Recent Developments In Novel Antidepressants Targeting α4β2-Nicotinic Acetylcholine Receptors

Li Fang Yu
Han Kun Zhang
Barbara J. Caldarone
J. Brek Eaton
Ronald J. Lukas

Barrow Neurological Institute, ronald.lukas@dignityhealth.org

See next page for additional authors

Follow this and additional works at: https://scholar.barrowneuro.org/neurobiology

Recommended Citation
Yu, Li Fang; Zhang, Han Kun; Caldarone, Barbara J.; Eaton, J. Brek; Lukas, Ronald J.; and Kozikowski, Alan P., "Recent Developments In Novel Antidepressants Targeting α4β2-Nicotinic Acetylcholine Receptors" (2014). Neurobiology. 266.
https://scholar.barrowneuro.org/neurobiology/266

This Article is brought to you for free and open access by Barrow - St. Joseph's Scholarly Commons. It has been accepted for inclusion in Neurobiology by an authorized administrator of Barrow - St. Joseph's Scholarly Commons. For more information, please contact molly.harrington@dignityhealth.org, andrew.wachtel@dignityhealth.org.
Recent Developments in Novel Antidepressants Targeting α4β2-Nicotinic Acetylcholine Receptors

Miniperspective

Li-Fang Yu,†,‡ Han-Kun Zhang,†,∥ Barbara J. Caldarone,‡ J. Brek Eaton,§ Ronald J. Lukas,§ and Alan P. Kozikowski*,†

†Department of Medicinal Chemistry and Pharmacognosy, University of Illinois at Chicago, 833 South Wood Street, Chicago, Illinois 60612, 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
§Division of Neurobiology, Barrow Neurological Institute, 350 West Thomas Road, Phoenix, Arizona 85013, United States
∥Institute of Drug Design and Development, Shanghai Engineering Research Center of Molecular Therapeutics and New Drug Development, East China Normal University, 3663 North Zhongshan Road, Shanghai 200062, China
¶Institute of Biomedical Sciences and School of Life Sciences, East China Normal University, 500 Dongchuan Road, Shanghai 200241, China

ABSTRACT: Nicotinic acetylcholine receptors (nAChRs) have been investigated for developing drugs that can potentially treat various central nervous system disorders. Considerable evidence supports the hypothesis that modulation of the cholinergic system through activation and/or desensitization/inactivation of nAChR holds promise for the development of new antidepressants. The introductory portion of this Miniperspective discusses the basic pharmacology that underpins the involvement of α4β2-nAChRs in depression, along with the structural features that are essential to ligand recognition by the α4β2-nAChRs. The remainder of this Miniperspective analyzes reported nicotinic ligands in terms of drug design considerations and their potency and selectivity, with a particular focus on compounds exhibiting antidepressant-like effects in preclinical or clinical studies. This Miniperspective aims to provide an in-depth analysis of the potential for using nicotinic ligands in the treatment of depression, which may hold some promise in addressing an unmet clinical need by providing relief from depressive symptoms in refractory patients.

INTRODUCTION

Depression is a common and frequently severe psychological condition with a distinct change of mood, characterized by sadness, loss of interest and pleasure, feelings of guilt or low self-worth, disturbed sleep or appetite, and feelings of tiredness and poor concentration, affecting approximately 120 million people worldwide.1 Numerous therapeutic agents exist for the treatment of depression that target monoamine transporters regulating the uptake of the neurotransmitters dopamine, serotonin, and norepinephrine.2 However, a considerable proportion of patients respond poorly to these drugs,3 as demonstrated by the NIMH-funded sequenced treatment alternatives to relieve depression (STAR*D) study conducted between 2001 and 2006, which highlighted the inadequacy of current medications for major depressive disorder (MDD).4 Therefore, there is still an urgent need for potent pharmacotherapies associated with novel biological mechanisms of action. In this Minipersepctive, we review the association between depression and nicotinic acetylcholine receptors (nAChRs), especially the α4β2-nAChR subtype, from the perspective of clinical and preclinical findings. We highlight the most recently developed α4β2-nAChR agonists and antagonists that exhibit antidepressant-like effects in vivo.

The cholinergic hypothesis of depression proposes that hyperactivity of the cholinergic system over that of the adrenergic system leads to depression (Figure 1).5 Several lines of evidence from rodent and human studies support this hypothesis. Flinders sensitive rats, a line selectively bred for increased cholinergic sensitivity, were found to exhibit several depression-like behaviors,6,7 and increased acetylcholine (ACh) signaling in the hippocampus was found to promote behaviors in mice related to anxiety and depression.8 In humans, physostigmine, which potentiates cholinergic transmission by inhibiting acetylcholinesterase (AChE), the enzyme that breaks down ACh, produces depressive-like symptoms in individuals with and without a history of depression.5 Administration of the
nonselective nicotinic antagonist mecamylamine (1) (Scheme 1),9−11 the partial agonist varenicline (2),12 or the muscarinic antagonist scopolamine (3)13,14 demonstrated putative antidepressant-like effects, especially in treatment-resistant patients receiving their regular psychotropic medications such as the selective serotonin reuptake inhibitor (SSRI) citalopram (4).9 Magnetic resonance imaging studies have shown that the levels of choline, the rate-limiting precursor to endogenous ACh, were elevated in the brains of patients with depression as well as in the frontal cortex of adolescents with depression.15,16 Additionally, a number of key antidepressants such as SSRIs (fluoxetine, sertraline (5), paroxetine, and citalopram 4), the norepinephrine reuptake inhibitor reboxetine (6), the norepinephrine dopamine reuptake inhibitor bupropion (7), and tricyclics (amitriptyline (8), imipramine (9), and nortriptyline)17 have all been shown to possess antagonistic activities at nAChRs,18−20 although, in most cases, drug concentrations achieved in the human brain would not be adequate to affect nAChR functions.21 Nicotine (10) itself, and some nicotinic agonists or antagonists, can potentiate the antidepressant-like effects of the SSRIs and SNRIs in rodent models,22,23 likely due to the common end point of reduced function due to receptor desensitization by agonists or antagonism. The development of nAChR ligands to attenuate cholinergic activity to treat depression could conceivably help to treat depressive symptoms in refractory patients.

Figure 1. Role of the cholinergic system in depression. The cholinergic hypothesis of depression postulates a hyperactivity of the cholinergic system over that of the adrenergic system in the brain. Choline (the rate-limiting precursor to endogenous ACh) crosses the blood−brain barrier to enter the brain and is actively transported into the cholinergic presynaptic terminals by an active uptake mechanism. The neurotransmitter ACh is synthesized from choline and acetyl coenzyme A, catalyzed by the enzyme choline acetyl transferase. ACh is sequestered into secretory vesicles by vesicular ACh transporters. Once released from the presynaptic terminals, ACh can interact with a variety of presynaptic and postsynaptic receptors. Two classes of the cholinergic ACh receptors are muscarinic (G protein-coupled) and nicotinic (ionotropic). Once activated, nAChRs form transient open cationic channels that allow the ions Na+, K+, and Ca2+ to flow across the plasma membrane and induce cellular responses. Prolonged exposure to ACh or nicotinic agonist causes a gradual decrease in the rate of this ionic response, leading to a high affinity, longer-lasting functionally inactive state, referred to as desensitization. ACh has its signal terminated primarily by the enzyme AChE, unlike many other monoaminergic neurotransmitters where reuptake mechanisms predominate.

