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Probing the Effects of Residues Located Outside the Agonist Binding Site on Drug-Receptor Selectivity in the Nicotinic Receptor

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Abstract

The nicotinic acetylcholine receptors (nAChRs) are a family of closely related but pharmacologically distinct neurotransmitter-gated ion channels. They are therapeutic targets for a wide range of neurological disorders, and a key issue in drug development is selective targeting among the greater than 20 subtypes of nAChRs that are known. The present work evaluates a proposed hydrogen bonding interaction involving a residue known as the "loop B glycine" that distinguishes receptors that are highly responsive to ACh and nicotine from those that are much less so. We have performed structure-function studies on the loop B site, including unnatural amino acid mutagenesis, in three different nAChR subtypes and found that the correlation between agonist potency and this residue is strong. Low potency receptor subtypes have a glycine at this key site, and mutation to a residue with a side chain converts a low potency receptor to a high potency receptor. Innately high potency receptors have a lysine at the loop B site and show a decrease in potency for the reverse mutation (*i.e.* introducing a glycine). This residue lies outside of the agonist binding site, and studies of other residues at the agonist binding site show that the details of how changes at the loop B glycine site impact agonist potency vary for differing receptor subtypes. This suggests a model in which the loop B residue influences the global shape of the agonist binding site rather than modulating any specific interaction.

Nicotinic acetylcholine receptors (nAChRs) are a diverse family of pentameric, neurotransmitter-gated ion channels responsible that play prominent roles in the central and peripheral nervous systems.[1–3] Among the roughly two dozen subtypes that have been characterized as important in mammals,[4] a clear pharmacological distinction is observed. nAChRs can be categorized into two groups: receptors that display relatively lower potency for the natural agonist ACh as well as nicotine and related agonists, and receptors that exhibit much greater agonist potency.[5] Prototypes of the low potency family include the nAChR of the neuromuscular junction, with subunit composition $(\alpha 1)_2\beta 1\gamma\delta$ (*i.e.* muscle-type), and the homopentameric CNS receptor $(\alpha 7)_5$. The prototype high potency receptors are the α4-containing receptors of the CNS that play a prominent role in nicotine addiction.[6] Interestingly, this pattern is mirrored in AChBP sequences from two different species (Figure 1). The AChBP from *Aplysia* has a glycine at the aligning position, while AChBP from *Lymnaea* has a serine. Binding studies find that, indeed, the *Lymnaea* protein shows higher affinity for ACh, nicotine, and related compounds.[7] Inspection of the two structures,

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however, reveals no obvious differences between the two in the regions considered here. All nAChRs show sequence *identity* among residues that are thought to make direct contact with bound agonists (Figure 1), and so the pharmacological selectivity must result from residues that are formally located outside of the agonist binding site.

One such discriminating site is in the α subunit on loop B of the agonist binding site (Figure 1).[5] In α1 subunit numbering this is position G153, and we will refer to the site generically as the "loop B glycine". It lies four residues from W149 (TrpB; the highly conserved aromatic residues of the agonist binding site are given designations according to which of four "loops" contains them (Figure 2).[1]). TrpB has been shown to make a cation-π interaction to most agonists.[8–9] In crystal structures of AChBPs, soluble proteins that have provided an excellent structural model of the nAChR agonist binding site,[10–11] there is a backbone hydrogen bond between loop B and loop C formed by the NH of G153 and the CO of residue 197 (muscle-type numbering). Residue 198 is TyrC2, another conserved aromatic amino acid of the agonist binding site. This interesting interaction is also present in the recently reported crystal structure of the invertebrate GluCl channel,[12] another member of the superfamily of Cys-loop (pentameric) receptors for which the nAChR is the prototype. The loop B glycine is conserved in the low potency $(\alpha7)_5$ receptor with the aligning residue G152, but not in the higher potency $(\alpha4)_2(\beta2)_3$ receptor, where the aligning residue is K158 (Figure 1). MD simulations have suggested that this sequence difference contributes to the distinction between low *vs.* high potency receptors.[5] Having a side chain at the loop B residue (as in α4 K158) facilitates the loop B-loop C hydrogen bond. However, the presence of glycine at this site weakens the hydrogen bond, and this impacts potency. Known mutations of the muscle-type receptor support this model.[13]

We recently showed that, indeed, a G153K mutation in the muscle-type receptor greatly increased potency of both ACh and nicotine.[8] The cause of the increased potency was a cation-π interaction to TrpB that was absent or weak in the wild type muscle-type receptor, but was strong in both α4-containing receptors and in the muscle-type receptor with the G153K mutation.

