11-13-2014

Enantiopure Cyclopropane-Bearing Pyridyldiazabicyclo[3.3.0]Octanes As Selective Î±4Î²2-Nachr Ligands

Oluseye K. Onajole

J. Brek Eaton

Ronald J. Lukas
Barrow Neurological Institute, ronald.lukas@dignityhealth.org

Dani Brunner

Lucinda Thiede

See next page for additional authors

Authors

Oluseye K. Onajole, J. Brek Eaton, Ronald J. Lukas, Dani Brunner, Lucinda Thiede, Barbara J. Caldarone, and Alan P. Kozikowski

ACS Medicinal Chemistry Letters

Letter

pubs.acs.org/acsmedchemlett

Enantiopure Cyclopropane-Bearing Pyridyldiazabicyclo[3.3.0]octanes as Selective α4β2-nAChR Ligands

Oluseye K. Onajole,[†] J. Brek Eaton,[‡] Ronald J. Lukas,[‡] Dani Brunner,[§] Lucinda Thiede,[§] Barbara J. Caldarone,[∥] and Alan P. Kozikowski*[,†]

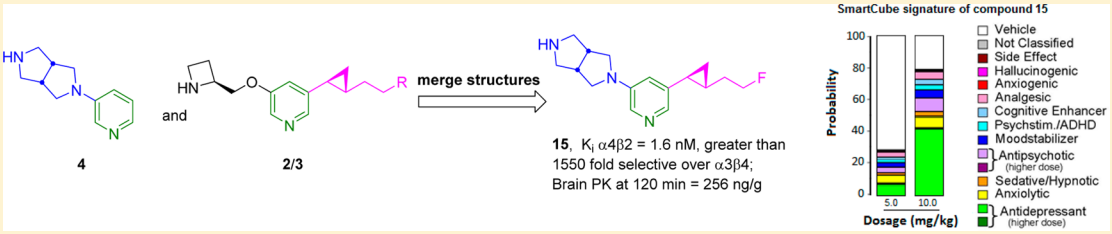
[†]Department of Medicinal Chemistry and Pharmacognosy, College of Pharmacy, University of Illinois at Chicago, 833 South Wood Street, Chicago, Illinois 60612, United States

[‡]Division of Neurobiology, Barrow Neurological Institute, 350 West Thomas Road, Phoenix, Arizona 85013, United States

[§]PsychoGenics, Inc., 765 Old Saw Mill River Road, Tarrytown, New York 10591, United States

[∥]NeuroBehavior Laboratory, Harvard NeuroDiscovery Center and Department of Neurology, Brigham and Women's Hospital, 77 Avenue Louis Pasteur, Boston, Massachusetts 02115, United States

Supporting Information



ABSTRACT: We report the synthesis and characterization of a series of enantiopure 5-cyclopropane-bearing pyridyldiazabicyclo[3.3.0]octanes that display low nanomolar binding affinities and act as functional agonists at α4β2-nicotinic acetylcholine receptor (nAChR) subtype. Structure−activity relationship studies revealed that incorporation of a cyclopropane-containing side chain at the 5-position of the pyridine ring provides ligands with improved subtype selectivity for nAChR β2 subunit-containing nAChR subtypes (β2*-nAChRs) over β4*-nAChRs compared to the parent compound **4**. Compound **15** exhibited subnanomolar binding affinity for α4β2- and α4β2*-nAChRs with negligible interaction. Functional assays confirm selectivity for α4β2-nAChRs. Furthermore, using the SmartCube assay system, this ligand showed antidepressant, anxiolytic, and antipsychotic features, while mouse forced-swim assay further confirm the antidepressant-like property of **15**.

KEYWORDS: *Nicotinic acetylcholine receptor, selective α4β2 partial agonist, N-pyridyldiazabicyclo[3.3.0]octane*

Nicotinic acetylcholine receptors (nAChRs) are expressed as pentameric complexes of single (homomeric) or multiple (heteromeric) subunits, which are encoded by 17 different genes (in vertebrates), thus creating a wide variety of nAChR subtypes. The most common nAChR subtypes present in the central nervous system (CNS) are heteropentamers containing α4 and β2 subunits or the homopentamer comprising α7 subunits, while the peripheral nervous system (PNS) consist mainly of α3 subunit combinations (predominately α3β4 heteromer).[1] nAChR subtypes possess unique pharmacological and physiological properties depending on their subunit makeup and identifying ligands that offer selectivity among these subtypes affords opportunities to develop novel therapeutic agents for use in various central nervous system disorders including schizophrenia, depression, Alzheimer's disease, tobacco addiction, and attention deficit hyperactivity disorder (ADHD).[2−4] Moreover, identifying selective ligands would help to attenuate adverse side effects associated with actions at ganglionic α3β4*-nAChRs (the asterisk indicates that the receptor complex is known to or may contain other subunits than those specified).[5,6] A growing body of evidence indicates that α4β2*-nAChR subtypes appear to play an essential role in depression as well as in cognition, attention, anxiety, and nicotine dependence.[2,4,7−10] For instance, varenicline, marketed as a smoking cessation pharmacotherapy, is an α4β2-nAChR partial agonist.[11,12] Studies have shown that varenicline possesses antidepressant-like effects and also improves cognition in animal models.[13,14] However, several side effects such as nausea, mood changes, sleep disturbance, and constipation have been associated with the use of varenicline for smoking cessation, effects that may be related in part to its α3β4 subtype activity coupled with its $5HT_3$ activity.[10,15−18] Additionally, efforts have been made to advance the noncompetitive nicotinic antagonist mecamylamine for use in depression; however, this compound failed to show efficacy in human clinical trials.[19] The development of other nAChR ligands for use in depression thus still represents a therapeutic opportunity.

