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Differential $\alpha 4(+) / (-) \beta 2$ Agonist-binding Site Contributions to $\alpha 4\beta 2$ Nicotinic Acetylcholine Receptor Function within and between Isoforms*

Two $\alpha 4\beta 2$ nicotinic acetylcholine receptor ($\alpha 4\beta 2$-nAChR) isoforms exist with ($\alpha 4)_2(\beta 2)_2$ and ($\alpha 4)_4(\beta 2)_2$ subunit stoichiometries and high versus low agonist sensitivities (HS and LS), respectively. Both isoforms contain a pair of $\alpha 4(+) / (-) \beta 2$ agonist-binding sites. The LS isoform also contains a unique $\alpha 4(+) / (-) \beta 2$ site with lower agonist affinity than the $\alpha 4(+) / (-) \beta 2$ sites. However, the relative roles of the conserved $\alpha 4(+) / (-) \beta 2$ agonist-binding sites in and between the isoforms have not been studied. We used a fully linked subunit concatemeric nAChR approach to express pure populations of HS or LS isoform $\alpha 4\beta 2$-nAChR. This approach also allowed us to mutate individual subunit interfaces, or combinations thereof, on each isoform background. We used this approach to systematically mutate a triplet of $\beta 2$ subunit (−)-face E-loop residues to their non-conserved $\alpha 4$ subunit counterparts or vice versa ($\beta 2$HQT and $\alpha 4$VFL, respectively). Mutant-nAChR constructs (and unmodified controls) were expressed in Xenopus oocytes. Acetylcholine concentration-response curves and maximum function were measured using two-electrode voltage clamp electrophysiology. Surface expression was measured with $^{125}$I-mAb 295 binding and was used to define function/nAChR. If the $\alpha 4(+) / (-) \beta 2$ sites contribute equally to function, making identical $\beta 2$HQT substitutions at either site should produce similar functional outcomes. Instead, highly differential outcomes within the HS isoform, and between the two isoforms, were observed. In contrast, $\alpha 4$VFL mutation effects were very similar in all positions of both isoforms. Our results indicate that the identity of subunits neighboring the otherwise equivalent $\alpha 4(+) / (-) \beta 2$ agonist sites modifies their contributions to nAChR activation and that E-loop residues are an important contributor to this neighbor effect.

Nicotinic acetylcholine receptors (nAChR) are ligand-gated ion channel neurotransmitter receptors. In mammals, they are expressed as pentameric combinations of homologous subunits, translated from 16 different genes ($\alpha 1$–$\alpha 7$, $\alpha 9$, $\alpha 10$, $\beta 1$–$\beta 4$, $\gamma$, $\delta$, and $\epsilon$). Functional diversity of nAChR is determined by subunit composition, producing nAChR subtypes with overlapping pharmacological and biophysical characteristics (1).

$\alpha 4\beta 2$-nAChR are the most prevalent central nervous system (CNS) nAChR subtype, comprising ~70% of all rodent CNS nAChR (2) and are implicated in a wide range of normal and pathological functions, including learning, memory, mood, and nicotine dependence among others (3–17). $\alpha 4\beta 2$-nAChR functionally interact with nicotine at concentrations found in smokers and are the target of varenicline, currently the most successful smoking cessation pharmacotherapy (12, 13). Initial studies suggested an ($\alpha 4)_4(\beta 2)_2$ subunit stoichiometry for these nAChR (18, 19). However, more recent work indicates that both native and heterologously expressed $\alpha 4\beta 2$-nAChR can exist in two isoforms with ($\alpha 4)_4(\beta 2)_2$ and ($\alpha 4)_2(\beta 2)_2$ subunit stoichiometries, respectively, displaying high and (predominantly) low sensitivities (HS and LS) to activation by acetylcholine (ACh) (20–25). The expression of $\alpha 4\beta 2$-nAChR isoforms appears to be physiologically significant. For example, multiple epilepsy-associated $\alpha 4$ and $\beta 2$ subunit mutants alter ratios of HS to LS $\alpha 4\beta 2$-nAChR isoforms (17, 26), and agonists capable of preferentially stimulating LS $\alpha 4\beta 2$-nAChR produce distinctive physiological effects (27–29). Accordingly, a better understanding of the respective roles of HS and LS $\alpha 4\beta 2$-nAChR isoforms is likely to have considerable translational implications.

Agonist binding to nAChR is primarily driven by interactions with a set of six peptide loops located at subunit interfaces. Three (loops A–C) are contributed from the subunit on the principal or (+)-side of the interface, with the remaining three (loops D–F) being contributed from the subunit on the complementary or (−)-side of the interface. The (−)-side subunit is oriented counterclockwise from the (+)-side subunit when viewed from extracellular space (Fig. 1A) (20). A high degree of conservation of critical agonist binding residues is seen across

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2 The abbreviations used are: nAChR, nicotinic acetylcholine receptor; ACh, acetylcholine; CRC, concentration response curve; HS, high sensitivity; HSP, high sensitivity (pentameric concatemer); LS, low sensitivity; LS(P), low sensitivity (pentameric concatemer); ANOVA, analysis of variance.
subunits. This includes residues within interfaces that do not harbor conventionally recognized canonical α(+)β-type agonist binding pockets (30–34). Both α4β2β2-nAChR isoforms host a pair of canonical orthosteric, high affinity α4(+)β2 agonist binding interfaces, but the LS (α4)2(β2)2-nAChR isoform also contains a unique, non-canonical, α4(+)β2 agonist-binding site (34–36). This α4(+)β2 site has lower affinity for ACh or nicotine than the α4(+)β2 site, making it responsible for the intrinsically biphasic ACh concentration-response profile of the LS (α4)2(β2)2-nAChR isoform. This complex CRC distinguishes it from the HS (α4)2(β2)2-nAChR isoform, which lacks an α4(+)β2 subunit interface and produces monophasic CRCs (34–36).

Activation of LS α4β2β2-nAChR via interactions with a sufficiently high agonist concentration to engage all three binding sites confers large increases in per receptor function compared with the HS isoform α4β2-nAChR, which can only be activated by agonist binding at the common α4(+)β2 sites (36). Importantly, activation of the HS phase of functional responsiveness by LS (α4)2(β2)2-nAChR can occur just by targeting the common pair of α4(+)β2 sites (either at agonist concentrations too low to engage the α4(+)β2 site or by highly selective agonists that do not engage the α4(+)β2 site at all). In this case, function per receptor closely resembles that of the HS (α4)2(β2)2-nAChR isoform (34, 36, 37). Although the α4(+)β2 interface retains the typical features of an nAChR agonist-binding site, it may therefore be thought of as effectively potentiating the response as would a co-agonist or positive allosteric modulator site (34–36). These previous studies by ourselves and others have implicitly treated the two canonical α4(+)β2 agonist-binding sites as a functionally equivalent pair. However, as illustrated in Fig. 1A, the nAChR pentameric assemblies of each isoform are pseudosymmetrical; the subunits that contribute the α4(+)β2 agonist-binding sites are surrounded by different neighbors. Because of this, it seemed possible that the two canonical agonist-binding sites might contribute differentially to activation (both within each isoform and between the two isoforms).

To test this hypothesis, we used a concatemeric (linked subunit) nAChR approach. This allowed us to express pure populations of both HS and LS isoform α4β2β2-nAChR and to systematically mutate agonist-binding residues of α4(+)β2 interfaces either individually or in combinations on either background (Fig. 1). Unlike our previous study (36), we wished to modify, not destroy, ligand binding at the targeted sites. Therefore, we systematically altered triplets of β2 subunit (−)-face E-loop residues to their non-conserved counterparts in the α4 subunit (β2V136H,F144Q,L146T; β2HQT) (Fig. 1B). This can convert agonist binding at α4(+)β2 sites to closely resemble that at an α4(+)β2 agonist-binding site (34, 38). If our hypothesis is correct, then making equivalent E-loop modifications in nominally equivalent α4(+)β2 interfaces should produce different outcomes. We also reciprocally mutated α4 subunit (−)-face E-loop residues (α4(H142V, Q150F,T152L); α4VFL (34)) to examine the effects of this substitution inside, outside, or in the absence of an α4(+)β2 interface, on both HS and LS backbones (Fig. 1C).

We demonstrate that the contributions of α4(+)β2 agonist-binding sites differ substantially within the HS isoform and between the two different isoforms upon β2HQT substitution. We further demonstrate that, unexpectedly, the α4VFL mutation produces very similar functional changes whether it is inserted into the LS isoform-unique α4(+)β2 agonist-binding site or not. Evidence for other allosteric effects of subunit (−)-face, E-loop, alterations also is obtained. These new insights may provide further opportunities to develop compounds that pharmacologically distinguish between the isoforms and thus increase our understanding of each isoform’s role in normal and disease physiology.

**Experimental Procedures**

**Chemicals—**Sazonidine-A and A-85380 were kindly provided by Drs. Alan Kozikowski (University of Illinois, Chicago) and F. Ivy Carroll (Research Triangle Institute, Research Triangle Park, NC), respectively. All other reagents were purchased from Sigma, unless noted otherwise.

**Preparation of Unlinked α4β2-nAChR Wild-type and Triple Mutant E-loop cDNA Constructs—**Unlinked nAChR human wild-type (WT) α4 (CHRNA4; NCBI reference sequence designation NM_000744.6) or β2 (CHRN2; NM_000748.2) subunit cDNAs were transcriptionally optimized, synthesized, and sequenced by GeneArt (ThermoFisher Scientific, Inc., Waltham, MA). Each subunit was subsequently excised from the GeneArt shuttle vector with the restriction enzymes XbaI and NotI and subcloned into a modified pCI expression vector containing an SwaI linearization site (vector was a gift from Dr. Isabel Bermudez, Oxford Brookes University, Oxford, UK). The unlinked triple mutant α4 (H142V,Q150F,T152L) (α4VFL) or β2(V136H,F144Q,L146T) (β2HQT) subunit cDNAs were also synthesized and sequenced by GeneArt as variants of their optimized WT parent subunits. These mutants were then subcloned into pCI as described previously.