In the present work we evaluate the role of the loop B glycine in both the muscle-type and $(\alpha7)_5$ receptors. G-to-K mutations enhance potency substantially, but the details of how the potency is enhanced differ in the two subtypes. We also evaluate whether the reverse K-to-G mutation has the opposite effect on the high potency $(\alpha4)_2(\beta2)_3$ receptor. Finally, we use unnatural amino acid mutagenesis to disrupt the proposed hydrogen bond in the $(\alpha4)_2(\beta2)_3$ receptor and evaluate the functional consequences.

RESULTS AND DISCUSSION

Probing the G153 Site in the Low Potency $(\alpha1)_2$ β1γδ (Muscle-type) Receptor

In the $(\alpha1)_2\beta1\gamma\delta$ receptor, we have previously shown[8] that the α1 G153K mutation produces a significant gain-of-function for both ACh and nicotine, with EC_{50} increasing 44- and 74-fold, respectively (Table 1; Supporting Information contains a more detailed presentation of the data, including error bars). We also showed that the G153K mutation strengthened the cation-π interaction between each agonist and TrpB. We now report the effect of the G153K mutation on epibatidine (Figure 3) at $(\alpha1)_2\beta1\gamma\delta$. Note that unlike nicotine, epibatidine is fairly potent at the wild type muscle-type nAChR, and it does show a cation-π interaction to TrpB in the wild type receptor.[14] Nevertheless, the G153K mutation produces a 75-fold increase in epibatidine potency, comparable to what is seen for nicotine (Table 1). The MD simulations noted above suggested that the substantial increase in potency observed for G153K-containing receptors was not specific to lysine, but simply required a side chain at the loop B glycine. We find that, indeed, mutation of G153 to either

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alanine or threonine produced receptors with a substantial gain-of-function phenotype, similar to the G153K phenotype (Supporting Table S1).

Fluorination of the TrpB position was examined in the background of the G153K mutant (Supporting Figure S2). Consistent with previous ACh and nicotine data[8], our results indicate that the G153K mutation also strengthens the cation-π interaction between epibatidine and TrpB of the receptor. This is indicated by an increase in sensitivity to progressive fluorination of the key Trp residue, as illustrated in a "fluorination plot" (Supporting Figure S3).

The AChBP crystal structure suggested that the backbone carbonyl of the TrpB residue can serve as a hydrogen bond acceptor for agonist molecules that possess an available hydrogen bond donor, such as nicotine and epibatidine (Figure 2). We have confirmed the importance of this interaction in nAChRs by using backbone ester substitution, converting the contributing carbonyl from an amide to an ester, the latter being a much poorer hydrogen bond acceptor (Figure 3). In the high affinity $(\alpha4)_2(\beta2)_3$ receptor this mutation has a large effect,[8] but previous studies on the $(\alpha1)_2\beta1\gamma\delta$ receptor revealed that both nicotine and epibatidine make modest backbone hydrogen bonds to the carbonyl (1.6- and 3.7-fold shifts, respectively).[14] To monitor if this hydrogen bonding interaction is affected by the loop B glycine, we performed the same backbone mutation in combination with the G153K mutation in $(\alpha1)_2\beta1\gamma\delta$. The G153K mutation strengthens the hydrogen bond between both nicotine and epibatidine to the TrpB carbonyl (Table 2). The amide-to-ester/G153K mutant results in 15- and 11-fold loss-of-function for nicotine and epibatidine, respectively. As anticipated, ACh is unperturbed by the backbone mutation, since ACh is a quaternary ammonium lacking a hydrogen bond donor.

Probing the G152 Site in the Low Potency $(\alpha7)_5$ Receptor

The homopentameric $(\alpha7)_5$ receptor is distinctive in many ways, including its mode of agonist binding. While most nAChR subtypes employ a cation-π interaction between TrpB and the agonist, the $(\alpha7)_5$ receptor eschews this common ligand binding mechanism.[15] Instead, in $(\alpha7)_5$, ACh forms a cation-π interaction to TyrA, and epibatidine forms a cation-π interaction to TyrC2 of the agonist binding site. It is a "low potency" receptor, with G152 aligning at the loop B glycine site. Given the unusual binding pattern observed in $(\alpha7)_5$, it was interesting to investigate whether changing the side-chain of the loop B glycine would increase agonist potency through a mechanism similar to that observed in $(\alpha1)_2\beta1\gamma\delta$. Introduction of lysine at this position (G152K) in $(\alpha7)_5$ did indeed result in a significant gain-of-function when tested with ACh, nicotine, and epibatidine (Table 1).