Received: March 29, 2014
Accepted: September 29, 2014
Published: September 29, 2014

Sazetidine-A (**1**), a 3-pyridyl ether possessing an alkynyl substituent at its 5-position, is a highly potent $\alpha4\beta2$-nAChR partial agonist (K_i = 0.4 nM) that possesses a 24,000-fold selectivity for $\alpha4\beta2$- over $\alpha3\beta4$-nAChRs (Figure 1).[20] Sazetidine-A also displays potent anxiolytic, analgesic, and antidepressant features as revealed in studies using animal models.[21−23]

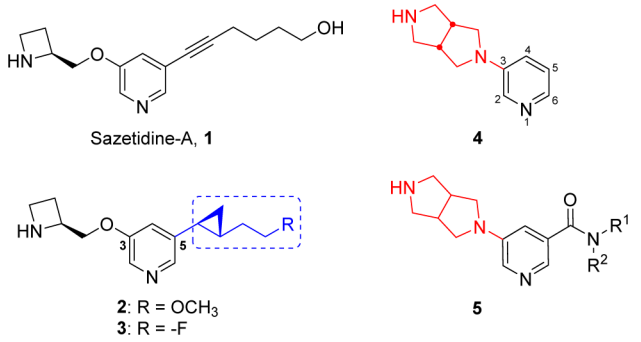


Figure 1. Selected nicotinic receptor ligands (**1**−**5**).

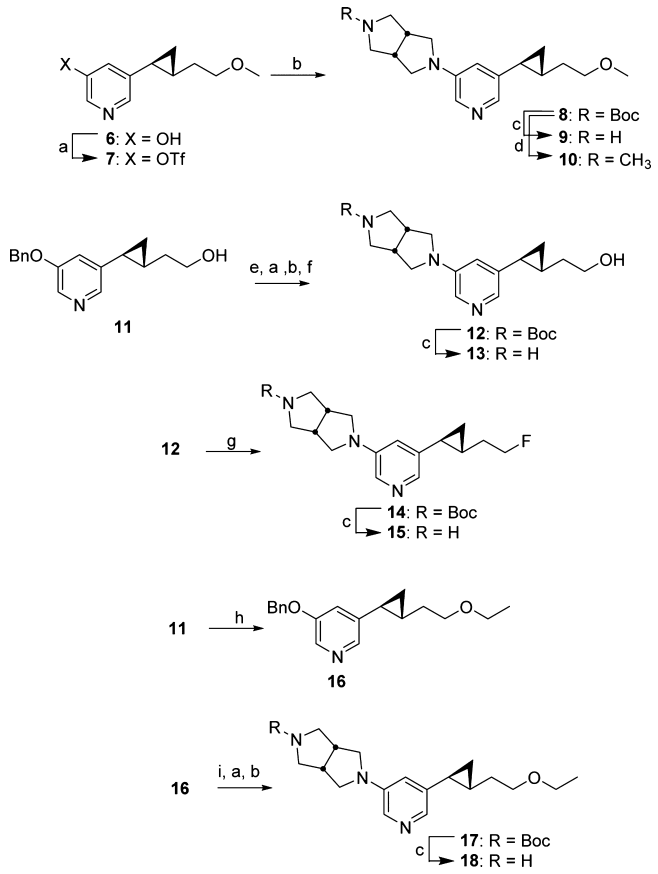
We recently reported the synthesis and biological characterization of a novel series of $\alpha4\beta2$-nAChR partial agonists bearing a cyclopropane ring in place of the acetylenic bond present in Sazetidine-A (**1**). The cyclopropane ring enforces an orientation of the side chain such that compounds possessing this motif maintained subtype selectivity for $\alpha4\beta2$-nAChRs.[24] Compounds **2** and **3** are highly selective $\alpha4\beta2$-nAChR partial agonists with subnanomolar binding affinities (K_i = 0.1 and 0.2 nM, respectively) and excellent subtype selectivity over $\alpha3\beta4$*- and $\alpha7$-nAChRs.[24,25] These compounds also show antidepressant activity in mouse forced swim studies. Compound **4**, a 3-pyridyl diazabicyclo[3.3.0]octane, is an $\alpha4\beta2$-nAChR agonist having subnanomolar binding affinity (K_i = 0.12 nM for a rat brain $\alpha4\beta2$* subtype) and approximately 400-fold selectivity over $\alpha7$-nAChRs.

The selectivity of these compounds for $\alpha4\beta2$- versus $\alpha7$-nAChRs can be improved depending on the nature of the R group at position 5 of the pyridine ring, with larger R groups generally showing improved selectivity for the $\alpha4\beta2$-nAChR subtype.[26] Compound **5**, a 3-pyridyl diazabicyclo[3.3.0]octane with a carboxamide group at position 5, resulted in compounds that generally possessed high binding affinity and selectivity for $\alpha4\beta2$- compared to $\alpha7$-nAChRs.[27] In this study, we selected our best ligands[24,25] and incorporated the cyclopropane-containing side chain scaffold onto the 5-position of the *N*-pyridyldiazabicyclo[3.3.0]octane motif **4**, in an attempt to improve subtype selectivity toward $\alpha4\beta2$*- over ganglionic $\alpha3\beta4$*-nAChRs.