NICOTINIC ACETYLCHOLINE RECEPTORS AND DEPRESSION

The two major types of cholinergic receptors are muscarinic ACh receptors (mAChRs) and nAChRs, both of which are widely distributed in the central and peripheral nervous systems.24 G protein-coupled mAChRs are believed to be involved in mood regulation and AChE-induced depressive behavior.5,13,14,25 Neuronal nAChRs belong to the ligand-gated ion channel superfamily of neurotransmitter receptors. Varying combinations of nAChR subunits (α1−α10, β1−β4, γ, δ, and ε; α2−α7 and β2−β4 are expressed in the brain) assemble into pentameric ion channels, allowing for diverse pharmacological properties.26 Each nAChR subunit consists of a large amino-terminal extracellular domain (ECD), a transmembrane domain comprising four α-helices (M1−M4), and a variable cytoplasmic domain between M3 and M4. ACh binding sites are thought to form between the subunit interfaces of the ECD containing the face of an α-type subunit and the face of an adjacent subunit. When acutely activated by endogenous ACh or exogenous nicotinic ligands, nAChRs form transient open cationic channels that allow the ions Na+, K+, and Ca2+ to flow across the plasma membrane and induce cellular responses.27 Prolonged exposure to ACh or nicotinic agonists causes a gradual decrease in the rate of this ionic response, leading to a longer-lasting functionally inactive state through a process referred to as desensitization. nAChRs have been found to contribute to mood...
control by regulating behavioral reinforcement in the mesolimbic dopamine system, corticotropin releasing factor and function in the hypothalamic–pituitary–adrenal (HPA) axis, circadian rhythms in the suprachiasmatic nucleus, and cytoplasticity in the hippocampus. Given nAChR subtype diversity and their involvement in the modulation of various key neurotransmitter
systems, including dopamine, serotonin, norepinephrine, glutamate, and \(\gamma\)-aminobutyric acid (GABA), nicotinic ligands have the potential to treat a multitude of neurological and psychiatric disorders, including depression.9,28

The \(\alpha 4/\beta 2\) heteropentameric and \(\alpha 7\) homopentameric subtypes are the two major nAChR subtypes expressed in the brain (Figure 2).29 Both subtypes are implicated in the mediation of the pharmacological and behavioral effects of compound 10 and in nAChR-mediated modulation of monoamine release30,31 and are likely involved in the antidepressant effects of nicotinic ligands. Studies investigating the role of nAChRs in depression have focused primarily on the \(\alpha 4/\beta 2\) (asterisk indicates possible assembly with other subunits) and \(\alpha 7\)-nAChR subtypes. \(\alpha 4/\beta 2\)-nAChRs are widely distributed in the neuroanatomic regions implicated in depression, including the thalamus, basal ganglia, striatum, hypothalamus, amygdala, ventral tegmental area (VTA), locus coeruleus, and dorsal raphe nucleus,9 and \(\alpha 7\)-nAChRs are highly expressed in the hypothalamus, hippocampus, and cortex.32,33 \(\alpha 4/\beta 2\)-nAChRs are thought to regulate the release of monoamine neurotransmitters through actions in these areas.34,35 \(\beta 2\)-knockout mice showed decreased immobility in the forced swim test (FST) compared to that of wild-type mice, indicating that the absence of \(\beta 2\)-nAChRs-mediated signaling could manifest in an antidepressant-like phenotype in vivo.36 The antidepressant-like effect of the nAChR antagonist compound 1 was diminished when the \(\beta 2\) or \(\alpha 7\)-subunits were knocked out.37 Similarly, the antidepressant-like effects of the nAChR agonist sazetidine-A (11)38 and the tricyclic antidepressant compound 836 were absent in mice lacking the \(\beta 2\)-subunit. Additionally, the efficacies of compounds 4 and 6 in the mouse FST were enhanced by agonists at either \(\alpha 4/\beta 2\)- or \(\alpha 7\)-nAChRs.33 These findings suggest the involvement of \(\beta 2\)- and \(\alpha 7\)-receptor subtypes in mediating the antidepressant-like effects of nicotinic ligands.

Clinical studies provide additional evidence for a relationship between \(\alpha 4/\beta 2\)-nAChRs and depression. Single photon emission computed tomography (SPECT) using the \(\alpha 4/\beta 2\) nAChR specific radioligand \[^{123}\text{I}\]5-I-A85380 \[^{125}\text{I}\]12 revealed that the \(\beta 2\)-nAChR availability across all brain regions in depressed patients was lower than that in healthy subjects.39 Additionally, positron emission tomography using 2-[\(^{18}\text{F}\)]fluoro-3-(2-[\(^{5}\text{F}\)]-azetidinylmethoxy)-pyridine showed reduced levels of ligand binding to \(\alpha 4/\beta 2\)-nAChR in Parkinson’s patients with depressive symptoms.40 It was recently reported that the clinical action of compound 6 may be at least partially due to its inhibitory action on \(\alpha 4/\beta 2\)-nAChR.41

Designing a nicotinic ligand to provide maximal therapeutic efficacy and minimal side effects depends on a ligand’s ability to specifically target the desired combination of nAChR subtypes. Observations that nAChR \(\alpha 6\) subunits are not widely distributed in the brain but are most prevalent in midbrain dopaminergic regions in the mammalian CNS suggest their potential involvement in mood control. As such, targeting \(\alpha 6\)-nAChRs may be indicated.11,42–44 In the basal ganglia, the VTA and substantia nigra, in particular, \(\alpha 6\)- and possibly nAChR \(\beta 3\) subunits, are included in \(\alpha 4/\beta 2\)-nAChRs that appear to have high affinity for nicotinic agonists.34 \(\alpha 3/\beta 4\)-nAChR subtypes are expressed at relatively low levels in the brain15 except for the interpeduncular nucleus, fasciculus retroflexus, and median habenula.46 However, activation or blockade of \(\alpha 3/\beta 4\)-nAChRs, which are also expressed in the peripheral nervous system, may result in side effects in vivo, including dysregulation of the autonomic nervous system.37,48 Selective and potent partial agonists of \(\alpha 4/\beta 2\)-nAChRs, especially those with low affinity for \(\alpha 3/\beta 4\)-nAChRs, are considered to have higher efficacy and likely fewer side effects in rodent behavioral models, although the involvement of \(\alpha 3/\beta 4\)-nAChRs in mood control cannot be completely ruled out.49–51 We also point out that because of their roles as “accessory” subunits that are incapable of forming functional receptors alone or even in combination with nAChR \(\alpha\) or \(\beta\) subunits (except, perhaps, as \(\alpha 7/\alpha 5\)-nAChRs), we have not delved deeply into the potential roles played by the \(\alpha 5\) subunits. However, \(\alpha 5\) subunits can integrate into \(\alpha 3/\beta 4\)- and \(\alpha 4/\beta 2\)-nAChRs and perhaps into \(\alpha 6\)-nAChRs to further extend the diversity in receptor subtypes and isoforms, which may affect pharmacological profiles.52,53 Continuing studies will extend our knowledge of the role of \(\alpha 5\) subunits in nAChRs.

The essential pharmacophore presented by nicotinic ligands consists of a cationic center (e.g., a quaternized or protonated nitrogen) and a hydrogen-bond acceptor (e.g., the pyridine nitrogen atom in the case of compound 10). The cationic nitrogen binds to a tryptophan residue of the principal \(\alpha\)-subunit,

Figure 2. Selected nAChR subtypes. The high sensitivity (HS) \(\alpha 4/\beta 2\)-nAChR has a presumed \(\alpha 4/\beta 2\) subunit ratio of 2:3 and exhibits comparatively high sensitivity to nicotinic agonists, whereas the low sensitivity (LS) \(\alpha 4/\beta 2\)-nAChR, at which nicotinic agonists have lower observed potency, is composed presumably of \(\alpha 4\) and \(\beta 2\) subunits in a 3:2 ratio.

Figure 3. Top view of X-ray crystal structures of Ac, Ls-, and Ct-AChBPs. The figure was generated using PDB files 2BR7, 119B, and 4BSD by PyMOL.
forming a cation−π interaction. The hydrogen-bond acceptor has been shown to bind to the complementary β-subunit, likely mediated by a water molecule to the backbone NH of a Leu residue in the α4/β2 receptor. Additionally, various studies support the idea that agonist interactions with the principal α-subunit are important for binding affinity, while interactions with key amino acids present in the complementary β-subunit affect agonist efficacy.