**Preparation of Concatemeric α4β2-nAChR cDNA Constructs Containing Wild-type and Triple Mutant E-loop Subunits—**Dr. Isabel Bermudez (Oxford Brookes University) provided a low sensitivity pentameric (LSP) α4β2β2-nAChR construct encoding concatenated human nAChR subunits in the order β2-α4-β2-α4 (21). This construct, cloned into the previously mentioned modified pCI expression vector, served as the parent plasmid for each of the concatemers engineered for this study. This included the high sensitivity pentameric isoform (β2-α4-β2-α4-β2; HSP) α4β2-nAChR construct (Fig. 1). The basic construction strategy has been described in detail elsewhere (21, 36).

Briefly, all but the first β2 subunit were absent their start codons and signal peptides, and all but the last were devoid of a stop codon. Each subunit was tethered to its neighbor by a short stretch of nucleotides encoding a series of 6 or 9 (Ala-Gly Ser) repeats, engineered to ensure a total linker length (including the C-terminal tail of the preceding subunit) of 40 ± 2 amino acids. A unique set of six restriction sites either flanking the entire concatemer or approximately bisecting each linker between subunits was introduced along the pentamer sequence (Fig. 1A). This permitted replacement of individual subunits (or cassettes of multiple subunits if desired) using standard restriction digestion and ligation methods. GeneArt was used to
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design, synthesize, and sequence-verify optimized WT and mutant subunits for substitution into the parent construct. These new subunits were variants of the unlinked optimized subunits previously described, with the addition of the flanking AGS-repeat linkers and restriction sites required for correct placement within the resulting new pentameric concatemers. A unique restriction site was also introduced into each synthetic mutant sequence destined for ligation within a concatemer. This allowed for unambiguous verification of every new construct.

**RNA Preparation and Oocyte Injection**—As described previously (36), both unlinked and concatenated plasmid cRNA constructs were Swal-linearized, proteinase K-treated, column-purified, and transcribed into cRNA (mMessage mMachine T7 kit, Ambion, ThermoFisher Scientific, Waltham, MA). Each cRNA sample was DNase I-treated, column-cleaned, and gel-analyzed for size and quality. Stage V/VI *Xenopus laevis* oocytes, purchased from Ecocyte LLC (Austin, TX), were injected with biased ratio combinations of mRNAs encoding unlinked subunits (1 or 10 ng) or with 20 ng of mRNA encoding a concatemeric construct. Injected oocytes were incubated at 13 °C for 6–10 days before testing.

**Two-electrode Voltage Clamp Electrophysiology**—Methodology for obtaining CRCs and maximal current responses from nAChR-injected oocytes has been published elsewhere (36, 39, 40). Briefly, at least 6 days post-injection, oocytes were voltage-clamped at −70 mV with an Axoclamp 900A amplifier (Molecular Devices, Sunnyvale, CA). Recordings were sampled at 10 kHz (low pass Bessel filter, 40 Hz; high pass filter, direct current), and the traces were extracted and analyzed using Clampfit software (Molecular Devices). Any oocytes with leak currents >50 nA were discarded. Drugs were applied at a flow rate of 4 ml min−1 using a 16-channel, gravity-fed perfusion system with automated valve control (AutoMate Scientific, Inc., Berkeley, CA) in OR2 buffer (NaCl, 82.5 mM; KCl, 2.5 mM; MgCl2, 1 mM, HEPES 5 mM, pH 7.6) at 22 °C. Solutions were supplemented with atropine sulfate (1.5 μM) to block any muscarinic responses. Agonists were acutely perfused for 1 s with a 60-s stimulus (ACh and H11349). All concentration-response recording sessions in oocyte; calculated as the mean of the individually measured max values obtained from the oocytes comprising the set of six used in each binding determination) to microampere/fmol. These specific function values were then compared among all E-loop mutant concatemers and to the non-E-loop mutant LSP and HSP controls.

**Data Analysis**—Log₁₀ EC₅₀ values were determined from individual CRCs by non-linear least squares curve fitting (Prism 5.0; GraphPad Software, Inc., La Jolla, CA). Unconstrained monophasic or biphasic logistic equations were used to fit all parameters, including Hill slopes and fractional contributions of function attributable to HS or LS nAChR, where applicable. A sum-of-squares F-test was used to verify when data were better fit by the biphasic rather than monophasic model. Note that precision in determining ACh log₁₀ EC₅₀ values from biphasic CRCs (S.E. in log₁₀ EC₅₀ values between 0.1 and 0.35) is substantially lower than for monophasic CRCs (log₁₀ EC₅₀ S.E. values ≤0.07). One-way analysis of variance (ANOVA) and Bonferroni’s multiple comparison tests were used to compare functional parameters across α4β2-nAChR variants (Prism 5.0 or SigmaPlot Version 12.5, Systat Software Inc., San Jose, CA).
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Results

Acetylcholine Concentration-Response Curves Generated from the β2HQT Chimeric E-loop Subunit Introduce into Either LS- or HS-based α4β2-nAChR Concatemers Reveal Position-, Copy-, and Isoform-specific Effects—As noted in the Introduction, the account describing how HS phase function arises in either LS or HS isoform α4β2-nAChR (34, 36) contains an implicit assumption. This is that the two α4+(+)/(−)β2 agonist-binding sites found in both isoforms (see Fig. 1A) are functionally equivalent (both to each other in a given pentameric backbone, and between HS and LS α4β2-nAChR isoforms). Fully linked pentameric constructs provide the ability to substitute E-loop mutant subunits at any chosen position or combination of positions in HS or LS isoform α4β2-nAChR. Using these concatemeric constructs, we were therefore able to systematically test this assumption for the first time, by introducing the β2HQT E-loop mutant (located on the (−)-side of the β2 subunit) into defined positions within LSP and HSP α4β2-nAChR (Fig. 1B). The resulting family of constructs represents every possible permutation of the β2HQT triple mutant subunit cloned into the WT LSP and HSP parent constructs.

In the case of the LSP-based constructs, substitution of the (−)α4-like β2HQT mutant subunit into either of the α4+(+)/(−)β2 agonist-binding sites (transforming the interface into something resembling the lower affinity α4+(+)/(−)α4 interface) abolished HS component function (Fig. 2A). The same was true when β2HQT substitution was performed at both α4+(+)/(−)β2 sites. The resulting monophasic CRCs produced by the three mutant LSP constructs had very similar log10 EC50 values to each other (EC50 ≈ 230 μM) and were approximately
TABLE 1
Effects of introducing 2HQT E-loop mutant subunits into the LSP and HSP α4β2 nAChR concatemer backgrounds (ACH CRCs)

Oocytes were injected with RNA encoding concatenated LSP or HSP α4β2 nAChR concatemers containing zero (LSP or HSP controls in boldface), one, or more copies of the 2HQT subunit at the position (s) shown in blue type. TEVC recording of agonist perfused oocytes was used to establish ACh CRCs (Fig. 2, “Experimental Procedures”). Least squares curve fitting was used to determine ACh log10 EC50 ± S.E. values. Data were fit to an unconstrained monophasic logistic model, unless data were better fit to a biphasic logistic model (determined using the extra sum-of-squares F-test). For biphasic fits, ACh log10 EC50 values derived from LSP background CRC data (including those measured for both LS and HS phases) were better fit to a biphasic logistic model (determined using the extra sum-of-squares F-test). Post hoc comparisons were performed using the Bonferroni correction and again showed that the low-sensitivity phase of un-modified (control) LSP responses had an log10 EC50 value significantly different to that of the control high-sensitivity phase response of the same construct. Further, the log10 EC50 values of the monophasic responses of all three LSP 2HQT mutant constructs were also significantly different from that of the HS-phase control response, but indistinguishable from each other and that of the low-sensitivity phase response of the control construct. The LS-like group log10 EC50 values from the control HSP phase response is denoted as 1. **p < 0.001.

††† One-way ANOVA determined significant differences among the log10 EC50 values from derived CRCs that could be classified into two groups (one or two-site unconstrained logistic model was made using the extra sum-of-squares F-test). Details of the obtained pharmacological parameters and the statistical analysis used to compare results are provided in Table 1. Data points represent the mean (±S.E.) of at least four oocytes (numbers provided in Table 1). CRCS obtained using wild-type LSP and HSP (Aγ2) parent constructs are included in both graphs for ease of comparison within and between isoforms.

one-half log unit higher than the estimated log10 EC50 value for the LS component of LSP control (EC50 ~60 μM; Fig. 2A, Table 1). In summary, 2HQT substitution effects on α4β2-nAChR LS isoform function were both position- and copy number-independent; in every case the resulting function was purely LS component-like.

In striking contrast to the LSP series, the HSP-derived family of 2HQT-containing concatemers generated a complex set of CRCSs that could be classified into three groups (Fig. 2B). The first group consisted of two concatemers hosting a single copy of 2HQT at positions 3 or 5, which yielded HS log10 EC50 values indistinguishable from that of the unmutated HSP control (EC50 ~2 μM; Table 1). Note that the 2HQT subunit in position 3 is part of an α4(+) /β2 binding pocket, although that in position 5 is not (Fig. 1B). In other words, these constructs had one (2HQTp3) or no (2HQTp5) α4/β2 interfaces converted to a mock α4(+) /α4 interface, retaining one or both natural α4(+)/β2 interfaces, respectively.