The synthesis of the chiral cyclopropylpyridine ligands **9**, **10**, **13**, **15** , and **18** is summarized in Scheme 1. The hydroxyl group of the optically pure pyridine intermediate **6**[24] was activated as its triflate **7** and subsequently reacted with *tert*-butyl *cis*-hexahydropyrrolo[3,4-*c*]pyrrole-2(1*H*)-carboxylate,[26] under slightly modified Buchwald−Hartwig conditions to obtain the precursor **8**. Deprotection with trifluoroacetic acid (TFA) yielded the secondary amine **9** as its trifluoroacetate salt. The Boc-protected amine **8** was reduced with $LiAlH_4$ to yield the *N*-methyl derivative **10**.

Next, acylation of **11** using isobutyric anhydride followed by removal of the benzyl group and Buchwald−Hartwig reaction

Scheme 1. Synthesis of Derivatives 9, 10, 13, 15, and 18[a]



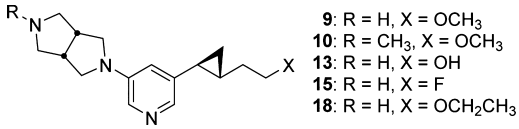
[a]Reagents and conditions: (a) $(CF_3SO_2)_2O$, C_5H_5N, 0 °C; (b) *tert*-butyl *cis*-hexahydropyrrolo[3,4-*c*]pyrrole-2(1*H*)-carboxylate,[26] tris(dibenzylideneacetone)dipalladium, 2-dicyclohexylphosphino-2′,4′,6′-triisopropylbiphenyl, K_3PO_4, 1,4-dioxane, microwave, 160 °C, 10 min; (c) CF_3COOH, CH_2Cl_2, rt; (d) $LiAH_4$, THF, reflux; (e) (i) isobutyric anhydride, cat. 4-(dimethylamino)pyridine, Et_3N, CH_2Cl_2, rt; (ii) 10% Pd/C, MeOH/EtOAc (4:1), rt, 2 h; (f) NaOMe, CH_3OH, 40 °C; (g) (i) TsCl, Et_3N, CH_2Cl_2, 0 °C to rt, (ii) $(n\text{-}Bu)_4NF$, THF, rt; (h) NaH, CH_3CH_2I, DMF, rt; (i) 10% Pd/C, MeOH/EtOAc (4:1), rt, 2 h.

generated **12** after hydrolysis of the isobutyrate protecting group. Cleavage of the Boc group with TFA gave the alcohol **13** as its TFA salt. To generate the fluoride **14**, the hydroxyl group of compound **12** was activated as its tosylate and this intermediate treated with *n*-tetrabutylammonium fluoride to yield the corresponding protected fluoride. Boc deprotection of **14** with TFA afforded the final product **15** as its TFA salt. To prepare the ethyl ether analogue **18**, the intermediate **11** was first subjected to the Williamson ether synthesis using ethyl iodide as the alkylating agent. Next, the benzyl group was removed via hydrogenolysis, the amine coupling reaction carried out, and then the Boc group cleaved from **17** to afford **18** as its TFA salt.

In vitro binding affinities (K_i) of all the synthesized 5-cyclopropane-bearing pyridyldiazabicyclo[3.3.0]octanes (**9**, **10**, **13**, **15**, and **18**) were determined using [^{3}H] epibatidine binding competition assays at seven rat nAChR subtypes.[28] As illustrated in Table 1, most of these compounds demonstrated relatively high binding affinities for both $\alpha4\beta2$- (K_i ranging from 0.4 to 60 nM) and $\alpha4\beta2$*-nAChRs (K_i ranging from 1.2 to 120 nM) with poor binding affinities for $\alpha3\beta4$-nAChRs (K_i > 2000 nM). This profile suggests a reduced risk of undesirable

dx.doi.org/10.1021/ml500129k | *ACS Med. Chem. Lett.* 2014, 5, 1196−1201

Table 1. Binding Affinities of 11 Ligands at Seven nAChR Subtypes Defined by Competition for [^{3}H]Epibatidine Binding



	K_i (nM)[a]							
compd	$\alpha2\beta2$	$\alpha2\beta4$	$\alpha3\beta2$	$\alpha3\beta4$	$\alpha4\beta2$	$\alpha4\beta2$*[b]	$\alpha4\beta4$	selectivity ($\alpha3\beta4/\alpha4\beta2$)
1[f]				10^4	0.40	0.90		24000
2[g]				$>10^4$	0.10	0.30		>100000
3[h]				3200	0.20	0.90		16000
4	0.3	46	2.7	200	0.50	1.5	27	400
9	0.30 ± 0.10	380	26 ± 7.0	$>10^4$	4.1 ± 2.0	1.2 ± 0.20	170	>2400
10	25 ± 3.0	$>10^4$	$>10^4$	2500	58 ± 18	120	1400	40
13	0.60 ± 0.10	260	19 ± 5.0	7900	3.1 ± 1.0	2.4 ± 0.40	110	2500
15	0.40	65	10	2500	1.6	3.6	37	1600
18	0.20	390	6.8	$>10^4$	0.40	1.9	160	>25000
nicotine[c]	5.5	70	29	260	4.9	9.8	23	53
varenicline[e]				86	0.40		110	210

