Total Synthesis of (+)-7-Bromotryptargine and Unnatural Analogues: Biological Evaluation Uncovers Activity at CNS Targets of Therapeutic Relevance

John T. Brogan,‡,§, Sydney L. Stoops, † Brenda C. Crews, † Lawrence J. Marnett, †,§,|| and Craig W. Lindsley†,‡,§,||

1Department of Pharmacology, †Vanderbilt Center for Neuroscience Drug Discovery, Vanderbilt University Medical Center, Nashville, Tennessee 37232, United States
†Department of Chemistry, †Vanderbilt Institute of Chemical Biology, Vanderbilt University, Nashville, Tennessee, 37232, United States
§ Supporting Information

ABSTRACT:

The first total synthesis of (+)-7-bromotryptargine, a β-carboline alkaloid from Ancornia sp. is reported. The synthesis proceeds in nine steps, eight steps longest linear sequence, in 36.9% overall yield. Biological characterization found that (+)-7-bromotryptargine is a H3 antagonist, and a selective inhibitor of the dopamine transporter (DAT) and norepinephrine transporter (NET), without inhibiting the serotonin transporter (SERT). Moreover, unlike electron rich congeners, (+)-7-bromotryptargine is not cytotoxic and thus represents an attractive starting point for chemical optimization; therefore, we piloted a number of chemistries for the synthesis of unnatural analogues.

Drug discovery based on natural products, and marine natural products in particular, has been a highly successful approach toward novel lead series and marketed therapeutics for both peripheral and central nervous system (CNS) indications.1,2 A number of marine natural products, such as aplysamine,2 verogamine,2 conessine,3 and dispyrin,4 have displayed both affinity for and inhibition of the histamine subtype 3 (H3) receptor (Figure 1).5–10 The H3 receptor is a presynaptic auto-receptor within the Class A GPCR family, but it also functions as a heteroreceptor modulating levels of neurotransmitters such as dopamine, acetylcholine, norepinephrine, serotonin, GABA, and glutamate.8–10 Thus, H3R has garnered a great deal of interest from the pharmaceutical industry for the possible treatment of obesity, epilepsy, sleep/wake, schizophrenia, Alzheimer’s disease, neuropathic pain, and ADHD.8–10 Importantly, conserved elements have been identified within small molecule H3 ligand scaffolds that resulted in a highly predictive pharmacophore model, and many marine natural products conform to this model.8–10

β-Carboline alkaloids are a prevalent class of biologically active natural products from marine organisms. They exhibit diverse structural features and distinct neuropharmacological profiles.11,12 Our lab has worked extensively in this arena,1,13 and we were recently attracted to a class of β-carboline alkaloids represented by the tryptargines 5–7 (Figure 2), as these alkaloids mapped well onto the H3 pharmacophore model and offered a synthetic challenge.15,16 Both tryptargine S15 and 6-hydroxytryptargine 616 are highly toxic alkaloids. (+)-7-Bromotryptargine 7, was only recently isolated by Quinn et al. from the Australian marine sponge Ancornia sp. and found to possess antimalarial activity.17 6-Bromotyramine 8 was isolated along with 7 in similar quantities, and it is believed to be a key biosynthetic precursor.17 Based on the neuropharmacological profiles of β-carbole alkaloids, and the electron-deficient nature of 7, relative to the electron-rich congeners 5 and 6, which might diminish the cytotoxicity, the total synthesis of 7 and biological evaluation seemed warranted.

Our retrosynthesis of 7 (Figure 3) afforded two approaches to close the tricyclic ring: either utilizing the recently reported Brønsted-acid-catalyzed, enantioselective Protio—Pictet—Spengler reaction18,19 or a Bischler—Napieralski reaction,14 followed by an asymmetric Noyori transfer hydrogenation protocol.20 Both routes required the synthesis of 6-bromotyramine 8. As shown in Scheme 1, nitro-olefination of 6-bromo-1H-indole 9, as prescribed by Büchi and Mak,21 proceeded smoothly affording 10 in 98% yield. Exhaustive reduction then provided natural 6-bromotyramine 8 in 76% yield.
With large quantities of 8 in hand, we evaluated both the Jacobsen thiourea Brønsted-acid-catalyzed, enantioselective Protio–Pictet–Spengler reaction as well as the Dixon chiral BINOL-derived phosphoric acid variation with known aldehyde 11 to produce the key, chiral β-carboline core 13 (Scheme 2). Interestingly, neither protocol afforded 13; however, electron rich congeners of 8, such as 12, proceeded smoothly, providing 14 in good ee and conversion. Thus, the Brønsted-acid-catalyzed, enantioselective Protio–Pictet–Spengler approach with the more electron deficient 8 was not tractable. Indeed, the original reports by Jacobsen and Klausen, and Dixon et al. utilized only electron rich substrates. Conversion to 13 could be forced under both protocols (~80% yield) at high temperatures, but enantioselectivity eroded. Thus, focus shifted toward a Bischler–Napieralski/Noyori asymmetric transfer hydrogenation approach.