The second HSP mutant group had just one member, the HSP concatemer containing a single 2HQT subunit at position 1. This 2HQTp1 construct also had one α4(+) /β2-to-mock α4(+) /α4 interface conversion but, like the 2HQTp3 mutant, preserved one α4(+) /β2 interface. This concatemer was the only HSP 2HQT mutant construct that generated a biphasic ACh CRC. The observed HS and LS phase EC50 values for this construct (~1.8 and ~60 μM, respectively) were indistinguishable from those of the LSP control (~2.8 and ~60 μM; Table 1). This biphasic response was so striking that it was further confirmed using two highly LS versus HS isoform-selective nicotinic agonists, A-85380 and the structurally
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ACh-induced Function Per Surface-expressed LS or HS α4β2-nAChR Concatemer Reveals Position-, Copy-, and Isoform-specific Effects of β2HQT Chimeric E-loops—In addition to exploring effects of β2HQT substitution at defined subunit positions on agonist activation affinities, we also wanted to assess effects on amounts of nAChR function. We previously have shown that cell surface levels of HSP and LSP α4β2-nAChR isoforms in oocytes injected with equivalent levels of pentamer cRNA are comparable (36). This indicated that the observed differences in amount of HSP versus LSP function were almost exclusively due to differences in function per surface-expressed nAChR, i.e. due to the intrinsic properties of the α4β2-nAChR isoforms. We have also shown that introducing mutations at subunit interfaces can significantly affect surface expression of the resulting nAChR constructs (36). Accordingly, we normalized function to the amount of nAChR surface expression (measured using β2-specific monoclonal antibody binding).

For the LSP β2HQT mutant constructs, measurements of maximum ACh-induced function (I_{max}) alone showed significant losses of function for both the position 1-only and double mutant β2HQT mutant constructs, reducing I_{max} to a level resembling that of the unmutated HSP control construct (Fig. 4A). The LSP position 3-only β2HQT mutant construct, in contrast, produced an unchanged I_{max} value compared with the unmutated LSP construct. However, as shown in Fig. 4B, surface expression of all three LSP β2HQT mutant constructs was significantly suppressed by incorporation of the mutant subunit(s). When we compensated for this effect (Fig. 4C), it became apparent that function of both single mutant LSP β2HQT mutant constructs was significantly increased, to approximately double that of the unmutated LSP control, on a per nAChR basis (Table 1). Also, on a per nAChR basis, function of the position 1 + 3 double LSP β2HQT mutant construct was statistically similar to that of the unmutated LSP α4β2-nAChR construct (Fig. 4C and Table 1). As in the case of log_{10} EC_{50} values (Fig. 2A), β2HQT-mediated functional enhancement in LSP was position-independent. However, copy number did affect the per nAChR amount of function, unlike effects on agonist log_{10} EC_{50} values that were the same regardless of whether one or both positions contained β2HQT mutant subunits (Fig. 2A).

The family of HSP β2HQT concatemers again revealed a more complicated response to incorporation of mutant subunits (Fig. 5 and Table 1). The single copy β2HQT position 1 construct (the only α4β2 HSP mutant to produce a b engaging CRC; Fig. 2B) exhibited significantly lower surface expression and I_{max}. On a per nAChR basis, these effects combined to produce an apparent, but not-quite-significant, reduction in per nAChR function. In contrast, the position 3-only β2HQT mutant (which did not affect the ACh concentration-response outcome; Fig. 2B) significantly increased I_{max} compared with the unmutated HSP control, while having no effect on surface expression. On a per nAChR basis, this resulted in a statistically significant doubling of function. Although the non-agonist-binding interface position 5 β2HQT single mutant HSP construct showed a modest but marginally significant increase in I_{max} compared with the non-mutant HSP control, this did not quite retain significance on a per nAChR basis. Neither did this

related compound sazetidine-A. A-58380 demonstrates an unusually high degree of agonist selectivity between HS and LS isoform α4β2-nAChR (24, 36, 45). In response to acute A-58380 stimulation, the HSP β2HQT position 1 construct generated a clearly biphasic CRC with an ~1:1 distribution of HS and LS components (Fig. 3), confirming the initial observation of a biphasic ACh CRC. Sazetidine-A (46) activates only HS isoform α4β2-nAChR with high efficacy (47) and may be used to selectively occupy (36, 37) and inactivate (by desensitization) responses arising from α4(+)/(−)β2 interfaces (36). A desensitizing concentration of sazetidine-A (3.16 nM (36)) was used to pretreat oocytes expressing the HSP isoform HS prior to acute A-58380 exposure. This led to complete suppression of the HS portion of the response, confirming that the resulting CRC must arise from A-85380 activity at the CRC; Fig. 2). Thus, in complete contrast to the effects of β2HQT mutant subunit incorporation on LSP α4β2-nAChR, effects in HSP α4β2-nAChR constructs were strongly influenced both by position and by copy number. Most importantly, effects on ACh CRC responses were radically different between the two constructs in which a single β2HQT mutant subunit was placed in either of the two nominally identical α4(+)/(−)β2 agonist binding pockets.

FIGURE 3. Sazetidine-A pretreatment abolishes HS component function in oocytes expressing the β2HQT position 1 HSP concatemer. Acute responses to the indicated range of A-58380 concentrations were measured before and after a 5-min pretreatment with 3.16 nM sazetidine-A in the β2HQT position 1 HSP concatemer. Without pretreatment, despite muting one of the canonical α4(+)/(−)β2 interfaces, a significant fraction of HS function was retained in this construct. A-58380 generated a strongly biphasic CRC (log_{10} EC_{50} HS = −7.64 ± 0.04, log_{10} EC_{50} LS = −5.09 ± 0.04, and fractional HS contribution = 0.51 ± 0.02). This CRC became monophasic (LS-only) following a desensitizing treatment with sazetidine-A (log_{10} EC_{50} HS = −5.09 ± 0.05); n = 4 oocytes per treatment. Note the inset that shows the location of the subunits carrying the mock α4(+)/(−)β2 interface surrounded by WT β2 neighbors which, among all of the mutant constructs generated in this study, uniquely mimics the structure of the unmutated LSP construct.

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The family of HSP β2HQT concatemers again revealed a more complicated response to incorporation of mutant subunits (Fig. 5 and Table 1). The single copy β2HQT position 1 construct (the only α4β2 HSP mutant to produce a b engaging CRC; Fig. 2B) exhibited significantly lower surface expression and I_{max}. On a per nAChR basis, these effects combined to produce an apparent, but not-quite-significant, reduction in per nAChR function. In contrast, the position 3-only β2HQT mutant (which did not affect the ACh concentration-response outcome; Fig. 2B) significantly increased I_{max} compared with the unmutated HSP control, while having no effect on surface expression. On a per nAChR basis, this resulted in a statistically significant doubling of function. Although the non-agonist-binding interface position 5 β2HQT single mutant HSP construct showed a modest but marginally significant increase in I_{max} compared with the non-mutant HSP control, this did not quite retain significance on a per nAChR basis. Neither did this
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FIGURE 4. β2HQT E-loop mutation effects on peak ACh-induced function (I_{max}) and nAChR surface expression within LSP concatemers. Oocytes expressing concatenated LSP constructs incorporating one or two copies of the β2HQT E-loop mutant subunit were screened for maximal ACh current responses, followed by 125I-mAb 295 binding to determine femtomoles of surface nAChR (assuming two β2-binding sites per LSP and three per HSP construct, see “Experimental Procedures”). All results, including the WT HSP control, were normalized to the unmutated LSP concatemer for at least four individual experiments (denoted with a dashed horizontal line in each panel; see Table 1 for non-normalized data and number of replicates/experiments performed). A, I_{max} was reduced ∼4-fold (close to HSP levels) for the LSP constructs harboring β2HQT mutations in position 1 or positions 1 + 3, although the position 3 variant was unchanged. B, surface nAChR expression levels were reduced 50–75% across all three LSP β2HQT mutant constructs. Note that the unmutated HSP construct had a similar level of surface expression as that of the unmutated LSP construct, confirming our earlier finding (36). C, I_{max} values were normalized to amounts of nAChR surface expression for each LSP β2HQT mutant concatemer. Function per surface nAChR was increased ∼2-fold for each of the single position LSP mutants, whereas the double position variant had WT levels of function. HSP typically produced ∼10% of LSP-mediated function per receptor in this study. Because data were collected for the complete set of mutants on the LSP backbone in each individual experiment (see “Experimental Procedures”), including all β2HQT and α4VFL mutant constructs, one-way ANOVA was applied to determine significant differences within the sets of I_{max} surface expression, or function per receptor values collected on the LSP backbone. One-way ANOVA determined that significant differences existed between LSP backbone groups in each panel as follows: A, F_{12,77} = 57.23; p < 0.001; B, F_{12,63} = 5.69; p < 0.001; C, F_{12,63} = 36.56; p < 0.001. Post hoc comparisons were performed in each case using the Bonferroni correction; differences from the unmutated LSP control are noted as follows: **, p < 0.01; ***, p < 0.001.

Although the agonist-pharmacology effects of α4VFL mutant subunit incorporation into LSP α4β2-nAChR were position- and copy number-independent, this was not the case position 5-only mutant construct produce any effect on ACh concentration-response (Fig. 2B). Interestingly, per nAChR function of two of the HSP double-β2HQT mutant constructs (positions 1 + 3 and 3 + 5) did not significantly differ from that of HSP control. However, when the position 1 β2HQT subunit was included with the off-interface position 5 β2HQT subunit, in either the double and triple mutant configurations (e.g. positions 1 + 5, or positions 1 + 3 + 5), there was a highly significant, ∼60%, reduction in function per nAChR. To summarize, position- and copy-dependent β2HQT mutant subunit effects on per nAChR function again exposed asymmetries between the nominally similar α4(+)/(−)β2-binding sites within the HSP α4β2-nAChR isoform.