[a]See Supporting Information. [b]$\alpha4\beta2$*, endogenous receptors prepared from rat forebrain. Besides $\alpha4$ and $\beta2$, other unidentified subunits may also be present. [c]K_i values for nicotine were taken from the PDSP Assay Protocol Book (http://pdsp.med.unc.edu/). [d]NA: not active, defined as <50% inhibition of binding in the primary assay at 10 μM. [e]K_i values for varenicline are from the literature.[29] [f]K_i values for **1** are from the literature.[29] [g]K_i values for **2** are from the literature.[24] [h]K_i values for **3** are from the literature.[25]

Table 2. Functional Potencies and Efficacies of Ligands: Agonism and inactivation of Human $\alpha4\beta2$-nAChRs.[a]

	agonism				inactivation		
compd	EC_{50} (nM)	pEC_{50}	HS-$\alpha4\beta2$ efficacy (%)	LS-$\alpha4\beta2$ efficacy (%)	IC_{50} (nM)	pIC_{50}	efficacy (%)
1[b]	5.8		100		4.8		63
2[c]	18		60		5.6		71
9	14	7.9 ± 0.10	76 ± 14	0.40 ± 5.1	11	8.0 ± 0.04	77 ± 1.0
10	>1000	<6.0	ND[d]	ND	$>10^3$	<6.0	ND
13	18	7.8 ± 0.10	100 ± 7.0	1.7 ± 4.0	15	7.8 ± 0.04	73 ± 2.0
15	25	7.6 ± 0.10	110 ± 7.0	−9.4 ± 4.0	20	7.7 ± 0.04	74 ± 2.0
18	20	7.7 ± 0.10	88 ± 4.0	−7.0 ± 4.0	12	7.9 ± 0.10	76 ± 4.0
nicotine	300	6.5 ± 0.10	120 ± 9.0	70 ± 6.0	430	6.4 ± 0.10	92 ± 2.0

[a]See Supporting Information for details. The term "inactivation" is used because compounds may be acting to desensitize receptors or as competitive or noncompetitive antagonists, and further work is needed to make such a distinction. Potencies (EC_{50} or IC_{50} values) and efficacies were measured for actions at a mixture of high-sensitivity (HS) and low-sensitivity (LS) $\alpha4\beta2$-nAChRs. Reported errors are the standard error of the mean (SEM) for all values. [b]Results for compound **1** were obtained from ref 18. [c]Results for compound **2** were obtained from ref 20. [d]ND: Not determined. The efficacy was not determined if the EC_{50} or the IC_{50} value was greater than 1000 nM.

side effects associated with binding to ganglionic $\alpha3\beta4$-nAChRs. These compounds also showed good selectivity for $\beta2$*-nAChRs ($\alpha2\beta2$-, $\alpha3\beta2$-, $\alpha4\beta2$-, and $\alpha4\beta2$*-nAChRs) over $\beta4$*-nAChRs ($\alpha2\beta4$-, $\alpha3\beta4$-, and $\alpha4\beta4$-nAChRs) compared to nicotine. The *N*-methyl-bearing analogue **10** showed decreased binding affinity for $\alpha4\beta2$-nAChRs (K_i = 58 nM) compared to the corresponding unsubstituted compound **9** (K_i = 4.1 nM), resulting in a 60-fold reduction in selectivity for $\alpha4\beta2$- over $\alpha3\beta4$-nAChRs. The binding affinity of ligand **13**, bearing a terminal hydroxyl group, at $\alpha4\beta2$-nAChRs was similar to its fluoro-containing counterpart **15**. However, alcohol **13** has an improved selectivity ratio ($\alpha3\beta4/\alpha4\beta2$) compared to **15**. Of the new analogues made and tested herein, the ethoxy derivative **18** displayed the best binding affinity for $\alpha4\beta2$-nAChRs (K_i = 0.40 nM), and it was found to be inactive at $\alpha3\beta4$-nAChRs (K_i = >10000 nM). Selected ligands were also tested at $\alpha7$- and $\alpha7$*-nAChRs, ($\alpha7$*, endogenous receptors prepared from rat forebrain) and they were found to be devoid of activity at the highest concentration used (10 μM), with the exception of **18** (K_i = 680 nM at $\alpha7$-nAChRs) (data not shown).

Functional activity of all compounds was characterized at human $\alpha4\beta2$-, $\alpha3\beta4$*-, and $\alpha1\beta1\gamma\delta$-nAChRs using SH-EP1-h$\alpha4\beta2$, SH-SY5Y, and TE671/RD cells, respectively, and $^{86}Rb^+$ ion efflux assays. Note that $\alpha4\beta2$-nAChRs actually exist as two isoforms differing in sensitivity to nicotine or acetylcholine: high sensitivity (HS) $(\alpha4)_2(\beta2)_3$-nAChRs and low sensitivity (LS) $(\alpha4)_3(\beta2)_2$-nAChRs. Sazetidine-A is unusual in that it is a fully efficacious agonist at HS $(\alpha4)_2(\beta2)_3$-nAChRs, but it has much weaker efficacy at the LS isoform relative to conventional agonists like ACh and nicotine. This is because sazetidine-A only activates the HS phase of LS receptor function but does not activate the LS phase due to its lack of activity at the $\alpha4/\alpha4$ subunit interface present in the LS isoform.[30] Efficacy of ligands at HS vs LS $\alpha4\beta2$-nAChR can be assayed by reference to proportions of those isoforms expressed in a given preparation of cells being studied as defined by function elicited by sazetidine-A. As seen in Table 2, the analogues tested share sazetidine-A's characteristic discrimination between HS- and LS-$\alpha4\beta2$ nAChR isoforms. Tested compounds had agonist activity at $\alpha4\beta2$-nAChRs with EC_{50} < 30 nM, with the exception of **10**, which showed no activity (Table 2). For the