Key acid 17 was prepared in 98% yield by treating 4-amino-butanoic acid 15 with anhydride 16 under microwave conditions (Scheme 3). Standard amide coupling conditions with 8 and 17...
provided amide 18. The Bischler–Napieralski reaction\textsuperscript{14,20} was facilitated by treatment with POCl\textsubscript{3} to imine 19 in 88% yield. Noyori asymmetric transfer hydrogenation with (S,S)-ruthenium\textsuperscript{20} catalyst delivered the β-carboline core 13 in 80% yield and 90% ee.\textsuperscript{20,22} Removal of the phthalimide moiety with hydrazine to afford amine 21, guanidation, and removal of the Boc protecting groups proceeded in 84% yield over the three steps, delivering, for the first time, (+)-7-bromotryptargine 7. Synthetic 7 exhibited physical and spectroscopic data identical to that of natural 7,\textsuperscript{17,22} confirming the structure and absolute stereochemistry. Overall, the synthesis proceeds in nine steps, eight steps longest linear sequence, in 36.9% overall yield which provided significant material to enable detailed biological evaluation.

As 5 and 6 are highly toxic alkaloids, we first evaluated 7 in a standard cytotoxicity assay and found 7 to be nontoxic up to 20 μM, suggesting the pharmacological profile might diverge from 5 and 6.\textsuperscript{23} This surprising result led us to study 7 in our standard HCT116 colon carcinoma cell viability assay.\textsuperscript{22} Here, as well, 7 had no effect on HCT116 cell viability after 48 h. In contrast, advanced intermediate 21, an unnatural analogue of 7, displayed an IC\textsubscript{50} of 3 μM in this assay, completely killing the cells after 48 h. These data prompted examination of unnatural analogue 21 in additional colon carcinoma (SW620 and H520) cell lines.\textsuperscript{25} Interestingly, 21 had dramatic effects inhibiting proliferation in BrdU assays as well as significant activity on cell viability.\textsuperscript{22} In contrast, 7 was devoid of activity in all of these assays. Collectively, these data informed us of two important points: (1) the pharmacology of the more electron deficient (+)-7-bromotryptargine (7) is distinct from 5 and 6 and warrants further biological evaluation, as it lacks toxicity; and (2) unnatural analogue 21 possesses an intriguing pharmacological profile warranting the synthesis and characterization of additional unnatural analogues of 7.

(+)-7-Bromotryptargine (7) was then evaluated in an external panel\textsuperscript{26} of 68 GPCRs, ion channels, and transporters in radioligand binding assays in an attempt to identify a discrete molecular target with therapeutic relevance, a strategy that has been highly successful.\textsuperscript{27} In this instance, 7 was found to have a very clean pharmacological profile, affording significant percent inhibition at only three targets: histamine H\textsubscript{3} (74%@10 μM), the dopamine transporter, DAT (81%@10 μM), and the norepinephrine transporter, NET (82%@10 μM). Interestingly, these are all targets for important pathologies of the CNS, and 7 did prove to possess activity at the H\textsubscript{3} receptor as envisioned. Indeed, 7 is now the fifth marine natural product with significant activity at H\textsubscript{3}, a target of interest for Alzheimer’s disease, schizophrenia, ADHD, and other indications.\textsuperscript{3–6} Full dose–response curves were generated for the three targets in both binding (K\textsubscript{i}) and functional (IC\textsubscript{50}) assays,\textsuperscript{22} proving that 7 both bound to and inhibited the three targets with moderate potencies (Table 1).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{target} & \textbf{% inhibition (@10 μM)} & \textbf{K\textsubscript{i} (μM)} & \textbf{IC\textsubscript{50} (μM)} \\
\hline
H\textsubscript{3} & 74 & 1.8 & 3.6 \\
DAT & 81 & 3.0 & 3.8 \\
NET & 82 & 1.9 & 1.9 \\
\hline
\end{tabular}
\caption{Pharmacological Profile of (+)-7-Bromotryptargine (7)}
\end{table}
norepinephrine, respectively. Drugs targeting MATs are blockbusters and target either serotonin reuptake (SSRIs), serotonin and norepinephrine reuptake (SNRIs), or uptake of all three (triple reuptake inhibitors). To date, only one drug, methylphenidate (Ritalin), targets only NET and DAT, making 7 a novel chemotype, and a most attractive starting point for further optimization for dual NET/DAT activity and/or H3 activity.