Acetylcholine Concentration-Response Curves and per nAChR Function of LS and HS nAChR Concatemers Reveal Symmetrical and Copy-dependent Effects of α4VFL Chimeric E-loop Mutant Subunit Introduction—In addition to the just-explored α4(+)/(−)β2 agonist-binding sites common to HSP and LSP α4β2-nAChR, we also wished to specifically target the unique α4(+)/(−)α4 interface present between positions 4 and 5 within the LSP (Fig. 1A, left panel). A previous study (34) had addressed this question using unlinked α4VFL mutant subunits. However, the unlinked subunit approach altered all three α4 subunits in the α4β2-nAChR LS isoform. In contrast, use of concatemeric constructs allowed us to assess effects of α4VFL mutant incorporation at each available position, either singly or in combination (see Fig. 1C).

Unexpectedly, CRCs obtained from the family of α4β2-nAChR LSP α4VFL-containing constructs were uniformly monophasic (Fig. 6A). This was true whether single or multiple positions were substituted and was independent of which position(s) was altered. Even the three LSP variants where the α4(+)/(−)α4 interface E-loop was not mutated (α4VFL in positions 2, 5, or 2 + 5; see Fig. 1C) displayed the same outcome. Even more surprisingly, statistically indistinguishable EC_{50} values (between 7 and 12 μM) were obtained from all of the LSP α4VFL mutant constructs; these EC_{50} values were intermediate between those of the HS (0.6 μM) and LS (∼60 μM) phases of unmutated LSP function (Fig. 6A and Table 2). This was true even though there was no change in numbers of α4(+)/(−)β2 or α4(+)/(−)α4 interfaces or even when the α4(+)/(−)α4 interface was replaced by an additional mock α4(+)/(−)β2 interface. In summary, effects of the α4VFL E-loop mutant were completely independent of position and copy number in the LSP α4β2-nAChR isoform. A very similar outcome was observed when introducing α4VFL mutant subunits into the α4β2-nAChR HSP isoform (where none of the mutant subunits could be introduced into an agonist binding pocket; see Fig. 1C). In every case, CRCs of α4VFL HSP mutant constructs remained identical to that of the non-mutant HSP control (EC_{50} = 2 μM; Fig. 6B and Table 2).

Although the agonist-pharmacology effects of α4VFL mutant subunit incorporation into LSP α4β2-nAChR were position- and copy number-independent, this was not the case...
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**FIGURE 5.** β2HQT E-loop mutation effects on peak ACh-induced function ($I_{\text{max}}$) and nAChR surface expression within HSP concatemers. Oocytes expressing concatenated HSP constructs incorporating one, two, or three copies of the β2HQT E-loop mutant subunit were screened for maximal ACh current responses, followed by $^{125}$I-mAb 295 binding to determine surface nAChR expression (accounting for three β2-binding sites per HSP construct, see “Experimental Procedures”). All results were normalized to the unmutated HSP concatemer for at least three individual experiments (denoted with a dashed horizontal line in each panel; see Table 1 for non-normalized data and number of experiments performed). A, $I_{\text{max}}$ values were significantly reduced for all β2HQT mutants compared with WT. The remaining four constructs showed no significant changes for the position 3 and 5 variant. B, surface nAChR expression levels were reduced ~75% in three of the four HSP β2HQT position 1-containing mutants, although the remaining four mutant concatemers had control levels of surface expression. C, function per surface nAChR was increased ~2-fold only for the single position 3 HSP mutant, whereas two of the constructs hosting β2HQT in positions 1 + 3 or 1 + 3 + 5 showed significant reductions compared with WT. The remaining four constructs showed no significant changes versus control HSP. Because data were collected for the complete set of mutants on the HSP backbone in each individual experiment (see “Experimental Procedures”), including all β2HQT and α4VFL mutant constructs, one-way ANOVA was applied to determine significant differences within the sets of $I_{\text{max}}$, surface expression, or function per receptor values collected on the HSP backbone. One-way ANOVA determined that significant differences existed between groups in each panel: A, $F_{1,11,3} = 65.38; p < 0.001$; B, $F_{1,1,3} = 9.1; p < 0.001$; C, $F_{1,1,3,3} = 19.9; p < 0.001$. Post hoc comparisons were performed in each case using the Bonferroni correction; differences from the unmutated LSP control are noted as follows: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

**FIGURE 6.** ACh concentration-response profiles for the α4VFL E-loop mutant series of concatenated LS and HS isoforms of α4β2 nAChR. A, oocytes expressing concatenated LSP constructs incorporating one, two, or three copies of the α4VFL E-loop mutant subunit (position(s) indicated by α4VFL) were acutely stimulated with the indicated range of ACh concentrations. CRCs generated from all seven mutant constructs were monophasic with nearly identical $EC_{50}$ values, which were intermediate between the HS and LS phases of the biphasic unmutated LSP construct CRC. B, HSP set of three α4VFL E-loop mutant single or double copy concatemers generated CRCs that were indistinguishable from the HSP control. Data points represented the mean (±S.E.) of at least three oocytes and were fit to unconstrained, one-, or two-site logistic equations (most appropriate assignment determined using the extra sum-of-squares F-test). Details of the pharmacological parameters calculated and of the applied statistical analyses are reported in Table 2. CRCs obtained from unmodified LSP (□) and HSP (△) parent constructs are included in both graphs for ease of comparison within and between isoforms.
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TABLE 2
Effects of introducing α4VFL E-loop mutant subunits into the LSP and HSP α4β2 nAChR concatemer backgrounds (ACH CRCs)

Oocytes injected with cRNA encoding concatenated LSP or HSP α4β2-nAChR constructs containing zero (LSP or HSP controls), one, or more copies of the α4VFL subunit at the position(s) shown in orange type were used in conjunction with TEVC to establish and analyze ACh CRCs (see Fig. 6, "Experimental Procedures"). Pharmacological parameters were determined as described in the legend to Table 1. Additionally, data representing ACh-activated maximal function (I_{max}, in nA, rounded to 1 or 2 significant digits) and I_{max} values corrected for surface nAChR (microampere/fnmol) were generated from (N) experiments testing six individual oocytes per concatemer per experiment (See Figs. 7 and 8 for these data shown relative to, and compared with, those obtained from control LSP and HSP concatemers respectively). Number of individual oocytes tested is given as n.

| Concatemer | ACh (log_{EC_{50}}) | EC_{50} (μM) | HS Fraction n | ACh I_{max} (μA) | nAChR μA/fmol | N |
|------------|---------------------|-------------|---------------|-----------------|---------------|---|
| α4β2α4α4α4α4 (LSP) | -4.35 ± 0.39 | 0.420 ± 0.10 | 0.53 ± 0.12 | 10 | 3900 ± 580 | 194.6 ± 13.8 | 7 |
| α4β2α4α4α4α4 (LSP) | -4.91 ± 0.04 | 1.30 ± 0.18 | 252.7 ± 6.2 | 6 |
| α4β2α4α4α4α4 (LSP) | -5.06 ± 0.06 | 1.30 ± 0.26 | 151.5 ± 13.4 | 6 |
| α4β2α4α4α4α4 (LSP) | -5.52 ± 0.25 | 1.90 ± 0.17 | 269.4 ± 27.6 | 4 |
| α4β2α4α4α4α4 (LSP) | -6.15 ± 0.25 | 4.25 ± 0.10 | 96.9 ± 28.2 | 4 |
| α4β2α4α4α4α4 (LSP) | -5.93 ± 0.01 | 1.42 ± 0.20 | 104.4 ± 26.3 | 6 |
| α4β2α4α4α4α4 (LSP) | -6.00 ± 0.33 | 1.22 ± 0.10 | 85.8 ± 1.3 | 7 |
| α4β2α4α4α4α4 (LSP) | -6.57 ± 0.33 | 1.30 ± 0.12 | 6.4 ± 0.1 | 7 |

1 One-way ANOVA was used to determine differences across log_{EC_{50}} values obtained from α4VFL-mutant variations on the LSP backbone, as described in Table 1. All α4VFL mutant constructs produced monophasic CRCs, unlike the biphasic CRC of the parent, unmodified, LSP control. Post hoc comparisons using the Bonferroni correction demonstrated that the log_{EC_{50}} values for all LSP backbone α4VFL-variant CRCs formed a single group, with lower ACh sensitivity than the HS-phase response of the control construct. Differences from the HS-phase response are shown as: *, p < 0.05; **, p < 0.01; ††, p < 0.001. In contrast, no significant differences were found by ANOVA among log_{EC_{50}} values derived from the universal monophasic responses of the HSP control construct, and α4VFL mutant variants thereof. All responses were therefore classified as HS-like.

unaltered α4β2-nAChR LSP control. This loss of per nAChR function was primarily driven by an ~50% loss of I_{max}, because changes in surface expression were quite similar across the range of single, double, and triple α4VFL-substituted LSP constructs. As shown in Fig. 7C and Table 2, the loss of function/ nAChR was the same in all three of the double α4VFL-substituted LSP constructs. The trend was extended in the case of the triple α4VFL-substituted LSP construct, where a further reduction (to ~3% of control) in per receptor function was seen (Fig. 7C and Table 2). In conclusion, function/nAChR effects of α4VFL substitution into α4β2-nAChR LSP are position-independent but are copy number-dependent.

This position-independent but copy number-dependent effect of α4VFL substitution was also seen in the α4β2-nAChR HSP background (Fig. 8). α4VFL substitution into either or both available α4 subunit positions suppressed I_{max} significantly compared with control and reduced nAChR surface expression by a little over 50% (Fig. 8, A and B). When function was normalized to a per nAChR basis, the two single-substituted α4VFL α4β2-nAChR HSP variants exhibited a similar not-quite-significant trend to lower function, although the double-substituted construct produced significantly less function (approx. 75% reduction; Fig. 8C and Table 2) when compared with the unmodified α4β2-nAChR HSP construct.