To determine whether an amplification of the cation-π interaction analogous to that seen in the muscle-type receptor would occur in $(\alpha7)_5$, we incorporated either F_3Trp at TrpB or F_3Phe at TyrA and TyrC2 in the background of the G152K mutant (Supporting Table S2). In contrast to $(\alpha1)_2\beta1\gamma\delta$, the consequences of fluorination at TrpB in the G152K mutant did not differ from wild type $(\alpha7)_5$ for ACh, nicotine, or epibatidine (Supporting Table S2). Similarly, introduction of G152K in $(\alpha7)_5$ does not enhance the naturally occurring cation-π interaction between ACh and TyrA.

A large perturbation, however, was observed for incorporating F_3Phe at TyrC2 in the G152K mutant. Full fluorination plots were produced for ACh and epibatidine, and compared to wild type $(\alpha7)_5$ plots (Supporting Figure S4). For ACh as agonist, the G152K mutant enhanced this binding interaction. A similar but less pronounced trend was observed for epibatidine as agonist.

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Additionally, we probed the effect of the G152K mutation on the backbone hydrogen bond to the carbonyl of TrpB using the amide-to-ester strategy. In wild type $(\alpha7)_5$, epibatidine participates in a modest backbone hydrogen bond (2.1-fold shift).[15] Interestingly, the G152K mutation does not affect the backbone hydrogen bond, displaying a 2.6-fold loss-of-function for epibatidine (Table 2). Consistent with previous trends, the backbone mutation had no effect on ACh binding.

Nicotine is not very potent at the $(\alpha7)_5$ receptor, which limits the kinds of studies we have been able to perform in the past. Introduction of the G152K mutation in $(\alpha7)_5$ produced hypersensitive receptors sufficient for examining nicotine as the agonist. As such, $(\alpha7G152K)_5$ mutant receptors allowed accurate measurement of nicotine-induced currents even after incorporation of highly fluorinated Phe derivatives. For such receptors, nicotine participates in a cation-π interaction with TyrC2, as indicated by a fluorination plot (Supporting Figure S4). For the backbone hydrogen bond, nicotine displayed a 7.8 fold loss-of-function in the background of the G152K mutation (Table 2).

Probing the K158 Site in the High Potency $(\alpha4)_2(\beta2)_3$ Receptor

A G-to-K mutation significantly increases potency of agonists in both the muscle-type and $(\alpha7)_5$ receptors. It seemed possible that the reverse mutation, K158G, in the high potency $(\alpha4)_2(\beta2)_3$ receptor would diminish potency. We now report that the K158G mutation in $(\alpha4)_2(\beta2)_3$ receptors is, indeed, a loss-of-function mutation (Table 1). However, the magnitude of the impact is significantly less than that seen for the G-to-K mutations in the low potency receptors.

For $(\alpha4)_2(\beta2)_3$ receptors containing the K158G mutation, fluorinated tryptophan derivatives were incorporated at TrpB, the site of a cation-π interaction for ACh and nicotine (Supporting Table S3).[8] The K158G mutation attenuated but did not completely abolish the existing cation-π interaction for both ACh and nicotine (Supporting Figure S5).

In wild type $(\alpha4)_2(\beta2)_3$, nicotine forms a strong hydrogen bond to the backbone carbonyl of TrpB, revealed by a 19-fold shift for the backbone ester mutation.[8] In $(\alpha4)_2(\beta2)_3$ receptors containing K158G, the amide-to-ester mutation revealed a 14-fold shift for nicotine (Table 2) indicating that this mutation has minimal impact on the backbone hydrogen bond.

It is possible that other residues positioned outside the immediate binding site could play a role in reshaping the agonist binding site. Taking into consideration the primary sequence of the α4 subunit and the crystal structure of AChBP, several residues were identified near the agonist binding site that could participate in ionic interactions with cationic agonists (D157, K158, K160, and E200 (located two residues after the key Cys-Cys motif)). Alanine substitution, side chain charge neutralization, and charge reversal were used to probe the importance of these residues in affecting agonist binding interactions. Residues were examined individually and in combination. While each mutation produced a modest loss-of-function, no significant trend was observed (Supporting Figure S6, Supporting Table S3).

Probing the Proposed Loop B–Loop C Hydrogen Bond

The present results have confirmed the influence of the loop B glycine site on agonist potency. These studies were inspired by the AChBP structure and simulations that indicated a hydrogen bond between loop B and loop C of the agonist binding site is formed to the backbone NH of the loop B glycine. Thus far, however, only side chain modifications have been considered, and these can only indirectly impact the putative hydrogen bond. As described above, backbone mutagenesis can directly probe hydrogen bonding, and so we have applied that strategy to the proposed hydrogen bond. We chose to study the $(\alpha4)_2(\beta2)_3$, high potency receptor, since this is the form for which the hydrogen bond is predicted to be

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stronger. We can mutate both components of the hydrogen bond by backbone mutagenesis: replacing the NH of K158 with an O by incorporating an α-hydroxy acid at position 158, and altering the backbone carbonyl acceptor of residue 201 by incorporating an α-hydroxy acid at position 202.

