

Morantel Allosterically Enhances Channel Gating of Neuronal Nicotinic Acetylcholine $\alpha 3\beta 2$ Receptors

Tse-Yu Wu, Caleb M. Smith, Steven M. Sine, and Mark M. Levandoski

Department of Chemistry, Grinnell College, Grinnell, Iowa (T.Y.W., C.M.S., M.M.L.); and Receptor Biology Laboratory, Department of Physiology and Biomedical Engineering, Mayo Clinic College of Medicine, Rochester, Minnesota (S.M.S.)

Received December 17, 2007; accepted April 29, 2008

ABSTRACT

We studied allosteric potentiation of rat $\alpha 3\beta 2$ neuronal nicotinic acetylcholine receptors (nAChRs) by the anthelmintic compound morantel. Macroscopic currents evoked by acetylcholine (ACh) from nAChRs expressed in *Xenopus laevis* oocytes increase up to 8-fold in the presence of low concentrations of morantel ($\leq 10 \mu\text{M}$); the magnitude of the potentiation depends on both agonist and modulator concentrations. It is noteworthy that the potentiated currents exceed the maximum currents achieved by saturating (millimolar) concentrations of agonist. Studies of macroscopic currents elicited by prolonged drug applications (100–300 s) indicate that morantel does not increase $\alpha 3\beta 2$

receptor activity by reducing slow (≥ 1 s) desensitization. Instead, using outside-out patch-clamp recordings, we demonstrate that morantel increases the frequency of single-channel openings and alters the bursting characteristics of the openings in a manner consistent with enhanced channel gating; these results quantitatively explain the macroscopic current potentiation. Morantel is a very weak agonist alone, but we show that the classic competitive antagonist dihydro- β -erythroidine inhibits morantel-evoked currents noncompetitively, indicating that morantel does not bind to the canonical ACh binding sites.

nAChRs mediate rapid synaptic transmission throughout the central and peripheral nervous systems and are implicated in a wide range of important pathologic conditions, the most pervasive of which is nicotine addiction (e.g., Berrettini and Lerman, 2005). With recent advances in high-resolution structure determination (Brejc et al., 2001; Unwin, 2005), and a clearer understanding of the agonist binding sites (for review, see Sine, 2002) and agonist-mediated conformational changes (e.g., Lyford et al., 2003; Mitra et al., 2004; Lee and Sine, 2005), the prospect of rational drug design applied to nAChRs is becoming a distinct possibility.

The anthelmintic compounds levamisole, pyrantel, and morantel are full agonists of nAChRs in lower species such as nematodes, where they are used widely to clear parasitic infections in livestock (Martin, 1997). However, for mammalian nAChRs, levamisole and pyrantel are generally poor agonists alone (e.g., Rayes et al., 2004) but allosterically

potentiate responses when coapplied with agonist (Levandovski et al., 2003).

A small number of compounds have been shown to potentiate neuronal nicotinic receptors from mammalian species. In addition to the aforementioned anthelmintics, these include curare (Cachelin and Rust, 1994), choline (Zwart and Vijverberg, 2000), and novel compounds such as PNU-120596 (Hurst et al., 2005) and various (2-amino-5-keto) thiazoles (Broad et al., 2006). More extensive work characterizing potentiation has focused on anticholinesterases, primarily physostigmine and galantamine (Pereira et al., 1994; Schrattenholz et al., 1996; Zwart et al., 2000). The diversity of modulator structures and nAChR subtypes represented in these studies suggest allosteric potentiation is a general phenomenon of nicotinic receptors.

However, mechanisms underlying allosteric potentiation and the binding sites involved remain poorly understood. Instead, studies have focused largely on finding new modulatory compounds with subtype specificity (Hurst et al., 2005; Broad et al., 2006). In fact, in the most-studied case of the anticholinesterases, fundamental disagreements remain: Vijverberg and coworkers suggest that these compounds potentiate competitively [i.e., by binding at the canonical acetylcholine (ACh) binding site] (Zwart et al., 2000; Smulders et

This work was supported by a Mellon 8 Sabbatical Award, National Institutes of Health AREA R15-NS043163-01A1 and Research Corporation Cottrell Award CC5765 (to M.M.L.) and National Institutes of Health R37-NS31744 (to S.M.S.).

Article, publication date, and citation information can be found at <http://molpharm.aspetjournals.org>.
doi:10.1124/mol.107.044388.