High-resolution crystal structures of integral membrane protein mammalian nAChRs are not yet available. Invertebrate pentameric acetylcholine binding protein (AChBP) subunits share 20–24% sequence identity with that of the homologous ECDs of nAChR subunits. However, the putative binding site and some aromatic residues found in nAChR subunits are reported to be conserved. Therefore, AChBPs have been characterized and used to provide insights into ligand recognition.
sites and other elements of nAChR subunit ECDs and ligand binding site interfaces. The majority of ligand-bound structures have been obtained with AChBP from Aplysia californica (Ac) or Lymnaea stagnalis (Ls) (Figure 3). The Ls-AChBP was postulated to be a more suitable surrogate of α4/β2-nAChR for a series of 1-(pyridin-3-yl)-1,4-diazepane analogues because the Trp 53 in Ls-AChBP subunits is Tyr in Ac-AChBP subunits, which interacts less favorably with the quaternized or protonated nitrogen of nicotinic ligands. Recently, the nonmolluscan acetylcholine binding protein from the marine anemid Capitella teleta (Ct), namely, Ct-AChBP, was identified\textsuperscript{84} and reported to more closely mimic α4/β2-nAChR than does the Ac-AChBP based on comparisons of the ligand binding affinities.\textsuperscript{85} The X-ray crystal structure of Ct-AChBP with lobeline or compound 2 bound along with mutagenic studies highlight the importance of key interactions that are responsible for receptor activation or desensitization and for location of key residues in loops D (W57) based on comparisons of the ligand binding a more closely mimic anxiolytic-like effects at α4/β2-nAChRs.\textsuperscript{65}

Because of the higher homology between Ct-AChBP and the human α4 and β2 subunits (as computed by ClustalX: α4/Ct-AChBP = 64.6% and β2/Ct-AChBP = 62.1%), especially for key residues involved in ligand recognition (Figure 4), a homology model was generated and refined based on a Ct-AChBP for the ligand binding domain of the human α4/β2-nAChR. A ribbon structure for the ECD modeled α4/β2-nAChR shows a 10-stranded β-sandwich capped by an N-terminal α-helix for each subunit (Figure SA), for which the modeled β-sandwich can be nicely superimposed on that of Ct-AChBP (Figure SB). This homology model may provide useful information for designing other selective α4/β2-nAChR ligands.\textsuperscript{83}

### nAChR AGONISTS AND ANTAGONISTS EXHIBITING ANTIDEPRESSANT-LIKE EFFECTS

The diversity of nAChR subtypes provides an opportunity to generate subtype-specific ligands that could treat a variety of conditions, although the high sequence homology across individual subtypes of brain nAChRs poses a substantial challenge for the development of subtype-selective nicotinic drugs. Both academia and industry have contributed to a growing literature considering the rational design of potential antidepressant ligands that more selectively target β2*-nAChR than does compound 10.

Rodent behavioral models have been used to assess antidepressant-like effects of these new chemical entities. The most widely used behavioral assay for antidepressant-like efficacy is the FST, in which a mouse or rat is placed in a beaker of water and the amount of time the animal spends passively floating is measured. Clinically therapeutic antidepressants typically reduce the time an animal will spend immobile. Similarly, the tail suspension test (TST) measures immobility time when the rodent is suspended by its tail. This test is relatively short in duration, and in the case where an antidepressant agent is given, the animal will struggle for longer periods of time compared to vehicle treated animals.\textsuperscript{64} The novelty-suppressed feeding (NSF) test is a behavioral paradigm originally utilized to measure anxiolytic-like effects of drugs, but more recently the NSF assay has been proposed as a behavioral platform sensitive to the chronic but not acute administration of antidepressants. In NSF, food-deprived mice experience a conflict between feeding and the fear of exploring the novel environment of a brightly lit open area or an unfamiliar cage containing food. Chronic treatment with antidepressants reduces latency to eat in the novel environment. Additionally, an alternative version of the NSF test is a behavioral paradigm to gauge the antidepressant efficacy of compounds.\textsuperscript{65}

#### nAChR ANTAGONISTS

(1R,2S,25,4S)-N,2,3,3-Tetramethylbicyclo[2.2.1]heptan-2-one, 13.

\[
\text{IC}_{50, \text{α4/β2}} = 0.5-3.2 \mu M, \text{IC}_{50, \text{β2/α4}} = 0.2-0.6 \mu M, \text{IC}_{50, \text{α7/β2}} = 1.2-4.6 \mu M, \text{and IC}_{50, \text{β1/β2}} = 0.6-2.2 \mu M.}
\]

The nicotinic ligand that has received the most attention as a potential antidepressant is compound 1, a racemic noncompetitive and nonselective antagonist of nAChRs (IC\textsubscript{50,α4/β4} = 91–610 nM, IC\textsubscript{50,β2/α4} = 0.6–2.5 μM, and IC\textsubscript{50,α7/β2} = 1.6–6.9 μM). Originally developed as an antihypertensive agent, anecdotal reports of mood modulation and a hypothesis that traditional antidepressants might be acting in part through noncompetitive antagonism of nAChRs\textsuperscript{19} led to a preliminary controlled study that demonstrated therapeutic effects of compound 1 for mood disorders, including MDD, that were corroborated with Tourette’s disorder.\textsuperscript{10,50} However, the subgroup sizes were very small, and the comorbidity with Tourette’s disorder precluded any conclusions from being drawn about the antidepressant efficacy of compound 1 monotherapy in patients who do not have Tourette’s disorder.

In studies using receptor expression in Xenopus oocytes, the 2S-(+)-enantiomer of compound 1, TC-5214 (13),\textsuperscript{51} was found to dissociate more slowly than 2R-(−)-mecamylamine (14) from α4/β2- and α3/β4-nAChRs, as well as more slowly from α4/β2- than α3/β4-nAChRs. IC\textsubscript{50} values for compound 13 at α3/β4-, α4/β2-, α7-, or α1/β1γδ-nAChRs are similar to those of compound 14 (IC\textsubscript{50,α3/β4} = 0.2–0.6 and 0.05–0.4 μM, IC\textsubscript{50,α4/β2} = 0.5–3.2 and 0.5–1.7 μM, IC\textsubscript{50,α7} = 1.2–4.6 and 2.2–5.8 μM, and IC\textsubscript{50,α1/β1γδ} = 0.6–2.2 and 0.3–1.1 μM).\textsuperscript{51} Further pharmacological studies suggested that compound 13 is a more efficacious antagonist of LS α4/β2-nAChRs than compound 1 and can act as a positive allosteric modulator at HS α4/β2-nAChRs.\textsuperscript{66} This was hypothesized to be mechanistically important; however, the positive allosteric modulation at α4/β2-nAChRs was inferred from a slight potentiation of the HS α4/β2-selective agonist TC-2559 (15) in a mixed population of HS and LS α4/β2-nAChRs. Potentiation of ACh was not demonstrated, and because the effect was not reproduced in a pure population of HS α4/β2-nAChRs, activation of LS α4/β2-nAChRs by the coapplication of compounds 15 and 13 was not excluded.

Compound 13 exhibited higher anxiolytic- and antidepressant-like effects in several animal models than racemic mecamylamine (forced swim and social interaction tests, light/dark assay). These behavioral activities were attributed to antagonist effects at α4/β2*-nAChRs.\textsuperscript{67} Moreover, compound 13 showed a superior preclinical safety profile compared to that of either the racemic compound or the 2R-(−)-enantiomer. Compound 13
is most potent as a 4-nAChR agonist that was tested in a phase 2 clinical trial as an augmentation in treatment resistant subjects with major depression.79,80 Weber et al.21 propose that compound 16, which was predicted to inhibit only 23% of α4/β2 nAChRs,81 would not translate into improved antidepressant efficacy.