As established above, the identity of the side chain at position 158 is not crucial, as long as it is not glycine, and we anticipated technical challenges in incorporating the α-hydroxy analog of lysine. As such, we chose to start from the K158L mutant, since Lah (leucine, α-hydroxy) is readily available and incorporates well by nonsense suppression. As expected, the K158L mutation has a very modest effect on receptor function (Table 1, Supporting Table S4). Referenced to K158L, the K158Lah mutation also has a small effect on receptor function (Table 1), and it is actually a slight gain-of-function for both ACh and nicotine. Similarly, the Y202Yah mutation produced a relatively small perturbation, but it is now a loss-of-function. It may be that the perturbation with nicotine as agonist is significant, but still the effect is smaller than comparable perturbations we have seen at other hydrogen bonding sites.

Implications for nAChR Function and Subtype Selectivity

A number of lines of evidence have established an important role for the loop B glycine in nAChR function. AChBP structures show its involvement in a loop B-loop C hydrogen bond,[10–11] and MD simulations indicate that the strength of the hydrogen bond has an impact on the potency of ACh and nicotine at nAChR receptor subtypes.[5] A mutation at this site in the muscle-type nAChR produces a myasthenic syndrome.[13] Furthermore, in the muscle-type receptor, the G153K mutation reshapes the agonist binding site, allowing nicotine to approach the key TrpB residue of the agonist binding site more closely, amplifying both a cation-π interaction and a hydrogen bonding interaction[8].

In the present work we have further probed the loop B glycine in three different nAChR subtypes: muscle-type, $(\alpha7)_5$, and $(\alpha4)_2(\beta2)_3$. In the muscle-type receptor, ACh, nicotine, and the nicotine analog epibatidine all show substantial increases in potency in response to the G153K mutation, which can be ascribed to an increased interaction with TrpB. As seen previously with nicotine, the cation-π interaction is strengthened for epibatidine when the G153K mutation is present. It has been proposed that the G153K mutation should not be unique; any amino acid with a side chain should have a similar impact. Indeed, we find in the muscle-type receptor that G153A and G153T show similar phenotypes to G153K. Also, in the high potency $(\alpha4)_2(\beta2)_3$ receptor, a K158L mutation, which in most contexts would be expected to be strongly perturbing, has a minimal impact, indicating that there is nothing special about the lysine side chain.

The $(\alpha7)_5$ nAChR is low potency like the muscle-type nAChR, but it shows a distinct pattern of agonist binding. As such, it was interesting to see if it would respond to mutations of the loop B glycine in a similar manner. Indeed, the G152K mutation does significantly enhance the potency of ACh, nicotine, and epibatidine in the $(\alpha7)_5$ nAChR, however, the effects are generally smaller than seen for the muscle-type receptor. Agonists do not make a cation-π interaction to TrpB in $(\alpha7)_5$, and the G152K mutation does not change this. Similarly, the hydrogen bond to the carbonyl of TrpB is weak in both the wild type and the G152K mutant. However, the G152K mutation does amplify a cation-π interaction between agonists and TyrC2. A weak interaction with ACh becomes stronger in the mutant, and a strong interaction with epibatidine is further enhanced. Recall that TyrC2 is adjacent to the carbonyl that acts as the acceptor to the proposed critical hydrogen bond. However, in the muscle-type receptor it is interactions with TrpB, which lies across the agonist binding site from TyrC2, that are impacted by mutations at the loop B glycine site. This suggests that mutation of the glycine site globally alters the shape of the agonist binding site, such that

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agonists that interact strongly with TrpB see that interaction enhanced, and agonists that interact with TyrC2 see that interaction enhanced.

Given these results it was reasonable to ask whether a high potency receptor could be converted to a low potency receptor by the reverse (K-to-G) mutation at the key loop B site. The binding interactions in the $(\alpha4)_2(\beta2)_3$ receptor are well characterized, and so we chose it as the target of such studies. We find that the K158G mutation does indeed diminish potency, but the effect is much less substantial than seen with the two G-to-K mutations. This suggests that in the optimized high potency receptor there are other modifications that contribute to the high potency. Conversely, in a low potency receptor the G-to-K mutation enhances potency considerably, and there may be other potential changes that could make the receptor even more "α4-like" and thus higher potency still.