ABBREVIATIONS: nAChR, nicotinic acetylcholine receptor; PNU-120596, 1-(5-chloro-2,4-dimethoxyphenyl)-3-(5-methylisoxazol-3-yl)urea; ACh, acetylcholine; DH β E, dihydro- β -erythroidine; Mor, Morantel (1,4,5,6-tetrahydro-1-methyl-2-(2-[3-methyl-2-thienyl]ethenyl)pyrimidine, tartrate salt); OR2, oocyte Ringer's medium; SEP-174559, (S)-desmethylopiclone.

al., 2005). In contrast, other groups suggest that these compounds are noncompetitive because physostigmine- and galantamine-evoked single-channel currents are not blocked by the competitive antagonists dihydro- β -erythroidine (DH β E), methyllycaconitine, or α -bungarotoxin (Pereira et al., 1993, 1994; Akk and Steinbach, 2005). Given the use of anticholinesterases to improve cognitive function (e.g., Ferreri et al., 2006), and the potential for developing allosteric modulators as a new class of therapeutic drugs, more work is needed to understand the mechanisms of action and binding sites of this important class of compounds.

We report here studies of the potentiation mechanism of the anthelmintic morantel, elucidated through combined macroscopic and single-channel current recordings. Morantel alone is a very weak agonist of rat nAChRs but substantially potentiates agonist-evoked responses in the low micromolar concentration range. We initially postulated that macroscopic potentiation could be explained by changes in either desensitization kinetics or channel gating. Our results distinguish between these two possibilities and show that morantel potentiates by enhancing channel gating through a binding site distinct from the canonical agonist binding site.

Materials and Methods

Chemicals and Rat Subunit Constructs

All reagents used, unless otherwise noted, were reagent grade and obtained from Sigma (St. Louis, MO). Morantel (Mor), shown as the inset of Fig. 1, is 1,4,5,6-tetrahydro-1-methyl-2-(2-[3-methyl-2-thienyl]ethenyl)pyrimidine, tartrate salt. pGEMHE-based vectors bearing the cDNA for rat α 3 and β 2 subunits were obtained from C. W. Luetje (University of Miami, Miami, FL) and were prepared using standard procedures (Levandoski et al., 2003). cRNA transcripts were made using the T7 mMESSAGE mMACHINE kit from Ambion (Austin, TX).

Oocyte Preparation and Injections

Whole ovaries from *Xenopus laevis* frogs were obtained from Nasco (Ft. Atkinson, WI). Oocytes were prepared from the ovaries as described in Levandoski et al. (2003). After collagenase treatment to remove the follicular cell layer, healthy stage V to VI oocytes were manually selected and maintained at 16°C in Barth medium (88 mM NaCl, 1.0 mM KCl, 2.5 mM NaHCO₃, 0.3 mM Ca(NO₃)₂, 0.41 mM CaCl₂, 0.82 mM MgSO₄, 15 mM HEPES, and 2.5 mM sodium pyruvate, pH 7.6) supplemented with 100 units/ml penicillin/streptomycin (Invitrogen, Carlsbad, CA), and 50 μ g/ml gentamicin (Lonza Walkersville, Inc., Walkersville, MD). Oocytes were injected with 23 ng of total cRNA in 46 nl of solution consisting of an equimolar ratio of both subunits using a Drummond Nanoject and maintained in the Barth antibiotic medium for 2 to 4 days before recording. For most of the single-channel experiments, 6 to 8 ng of cRNA was injected to achieve a lower receptor density. Throughout the text, the number of "donors" refers to the number of oocyte batches prepared from separate frogs.

Electrophysiological Recordings and Analysis

Macroscopic Currents. Drug-evoked currents were measured from injected oocytes using the two-electrode voltage clamp method with a GeneClamp 500B amplifier (Axon Instruments, Foster City, CA). Unless otherwise noted, the membrane potential was held at -60 mV. Oocytes were perfused with oocyte Ringer's medium (OR2; 115 mM NaCl, 2.5 mM KCl, 1.8 mM CaCl₂, and 10 mM HEPES, pH 7.3). Concentrated stocks of the various drugs (in water) were diluted directly in OR2. Recordings were performed in a RC-1Z chamber (Warner Instruments, Hamden, CT) with an incubation volume of

~ 300 μ l and a gravity perfusion flow of 5 to 10 ml/min. The flow of the various drug solutions was controlled using solenoid valves driven by Warner VC-6 valve controllers. Electrodes of resistance 0.5 to 4.0 M Ω were filled with 3 M KCl. Data were acquired on a personal computer using pClamp 9 software, through an Digidata 1322A (Axon Instruments) analog/digital converter.

Measurements of current response for each drug concentration were made one to three times on each oocyte. Applications were typically 5 s, but 10-, 30-, and 100-s applications were also used. After each application, 100- or 200-s washout by continuous perfusion ensured baseline current for at least 30 s before the next application. Most experiments included applications of 100 μ M ACh and 100 μ M ACh + 10 μ M Mor for standardization purposes. No appreciable rundown of the response was observed. Repeat measurements from the same oocyte were averaged; the normalization used depended on the experiment and is described in the figure legends. Data are reported as means \pm S.E.M.