dx.doi.org/10.1021/ml500129k | ACS Med. Chem. Lett. 2014, 5, 1196−1201

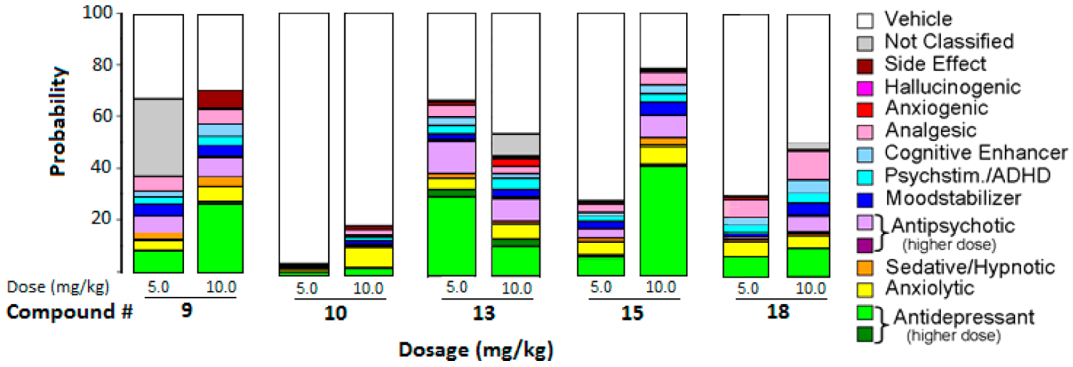


Figure 2. Behavioral SmartCube signatures of all diazabicyclo[3.3.0]octane. Compounds **9**, **13**, **15**, and **18** produced a signature of activity suggesting a potential antidepressant-like effect. The drug was injected ip, 15 min before testing.

ligands evaluated, there was neither agonist nor antagonist activity at ganglionic $\alpha3\beta4$*- or muscle-type $\alpha1\beta1\gamma\delta$-nAChRs or the potency was too low to characterize without testing at concentrations above 10 μM. The methoxy analogue **9** showed similar EC_{50} and IC_{50} values (14 and 11 nM) to those for the azetidine-containing ligand **2** (EC_{50} = 18 nM and IC_{50} = 5.6 nM, Table 2). Interestingly, the hydroxyl (**13**) and fluoro (**15**) analogues showed the highest efficacies at 100% and 110%, respectively, for stimulation of HS $(\alpha4)_2(\beta2)_3$-nAChRs.

Compounds **13** and **15**, however, had functional inactivation efficacies similar to those of other compounds tested in this study (Table 2). The ethoxy analogue **18**, which had the best binding affinity to $\alpha4\beta2$-nAChRs (K_i = 0.40 nM) among the compounds tested here, also showed excellent activity at $\alpha4\beta2$-nAChRs in functional agonism and inactivation assays (EC_{50} = 20 nM and IC_{50} = 12 nM). Of note, none of the tested ligands appear to have any significant intrinsic activity at LS $(\alpha4)_3(\beta2)_2$-nAChRs but have apparent efficacies ranging from 76% to 110% at HS $(\alpha4)_2(\beta2)_3$-nAChRs.

Preliminary *in vivo* evaluation of the nicotinic ligands for behavioral effects was carried out using SmartCube, an automated system that analyzes the behaviors of compound-treated mice captured on digital video with the aid of computer algorithms.[31] The behavioral signature of a test compound is compared with a database of behavioral signatures obtained from a large set of diverse reference compounds. Thus, we are able to make predictions as to the possible neuropharmacological activity of a test compound relative to major classes of compounds such as anxiolytics, antipsychotics, and antidepressants. All compounds were administered at doses of 5 or 10 mg/kg. Compounds **9**, **13**, **15**, and **18** were found to produce behavioral signatures that have features of antidepressants, anxiolytics, and antipsychotics with little or no side effect profiles (Figure 2). Consistent with its lower potency in the radioligand binding and functional studies, compound **10** is relatively inactive in SmartCube and does not show the behavioral signature of compounds **9**, **13**, **15**, and **18**.

Next, to further establish the ability of these compounds to penetrate the blood–brain barrier, compound **15** was selected for mouse *in vivo* pharmacokinetic (PK) studies. The plasma and brain concentrations of compound **15** in male CD-1 mice after a single intraperitoneal (IP) injection at a dose of 10 mg/kg were measured. The concentration of **15** reached a value of 197 and 256 ng/g at 30 and 120 min in the brain and 828 and 146 ng/mL at 30 and 120 min in plasma (Table 3). The brain to plasma ratio of compound **15** was found to be 0.24 at 30 min and 1.75 at 120 min, indicating acceptable CNS penetration.