Although these and other studies of the loop B glycine have probed the effects of side chain mutations, the key proposed interaction actually involves a backbone hydrogen bond. This is an attractive model because, as noted above, the residue contributing the carbonyl is adjacent to TyrC2, a conserved contributor to the "aromatic box" of the agonist binding site. The unnatural amino acid methodology allows us to probe such backbone hydrogen bonds, replacing the NH donor with an O or replacing the amide (peptide) carbonyl with an ester carbonyl, a much weaker hydrogen bond acceptor.

We have performed both mutations in the high potency $(\alpha4)_2(\alpha2)_3$ receptor, which is predicted to have a strong hydrogen bond, probing the response to both ACh and nicotine. In all cases, the impact is small, ranging from a 2-fold to a 5-fold change in potency. This is consistent with the argument given above that, in the optimized high potency $(\alpha4)_2(\alpha2)_3$ receptor, features other than just the backbone hydrogen bond contribute to increasing potency. Furthermore, it is possible that these features are able to compensate for single disruptions in agonist binding (*i.e.* disrupting the proposed loop B-loop C hydrogen bond). It is surprising that the two approaches to modulate the hydrogen bond have opposite effects: one is a loss-of-function and one is actually a gain-of-function. Again, the effects are small, and we hesitate to attempt to provide detailed interpretation.

Overall, these results provide strong support for the notion that the identity of the side chain at the loop B glycine site strongly influences nAChR function. With any residue other than glycine (and likely proline), the agonist binding site is shaped properly to allow strong interactions with agonists. However, when this key residue is glycine, the agonist binding site is distorted such that optimal drug-receptor interactions cannot occur. This happens regardless of whether key drug-receptor interactions involve TrpB or TyrC2, and so we prefer a model that emphasizes a global reorganization of the agonist binding site, rather than just the repositioning of a single residue. Interestingly, although the model is based on the behavior of a proposed hydrogen bond, directly modifying that hydrogen bond has a smaller effect on receptor function than presumed indirect effects brought about by side chain modifications.

METHODS

Molecular Biology

All nAChR subunit genes were in the pAMV vector (mouse α1, β1, γ, and δ; rat α4, β2, and α7). Site-directed mutagenesis was performed using the QuikChange protocol (Stratagene). For nonsense suppression experiments,[16] the site of interest within the nAChR subunit was mutated to an amber stop codon (TAG). Circular DNA was linearized with Not I. After purification (Qiagen), linearized DNA was used as a template for runoff *in vitro* transcription using T7 mMessage mMachine kit (Ambion). hRIC-3 cDNA in pGEM vector

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was obtained from Dr. Miller Treinin at Hebrew University.[17] Circular hRIC-3 DNA was linearized with Xho I, and mRNA was prepared as previously described.

THG73[18] was used as the amber suppressor tRNA. Nitroveratryloxycarbonyl (NVOC) protected cyanomethyl esters of unnatural amino acids and α-hydroxy amino acid cyanomethyl esters were synthesized, coupled to dinucleotide dCA, and enzymatically ligated to 74-nucleotide THG73 $tRNA_{CUA}$ as previously reported.[16] Crude tRNA-amino acid product was used without desalting, and the product was confirmed by MALDI-TOF MS on 3-hydroxypicolinic acid (3-HPA) matrix. Deprotection of the NVOC group on the tRNA-amino acid was carried out by photolysis for 5 minutes prior to co-injection with mRNA containing the UAG mutation at the site of interest.

Microinjection

Stage V-VI *Xenopus laevis* oocytes were employed. For muscle-type nAChR experiments, α1:β1:γ:δ mRNA was injected at a ratio of 2:1:1:1 by mass for wild type protein. Note that for all experiments reported, we use a previously reported L9'S mutation in the β1 subunit to increase receptor sensitivity.[8–9] If an unnatural amino acid was to be incorporated into the α1 subunit, then an mRNA ratio of 10:1:1:1 was employed. For wild type and nonsense suppression experiments, the total mRNA injected was 30–65 ng/oocyte.