Mutant E-loop Concatenated and Unlinked α4β2-nAChR Subunit Results Compare Favorably—As shown previously, α4β2-nAChR pentameric and concatemeric constructs can be expressed without degradation and/or rearrangement of subunit ordering (21, 35, 36). Importantly, these previous studies demonstrate that concatenated subunit pentameric constructs

![FIGURE 7. α4VFL E-loop mutation effects on peak ACh-induced function (I_{max}) and nAChR surface expression within LSP concatemers. Oocytes expressing concatenated LSP constructs incorporating one, two, or three copies of the α4VFL E-loop mutant subunit were screened for maximal ACh current responses, followed by 125I-mAb 295 binding to determine surface nAChR expression. All results were normalized to the unmutated LSP concatemer for at least four individual experiments (denoted with a dashed horizontal line in each panel; see Table 2 for the exact number of experiments performed in each case). A, I_{max} was reduced in all seven members of the α4VFL mutant series of constructs in a copy-dependent, position-independent manner. Single copies of α4VFL reduced function by ~50%, double copies by ~90%, and the triple copy variant exhibited a 99% loss of function versus the unmodified LSP control. B, surface nAChR expression levels were reduced 50–80% in all seven of the LSP α4VFL mutants independent of position or copy number. C, function per surface nAChR retained copy dependence and position independence for all mutant constructs as in A. α4VFL single copy constructs had WT levels of LSP function; double copies saw a 50% drop in function, and the triple mutant lost 97% of its per receptor function. One-way ANOVA was performed as described in the legend to Fig. 4 and determined that significant differences existed between groups in each panel. Post hoc comparisons were made using the Bonferroni correction; differences from the unmutated LSP control are noted as follows: *, p < 0.05; **, p < 0.01; †††, p < 0.001.](http://www.jbc.org/)
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Oocytes were injected with biased ratios of RNA encoding unlinked wt, α4VFL, or β2HQT subunits to generate predominantly HS (α4)(β2)2- or LS (α4)(β2)2-nAChR isofoms (see “Experimental Procedures” for details). ACh-activated Imax and CRC log10 (M) EC50 values collected in this study are shown in regular font. Previously published (34) injection ratios and pharmacological parameters generated from nAChR containing the indicated wt or E-loop mutant subunits are shown (in parentheses and italicized) for comparison, where possible; ND = not determined. Numbers of oocytes tested are shown for both our, and the previously-published, results.

| Subunits | Isoform | Injection Ratio | Imax (nA) | ACh (log10 M) | EC50 (HS) | EC50 (LS) | HS fraction | n |
|----------|---------|-----------------|-----------|--------------|-----------|-----------|-------------|---|
| αβ2      | HS      | 1:10 (1:4)      | 470 ± 107 | -5.65 ± 0.03 | -5.80     | 6         | 6           | 3 |
|          | LS      | 10:1 (4:1)      | 2800 ± 260 | -4.97 ± 0.03 | -4.40     | 6         | 6           | 3 |
| αE4VFLβ2 | HS      | 1:10 (1:4)      | 140 ± 43  | -5.72 ± 0.03 | -5.49     | 6         | 6           | 3 |
|          | LS      | 10:1 (4:1)      | 430 ± 87  | -5.43 ± 0.04 | -5.49     | 6         | 6           | 3 |
| αβ2HQT   | HS      | 1:10 (1:4)      | 130 ± 22  | -3.64 ± 0.02 | -3.85     | 6         | 6           | 3 |
|          | LS      | 10:1 (4:1)      | 2800 ± 360 | -3.64 ± 0.02 | -3.85     | 6         | 6           | 3 |
| αE4VFL2HQT| HS     | 1:10 (1:4)      | 60 ± 13   | -3.85 ± 0.02 | -3.85     | 6         | 6           | 3 |
|          | LS      | 10:1 (4:1)      | 240 ± 55  | -3.91 ± 0.01 | -3.85     | 6         | 6           | 3 |

a Extra sum-of-squares F-test indicates a preferred biphasic fit: F1,51 = 11.8; p < 0.0001.

b The concatenated version of this all-position-mutated HS isoform had an Imax of 6 ± 1 nA (n = 22) and an ACh CRC (log10 M) EC50 = −3.98 ± 0.01 (n = 10).

c The concatenated version of this all-position-mutated LS isoform was non-functional.

TABLE 3

E-loop mutation effects on ACh-mediated function in unlinked HS and LS α4β2-nAChR isoforms

Oocytes were injected with biased ratios of RNA encoding unlinked wt, α4VFL, or β2HQT subunits to generate predominantly HS (α4)(β2)2- or LS (α4)(β2)2-nAChR isofoms (see “Experimental Procedures” for details). ACh-activated Imax and CRC log10 (M) EC50 values collected in this study are shown in regular font. Previously published (34) injection ratios and pharmacological parameters generated from nAChR containing the indicated wt or E-loop mutant subunits are shown (in parentheses and italicized) for comparison, where possible; ND = not determined. Numbers of oocytes tested are shown for both our, and the previously-published, results.

Mutant E-loop Effects on α4β2-nAChR CRCs Are Similar between ACh and Nicotine—To determine whether the effects of E-loop mutations on ACh potency were unique, or whether they might be more generalizable, we performed an equivalent set of CRC experiments for nicotine (Fig. 9 and Table 4). Although nicotine is less discriminating between HS and LS phase function than ACh (24), very similar outcomes were clearly visible (compare outcomes in Fig. 9 to those in Figs. 2 and 6). Mutant constructs that exhibited increased ACh potency also showed increased nicotine potency. Mutant constructs that exhibited decreased ACh potency also did so for nicotine. Most compellingly, the position-1 β2HQT HS back-bone variant showed a significantly shallower Hill slope for nicotine activation and a significantly decreased log10 EC50 value. These are indicators of a composite CRC containing a new nicotine-evoked response component with lower nicotine sensitivity compared with the parent construct (as seen for the same construct when stimulated with the more HS versus LS phase-discriminating agonists ACh and A-85380 (Figs. 2 and 3).

FIGURE 8. α4VFL E-loop mutation effects on peak ACh-induced function (Imax) and nAChR surface expression within HSP concatemers. Oocytes expressing concatenated HSP constructs incorporating one or two copies of the α4VFL E-loop mutant subunit were screened for maximal ACh current responses, followed by 125I-mAb 295 binding to determine surface nAChR expression. All results were normalized to the unmutated HSP control per panel; see Table 2 for the exact number of experiments performed in each case). A, Imax was reduced in all three of the α4VFL mutant constructs in a copy-dependent, position-independent manner with both single copies reduced ~75%, and the double copy showed a 95% functional loss versus the HSP control. B, surface nAChR expression levels were reduced 60–75% in all three of the HSP α4VFL mutants. C, function per surface nAChR retained copy dependence and position independence for all mutant constructs as in A. Both α4VFL single copy constructs had similar reductions of function per receptor but did not quite reach statistical significance versus the level of non-mutated HSP function. The double copy variant saw a significant ~75% drop in function. One-way ANOVA was performed as described in the legend to Fig. 5 and determined that significant differences existed between groups in each panel. Post hoc comparisons were made using the Bonferroni correction; differences from the unmuted LSP control are noted as follows: *, p < 0.05; **, p < 0.01; ***, p < 0.001.

are capable of accurately replicating the salient functional pharmacological features of HS and LS α4β2-nAChR isofoms. To test this point further, we compared results from the concate-
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**Discussion**

**Major Findings, Differentially Functional Effects of Mutating Nominally Identical $\alpha_4(+)/(−)\beta_2$ Agonist Binding Pockets; Dependence on HSP Versus LSP Background**—In a pioneering study, it was first noted explicitly that LS isoform $\alpha_4\beta_2$-nAChR produce a small proportion of intrinsic HS-like function (34). Our subsequent finding was that this fraction of HS phase function produced by the LS isoform was similar in terms of function per receptor to the entire response of HS isoform $\alpha_4\beta_2$-nAChR (36). These data suggested that HS phase function in both $\alpha_4\beta_2$-nAChR isoforms may be produced by activation of the pair of $\alpha_4(+)/(−)\beta_2$ interfaces common to each isoform. This concept was reinforced by two further observations (36). First, HS phase function could be selectively eliminated by presensitization with the strongly HS activation-preferring compounds sazetidine-A and A-85380. Second, mutations at desensitization with the strongly HS activation-preferring nAChR (36). These data suggested that HS phase function in both $\alpha_4\beta_2$-nAChR isoforms is produced by activation of the pair of $\alpha_4(+)/(−)\beta_2$ interfaces common to each isoform. This possibility arises because the environments in which the agonist sites are found are not identical; subunits that contribute the $\alpha_4(+)/(−)\beta_2$ agonist-binding sites are surrounded by different neighbors. Please note that because our experiments with ACh and nicotine both produced very similar outcomes, we will henceforth predominantly discuss our data obtained with ACh, for the sake of clarity. An overview of our major findings is presented in Fig. 10. It illustrates that insertion of the E-loop mutant at one or the other of the two apparently equivalent $\alpha_4(+)/(−)\beta_2$ agonist-binding sites in the HS $\alpha_4\beta_2$-nAChR isoform produces different changes in ACh sensitivity and/or levels of function per surface nAChR. We also demonstrate that nominally identical changes made at the same $\alpha_4(+)/(−)\beta_2$ interfaces in the LS $\alpha_4\beta_2$-nAChR isoform give markedly different functional outcomes from those seen on the HS isoform background. We conclude that the two conserved $\alpha_4(+)/(−)\beta_2$ agonist-binding sites contribute differently to HS $\alpha_4\beta_2$-nAChR isoform function and between LS and HS $\alpha_4\beta_2$-nAChR isoforms.