Table 3. Pharmacokinetic Parameters of 15 in Mouse Plasma and Brain Following IP (10 mg/kg) Administration

dose of **15**	plasma		brain	
(mg/kg)	time (min)	concentration (ng/mL)	time (min)	concentration (ng/g)
10	30	828	30	197
10	120	146	120	256

Furthermore, the binding of **15** to protein in male CD-1 mouse plasma and brain tissue was determined using equilibrium dialysis. Binding of **15** was evaluated at a final concentration of 1 μM. The percentage of binding of compound **15** in mouse plasma and brain tissue was 27% and 73%, respectively, after a 6 h incubation period. These results thus indicate that sufficient amounts of the unbound drug are available in the brain to exert a pharmacological action

On the basis of the SmartCube data and brain concentration levels of compound **15**, we decided to further probe the possible antidepressant action of compound **15**. We thus examined the effects of compound **15** in the classical mouse forced-swim test,[32] an assay in which mice are placed into a beaker of water, and the time spent passively floating in the water (immobility) is recorded (Figure 3). Most traditional

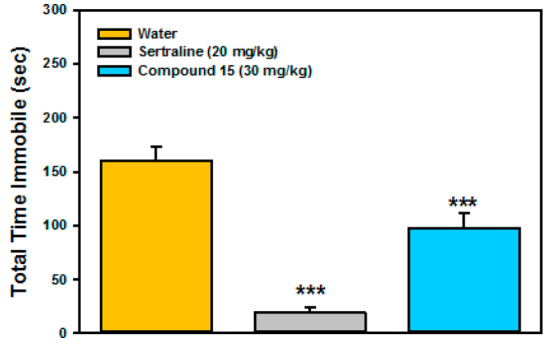


Figure 3. Mouse forced-swim data for compound **15**.

antidepressants decrease the amount of time the mouse spends immobile. Mice were administered compound **15** (30 mg/kg of the free base) 15 min prior to testing or the selective serotonin reuptake inhibitor sertraline, as a positive control (20 mg/kg). Compound **15** exhibited an antidepressant-like effect when administered IP with a significant reduction in immobility at a single dose as displayed in the bar graph in Figure 3.

dx.doi.org/10.1021/ml500129k | *ACS Med. Chem. Lett.* 2014, 5, 1196–1201

In summary, we describe the synthesis, pharmacological evaluation, and behavioral characterization of some 5-cyclopropane-bearing pyridyldiazabicyclo[3.3.0]octanes as nAChR ligands. All tested ligands with the exception of compound **10** showed excellent binding affinities for both $\alpha4\beta2$- and $\alpha4\beta2$*-nAChRs from the rat (K_i values ranging from 0.4 to 4.1 nM) and poor affinity for rat $\alpha3\beta4$-nAChRs (K_i >2400 nM). In functional studies, these ligands acted as potent agonists at human $\alpha4\beta2$-nAChRs and were inactive at both ganglionic $\alpha3\beta4$*- or muscle-type $\alpha1\beta1\gamma\delta$-nAChRs. In this series, the fluoro-analogue **15** was found to possess subnanomolar binding affinity, a 1550-fold selectivity for $\alpha4\beta2$- versus $\alpha3\beta4$-nAChRs, as well as good agonist efficacy in the functional studies. Compound **15** achieves a brain concentration of ∼0.70 μM at 30 min, and this is over 400-times more than its binding affinity at the $\alpha4\beta2$-nAChR. Compound **15** was found to display antidepressant-like properties in the mouse forced-swim test. The above data support our hypothesis that the incorporation of the cyclopropane side chain at the 5-position of the pyridyldiazabicyclo[3.3.0]octanes would improve subtype selectivity for $\alpha4\beta2$- over $\alpha3\beta4$-nAChRs when compared to the parent compound **4**, thus implying that the nature of the substitution at the position 5 plays a vital role in attenuating possible side effects associated with ganglionic $\alpha3\beta4$*-nAChRs. These potent and selective nAChR ligands produced antidepressant/anxiolytic-like properties in the SmartCube test, and thus, they may serve as chemical probes in further exploring various aspects of nicotinic receptor function related to mood disorders.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures and analytical data. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +1-312-996-7577. Fax: +1-312-996-7107. E-mail: kozikowa@uic.edu.

Funding

This research was supported by Award Number U19MH085193 from the National Institute of Mental Health.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the PDSP program for performing the binding affinity assays. We thank Drs. Joel Bergman and Li-fang Yu for their assistance in proofreading the manuscript. We thank Dr. Afshin Ghavami of PsychoGenics Inc. for his helpful discussions.

■ ABBREVIATIONS

nAChR, nicotinic acetylcholine receptor; ADHD, attention deficit hyperactivity disorder; TFA, trifluoroacetic acid; NIMH-PDSP, National Institute of Mental Health Psychoactive Drug Screening Program; HS, high sensitivity; LS, low sensitivity; IP, intraperitoneal

■ REFERENCES

(1) Gotti, C.; Clementi, F.; Fornari, A.; Gaimarri, A.; Guiducci, S.; Manfredi, I.; Moretti, M.; Pedrazzi, P.; Pucci, L.; Zoli, M. Structural and functional diversity of native brain neuronal nicotinic receptors. *Biochem. Pharmacol.* **2009**, *78*, 703−711.

(2) Gotti, C.; Riganti, L.; Vailanti, S.; Clementi, F. Brain neuronal nicotinic receptors as new targets for drug discovery. *Curr. Pharm. Des.* **2006**, *12*, 407−428.

(3) Romanelli, M. N.; Gratteri, P.; Guandalini, L.; Martini, E.; Bonaccini, C.; Gualtieri, F. Central nicotinic receptors: Structure, function, ligands, and therapeutic potential. *ChemMedChem* **2007**, *2*, 746−767.