Although it is possible that compound 13 could be an effective monotherapy, given its poor nAChR subtype selectivity and the failure in the phase 3 clinical trial, it seems unlikely that this ligand will have a future in the treatment of depressive disorders. The disappointing failure of compound 13 illustrates the need for a better understanding of the optimal pharmacological properties to maximize clinical antidepressant efficacy. More potent nAChR inhibitors that block >25% α4/β2 nAChR would likely be more effective than compound 1 or compound 13. Inhibition may be achieved with more potent antagonists, partial agonists with very low intrinsic activity, or desensitizing agents.

2-(tert-Butylamino)-1-(3-chlorophenyl)propan-1-one, 7.

Compound 782 is an α-aminoketone believed to elicit antidepressant effects by acting as a dopamine and norepinephrine reuptake inhibitor. It was first reported to show efficacy as a smoking-cessation aid in nondepressed patients in 1994 and has subsequently proven to be a noncompetitive antagonist at a variety of nAChR subtypes 83,84 Compound 7 is most potent as a dopamine reuptake inhibitor, with an IC₅₀ of 550 nM, while potencies at norepinephrine transporters and a number of nAChR subtypes fall in the low micromolar range. However, it has long been appreciated that clinical outcomes correlate poorly with plasma concentrations of compound 785 and that active metabolites reaching higher and longer-lasting concentrations in plasma likely play the leading role. The principal metabolite, 2S,3S-hydroxybupropion (17), has reduced potency at dopamine transporters and most nAChR subtypes, whereas its potency at norepinephrine transporters and α4/β2 nAChRs is enhanced.96 It appears that a determining factor of compound 7’s efficacy is its metabolism to sufficiently high concentrations of compound 17, as differences in its plasma concentrations between responders and nonresponders was the most statistically significant difference in a 2006 study.86 Plasma concentrations reported for compound 17 were in the low micromolar range. Although compound 7 and another active metabolite, threo-hydrobupropion, were present at lower concentrations, they may have additive effects in combination with the principal metabolite that provide a significant contribution to a complex pharmacology mediated by norepinephrine transporters, dopamine transporters, and α4/β2 nAChRs. Evaluation of compound 7 and its hydroxyl metabolites in the mouse FST showed that compound 17 was equally potent to that of compound 7, whereas the 2S,3R-isomer showed no effect on immobility.83 The 2S,3S-isomer was also a more potent inhibitor of [³H]-norepinephrine uptake and [³H]dopamine update as well as a more potent antagonist of α4/β2 nAChR function than that of the
Modulation of nAChRs with partial agonists is pharmacologically complex, as it involves potentially simultaneous and interacting effects. Under acute conditions, partial agonists elevate baseline cholinergic tone while simultaneously lowering the ceiling of nAChR-mediated signaling. Depending on potency, dose, and exposure, partial agonists could have an additive effect with endogenous ACh, thereby lowering the threshold for ACh signaling while simultaneously lowering the efficacy of that signal. Under conditions of chronic administration, partial agonists desensitize nAChR, and it is believed that the resulting attenuation of cholinergic signaling is the principal pharmacotherapeutic end point.

nAChR AGONISTS

Dihydro-β-erythroidine (DHβE, 18) is an alkaloid that is isolated from the seeds of Erythrina L., a genus of trees and shrubs that is found in the tropics and subtropics around the globe. In Central America, Erythrina had an important role in folk medicine during precolonial times. Compound 18 acts as a competitive antagonist at α4β2-nAChRs (IC50,α4β2 = 30 nM and IC50,α3β4 = 23 μM) that blocks compound 10-induced dopamine release from rat striatal slices (IC50 = 30 nM).88 Compound 18 shows antidepressant-like effects in the mouse FST (3.0 mg/kg) and TST (1.0 and 3.0 mg/kg) without affecting locomotor activity.89 Additionally, compound 18 is able to potentiate the antidepressant-like effects of compound 9 (4 and 20 mg/kg) in the TST.22

(1S,2S,4S,5S,6S)-2-Methoxy-2,3,5,6,8,9,10,13-octahydro-1H,12H-pyran-3-yl is a complex diterpenoid alkaloid isolated from the seeds of Delphinium brownii, is a competitive and selective α7-nAChR antagonist with an IC50 value in the subnanomolar range, as tested in Xenopus oocytes and α7- transfected SH-SY5Y cells.92,93 Compound 19 was found to partially inhibit anatoxin-evoked dopamine release from rat striatal slices26 and decrease the time spent immobile in NMRI female mice in the mouse FST (10 mg/kg) and TST (10 mg/kg) without affecting locomotor activity.90 Another study, however, found no effect of compound 19 (10 mg/kg) in the FST in BALB/c male mice.38 The discrepancies between these studies, which may be related to mouse strain, gender, or procedural differences, warrant further investigation into the role of α7 nAChR inhibition and antidepressant function.

7-(Pyridin-3-yl)-1,7-diazaspiro[4.4]nonane, 20.

Another α4β2-nAChR antagonist is the Targacept compound TC-2216 (20).95 This compound was reported to show beneficial effects in preclinical studies, thereby promoting its further development for the treatment of depression and anxiety disorders.96 A phase 1 clinical trial of racemic compound 20 was initiated in 2008, but no further trials were conducted.
SAR studies of cytisine analogues revealed that phenyl ring replacements of the pyridine ring of compound 21 reduced the binding affinities and functional efficacies.77 Substitution of 21 at the C-3 (–CH=CH2, 102 –NO2, 103 or pyridyl)95, C-4 (–CH3),95,102 or C-5 (–Br)78 position could lead to the same or improved α4β2-nAChR binding affinity, whereas substitution at the piperidine nitrogen,97,103,104 the C-3 position (aromatic rings),103 or the C-12 position (–CO2CH3 or –COCH3CH2)102 reduced affinity. Introduction of substituents on the piperidine ring nitrogen,97–99 C-4 (–CH3 or –CH2OH),102 or the C-5 (–NO2)105 position increases the selectivity for α4β2 receptor. Among these substituted cytisine analogues, 3-(2-pyridyl)cytisine (22)95 and 5-bromocytisine (23)95 were further tested in mouse antidepressant efficacy models. Both compounds displayed high affinity at α4β2*-nAChRs (Kiα,β: 0.9 nM for 22 and 0.3 nM for 23), whereas compound 22 was found to show lower affinities at α3β4*-nAChRs and α7*-nAChRs (Kiα,β*: 119 nM and Kiα,β: 1100 nM for 22 vs Kiα,β*: 43 nM and Kiα,β: 28 nM) for 23. In electrophysiology assays, compound 22 activates both HS and LS α4β2*-nAChRs (EC50,LS = 12 nM and EC50,HS = 31 nM) expressed in oocytes with low efficacies (less than 10% relative to the efficacy of ACh at both HS and LS receptors) while exhibiting little agonism at α3β4*.95 In the same assays, compound 23 activated both HS and LS α4β2*-nAChRs with similar potencies (EC50,LS = 13 nM and EC50,HS = 15 nM) and efficacies (17% relative to ACh). A comparison of binding and functional data for compound 21 and its selected analogues are presented in Table 1.