As outlined in the Introduction, our hypothesis stated that the two canonical agonist-binding sites might contribute differentially to activation (both within each isoform and between the two isoforms). This possibility arises because the environments in which the agonist sites are found are not identical; subunits that contribute the $\alpha_4(+)/(−)\beta_2$ agonist-binding sites are surrounded by different neighbors. Please note that because our experiments with ACh and nicotine both produced very similar outcomes, we will henceforth predominantly discuss our data obtained with ACh, for the sake of clarity. An overview of our major findings is presented in Fig. 10. It illustrates that insertion of the E-loop mutant at one or the other of the two apparently equivalent $\alpha_4(+)/(−)\beta_2$ agonist-binding sites in the HS $\alpha_4\beta_2$-nAChR isoform produces different changes in ACh sensitivity and/or levels of function per surface nAChR. We also demonstrate that nominally identical changes made at the same $\alpha_4(+)/(−)\beta_2$ interfaces in the LS $\alpha_4\beta_2$-nAChR isoform give markedly different functional outcomes from those seen on the HS isoform background. We conclude that the two conserved $\alpha_4(+)/(−)\beta_2$ agonist-binding sites contribute differently to HS $\alpha_4\beta_2$-nAChR isoform function and between LS and HS $\alpha_4\beta_2$-nAChR isoforms.

**FIGURE 9. Nicotine concentration-response profiles for the β2HQT and α4VFL E-loop mutant series of concatenated LS and HS α4β2-nAChR isoforms.** Oocytes expressing concatenated LSP (A) or HSP (B) constructs incorporating one or more copies of the β2HQT E-loop mutant subunit (position(s) indicated by β2HQT) were acutely stimulated with the indicated range of nicotine concentrations. Responses were normalized to the maximum current measured for each individual oocyte. Corresponding CRC data are shown for concatenated LSP (C) or HSP (D) constructs incorporating one or more copies of the α4VFL E-loop mutant subunit (position(s) indicated by α4VFL). Details of the obtained pharmacological parameters and the statistical analysis used to compare results are provided in Table 4. Data points represent the mean ($±$ S.E.) of at least six oocytes (numbers provided in Table 4). CRCs obtained using wild-type LSP (■) and HSP (△) parent constructs are included in both graphs for ease of comparison within and between isoforms.
TABLE 4
Effects of introducing β2HQT or α4VFL E-loop mutant subunits into the LSP and HSP αβ2 nAChR concate

Oocytes injected with RNA encoding concatenated LSP or HSP αβ2 nAChR constructs containing zero (LSP or HSP controls), one, or more copies of the β2HQT or α4VFL subunits at the position(s) shown in blue or orange type, respectively, were used in conjunction with two-electrode voltage clamp to establish and analyze nicotide CRCs (see Fig. 9, “Experimental Procedures”). Pharmacological parameters were determined as previously described for ACh, and are presented as means ± S.E. Numbers of oocytes tested for each parent construct or variant are indicated, and data were collected across three biological replicates. Because nicotine is less discriminating than ACh, none of the CRCs could be fit using a two-site model (fits would not converge). Accordingly, single-site fits were applied to data from all constructs. The resulting Hill slope values were uniformly close to 1, with the exception of HSP β2HQT position 1 (0.73 ± 0.09 versus. 1.06 ± 0.10 for unmodified HSP; p = 0.037 by Student’s t test).

| Contenter (β2HQT variants) | Nicotine log(E80) (M) | n | Concentrator (α4VFL variants) | Nicotine log(E80) (M) | n |
|-----------------------------|------------------------|---|--------------------------------|------------------------|---|
| β2aeβ2α4aα4e (LSP)          | -5.43 ± 0.06           | 9 | β2aeβ2α4aα4e (HSP)            | -6.35 ± 0.11           | 8 |
| β2aeβ2α4aα4e                | -6.43 ± 0.04***        | 6 | β2aeβ2α4aα4e                 | -6.39 ± 0.08           | 7 |
| β2aeβ2α4aα4e                | -7.76 ± 0.04**         | 10| β2aeβ2α4aα4e                | -6.43 ± 0.08           | 6 |
| β2aeβ2α4aα4e                | -4.41 ± 0.03**         | 6 | β2aeβ2α4aα4e                 | -6.38 ± 0.10           | 7 |

**One-way ANOVA was used to determine differences across log(E80) values obtained from β2HQT and α4VFL mutant variants on the HSP and LSP backbones (F1,11,24 = 113.3, p < 0.0001, and F1,17,3 = 127.5, p < 0.0001, respectively).

Post hoc comparisons using the Bonferroni correction were used to identify variant constructs with significantly different log(E80) values compared to those calculated for their parent HSP or LSP backbone constructs.

Introduction of β2HQT subunits has been proved to alter agonist binding at α4(+)/(−)/β2 interfaces, making it resemble more closely binding at an α4(+)/(−)/α4 site (34, 38). In this study, placement of β2HQT mutant subunits into the (−) side of the conserved canonical α4(+)/(−)/β2 agonist binding interfaces produced very similar outcomes in the LSP (α4b2-LSP) isoform. For example, β2HQT insertion into either possible position produced indistinguishable changes in agonist pharmacology and per receptor function. These outcomes indicate that, in partial contradiction of our original hypothesis, the two canonical α4(+)/(−)/β2 agonist-binding sites within the LS isoform α4β2-nAChR likely contribute in similar ways to receptor activation.

However, the same is not true in the context of the HS isoform. Here, β2HQT insertion into the first versus the second concatameric α4(+)/(−)/β2 agonist binding interface resulted in dramatically different ACh CRC outcomes. Effects on per receptor function also differed considerably between these two singly substituted HSP mutants. These results are the first demonstration that, despite the fact that the composition of these canonical α4(+)/(−)/β2 agonist-binding sites is completely conserved, they make significantly different contributions to HS isoform α4β2-nAChR activation. This finding is in marked contrast to the position-independent situation in LS isoform α4β2-nAChR (Fig. 10). Together, these two outcomes confirm our original hypothesis.

Effects of α4VFL Mutant Subunit Introduction, Position and Background Independence—The HSP-α4β2-nAChR construct contains no α4(+)/(−)/α4 interfaces, so no direct effect would be anticipated on agonist binding following introduction of the E-loop α4VFL mutation into α4(+)-interfaces. As shown in Fig. 6B, this expectation was met; CRCs were indistinguishable across all of the α4β2-HSP constructs. Effects on surface expression and per receptor function were noted, and these were symmetrical (Figs. 7 and B and C, and 10). Similar trends were observed for per receptor function.

However, results from the LSP-α4β2-nAChR construct family, all members of which do contain an α4(+)/(−)/α4 interface, were much more surprising. Here, substitution of the α4VFL mutant subunit into any position, or combination of positions, resulted in an identical outcome (Fig. 6A). Similar to the outcome seen in the α4β2-HSP-nAChR context, LSP per receptor function was progressively reduced as the number of α4VFL mutant subunits introduced was increased, and no position dependence was seen (Figs. 7C and 10). These findings are surprising given that the α4(+)/(−)/α4 interface within the α4β2-LS-nAChR isoform has been shown directly, by multiple approaches, to correspond to an agonist-binding site (35, 36). From these findings, we conclude that α4(−)-face E-loop contributions to α4β2-nAChR function are principally allosteric at both isoforms (rather than being dominated by direct interactions with ACh at the α4(+)/(−)-α4-binding site, in the context of the LS isoform). This is not to imply that other parts of the α4(+)/(−)-α4-binding site do not directly interact with ACh or other agonists; in fact our work and the work of others indicates that they do (35–37).

Value of Using Tethered nAChR Pentamers and nAChR Cell Surface Binding Assays—The concatenated nAChR subunit approach offers substantial advantages in terms of expressing completely defined nAChR subtypes, including difficult-to-combine subunits (39, 40, 44). It also allows site-directed mutagenesis to be targeted to particular subunits when multiple copies are present in a pentameric complex (35–37). As shown in Tables 1–3, functional parameters are very similar across all comparable nAChR compositions, whether expressed from linked or unlinked subunits. Critically, this validates the utility of concatameric nAChR as a model in our studies of position-by-position subunit manipulation and our central discoveries revealed by systematic nAChR subunit interface alterations.

This study also illustrates the importance of measuring the effects of subunit mutation on cell surface expression of pure nAChR populations. Without the ability to normalize for cell surface nAChR expression, interpretation of differences between constructs in ion channel function per se would not be possible.

Although it is certainly true that precise interpretation of structure-activity relationships using only macroscopic CRCs can be problematic (48), previously published results allow us to make predictions. Changes in function per receptor must arise from altered single-channel conductance and/or open probability. A previous study of HS and LS isoform single-channel amplitudes indicates that the LS isoform may be associated with higher calculated chord conductance than the HS isoform (29 versus 21 pico siemens, respectively (22)). However, this difference is far less than required to account for the difference in function per receptor for these two isoforms as measured in this study.
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FIGURE 10. Reciprocal E-loop mutations placed within or outside of α4(+)/(−)β2 nAChR agonist binding interfaces reveal intra- and inter-isoform functional differences. An overview is provided of the major findings generated by employing systematic E-loop substitution in concatenated α4β2-nAChR isoforms. In the case of the β2HQT series of concatemers (center columns), E-loop probing revealed differential functional effects of altering nominally identical α4(+)/(−)β2-binding sites within the HSP background (outcomes were strongly dependent on position and copy number for EC50 and Imax/nAChR determinations). Contrasting results were seen following ostensibly identical manipulations performed on the LSP background (outcomes were predominantly position-independent). Conversely, α4VFL subunits placed within either isoform (flanking columns) yielded highly similar results in terms of within and between the HSP and LSP backgrounds. Position and copy independence was observed when considering EC50 values, and position independence and copy dependence were typical features when considering per receptor function. Because functional changes resulting from introduction of the α4VFL mutant subunit were α4(+)/(−)α4 interface-independent, they are likely to be predominantly allosteric in nature, rather than driven by a direct E-loop interaction with agonist at this site.

study (10-fold greater for LS versus HS isoform α4β2-nAChR). Accordingly, we predict that the predominant effect of engaging the α4(+)/(−)α4 allosteric-like site is to increase channel-open probability. This would certainly be compatible with other prior findings. For example, it has been demonstrated that binding to the α4(+)/(−)α4 site is required for full agonist efficacy at LS isoform α4β2-nAChR (37). Furthermore, different parts of the same interface are known to form an allosteric Zn2+ potentiation site (49), and it has been shown that the principal effect of Zn2+ potentiation on α4β4-nAChR is to increase burst duration and therefore open probability (50). Therefore, it seems reasonable to hypothesize that altered open probabilities will also be the predominant factor driving the often large changes in per receptor function that are induced by incorporation of E-loop mutant subunits. This is especially so because E-loop mutations are located far from the channel domain; direct effects on channel conductance would not be anticipated.