(4) Lemoine, D.; Jiang, R.; Taly, A.; Chataigneau, T.; Specht, A.; Grutter, T. Ligand-gated ion channels: New insights into neurological disorders and ligand recognition. *Chem. Rev.* **2012**, *112*, 6285−6318.

(5) Lee, C.-H.; Zhu, C.; Malysz, J.; Campbell, T.; Shaughnessy, T.; Honore, P.; Polakowski, J.; Gopalakrishnan, M. Alpha 4 beta 2 neuronal nicotinic receptor positive allosteric modulation: An approach for improving the therapeutic index of alpha 4 beta 2 nAChR agonists in pain. *Biochem. Pharmacol.* **2011**, *82*, 959−966.

(6) Meyer, M. D. Neuronal nicotinic acetylcholine receptors as a target for the treatment of neuropathic pain. *Drug Dev. Res.* **2006**, *67*, 355−359.

(7) Arneric, S. P.; Holladay, M.; Williams, M. Neuronal nicotinic receptors: A perspective on two decades of drug discovery research. *Biochem. Pharmacol.* **2007**, *74*, 1092−1101.

(8) Philip, N. S.; Carpenter, L. L.; Tyrka, A. R.; Price, L. H. Nicotinic acetylcholine receptors and depression: a review of the preclinical and clinical literature. *Psychopharmacology* **2010**, *212*, 1−12.

(9) Wilens, T. E.; Decker, M. W. Neuronal nicotinic receptor agonists for the treatment of attentioon-deficit/hyperactivity disorder: Focus on cognition. *Biochem. Pharmacol.* **2007**, *74*, 1212−1223.

(10) Taly, A.; Corringer, P.-J.; Guedin, D.; Lestage, P.; Changeux, J.-P. Nicotinic receptors: allosteric transitions and therapeutic targets in the nervous system. *Nat. Rev. Drug Discovery* **2009**, *8*, 733−750.

(11) Coe, J. W.; Brooks, P. R.; Vetelino, M. G.; Wirtz, M. C.; Arnold, E. P.; Huang, J. H.; Sands, S. B.; Davis, T. I.; Lebel, L. A.; Fox, C. B.; Shrikhande, A.; Heym, J. H.; Schaeffer, E.; Rollema, H.; Lu, Y.; Mansbach, R. S.; Chambers, L. K.; Rovetti, C. C.; Schulz, D. W.; Tingley, F. D.; O'Neill, B. T. Varenicline: An alpha 4 beta 2 nicotinic receptor partial agonist for smoking cessation. *J. Med. Chem.* **2005**, *48*, 3474−3477.

(12) Mihalak, K. B.; Carroll, F. I.; Luetje, C. W. Varenicline is a partial agonist at alpha 4 beta 2 and a full agonist at alpha 7 neuronal nicotinic receptors. *Mol. Pharmacol.* **2006**, *70*, 801−805.

(13) Rollema, H.; Guanowsky, V.; Mineur, Y. S.; Shrikhande, A.; Coe, J. W.; Seymour, P. A.; Picciotto, M. R. Varenicline has antidepressant-like activity in the forced swim test and augments sertraline's effect. *Eur. J. Pharmacol.* **2009**, *605*, 114−116.

(14) Rollema, H.; Hajos, M.; Seymour, P. A.; Kozak, R.; Majchrzak, M. J.; Guanowsky, V.; Horner, W. E.; Chapin, D. S.; Hoffmann, W. E.; Johnson, D. E.; McLean, S.; Freeman, J.; Williams, K. E. Preclinical pharmacology of the alpha 4 beta 2 nAChR partial agonist varenicline related to effects on reward, mood and cognition. *Biochem. Pharmacol.* **2009**, *78*, 813−824.

(15) Lummis, S. C. R.; Thompson, A. J.; Bencherif, M.; Lester, H. A. Varenicline is a potent agonist of the human 5-hydroxytryptamine(3) receptor. *J. Pharmacol. Exp. Ther.* **2011**, *339*, 125−131.

(16) Jorenby, D. E.; Hays, J. T.; Rigotti, N. A.; Azoulay, S.; Watsky, E. J.; Williams, K. E.; Billing, C. B.; Gong, J.; Reeves, K. R. Efficacy of varenicline, an alpha 4 beta 2 nicotinic acetylcholine receptor partial agonist, vs placebo or sustained-release bupropion for smoking cessation: A randomized controlled trial. *JAMA, J. Am. Med. Assoc.* **2006**, *296*, 56−63.

(17) Stokes, C.; Papke, R. L. Use of an alpha 3 beta 4 nicotinic acetylcholine receptor subunit concatamer to characterize ganglionic receptor subtypes with specific subunit composition reveals species-specific pharmacologic properties. *Neuropharmacology* **2012**, *63*, 538−546.

(18) Leung, L. K.; Patafio, F. M.; Rosser, W. W. Gastrointestinal adverse effects of varenicline at maintenance dose: a meta-analysis. *BMC Clin. Pharmacol.* **2011**, *11*, 15.