In order to optimize the dual NET/DAT activity, we would need to have reliable chemistry to prepare unnatural analogues of 7 (Figure 4) in short order, while also removing functionality, such as the guanidine, that would limit brain penetration. Thus, we piloted a number of classical reactions (reductive amination, acylation, sulfonylation, Suzuki coupling, etc.) that are mainstays in the pharmaceutical industry en route to unnatural analogues of 7 (Scheme 4). Prior to removal of the phthalimide moiety, the reaction was transferred to a 1 L separatory funnel, rinsing with DCM for loss of starting indole by thin layer chromatography. After 15 min, the reaction was monitored by dropwise via syringe to the stirred solution. The reaction was allowed to warm to room temperature overnight. The reaction was monitored by THF (600.1 MHz, DMSO) δ (ppm): 138.9, 137.1, 134.1, 132.8, 124.9, 124.1, 122.6, 116.3, 115.8, 108.6. HRMS (TOF, ES+) C10H8N2O2Br [M+H]+ calc., 266.9769; found, 266.9769.

**METHODS**

**General.** The general chemistry, experimental information, and spectral data of all new compounds are supplied in the Supporting Information. Purity of all final compounds was determined by HPLC analysis and is >98%.

**Total Synthesis of (+)-Bromotrypargine (7).** 6-Bromo-3-(2-nitrovinyl)-1H-indole (10). 1-(Dimethylamino)-2-nitroethylen (1.6 g, 13.72 mmol) was dissolved in 20 mL of trifluoroacetic acid and stirred for 5 min. 6-Bromoindole (9) (3.23 g, 16.47 mmol) was dissolved in 15 mL of dichloromethane (DCM) and added to the stirring solution. The mixture was stirred for 15 min at room temperature and monitored for loss of starting indole by thin layer chromatography. After 15 min, the reaction was transferred to a 1 L separatory funnel, rinsing with DCM and then quenched with 200 mL water. The aqueous phase was extracted three times with DCM, and the combined organic phase was dried over MgSO4, filtered, and concentrated onto 10 g of silica. The product was purified on silica (EtOAc/hexanes 1:2) and yielded 3.61 g (98%) 6-bromo-3-(2-nitrovinyl)-1H-indole as a yellow solid. 1H NMR (600.1 MHz, DMSO) δ (ppm): 8.39 (d, J = 13.5 Hz, 1H), 8.25 (s, 1H), 8.02 (d, J = 13.5 Hz, 1H), 7.95 (d, J = 8.5 Hz, 1H), 7.71 (d, J = 1.75 Hz, 1H), 7.35 (dd, J = 1.85, 8.51 Hz, 1H); 13C NMR (150 MHz, DMSO) δ (ppm): 138.9, 137.1, 134.1, 132.8, 124.9, 124.1, 122.6, 116.3, 115.8, 108.6. HRMS (TOF, ES+) C10H8N2O2Br [M+H]+ calc., 266.9769; found, 266.9769.