All studies of the $(\alpha7)_5$ receptor contain a T6'S mutation in the M2 transmembrane helix, which serves to decrease desensitization without altering other aspects of receptor pharmacology.[19] As in previous $(\alpha7)_5$ experiments,[15] 10 ng of hRIC-3 mRNA was co-injected with 10 ng α7 mRNA per oocyte, as co-expression of hRIC-3 enhances surface expression of α7 receptors, presumably by aiding the folding, assembly, and/or trafficking of the α7 protein. In the case of nonsense suppression experiments, 20 ng α7 mRNA was co-injected with 25 ng of hRIC-3 mRNA per oocyte.[15]

In accordance with previously reported protocols,[8] all α4β2 receptors contain a L9'A mutation in the α4 subunit to increase receptor expression. Co-injection of α4:β2 mRNA at a ratio of 1:1 by mass yielded wild-type $(\alpha4)_2(\beta2)_3$ receptors. For $(\alpha4)_2(\beta2)_3$ nAChRs with conventional mutations located outside the immediate binding site (*i.e.* K158G, D157N, etc.), an injection ratio of 1:1 for α4:β2 mRNA by mass was employed (Supporting Table S5). For wild type recovery experiments incorporating a tryptophan into the α4 subunit to produce $(\alpha4)_2(\beta2)_3$ receptors, a mass ratio of 1:1 for α4:β2 mRNA was injected into each oocyte. However, for subsequent nonsense suppression experiments incorporating fluorinated tryptophan derivatives into the α4 subunit, a mass ratio of 3:1 for α4:β2 mRNA was injected into each oocyte to account for the decreased suppression efficiency. The total α4β2 mRNA injected was 30–72 ng/oocyte depending on the relative expression level. All $(\alpha4)_2(\beta2)_3$ nAChR stoichiometries were confirmed by voltage jump experiments.[8]

For all suppression experiments, approximately 15 ng of tRNA per cell was used. Each oocyte was injected with 50 nL of RNA solution, and the oocytes were incubated for 24–48 hours at 18 °C in ND96 buffer (96 mM NaCl, 2 mM KCl, 1 mM $MgCl_2$, 1.8 mM $CaCl_2$, and 5 mM HEPES, pH 7.5) with 0.005% (w/v) gentamycin and 2% (v/v) horse serum. In the case of low-expressing mutant receptors, a second injection of mRNA/tRNA was required 24 hour after the first injection. As a negative control for all suppression experiments, 76-nucleotide tRNA (dCA ligated to 74-nucleotide tRNA) was co-injected with mRNA in the same manner as fully charged tRNA.

Electrophysiology

Acetylcholine chloride and (−)-nicotine tartrate were purchased from Sigma/Aldrich/RBI (St. Louis, MO) and drug dilutions were prepared from 1M *aq* stock solutions. (±)-

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Epibatidine was purchased from Tocris and drug dilutions were prepared from a 50mM stock solution (1:1 H_2O:EtOH). For $(\alpha1)_2\beta1\gamma\delta$ and $(\alpha4)_2(\beta2)_3$ experiments, drug dilutions were prepared in Ca^{2+}-free ND96 buffer. For $(\alpha7)_5$ experiments, drug dilutions were prepared in Ca^{2+}-containing ND96 buffer.

Ion channel function was assayed using the OpusXpress 6000A (Molecular Devices Axon Instruments) in two-electrode voltage clamp mode. Oocytes were clamped at a holding potential of −60mV. For $(\alpha1)_2\beta1\gamma\delta$ and $(\alpha4)_2(\beta2)_3$ receptors, 1 mL of each drug solution was applied to the clamped oocytes for 12 sec, followed by a 2 minute wash with Ca^{2+}-free ND96 buffer between each concentration. In the case of hypersensitive $(\alpha1G153K)_2\beta1\gamma\delta$ receptors, a 1.5 min drug application was used to ensure maximum peak response when using very low concentrations of agonist. For $(\alpha7)_5$ receptors, 1 mL of each drug solution was applied for 30s, followed by a five minute wash step with Ca^{2+}-containing ND96 buffer between each concentration. Data were sampled at 50 Hz and filtered at 20 Hz. Voltage jump experiments were sampled at 5000 Hz and filtered at 180 Hz.

Data Analysis

Dose-response data were obtained for at least 6 concentrations of agonists and for a minimum of 5 oocytes (from two different batches). Mutants with I_{max} of at least 100 nA of current were defined as functional. EC_{50} and Hill coefficients (n_H) were calculated by fitting the averaged, normalized dose-response relation to the Hill equation. All data are reported as mean ± S.E.