(19) Ledford, H. Depression drug disappoints. *Nature* **2011**, *479*, 278−278.
(20) Xiao, Y.; Fan, H.; Musachio, J. L.; Wei, Z.-L.; Chellappan, S. K.; Kozikowski, A. P.; Kellar, K. J. Sazetidine-A, a novel ligand that desensitizes alpha 4 beta 2 nicotinic acetylcholine receptors without activating them. *Mol. Pharmacol.* **2006**, *70*, 1454−1460.
(21) Cucchiaro, G.; Xiao, Y.; Gonzalez-Sulser, A.; Kellar, K. J. Analgesic effects of Sazetidine-A, a new nicotinic cholinergic drug. *Anesthesiology* **2008**, *109*, 512−519.
(22) Kozikowski, A. P.; Eaton, J. B.; Bajjuri, K. M.; Chellappan, S. K.; Chen, Y.; Karadi, S.; He, R.; Caldarone, B.; Manzano, M.; Yuen, P.-W; Lukas, R. J. Chemistry and pharmacology of nicotinic ligands based on 6-[5-(azetidin-2-ylmethoxy)pyridin-3-yl]hex-5-yn-1-ol (AMOP-H-OH) for possible use in depression. *ChemMedChem* **2009**, *4*, 1279−1291.
(23) Turner, J. R.; Castellano, L. M.; Blendy, J. A. Nicotinic partial agonists varenicline and sazetidine-A have differential effects on affective behavior. *J. Pharmacol. Exp. Ther.* **2010**, *334*, 665−672.
(24) Zhang, H.; Tueckmantel, W.; Eaton, J. B.; Yuen, P.-W.; Yu, L.-F.; Bajjuri, K. M.; Fedolak, A.; Wang, D.; Ghavami, A.; Caldarone, B.; Paterson, N. E.; Lowe, D. A.; Brunner, D.; Lukas, R. J.; Kozikowski, A. P. Chemistry and behavioral studies identify chiral cyclopropanes as selective alpha 4 beta 2-nicotinic acetylcholine receptor partial agonists exhibiting an antidepressant profile. *J. Med. Chem.* **2012**, *55*, 717−724.
(25) Zhang, H.-K.; Eaton, J. B.; Yu, L.-F.; Nys, M.; Mazzolari, A.; van Elk, R.; Smit, A. B.; Alexandrov, V.; Hanania, T.; Sabath, E.; Fedolak, A.; Brunner, D.; Lukas, R. J.; Vistoli, G.; Ulens, C.; Kozikowski, A. P. Insights into the structural determinants required for high-affinity binding of chiral cyclopropane-containing ligands to alpha 4 beta 2-nicotinic acetylcholine receptors: An integrated approach to behaviorally active nicotinic ligands. *J. Med. Chem.* **2012**, *55*, 8028−8037.
(26) Bunnelle, W. H.; Tietje, K. R.; Frost, J. M.; Peters, D.; Ji, J.; Li, T.; Scanio, M. J. C.; Shi, L.; Anderson, D. J.; Dyhring, T.; Gronlien, J. H.; Ween, H.; Thorin-Hagene, K.; Meyer, M. D. Octahydropyrrolo-[3,4-c]pyrrole: A diamine scaffold for construction of either alpha 4 beta 2 or alpha 7-selective nicotinic acetylcholine receptor (nAChR) ligands. Substitutions that switch subtype selectivity. *J. Med. Chem.* **2009**, *52*, 4126−4141.
(27) Scanio, M. J. C.; Shi, L.; Bunnelle, W. H.; Anderson, D. J.; Helfrich, R. J.; Thorin-Hagene, K. K.; Van Handel, C. E.; Marsh, K. C.; Lee, C.-H.; Gopalakrishnant, M. Structure-activity studies of diazabicyclo 3.3.0 octane-substituted pyrazines and pyridines as potent alpha 4 beta 2 nicotinic acetylcholine receptor ligands. *J. Med. Chem.* **2011**, *54*, 7678−7692.
(28) K_i determinations were generously provided by the National Institute of Mental Health's Psychoactive Drug Screening Program, Contract # HHSN-271-2008-00025-C (NIMH PDSP). The NIMH PDSP is Directed by Bryan L. Roth MD, PhD., at the University of North Carolina at Chapel Hill and Project Officer Jamie Driscol at NIMH, Bethesda MD, USA.
(29) Rollema, H.; Shrikhande, A.; Ward, K. M.; Tingley, F. D., III; Coe, J. W.; O'Neill, B. T.; Tseng, E.; Wang, E. Q.; Mather, R. J.; Hurst, R. S.; Williams, K. E.; de Vries, M.; Cremers, T.; Bertrand, S.; Bertrand, D. Pre-clinical properties of the alpha 4 beta 2 nicotinic acetylcholine receptor partial agonists varenicline, cytisine and dianicline translate to clinical efficacy for nicotine dependence. *Br. J. Pharmacol.* **2010**, *160*, 334−345.
(30) Eaton, J. B.; Lucero, L. M.; Stratton, H.; Chang, Y.; Cooper, J. F.; Lindstrom, J. M.; Lukas, R. J.; Whiteaker, P. The unique alpha 4(+)/(−) a4 agonist binding site in (alpha 4)(3)(beta 2)(2) subtype nicotinic acetylcholine receptors permits differential agonist desensitization pharmacology versus the (alpha 4)(2)(beta 2)3 subtypes. *J. Pharmacol. Exp. Ther.* **2014**, *348*, 46−58.
(31) Roberds, S. L.; Filippov, I.; Alexandrov, V.; Hanania, T.; Brunner, D. Rapid, computer vision-enabled murine screening system identifies neuropharmacological potential of two new mechanisms. *Front. Neurosci.* **2011**, *5*, 103.
(32) Porsolt, R. D.; Bertin, A.; Jalfre, M. Behavioral despair in mice: Primary screening-test for antidepressants. *Arch. Int. Pharmacodyn. Ther.* **1977**, *229*, 327−336.