relationship

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