General Rules, Broad Contributions of Particular Subunit Interfaces to α4β2-nAChR Function—Some generalizable features are revealed by viewing our findings first in terms of alterations in agonist-recognition subunit interfaces. Nearly every time that an α4(+)/(−)β2 interface is converted to a mock α4(+)/(−)α4 interface, the result is a nAChR with LS-like features (EC50 value ≈60 μM). Conversely, there is never an LS profile for sensitivity to ACh when a natural α4(+)/(−)α4 interface is eliminated in the LSP backbone. These observations confirm and extend previous findings indicating that introduction of β2HQT subunits at α4(+)/(−)β2 interfaces makes them more closely resemble α4(+)/(−)α4 sites with lower ACh sensitivity (34, 38) and that α4(+)/(−)β2 interfaces contribute to higher agonist sensitivity. However, this approach is not sufficient to explain all of the findings of this study. As already discussed, introduction of an α4VFL mutant subunit anywhere in the LS isoform background (not just in the α4(+)/(−)α4 interface) produces a reduction in ACh EC50. In addition, as will be discussed next, this agonist-binding-site-only model is not adequate to explain several more observations.

Exceptions to the General Rules, the Importance of Neighbors and the E-loop—Defining the precisely detailed mechanisms underlying differential α4(+)/(−)β2 agonist site contributions to HS and LS isoform α4β2-nAChR activation (such as changes in binding site affinity, interactions between the multiple binding sites present, and the extent of site-to-site cooperativity) is likely to require a sophisticated and extensive single-channel kinetics analysis, far beyond the scope of this study (48). However, the hypothesis that introducing mutations into the E-loops of α4β2-nAChR isoforms can significantly alter the allosteric activation mechanism of the host nAChR could also apply to β2HQT mutant subunits. In fact, this new hypothesis can explain our further otherwise-surprising observations (in addition to the position independence of the α4VFL subunit’s effects).

In the first example, only the position 1 β2HQT mutant on an HSP backbone exhibits biphasic ACh activation (Figs. 2B and 3). This concatemer and the LSP construct are the only...
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ones featuring an α4(+)/(−)ε4-like agonist binding pocket flanked by unmutated β2 subunits (see inset to Fig. 3 for a circularized representation of the assembled position 1 β2HQT HSP construct). In the second example, a single β2HQT mutant-subunit substitution in either position 3 (where it does participate in an α4(+)/(−)β2 agonist binding pocket) or position 5 (where it does not participate in an agonist-binding site) has no effect on the resulting agonist CRCs (Fig. 2B). However, combining these two mutations, which are individually without effect, results in a substantial loss of agonist potency. This constitutes direct evidence that the E-loop status of a neighboring subunit can affect the functional contribution of a canonical α4(+)/(−)β2 agonist-binding site. It therefore appears that the functional effects of the β2HQT mutation are mediated allosterically in addition to its recently demonstrated effect on agonist binding potency (38). In the third example, and related to the preceding point, function per nAChR in the HSP β2HQT mutant series (Fig. 5) is significantly reduced only if both subunits at the β2(+)/(−)β2 interface are mutated (HSP β2HQTp1p5, and β2HQTp1p3p5). In addition, on the HSP backbone, the presence of just one α4(+)/(−)β2 interface is adequate to yield HS function except in the presence of β2HQTp5 altering the β2(+)/(−)β2 interface. These observations suggest that a wild-type β2(+)/(−)β2 interface is an important factor in HSP function. As a corollary to this observation, the LSP isoform, which lacks a β2(+)/(−)β2 interface, loses all HS component function with just one β2HQT substitution. Our results imply that E-loop allosteric effects constitute an important part of the context that results in otherwise identical α4(+)/(−)β2 agonist-binding sites contributing differentially to nAChR agonist activation both within HS isoform α4β2-nAChR and between the two α4β2-nAChR isoforms.

Interestingly, the current findings dovetail with and also help to explain observations in other studies (of α6β2−nAChR) that pointed to the importance of α6 (−)−face E-loop effects on functional levels and agonist sensitivities (51−53). In those publications, mouse (Asp-143 and Val-145) or human (Asn-143 and Met-145) α6 subunit residues determined in a species-specific manner functional effects of β3 subunit co-assembly into α6ε4-nAChR containing β2 or β4 subunits. These residues are nested between the α4 and β2 subunit E-loop residues that were targeted in this study. A very recent publication (54) also demonstrated interactions of an α4 (−)−face E-loop engineered into the binding pocket of Lymnaea stagnalis acetylcholine-binding protein with a neighboring subunit. These interactions differed according to which particular ligand was bound (at least for compounds that are exceptionally selective between HS and LS phase activation), and appeared likely to impact receptor activation (54). If somewhat analogous interactions occur at interfaces not bound by agonist, this may provide at least a partial mechanistic basis for E-loop involvement in the neighbor effects noted in this study.

Our findings illustrate previously unappreciated complexity in the agonist activation mechanism of α4β2-nAChR, which are a predominant and physiologically important non-muscle nAChR subtype. It seems likely that similar phenomena may be seen in other Cys-loop receptors, given the high degree of structural similarity across members of the superfamily.

Author Contributions—L. M. L. assisted with experimental design and interpretation, engineered the new concatenated nAChR constructs used in this study, performed electrophysiology experiments, and assisted with manuscript preparation (including figures and tables). M. M. W. and J. B. E. performed electrophysiology experiments and assisted with manuscript preparation (including figures and tables). J. F. C. produced 125I-mAb 295 and provided essential guidance on experimental design. J. M. L. assisted with manuscript drafting and provided critical revision of its content. R. J. L. assisted with experimental design and interpretation and with manuscript writing and revisions. P. W. conceived and coordinated the study, performed the 125I-mAb 295 binding experiments, and (with advice and counsel from the other authors) was principally responsible for data interpretation and manuscript writing. All authors reviewed the results and approved the final version of the manuscript.

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References

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

2. Marks, M. J., Laverty, D. S., Whiteaker, P., Salminen, O., Grady, S. R., McIntosh, J. M., and Collins, A. C. (2010) John Daly’s compound, epibatidine, facilitates identification of nicotinic receptor subtypes. J. Mol. Neurosci. 40, 96−104

3. Lindstrom, J. M. (2003) Nicotinic acetylcholine receptors of muscles and nerves: comparison of their structures, functional roles, and vulnerability to pathology. Ann. N. Y. Acad. Sci. 998, 41−52

4. Cordero-Erausquin, M., Marubio, L. M., Klink, R., and Changeux, J. P. (2000) Nicotinic receptor function: new perspectives from knockout mice. Trends Pharmacol. Sci. 21, 211−217

5. Steinlein, O. K. (2001) Genes and mutations in idiopathic epilepsy. Am. J. Med. Genet. B 106, 139−145

6. Picciotto, M. R., Zoli, M., Léna, C., Bessis, A., Lallemend, Y., Le Novère, N., Vincent, P., Pich, E. M., Brület, P., and Changeux, J. P. (1995) Abnormal avoidance-learning in mice lacking functional high-affinity nicotine receptor in the brain. Nature 374, 65−67

7. Govind, A. P., Vezina, P., and Green, W. N. (2009) Nicotinic-induced up-regulation of nicotinic receptors: underlying mechanisms and relevance to nicotine addiction. Biochem. Pharmacol. 78, 756−765

8. Dani, J. A., and Bertrand, D. (2007) Nicotinic acetylcholine receptors and nicotinic cholinergic mechanisms of the central nervous system. Annu. Rev. Pharmacol. Toxicol. 47, 699−729

9. Stitzel, J. A. (2008) Naturally occurring genetic variability in the nicotinic acetylcholine receptor α4 and α7 subunit genes and phenotypic diversity in humans and mice. Front. Biosci. 13, 477−491

10. Levin, E. D., McClesney, F. J., and Rezvani, A. H. (2006) Nicotinic effects on cognitive function: behavioral characterization, pharmacological specification, and anatomic localization. Psychopharmacology 184, 523−539

11. Hurst, R., Rollem, H., and Bertrand, D. (2013) Nicotinic acetylcholine receptors: from basic science to therapeutics. Pharmacol. Ther. 137, 22−54

12. Coe, J. W., Brooks, P. R., Vetelino, M. G., Wirtz, M. C., Arnold, E. P., Huang, J., Sands, S. B., Davis, T. L., Lebel, L. A., Fox, C. B., Shrikhande, A.,
Unequal α4(+)/(--)/β2 Nicotinic Receptor Agonist Site Effects

Heym, J. H., Schaeffer, E., Rollema, H., Lu, Y., et al. (2005) Varenicline: an α4β2 nicotinic receptor partial agonist for smoking cessation. J. Med. Chem. 48, 3474–3477