Supplementary Material

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	Loop A								Loop B								Loop C												Loop D					
BPLs	W	V	P	D	L	A	A	Y	W	T	H	H	S	R	E	I	Y	S	C	C	P	E	-	A	Y	I	D		BPLs	W	Q	Q	T	T	W
BPAc	W	T	P	D	I	T	A	Y	W	V	Y	S	G	F	E	I	Y	S	C	C	P	E	-	P	Y	D	D		BPAc	Y	E	Q	Q	R	W
α1	W	R	P	D	V	V	L	Y	W	T	Y	D	G	S	V	V	Y	S	C	C	P	T	T	P	Y	L	D		γ	W	I	E	M	Q	W
α2	W	I	P	D	I	V	L	Y	W	T	Y	D	K	A	K	I	Y	D	C	C	A	E	-	I	Y	P	D		δ	W	I	D	H	A	W
α3	W	K	P	D	I	V	L	Y	W	S	Y	D	K	A	K	I	Y	N	C	C	E	E	-	I	Y	P	D								
α4	W	R	P	D	I	V	L	Y	W	T	Y	D	K	A	K	I	Y	E	C	C	A	E	-	I	Y	P	D		β2	W	L	T	Q	E	W
α6	W	K	P	D	I	V	L	Y	W	T	Y	D	K	A	E	I	Y	N	C	C	E	E	-	I	Y	T	D		β4	W	L	K	Q	E	W
α7	W	K	P	D	I	L	L	Y	W	S	Y	G	G	W	S	L	Y	E	C	C	K	E	-	P	Y	P	D		α7	W	L	Q	M	S	W
α9	W	R	P	D	I	V	L	Y	W	T	Y	N	G	N	Q	V	Y	G	C	C	S	E	-	P	Y	P	D		α9	W	I	R	Q	I	W
α10	W	R	P	D	I	V	L	Y	W	T	H	G	G	H	Q	L	Y	G	C	C	S	E	-	P	Y	P	D		α10	W	I	R	Q	E	W
								TyrA	TrpB								TyrC1							TyrC2						TrpD					

Figure 1.

Sequence alignment for Loops A, B, C, and D in the nAChR agonist binding site. BPLs is AChBP from *Lymnaea stagnalis*. BPAc is AChBP from *Aplysia californica*. α1, β, and δ are from mouse; the human sequence differs from mouse at only one residue: the CCPTT sequence of mouse loop C is CCPDT in human. α4, β2, and α7 are rat; the human sequences are identical to rat for the residues shown. All other sequences are human. The five, universally conserved, residues of the "aromatic box": TyrA, TrpB, TyrC1, TyrC2, and TrpD are highlighted in blue. The loop B Gly/Lys site and it hydrogen bonding partner in loop C are highlighted in pink. The backbone carbonyl that hydrogen bonds to the $N^{+}H$ of agonists is probed using the amide-to-ester strategy, highlighted in yellow.

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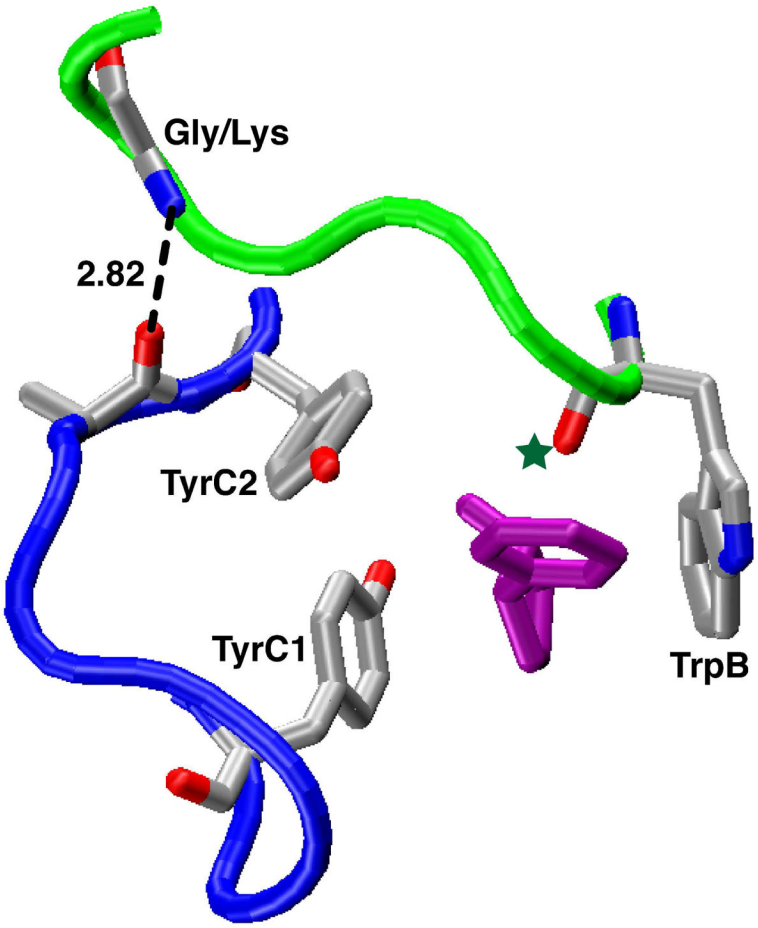

Figure 2.