6-Bromotryptamine (8). A 250 mL Schlenk flask equipped with a stir bar and septa was flame-dried under vacuum. LiAlH4 (2.03 g, 53.69 mmol) was added, and the flask then was sealed and vacuum purged three times, refilling with argon. Tetrahydrofuran (THF; 89 mL) was added, and the solution was stirred 5 min at room temperature before being cooled to −78 °C for 10 min. 6-Bromo-3-(2-nitrovinyl)-1H-indole (10 (2.39 g, 8.94 mmol) was dissolved in 89 mL of THF and added dropwise via syringe to the stirred solution. The reaction was allowed to warm to room temperature overnight. The reaction was monitored by thin layer chromatography over 24 h. After 24 h, the flask was placed in an ice bath and cooled for 5 min before the careful addition of 2 mL of water, followed by 2 mL of 15%aq. NaOH, followed by 6 mL of water. The flask was stirred for 30 min, and a small amount of MgSO4 was added. The mixture was then filtered through a glass frit, washing the formed solid with dichloromethane. The resulting brown solution was then concentrated to afford a crude brown oil. The product was purified on silica (80:18:2 CHCl3/MeOH/NH4OH) and yielded 1.63 g (76%) 8.
as a brown solid. $^1$H NMR (600.1 MHz, MeOD) $\delta$ (ppm): 7.56 (d, $J$ = 1.65 Hz, 1H), 7.51 (d, $J$ = 8.51 Hz, 1H), 7.21 (s, 1H), 7.18 (d, $J$ = 7.51 Hz, 1H), 3.24 (t, $J$ = 7.63 Hz, 2H), 3.12 (t, $J$ = 7.63 Hz, 2H). $^{13}$C NMR (150 MHz, MeOD) $\delta$ (ppm): 137.5, 126.2, 122.9, 121.2, 119.2, 114.3, 113.7, 41.5. 27.8. HRMS (TOF, ES+) $C_{18}H_{19}N_3Br [M+H]^+$ + calcld, 393.0814; found, 393.0814.

$N$-[(2-6-Bromo-1H-indol-3-yl)-ethyl]-4-(1,3-dioxoisindolin-2-yl)-butanamide (18). 6-Bromotryptamine (8) (1.0 g, 4.18 mmol), 4-(1,3-dioxoisindolin-2-yl)butanoic acid (17) (1.17 g, 5.01 mmol), EDC (1.60 g, 8.36 mmol), and HOBT (1.12 g, 8.36 mmol) were dissolved in DCM. The combined organic phase was dried over MgSO$_4$ and concentrated under reduced pressure. The product was purified on silica (80:18:2 CHCl$_3$/MeOH/NH$_4$OH) and yielded 213.73 mg (98%) as a brown solid. [a]$_D^{28}$ 35.8$^\circ$ (c = 2.0, MeOH).

$^{13}$N NMR (600.1 MHz, MeOD) $\delta$ (ppm): 7.56 (d, $J$ = 1.58 Hz, 1H), 7.39 (d, $J$ = 8.43 Hz, 1H), 7.17 (dd, $J$ = 1.58, 8.43 Hz, 1H), 4.77 (q, $J$ = 4.41 Hz, 1H), 3.75 (m, 1H), 3.49 (m, 1H), 3.07 (m, 4H), 2.34 (m, 1H), 2.11 (m, 1H), 1.97 (m, 2H). $^{13}$C NMR (150 MHz, MeOD) $\delta$ (ppm): 161.1, 160.9, 137.6, 129.1, 124.9, 119.2, 115.4, 113.9, 106.5, 52.5, 41.2, 38.7, 26.8, 22.18. HRMS (TOF, ES+) $C_{16}H_{18}N_3Br [M+H]^+$ + calcld, 308.0862; found, 308.0759.

(+)-7-Bromotryptargine (7). A 50 mL round-bottom flask was charged with 21 (231 mg, 0.749 mmol) and DCM (5 mL). $N$-$N'$-Bis-(Boc)-1H-pyrrole-1-carboxamide (255.8 mg, 0.824 mmol) and triethylamine (156 uL, 1.12 mmol) were then added. The flask was then stirred for 3 h and monitored by TLC and LCMS. After 3 h, 5 mL of trifluoroacetic acid was added and the reaction was stirred for 4 h. Reaction progress was monitored by LCMS. After 4 h, the reaction was concentrated and the product was purified by reverse phase high performance liquid chromatography using acetonitrile and 0.1% TFA/water (gradient: 10:90 to 90:10) and yielded 225 mg (86% over two steps) as a glassy yellow solid. [a]$_D^{28}$ 40.0$^\circ$ (c = 1.0, MeOH).

$H$ NMR (600.1 MHz, DMSO) $\delta$ (ppm): 11.3 (s, 1H), 9.49 (s, 1H), 9.00 (s, 1H), 7.73 (br s, 1H), 7.56 (d, $J$ = 1.68 Hz, 1H), 7.46 (d, $J$ = 8.50 Hz, 1H), 7.20 (br s, 2H), 7.18 (br s, 2H), 7.18 (dd, $J$ = 1.68, 8.50 Hz, 1H), 6.96 (s, 1H), 3.58 (m, 1H), 3.34 (m, 1H), 3.34 (m, 1H), 2.93 (t, $J$ = 5.5 Hz, 2H), 2.11 (m, 1H), 1.90 (m, 1H), 1.69 (m, 1H). $^{13}$C NMR (150 MHz, DMSO) $\delta$ (ppm): 157.2, 137.5, 131.4, 125.2, 122.4, 120.3, 118.5, 114.9, 114.3, 106.6, 52.2, 40.9, 40.7, 28.9, 24.7, 18.4. HRMS (TOF, ES+) $C_{14}H_{19}N_3Br [M+H]^+$ + calcld, 360.0980; found, 359.0982.