Nitration of benzazepine 24 in the presence of 2 equiv of nitronium tri fluoride (CF3SO3O−) in dichloromethane afforded the 4,5-dinitrated benzazepine 26105 with an unexpected regioselectivity (the meta-isomer was found to be less than 10% of the mixture). Reduction of 26 to the diamine, condensation with glyoxal, and deprotection followed by salt formation provided compound 22 (Figure 6).105 This achiral quinoxaline 2 is the most publicized cytisine analogue, which is known as varenicline. Its tartrate salt has been launched and marketed by Pfizer for smoking cessation in the U.S. (Chantix), Canada, Europe, and other countries (Champix). Compound 2 is a potent partial agonist at α4β2*-nAChRs, with a Kα: value of 4.0 nM and an agonist efficacy of 40–60% of that of compound 10.109,110 In Xenopus laevis oocytes expressing α4β2*-nAChRs, compound 2 was found to have an ECαβ of 2.3 μM and an efficacy of 13.4% relative to that of ACh.109 It potently blocks compound 10 binding to α4β2*-nAChRs and produces a sustained increase in dopamine release to 60% of the maximal effect of compound 10 (188% at 0.32 mg/kg sc).110 In addition, 1 mg/kg po compound 2 reduced the dopamine-enhancing effects of a subsequent dose of 0.32 mg/kg sc compound 10 to the level of the effect of compound 2 alone.110 In a SPECT imaging study, compound 2 (0.5 mg) was found to completely saturate α4β2*-nAChRs in human brain.111 The dissociation half-life of compound 2 is about 5.4 h in a mouse ex vivo receptor occupancy study.128 Compound 2 alone has antidepressant-like effects in the FST and was able to augment the effects of compound 5 when administered in combination.121,111 It enhanced the mood and cognitive function associated with compound 10 withdrawal in patients in clinical trials for smoking cessation.12 In an 8 week open-label study, compound 2 augmented the effects of traditional antidepressants in depressed smokers who derived minimal benefit from standard antidepressant treatment.12 Recently, studies on a larger scale of community volunteers who wanted to quit smoking revealed that 12 week administration of compound 2 (0.5 mg/day for days 1–3 followed by 0.5 mg twice a day for days 4–7 and 1 mg twice a day thereafter) was coupled with a generalized suppression of

Table 1. Binding Affinities and Maximal Responses and Potencies of Compounds 2 and 21–23 with Respect to Activation of nAChRs Expressed in Oocytes95,101

<table>
<thead>
<tr>
<th>ID</th>
<th>ref</th>
<th>a4β2 activation</th>
<th>a4β2 inactivation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>a4β2</td>
<td>a4β2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EC50 (nM)</td>
<td>EC50 (nM)</td>
</tr>
<tr>
<td>ACh</td>
<td>95</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>101</td>
<td>22%</td>
<td>1400</td>
</tr>
<tr>
<td>21</td>
<td>101</td>
<td>6.5%</td>
<td>2000</td>
</tr>
<tr>
<td>22</td>
<td>95</td>
<td>3%</td>
<td>8%</td>
</tr>
<tr>
<td>23</td>
<td>95</td>
<td>17%</td>
<td>17%</td>
</tr>
</tbody>
</table>

antidepressant-like effects of compound 22 were demonstrated in the TST (0.6 mg/kg, but not at 0.3 or 0.9 mg/kg), FST (0.3–0.9 mg/kg), and chronic NSF tests (15 days at 0.3 mg/kg, but not at 0.6 mg/kg) in C57BL/6 mice. On the other hand, compound 23 (0.3–1.2 mg/kg) failed to show any significant effects in the same tests 30 min postintrapertioneal injection.95 It has been suggested that the lack of efficacy of compound 23 was likely due to the low brain penetration, as 50 nG of the compound in 1 μL of artificial cerebrospinal fluid showed a significant antidepressant-like effect in the TST when administered centrally.
A-85380 AND ANALOGUES

(S)-3-(Azetidin-2-ylmethoxy)pyridine, 27.

The pyridine ether-based ligands, in which a CH₂O linker is inserted between the pyrrolidine ring (or in case of its analogues, an azetidine ring) of compound 10 and its pyridine ring have attracted considerable interest as α4β2-nAChR agonists due to their high potency.115 A-85380 (27)116 is a 3-pyridyl ether that exhibits both high potency and selectivity for β2-containing nAChRs, primarily α4β2 in brain (Kᵢ,α4β2 = 0.02–0.05 nM for rat brain receptors and 0.04 nM for human brain receptors) relative to that of human α7-nAChRs (Kᵢ,α7 = 148 nM) or muscle-type α1β1γδ- nAChRs (Kᵢ,α1β1γδ = 314 nM).119,120 Functionally, compound 27 acts as a potent activator of both human α4β2-nAChRs (EC₅₀ = 0.7 μM) and ganglionic α3/β4*- nAChRs (EC₅₀ = 0.8 μM), the effects of which are blocked by pretreatment with compound 1. In the FST, compound 27 was found to have antidepressant-like effects that could be blocked by pretreatment with the nAChR antagonists compounds 1 and 18, as well as by the nonselective serotonin receptor antagonist methiothepin, suggesting that compound 27 exerts its effects via neuronal nicotinic receptor activation of serotonergic pathways.119,121 As exemplified by compound 12120 (Kᵢ,α4β2 = 0.01 nM), introduction of a halogen substituent at the C-2 (fluoro only), C-5, or C-6 position of compound 27 leads to ligands that retain subnanomolar affinity for the α4β2*-nAChRs, as measured by radioligand binding assays utilizing rat brain membrane preparations.120 Similar to compound 27, 12 was also found to decrease immobility in the mouse FST.38 Recently, β2*-nAChR availability was found to be decreased across brain regions in depressed patients compared to that of healthy subjects using SPECT with the β2*-selective radioligand tracer [¹²³I]112A. A unifying explanation of these effects stems from the idea that desensitization and antagonism provide similar end points for agonists and antagonists. However, because agonists have an acute activation phase, behavioral assays may measure effects due to activation and/or inactivation of nAChRs. In this context, one would expect coadministration of an antagonist to reduce the behavioral signature of an agonist administered alone. More complicated explanations involving multiple nAChR subtypes also can be made, but they are highly speculative. (S)-5-(Azetidin-2-ylmethoxy)-3-methylisoxazole, 28.

Replacement of the pyridine core of these ether-based ligands with a methylisoxazole group led to compound 28, which binds to α4β2-nAChRs with higher affinity than to the α3/β4-nAChRs (Kᵢ,α3β4 = 4.6 nM vs Kᵢ,α4β2 = 692 nM).122 The functional potency of compound 28 (1.2 μM) at the α4β2-nAChR is similar to that of compound 2 (1.4 μM), whereas the efficacy of compound 28 is higher (110% vs 53%) in cells heterologously expressing a mixture of HS and LS α4β2-nAChRs (Table 2). Broad screening showed that this compound was highly selective for nAChRs and did not have significant binding affinity to the other 45 neurotransmitter receptors and transporters tested. In the mouse FST, compound 28 was found to decrease immobility at 1–5 mg/kg i.p. and 5 mg/kg po. This compound showed no significant hERG or CYP (1A2, 2B6, 2C9, 2C19, 2D6, and 3A4) inhibition at 10 μM. Between 53.4 and 73.7% of compound 28 was found to remain unchanged after 60 min incubation with mouse or human liver microsomes (1 and 10 μM).122

dx.doi.org/10.1021/jm401937a J. Med. Chem. 2014, 57, 8204–8223

Figure 6. Selected nicotinic benzazepine analogues.
Table 2. Functional Potencies and Efficacies of Ligands 2, 10, 11, and 28–31: Agonism and Inactivation at Human α4β2-nAChRs\textsuperscript{122–125}

<table>
<thead>
<tr>
<th>compound</th>
<th>IC\textsubscript{50} (nM)</th>
<th>efficacy (%)\textsuperscript{a}</th>
<th>efficacy HS (%)\textsuperscript{b}</th>
<th>IC\textsubscript{50} (nM)</th>
<th>efficacy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1400</td>
<td>53</td>
<td>110</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>5.8</td>
<td>55</td>
<td>100</td>
<td>4.8</td>
<td>37</td>
</tr>
<tr>
<td>12</td>
<td>1200</td>
<td>110</td>
<td>169</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>19</td>
<td>21</td>
<td>9.4</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>30</td>
<td>22</td>
<td>31</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>8.4, 2300\textsuperscript{5}</td>
<td>21</td>
<td>58</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>290</td>
<td>88</td>
<td>430</td>
<td>93</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a}The efficacy were measured in a mixture of HS and LS α4β2-nAChRs. \textsuperscript{b}The efficacy values were extrapolated using compound 11 defined as a full agonist at the HS α4β2-nAChR. 