Image of the nAChR agonist binding site, based on the structure of AChBP with nicotine bound (pdb: 1UW6).[20] Loop B is in green and loop C is in blue. Three of the five residues that form the "aromatic box" of the agonist binding site are shown, and nicotine is shown in purple. A green star marks the backbone carbonyl that hydrogen bonds to the $N^{+}H$ of agonists, and the proposed loop B–loop C hydrogen bond that is a major focus of the present work is highlighted.

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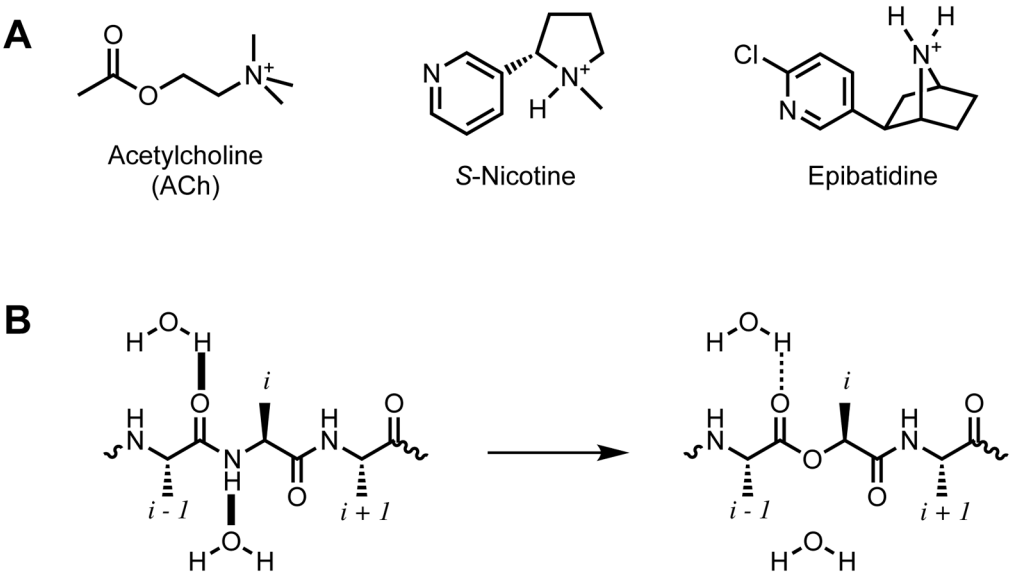

Figure 3.

A. Structures of agonists considered here. B. The backbone ester strategy for modulating hydrogen bonding interactions.

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Table 1

EC_{50} values (μM). Values in brackets represent ratio of wild type EC_{50} to mutant EC_{50}, such that ratios > 1 represent gain-of-function, and ratios < 1 represent loss-of-function. For the K158Lah mutant, the reference "wild type" receptor is K158L. See Experimental for details on receptor expression. Complete data tables with Hill coefficients and standard errors are given the Supplemental Information. WT = wild type; ND = not determined.

	$(\alpha1)_2\beta1\gamma\delta$		$(\alpha7)_5$		$(\alpha4)_2(\beta2)_3$				
	WT	**G153K**	**WT**	**G152K**	**WT**	**K158G**	**K158L**	**K158Lah**	**Y202Yah**
ACh	1.2	0.027 [44]	66	3.7 [18]	0.42	1.3 [0.32]	0.13	0.060 [2.2]	0.73 [0.58]
Nic	56	0.76 [74]	23	0.76 [30]	0.08	0.30 [0.27]	0.035	0.011 [3.2]	0.42 [0.19]
Epi	0.83	0.011 [75]	0.26	0.016 [16]	0.00035	ND	ND	ND	ND

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Table 2

Amide-to-ester experiments for the backbone carbonyl of TrpB residue. EC_{50} values (μM). Values in brackets represent ratio of wild type EC_{50} to mutant EC_{50}, such that ratios > 1 represent gain-of-function, and ratios < 1 represent loss-of-function. Complete data tables with Hill coefficients and standard errors are given the Supporting Information. ND = not determined.

	(α1 G153K)$_2$β1γδ		**(α7 G153K)$_5$**		**(α4 K158G)$_2$(β2)$_3$**	
	Thr	**Tah**	**Thr**	**Tah**	**Thr**	**Tah**
ACh	0.024	0.028 [0.86]	1.7	0.58 [2.9]	0.99	0.53 [1.9]
Nic	0.62	9.0 [0.069]	0.29	2.3 [0.13]	0.25	3.4 [0.074]
Epi	0.012	0.13 [0.092]	0.012	0.031 [0.39]	ND	ND