Cell Culture and HCT116 Viability Assay. HCT116 cells (ATCC CCL-247, passage 8, mycoplasma-negative on 07/14/09) were used in 96-well plates and allowed to attach for 24 h. No cells were plated in the first batch. Fresh DMEM + 10% FBS + penicillin/streptomycin (100 u) containing the final concentrations of dimethyl sulfoxide (DMSO) or epi-Lucentamycin A or podophyllotoxin dilutions in DMSO (DMSO concentration maintained at 0.1%) was replaced in each well. After 48 h of cell growth with respective treatments, WST-1 Cell Proliferation (medium only plus WST-1, first column) was measured.
penicillin-streptomycin. The CycLex Cellular BrdU ELISA Kit from MBL International (Woburn, MA) was used to measure proliferation. The RPMI medium was removed and replaced with 100 μL of 1 × BrdU label mix in RPMI media for 2 h at 37 °C in 5% CO2 in the air. The BrdU label mix was removed, and 200 μL of the fix/denature solution was added and incubated for 30 min at room temperature. The plate was drained, incubated with 50 μL of primary antibody for 1 h at room temperature, rinsed with wash buffer, and incubated with 50 μL of secondary antibody. The wells were rinsed with wash buffer followed by a single rinse with phosphate-buffered saline and drained. Fifty microliters of substrate solution was added and incubated for 6 min followed immediately by 50 μL of stop solution. The change in proliferation was quantified by measuring the absorbance of the dye solution at 450 nm on a microtiter plate reader.

**Invasion Analysis.** SW620 cells (2.5 × 104/ mL) were seeded in 6-well plates prior to treatment. Cells were treated with 10 μM concentration of synthesized compound for 24 h in RPMI 1640 supplemented medium and 100 μg/mL penicillin-streptomycin. An amount of 40 μL (2.5 mg/mL) of BD Matrigel Basement Membrane Matrix (BD Biosciences, Bedford, MA) was added to top of Fluoroblok invasion chambers (BD Biosciences). Then the cells were trypsinized and 3 × 105/250 μL cells were added to the top of the chamber in serum-free RPMI medium, and 1 mL of RPMI medium with 10% FBS was added to the bottom of the well. Then the plates were incubated for 72 h at 37 °C in 5% CO2 in air. Invading cells were stained with Calcein AM as a fluorescent dye to count invading cells using a fluorometer (Molecular Devices Spectramax M5). All experiments were done in triplicate with a total of three independent replicates.

**Radioligand Binding and Functional Assays.** All biological assays were conducted at Ricerca Pharma according to published protocols.26

## ASSOCIATED CONTENT

### Supporting Information.
Experimental procedures and spectroscopic data for selected compounds and detailed pharmacology methods. This material is available free of charge via the Internet at http://pubs.acs.org.

### AUTHOR INFORMATION

**Corresponding Author**
*Telephone: 615-322-8700. Fax: 615-936-4381. E-mail: craig.lindsley@vanderbilt.edu. Mailing address: Department of Pharmacology, 12415D MRBIV/Vanderbilt University Medical Center, 2213 Garland Ave., Nashville, TN 37232.

**Author Contributions**
C.W.L. conceived and directed the project and wrote the manuscript. J.T.B. performed all chemical synthesis. S.L.S. and B.C.C. performed cytotoxicity assays, and L.J.M. directed the efforts of S.L.S. and B.C.C.

**Funding Sources**
This work was supported, in part, by the Department of Pharmacology and Vanderbilt University. Funding for the NMR instrumentation was provided in part by a grant from NIH (S10 RR019022).

## ACKNOWLEDGMENT

Vanderbilt is a member of the MLPCN and houses the Vanderbilt Specialized Chemistry Center for Accelerated Probe Development.

## REFERENCES


(22) See the Supporting Information for complete details.


(26) For information on the Lead Profile Screen, see: www.ricerca.com.