Compound 11, an analogue of compound 27 having an alkynyl substituent attached to the 5-position of the pyridine ring, was identified as a highly potent full agonist at HS α4β2-nAChR and a low efficacy agonist at LS nAChR (Table 2).\textsuperscript{126} Compared with compound 27, the selectivity of compound 11 at α4β2- relative to ganglonic α3β4*- and homeric α7*-nAChRs is greatly improved.\textsuperscript{127,128} Compound 11 potently binds to α4β2-nAChRs (\(K_i = 0.4\) nM) but not to α3β4*- (\(K_i > 10^4\) nM) or α7*-nAChRs (\(K_i > 10^4\) nM). Ex vivo receptor occupancy in the thalamus showed prolonged receptor occupancy. The dissociation half-life of compound 11 (8–24 h) was found to be significantly longer compared with that of compound 12 (3–5 h),\textsuperscript{38} which is likely due to the presence of the side chain in compound 11.

Robust antidepressant-like effects of compound 11 were observed in the FST, TST, and NIH assays, with no effect on baseline locomotor activity when given chronically.\textsuperscript{35,38,129} Compound 11 (1 mg/kg) significantly reduced immobility 2, 3, and 4 h but not 5 h after administration in the mouse FST. Repeated administration of compound 11 in the FST at 1 and 3 mg/kg doses for 2 weeks did not result in tolerance. Moreover, its activity in the FST was completely blocked by either compound 18 or compound 1,\textsuperscript{38} suggesting that activation of nAChRs may responsible for the activity of compound 11 in this behavioral model of antidepressant efficacy. In addition, β2 subunit knockout mice did not show any antidepressant response to compound 11 in the FST, suggesting that interaction with β2-nAChRs plays a key role in the behavioral activity of compound 11.\textsuperscript{38} Stimulation of dopamine and noradrenaline release in rat striatal slices was observed with compound 11, an effect that was blocked by nicotinic antagonists 18 and compound 1.\textsuperscript{126} In addition, the α6*-selective antagonist α-conotoxin MII (100 nM) reduced the maximum effect of compound 11-induced dopamine release in rat by 48%, suggesting that α6*-nAChRs may be involved in the antidepressant-like effects of compound 11.\textsuperscript{126}

Compound 11 has been reported to have other behavioral effects including increased hyperthermia.\textsuperscript{130,131} It is unlikely that the hypnotic effects of compound 11 are related to its antidepressant-like effects observed in the FST. Although reduced, β2 knockout mice still showed a hypnotic response to compound 11,\textsuperscript{131} whereas the antidepressant-like effects of compound 11 was completely abolished in β2 knockout mice.\textsuperscript{38} The hypnotic effects of compound 11 (1 mg/kg) returned to baseline approximately 2 h postinjection,\textsuperscript{132} whereas the antidepressant-like effect persisted up to 4 h.\textsuperscript{38} Compound 11 has shown additional beneficial behavioral effects in animal models including analgesia,\textsuperscript{133} improving attentional function after disruption with compound 3 or MK-801,\textsuperscript{132,134} reducing anxiety following withdrawal from chronic treatment,\textsuperscript{135} decreasing body weight gain following chronic treatment,\textsuperscript{136} and decreasing compound 10 self-administration and alcohol consumption.\textsuperscript{137–139} Interestingly, unlike compound 10 or compound 2, compound 11 did not upregulate nAChR in the brain after chronic administration\textsuperscript{136} and did not maintain receptor upregulation following chronic compound 10 administration,\textsuperscript{136} providing further evidence that compound 11 may exert its behavioral effects through a unique mechanism.

(S)-6-(5-(Azetidin-2-ylmethoxy)pyridin-3-yl)hex-5-yn-1-ol, 11.

Table 3. Binding Affinities of Compounds 10, 11, and 27–31 at Seven nAChR Subtypes\textsuperscript{122–125}

<table>
<thead>
<tr>
<th>compound</th>
<th>(a2\beta2)</th>
<th>(a2\beta4)</th>
<th>(a3\beta2)</th>
<th>(a3\beta4)</th>
<th>(a4\beta2)</th>
<th>(a4\beta4)</th>
<th>(a4\beta2)</th>
<th>selectivity (a4\beta2/a3\beta4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>&gt;10 000</td>
<td>0.3</td>
<td>0.9</td>
<td>24 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>4.3</td>
<td>311</td>
<td>8.7</td>
<td>692</td>
<td>4.6</td>
<td>86.0</td>
<td>12.0</td>
<td>150</td>
</tr>
<tr>
<td>28</td>
<td>0.1</td>
<td>249</td>
<td>3.0</td>
<td>6520</td>
<td>0.1</td>
<td>82.6</td>
<td>0.5</td>
<td>65 200</td>
</tr>
<tr>
<td>29</td>
<td>1.0</td>
<td>935</td>
<td>15.4</td>
<td>&gt;10 000</td>
<td>0.6</td>
<td>1790</td>
<td>3.0</td>
<td>&gt;16 300</td>
</tr>
<tr>
<td>30</td>
<td>1.7</td>
<td>559</td>
<td>40.6</td>
<td>5640</td>
<td>1.2</td>
<td>16.9</td>
<td>1.4</td>
<td>4700</td>
</tr>
<tr>
<td>31</td>
<td>5.5</td>
<td>70</td>
<td>29</td>
<td>260</td>
<td>4.9</td>
<td>23</td>
<td>9.8</td>
<td>53</td>
</tr>
</tbody>
</table>

\textsuperscript{a}The dissociation half-life of compound 11 (8–24 h) was found to be significantly longer compared with that of compound 12 (3–5 h),\textsuperscript{38} which is likely due to the presence of the side chain in compound 11.

\(K_i\) values were determined by competition for \([3H]\)epibatidine binding sites using radioligand binding. \(\alpha4\beta2\) selective agonist prepared from rat forebrain.
Replacing the acetylene bond of compound 11 with a substituted cyclopropane or an isoxazole ring lead to compounds 29 and 30, respectively. Introduction of different amino groups at the S-position of the pyridine ring yielded a series of 3-alkoxy-5-aminopyridine derivatives exemplified by compound 31. These compound 11 analogues (29–31) act as α4/2-nAChRs partial agonists (Table 2) with low nanomolar binding affinities \( (K_i = 0.1–1.2 \text{ nM}) \) and excellent subtype selectivity at β2*- over β4*-nAChRs (Table 3). Compound 29 has been cocrystallized with Ct-AChBP, and its binding mode was found to be similar to that reported for compound 2; both compounds rely on the presence of two cationic centers spaced ~5.8 Å from each other for their binding interactions, including cation–π interactions with W153 (loop B) and Y201 (loop C) as well as a set of H-bonds with the backbone atoms of W153 (loop B), Q116 (loop E), and I128 (loop E). (Figure 7.) The hydroxyethyl group of compound 29 appears to be flexible and is able to adopt different orientations, thus highlighting the ability to carry out structural modifications of this appendage without causing significant alterations in activity. The antidepressant-like properties of compounds 29–31 were demonstrated in the classical mouse FST (1–30 mg/kg). The lack of significant interactions with other neurotransmitter receptors and transporters widely distributed throughout the CNS as well as the favorable preliminary absorption, distribution, metabolism, excretion, and toxicity (ADME-Tox) profiles place these specific α4/2-nAChR ligands in a favorable position to be further studied as new antidepressant drug candidates.