Rollema, H., Coe, J. W., Chambers, L. K., Hurst, R. S., Stahl, S. M., and Williams, K. E. (2007) Rationale, pharmacology and clinical efficacy of partial agonists of α4β2 nACh receptors for smoking cessation. Trends Pharmacol. Sci. 28, 316–325

Hutchison, K. E., Allen, D. L., Filbey, F. M., Jepson, C., Lerman, C., Benowitz, N. L., Stitzel, J., Bryan, A., McCaig, J., and Haughey, H. M. (2007) CRHNA4 and tobacco dependence–from gene regulation to treatment outcome. Arch. Gen. Psychiatry 64, 1078–1086

Voinekos, S., De Luca, V., Mensah, A., Vincent, J. B., Potapova, N., and Kennedy, J. L. (2007) Association of α4β2 nicotinic receptor and heavy smoking in schizophrenia. J. Psychiatry Neurosci. 32, 412–416

Saccone, N. L., Schwantes-An, T. H., Wang, J. C., Grucza, R. A., Breslau, A. C., and Marks, M. J. (2008) Partial deletion of the nicotinic cholinergic receptor-α4 subunit genes changes the acetylcholine sensitivity of α4β2 nicotinic acetylcholine receptors in central nervous system disorders. Mol. Pharmacol. 73, 1796–1807

Carbone, A. L., Moroni, M., Groot-Kormelink, P. J., and Bermudez, I. (1991) Neuronal nicotinic acetylcholine-receptors expressed in Xenopus oocytes have a pentameric quaternary structure. J. Biol. Chem. 266, 11192–11198

Kohlihaas, K., Olsen, G. M., and Ahrling, P. K. (2012) Augmentation of cognitive function by MS9283, a stoichiometry-dependent positive allosteric modulator of α2- and α4-containing nicotinic acetylcholine receptors. Br. J. Pharmacol. 167, 164–182

Celie, P. H., van Rossum-Fikkert, S. E., van Dijk, W. J., Brejc, K., Smith, A. B., and Sixma, T. K. (2004) Nicotine and carbamylcholine binding to nicotinic acetylcholine receptors as studied in AChBP crystal structures. Neuron 41, 907–914

Brejc, K., van Dijk, W. J., Smith, A. B., and Sixma, T. K. (2002) in Ion Channels: From Atomic Resolution Physiology to Functional Genomics (Bock, G. and Goode, J. A., eds) pp. 22–32, John Wiley and Sons, Ltd, Chichester, UK

Corry, P. J., Le Novère, N., and Changeux, J. P. (2000) Nicotinic receptors at the amino acid level. Annu. Rev. Pharmacol. Toxicol. 40, 431–458

Xiu, X., Puskar, N. L., Shanata, J. A., Lester, H. A., and Dougherty, D. A. (2009) Nicotine binding to brain receptors requires a strong cation-π interaction. Nature 458, 534–537

Harpsée, K., Ahrling, P. K., Christensen, J. K., Jensen, M. L., Peters, D., and Balle, T. (2011) Unraveling the high- and low-sensitivity agonist responses of nicotinic acetylcholine receptors. J. Neurosci. 31, 10759–10766

Mazzaferrro, S., Benalleuq, N., Carbone, A., Gasparri, F., Vijayan, R., Biggin, P. C., Moroni, M., and Bermudez, I. (2011) Additional acetylcholine (ACh) binding site at α4/β4 interface of α4β2 nicotinic receptor influences agonist sensitivity. J. Biol. Chem. 286, 31043–31054

Ehren, J. B., Lucero, L. M., Stratton, H., Chang, Y., Cooper, J. F., Lindstrom, J. M., Lukas, R. J., and Whiteaker, P. (2014) The unique α4(+)/(--)/α4 agonist-binding site in α4β2 subtype nicotinic acetylcholine receptors permits differential agonist desensitization pharmacology versus the α4β2 subtype. J. Pharmacol. Exp. Ther. 348, 46–58

Mazzaferrro, S., Gasparri, F., New, K., Alcaíno, C., Faundez, M., Iurria-Vasquez, P., Vijayan, R., Biggin, P. C., and Bermudez, I. (2014) Non-equivalent ligand selectivity of agonist sites in (α4β2)2α4 nicotinic acetylcholine receptors: a key determinant of agonist efficacy. J. Biol. Chem. 289, 21795–21806

Ahrling, P. K., Olsen, J. A., Nielsen, E. Ø., Peters, D., Pedersen, M. H., Røhde, L. A., Kastrup, J. S., Shahsavari, A., Indurthi, D. C., Chebib, M., Gajhede, M., and Balle, T. (2015) Engineered α4β2 nicotinic acetylcholine receptors as models for measuring agonist binding and effect at the orthosteric low-affinity α4–α4 interface. Neuropharmacology 92, 135–145

George, A. A., Lucero, L. M., Damaj, M. I., Lukas, R. J., Chen, X., and Whiteaker, P. (2012) Function of human α3β4δ5 α4 nicotinic acetylcholine receptors is reduced by the α5(D398N) variant. J. Biol. Chem. 287, 25151–25162

Moretti, M., Zoli, M., George, A. A., Lukas, R. I., Pistillo, F., Maskos, U., Whiteaker, P., and Gotti, C. (2014) The novel α7β2-nicotinic acetylcholine receptor subtype is expressed in mouse and human basal forebrain: biochemical and pharmacological characterization. Mol. Pharmacol. 86, 306–317

Whiting, P., and Lindstrom, J. (1987) Purification and characterization of a nicotinic acetylcholine-receptor from rat-brain. Proc. Natl. Acad. Sci. U.S.A. 84, 595–599

Lai, A., Parmeswaran, N., Khwaja, M., Whiteaker, P., Lindstrom, J. M., Fan, H., McIntosh, J. M., Grady, S. R., and Quik, M. (2005) Long-term nicotine treatment decreases striatal α6 nicotinic acetylcholine receptor sites and function in mice. Mol. Pharmacol. 67, 1639–1647

Whiteaker, P., Cooper, J. F., Salminen, O., Marks, M. J., McClure-Begley, T. D., Brown, R. W., Collins, A. C., and Lindstrom, J. M. (2006) Immunolabeling demonstrates the interdependence of mouse brain α4 and β2 nicotinic acetylcholine receptor subunit expression. J. Comp. Neurol. 499, 1016–1038

Kuryatov, A., and Lindstrom, J. (2011) Expression of functional human α6β2β3* acetylcholine receptors in Xenopus laevis oocytes achieved through subunit chimeras and concatamers. Mol. Pharmacol. 79, 126–140

Abréo, M. A., Lin, N.-H., Garvey, D. S., Gunn, D. E., Hettinger, A.-M., Wasicak, I. T., Pavlik, P. A., Martin, Y. C., Donnelly-Roberts, D. L., Anderson, D. J., Sullivan, J. P., Williams, M. Arneric, S. P., and Holladay, M. W. (1996) Novel 3-pyridyl ethers with subnanomolar affinity for central neuscience.
ronal nicotinic acetylcholine receptors. J. Med. Chem. 39, 817–825
46. Xiao, Y., Fan, H., Musachio, J. L., Wei, Z. L., Chellappan, S. K., Kozikowski, A. P., and Kellar, K. J. (2006) Sazetidine-A, a novel ligand that desensitizes αβ2 nicotinic acetylcholine receptors without activating them. Mol. Pharmacol. 70, 1454–1460
47. Zwart, R., Carbone, A. L., Moroni, M., Bermudez, I., Mogg, A. I., Folly, E. A., Broad, L. M., Williams, A. C., Zhang, D., Ding, C., Heinz, B. A., and Sher, E. (2008) Sazetidine-A is a potent and selective agonist at native and recombinant αβ2 nicotinic acetylcholine receptors. Mol. Pharmacol. 73, 1838–1843
48. Colquhoun, D. (1998) Binding, gating, affinity and efficacy: the interpretation of structure-activity relationships for agonists and of the effects of mutating receptors. Br. J. Pharmacol. 125, 924–947
49. Moroni, M., Vijayan, R., Carbone, A., Zwart, R., Biggin, P. C., and Bermudez, I. (2008) Non-agonist-binding subunit interfaces confer distinct functional signatures to the alternate stoichiometries of the αβ2 nicotinic receptor: an αα-αβ interface is required for Zn2+ potentiation. J. Neurosci. 28, 6884–6894
50. Hsiao, B., Mihalak, K. B., Magleby, K. L., and Luetje, C. W. (2008) Zinc potentiates neuronal nicotinic receptors by increasing burst duration. J. Neurophysiol. 99, 999–1007
51. Dash, B., Bhakta, M., Chang, Y., and Lukas, R. J. (2011) Identification of N-terminal extracellular domain determinants in nicotinic acetylcholine receptor (nAChR) α6 subunits that influence effects of wild-type or mutant β3 subunits on function of α6β2*- or α6β4*-nAChRs. J. Biol. Chem. 286, 37976–37989
52. Dash, B., and Lukas, R. J. (2012) Modulation of gain-of-function α6*-nicotinic acetylcholine receptor by β3 subunits. J. Biol. Chem. 287, 14259–14269
53. Dash, B., Li, M. D., and Lukas, R. J. (2014) Roles for N-terminal extracellular domain of nicotinic acetylcholine receptor (nAChR) β3 subunits in enhanced functional expression of mouse α6β2β3- and α6β4β3-nAChRs. J. Biol. Chem. 289, 28338–28351
54. Shahsavas, A., Ahring, P. K., Olsen, J. A., Krintel, C., Kastrup, J. S., Balle, T., and Gajhede, M. (2015) AChBP engineered to mimic the α4-β4 binding pocket in αβ2 nicotinic acetylcholine receptors reveals interface specific interactions important for binding and activity. Mol. Pharmacol. 88, 697–707
Differential α4(+)/(−)β2 Agonist-binding Site Contributions to α4β2 Nicotinic Acetylcholine Receptor Function within and between Isoforms
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