**OTHER LIGANDS**

(S)-2-(5-(Azetidin-2-ylmethoxy)pyridin-3-yl)isoxazol-3-yl)ethan-1-ol, 30.

(5)-N-Phenyl-5-(pyrrolidin-2-ylmethoxy)pyridin-3-amine, 31.

TC-1734 (AZD-3480), 32.

TC-1734 (32) is a potent α4/2-nAChR partial agonist \( (K_i = 11 \text{ nM}) \) and is selective over α7-nAChRs \( (K_i > 50 000 \text{ nM}) \). Compound 32 (10 μM) showed no significant inhibition when tested at 135 other receptor and enzyme systems. In functional studies, the agonist activity of compound 32 was measured using a Sr2+ efflux assay in rat thalamic synaptosomes (α4/2 subtype, \( EC_{50} = 220 \text{ nM}, \text{efficacy} = 57\% \)) and the dopamine-release assay in striatal synaptosomes (\( α4/2/α6/α3/2, EC_{50} = 106 \text{ nM}, \text{efficacy} = 55\% \)). Compound 32 (up to 100 μM) did not show any detectable effects at either muscle-type (\( α1/β1/δ \)) or gangliionic (\( α3/β4 \)) nAChRs. Compound 32 had favorable pharmacokinetic and metabolic profiles and was well-tolerated in acute and chronic oral toxicity studies in various animal species (mice, rats, and dogs), as well as in a human clinical studies using either single- or repeated-dose oral administration. Compound 32 exhibited antidepressant-like effects in the mouse FST when administered intraperitoneally, with a significant reduction in immobility at the minimal dose of 1 μmol/kg, and locomotor activity was not affected by repeated administration. In clinical trials, compound 32 has been studied in a variety of indications characterized by varying types and degrees of cognitive impairment, such as attention deficit/hyperactivity disorder, mild cognitive impairment, and age-associated memory impairment. Currently, Targacept is recruiting patients for a phase 2b study with this compound in order to assess efficacy, safety, and tolerability in patients with mild to moderate dementia due to Alzheimer’s disease.

(5)-3-Ethynyl-5-(1-methylpyrrolidin-2-yl)pyridine, 33.

SIB-1508Y (33) is a selective α4/2-nAChR partial agonist \( (EC_{50} = 1.8 \text{ μM}, \text{efficacy} = 49\% \) relative to that of compound 10), having no activity at homeric α7- or muscle-type α1/β1/δ-
nAChRs and weak activity at ganglionic α3β4-nAChRs (EC<sub>50</sub> = 23 μM; efficacy = 52% relative to that of compound 10).<sup>148</sup> In vitro, compound 33 stimulated dopamine release from slices of rat striatum prepared from various brain regions, and the effect was blocked by nAChR antagonists compound 1 or compound 18.<sup>149</sup> On the other hand, compound 33 was found to show relatively weak effects on NE or 5-HT release. Subchronic or chronic administration of compound 33 demonstrated robust antidepressant-like effects in the learned helplessness model in rat, which were significantly blocked by nAChR antagonist compound 1 in the subchronic study.<sup>150</sup> In addition, compound 33 was also found to improve cognitive and motor function in monkey models of Parkinson’s disease.<sup>131,152</sup>

1-(5-Chloropyridin-3-yl)-1,4-diazepane, 34.

NS3956 (34)<sup>23</sup> was found to be a partial agonist at human α4/2-nAChRs (K<sub>i</sub> = 0.36 nM) with good selectivity (K<sub>i</sub>α7 = 399 nM and K<sub>i</sub>α4 = 944 nM). In the oocyte expression system, this compound was very potent at HS α4/2-nAChRs (EC<sub>50</sub> = 11 nM), with an efficacy of 47% of the response to a maximally efficacious concentration of ACh.<sup>23</sup> At LS α4/2-nAChRs, potency and efficacy were both reduced, with an EC<sub>50</sub> of 604 nM and an efficacy of 38% relative to that of ACh. In reference to the subtype selectivity and off-target activity, actions at α7- or α3β4-nAChRs of compound 34 were weak or absent, and it did not show any significant interactions with the monoamine transporters, including 5-HT, DA, and NE. Moreover, compound 34 exhibited an ED<sub>50</sub> value of 0.033 mg/kg in the [<sup>3</sup>H]epibatidine binding assay when tested in vivo, indicating that it was able to cross the BBB. Interestingly, compound 34 (0.3–3.0 mg/kg) was shown to be inactive in the mouse FST when tested alone, whereas when tested as a combination therapy, it significantly enhanced the antidepressant-like effects of the SSRI compound 4 and the SNRI compound 6 at 1.0 mg/kg.<sup>23</sup> These results suggest the possibility of a synergistic interaction between nicotinic agonism and the action of antidepressant medications. In vitro binding studies along with the detailed interactions with Ls-AChBP revealed that a bromine substitution at the 6-position increased the efficacy at HS α4/2-nAChR, and a relatively small substitution, such as chloro, bromo, or ethoxy, at the 5-position of the pyridine ring in a 1-(pyridin-3-yl)-1,4-diazepane scaffold improved selectivity for α4/2- over α7-nAChRs.<sup>57</sup>

(R)-4-Chloro-N-(quinuclidin-3-yl)benzamide, 35.
antidepressant-like effect of the SSRI compound 4 or the SNRI compound 6.23

**CONCLUSIONS**

Considerable evidence supports the hypothesis that hyperactivity of the cholinergic system over that of the adrenergic system leads to depression. Clinical and preclinical studies provide evidence that modulating nAChRs may lead to antidepressant effects when given alone and in combination with traditional antidepressants (summarized in Table 4). Compound 10 has a clear and long-recognized activity as an antidepressant, and a childhood history of depression elevates the risk for those individuals becoming users of tobacco products, reflecting self-medication with compound 10 as a “street” antidepressant.154 It is difficult to determine the critical drug features that are responsible for compound 10’s antidepressant activity, given the pharmacodynamic and pharmacokinetic variables and the various effects of compound 10 on nAChRs in vitro. Our understanding is incomplete about where and which nAChR subtypes are involved in excitatory neurotransmission and/or in modulation of neurotransmission mediated by monoamines or other chemical messengers implicated in mood regulation. Pharmacokinetics bring additional uncertainties with regard to drug availability and efficacy in vivo and translation of ligand activities in vitro to those in vivo. For example, effects of several agonists in animal models are attenuated by coadministered antagonists, suggesting that nAChR activation contributes to some antidepressant-like drug effects. Antagonists alone also elicit antidepressant-like effects, suggesting that inhibition of nAChR function through processes such as desensitization also contribute to antidepressant efficacy, consistent with the cholinergic/adrenergic hypothesis. Moreover, compound 10 and many nicotinic ligands have limited selectivity across nAChR subtypes or subtype isoforms, meaning that they could have a matrix of effects across subtypes as well as on the activation—inactivation axis. There still is a need for reliable assays for several nAChR subtypes, in vitro, complicating the interpretation of results and strategies in identification of promising compounds. It is also important to be mindful that behavioral tests in animals measure changes in behavior that correlate with clinical efficacies of currently available antidepressants and do not necessarily predict effective antidepressant activity in humans, particularly in treatment-resistant patients.

Recent phase 3 findings indicated that the nAChR antagonist compound 13, the 2S-(+)-enantiomer of the broad-spectrum, noncompetitive nAChR antagonist, compound 1, did not show efficacy as an adjunct therapy for patients that were nonresponders to traditional antidepressant treatment. This suggests that simple antagonism of what is likely to be a number of nAChR subtypes has an insufficient antidepressant effect. However, the lack of nAChR subtype specificity and the marginal free concentration in brain are also significant issues for compound 13 that may have contributed to the negative outcomes in the phase 3 trials. Those outcomes are not likely to be accurate predictors of effects of nicotinic full or partial agonists with greater nAChR subtype selectivity.

Designing a compound that has actions more like those of compound 10 (short-lived nAChR agonism mediated by binding to the orthosteric sites followed by receptor desensitization) may produce a more efficacious antidepressant. Factors outlined above need to be addressed toward optimization of ligand action of the desired type and at the appropriate nAChR subtypes. These challenges aside, preclinical evidence shows potent antidepressant-like efficacy of compound 11 and some of its analogues in the mouse FST. These ligands have high selectivity at α4β2*-nAChR over other nAChR subtypes and act as partial agonists at the (α4)β2-nAChR isofrom. These findings suggest and support the hypothesis that ligands selectively targeting the (α4)β2-nAChR isofrom may hold significant promise as efficacious antidepressants. These ligands would offer advantages over nicotinic agents that are relatively nonselective and produce adverse side effects through actions at peripheral nAChRs or at central non-α4β2*-nAChRs.

Aside from their selectivity for α4β2*-nAChR, compound 11 and its analogues have favorable pharmacokinetic and toxicological profiles. Advancement of the best of these ligands to and through clinical trials still requires substantial investment of effort and capital. Our work funded under a National Cooperative Drug Discovery and Development program has provided important impetus to such advancement, but private sector engagement and commitment to treatment of depression or other psychiatric disorders will be necessary. This poses an additional challenge given the perhaps more proximal benefit of attention on new drugs to treat diseases of aging and metabolism and acute/chronic pain than to treat psychiatric disorders that are poorly understood, perhaps because of their etiopathogenic heterogeneity. If nAChR ligands are to be prescribed as antidepressants, then it may happen through the inverse route that compound 7 took to be prescribed as a smoking-cessation aid. α4β2*-selective agonists and partial agonists that are attractive as potential antidepressants may also be efficacious as smoking-cessation aid. It is entirely possible that this class of compounds will first reach the clinic as an improvement over compound 2 and that antidepressant efficacy is ascertained thereafter. Regardless, studies with α4β2*-nAChR-selective ligands have already contributed to an improved understanding about nAChR subtypes and isoforms, and elucidation of roles played by the nicotinic system in the effects of these ligands certainly have illuminated the neurobiology underlying depression.

**AUTHOR INFORMATION**

**Corresponding Author**

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

**Notes**

The authors declare no competing financial interest.

**Biographies**

Li-Fang Yu received a Bachelor of Science degree in chemistry at Beijing Normal University (2004). She subsequently pursued graduate studies at Shanghai Institute of Materia Medica Chinese Academy of Sciences, where she obtained her Ph.D. in Medicinal Chemistry (2009) under the mentorship of Dr. Fa-Jun Nan. She completed her postdoctoral training at the University of Illinois at Chicago in the laboratory of Dr. Alan P. Kozikowski, where she worked on developing nicotinic ligands for use in depression. She is currently an associate professor of Medicinal Chemistry at East China Normal University. Her research interests are CNS drug design and development.

Han-Kun Zhang completed his Ph.D. in Medicinal Chemistry in 2009 at Shanghai Institute of Materia Medica, Chinese Academy of Sciences, under the mentorship of Dr. Li-Hong Hu. His dissertation research centered on the discovery of novel antidiabetic and antitumor agents derived from natural products. He began his postdoctoral research career at the University of Illinois at Chicago, under the direction of Dr.
Alan P. Kozikowski, where his research focus was on the development of novel nAChR ligands and HDAC inhibitors. In 2013, he joined the School of Life Sciences, East China Normal University, as an Associate Professor, and his current research interests are focused on GPCR-based drug discovery.

Barbara J. Caldarone is the Director of the Neurobehavior Laboratory at the Harvard NeuroDiscovery Center and an Instructor at Brigham and Women’s Hospital in Boston, Massachusetts. She completed her postdoctoral training at Yale University School of Medicine, where she began studying the relationship between nicotinic acetylcholine receptors and depression; she continued this work in industry at PsychoGenics, where she worked on characterizing novel nicotinic ligands for the treatment of depression. She currently works with investigators from the Harvard research community in utilizing mouse behavioral models to help understand and develop treatments for neurodegenerative and psychiatric disorders.

J. Brek Eaton received a Bachelor of Science degree in Microbiology from Arizona State University with an emphasis on Molecular Biology and Immunology in 1998 after studying engineering at Florida Institute of Technology. He is currently a research technician at Barrow Neurological Institute employed in the Neurochemistry Laboratory of Dr. Ronald J. Lukas. Current research is focused on the discovery of novel ligands targeting neuronal nicotinic acetylcholine receptors, both for use as therapeutics and as research tools to advance understanding of the biophysics underlying nicotinic acetylcholine receptor function.

Ronald J. Lukas received undergraduate and early graduate training in Physics at the State University of New York (SUNY) and Columbia University before earning a Ph.D. in Biophysics from the SUNY Health Sciences Center in Brooklyn and serving as a postdoctoral fellow in Chemical Biodynamics at the University of California, Berkeley, and in Neurobiology at Stanford University. He since has directed the Laboratory of Neurochemistry at the Barrow Neurological Institute, conducting multidisciplinary work concerning nicotinic acetylcholine receptor structure, function, and roles in neuropsychiatric disorders.

Alan P. Kozikowski is a Professor of Medicinal Chemistry and Pharmacognosy at the University of Illinois at Chicago. He has previously held positions at the University of Pittsburgh, the Mayo Clinic, and the Georgetown University Medical Center. He has made numerous contributions to the CNS and cancer fields and published over 500 research articles. His interest in epigenetics led to the identification of highly selective HDAC6 inhibitors for application to orphan indications such as Rett syndrome and Charcot–Marie–Tooth disease. Some of his designed PSMA inhibitors have been advanced to orphan indications such as Rett syndrome and Charcot identi

References


Acknowledgments

We thank the National Institute of Mental Health (NIMH grant U19MH085193) for research support. The Phoenix research component was also supported in part by the Barrow Neurological Foundation, and work by this team was conducted in part in the Charlotte and Harold Simensky Neurochemistry of Alzheimer’s Disease Laboratory.

Abbreviations Used

STAR*D, sequenced treatment alternatives to relieve depression; MDD, major depressive disorder; nAChR(s), nicotinic acetylcholine receptor(s); SSRI(s), selective serotonin reuptake inhibitor(s); SNRI(s), serotonin norepinephrine reuptake inhibitor(s); ACh, acetylcholine; AChE, acetylcholinesterase; mAChRs, muscarinic ACh receptors; ECD, extracellular domain; HPA, hypothalamic–pituitary–adrenal; GABA, γ-aminobutyric acid; LS, low sensitivity; HS, high sensitivity; VTA, ventral tegmental area; SPECT, single photon emission computed tomography; CNS, central nervous system; AChBP(s), acetylcholine binding protein(s); Ac, Aplysia californica; Ls, Lymnaea stagnalis; Ct, Capitella teleta; FST, forced swim test; TST, tail suspension test; NSF, novelty-suppressed feeding; NIH, novelty-induced hypophagia; ADME-Tox, absorption, distribution, metabolism, excretion, and toxicity.


(53) Dash, B.; Chang, Y.; Lukas, R. J. Reporter mutation studies show that nicotinic acetylcholine receptor (nAChR) alpha5 subunits and/or variants modulate function of alpha6/alpha5 nAChR. *J. Biol. Chem.* 2011, 286, 37905–37918.


(96) Mineur, Y. S.; Somenzi, O.; Picciotto, M. R. Cytisine, a partial agonist of high-affinity nicotinic acetylcholine receptors, has antidepressant-like properties in male C57BL/6 mice. *Neuropharmacology* 2007, 52, 1256−1262.