Single-Channel Currents. Cell-attached and outside-out patch recordings from oocytes were made generally according to the methods of Cooper et al. (1996). The vitelline membrane was removed with fine forceps after incubation for ~ 10 min in the standard hypertonic solution. Oocytes were bathed in OR2 for recording. For cell-attached patches, the pipette contained drugs dissolved in the bath solution from concentrated stocks made up in water. For outside-out patch recordings, the pipette was filled with internal solution 80 mM potassium fluoride, 20 mM KCl, 10 mM HEPES, and 10 mM EGTA, adjusted to pH 7.2. Oocytes were placed in 35-mm dishes containing 3.0 ml of bath solution. After forming stable outside-out patches and establishing a membrane potential of -60 mV, recordings for 3 to 4 min in the absence of agonist served as a negative control. An aliquot of a concentrated stock of ACh was then added to the bath, and agonist-evoked currents were recorded only after 5 min had elapsed to allow for diffusion of agonist. This procedure was then used to expose the same patch to morantel in the presence of ACh, again waiting 5 min for diffusion of the drug. We found empirically that this was sufficient time for diffusion by observing a dye in control experiments, as well as by noting steady channel activity after this period. All told, experiments on individual patches lasted 30 – 45 min, with no detectable rundown. This is in contrast to some reports of nAChR single-channel recordings (e.g., Papke and Heinemann, 1991; Hsiao et al., 2008) and may be due to the low ACh concentrations used and the low inherent activity of α 3 β 2 receptors.

Data were sampled at 50 kHz and recorded via Acquire software. To determine unitary conductances, a subset of events (100–300 per record) for each voltage was analyzed using TAC (Bruxton Corp., Seattle, WA) in the track events mode. The resulting amplitude distribution was then fitted to a single Gaussian function using TACFit. Subsequent detailed analysis of patches used the half-amplitude threshold criterion and cubic spline interpolation of the digital signal (Colquhoun and Sigworth, 1985). Open- and closed-time distributions were fitted by maximum likelihood using TACFit. Control experiments included recording from uninjected or sham-injected oocytes. In addition, in 5 outside-out experiments on oocytes expressing receptors, morantel was added before ACh; for morantel alone, events were very infrequent (<0.08 s⁻¹) but increased upon adding ACh to levels observed in the other ACh + Mor experiments. P_{open} values were stable over 5 to 10 min of recording with ACh or ACh + Mor.

In the various recordings for a given experiment, single-channel currents were identified by their conductance and kinetic properties. In most patches, several unitary current amplitudes were observed; we analyzed the predominant form, for which the effect of morantel addition was obvious on inspection. Unitary conductances, determined as the slope of the current-voltage plot for three or four voltages in the range -20 to -100 mV, were 19.3 ± 1.6 pS (range, 11.3 – 30.2; $n = 14$ from five donors) and are in good agreement with those reported for rat α 3 β 2 (Papke and Heinemann, 1991). Closed time distributions were fitted to four exponential components, except

for two patches (at 10 μ M ACh and 10 μ M Mor) that required five components. Open time distributions were fitted to two components. Following previous work (see Mathie et al., 1991; Papke and Heinemann, 1991; Lee and Sine, 2004), burst durations were defined by the point of intersection of the second and third briefest closed-time components (τ_{c2} and τ_{c3} ; Fig. 4A, arrows). This time is dependent on agonist and modulator concentrations, and the closed times shorter than this value are assumed to represent closures of the fully liganded receptor. Critical times ranged from 2 to 8 ms. However, other critical closed times were tested, and the effect of morantel was clear regardless of this choice.

Results

Morantel Greatly Enhances Macroscopic Currents. Morantel, shown in the inset of Fig. 1, substantially increases currents when coapplied with ACh but is a very weak agonist alone. Figure 1 shows a continuous trace for current responses evoked from an oocyte expressing $\alpha 3\beta 2$ receptors. In this recording, a low concentration of morantel (0.3 μ M) enhances the peak response evoked by 10 μ M ACh by 3-fold. Morantel applied alone elicits a negligible response (Fig. 1, peak d and first 100 s of f). We can appreciate the efficacy of morantel by noting that adding 0.3 μ M morantel to 10 μ M ACh (Fig. 1, response c versus b) elicits 45% more current than a 10-fold increase in ACh concentration (Fig. 1, compare responses a versus b).

After a screen of agonists and anthelmintics coapplied to rat neuronal nAChRs, we focused on Mor because of its considerably larger potentiation compared with that of levamisole (Levandovski et al., 2003). For the four receptor types formed by the pair-wise combinations of $\alpha 3$, $\alpha 4$, $\beta 2$, and $\beta 4$ subunits, potentiation by morantel was the largest for $\alpha 3\beta 2$ receptors. For example, in the presence of an EC_{50} concentration of ACh, 10 μ M Mor potentiates responses by 1.5-fold for $\alpha 3\beta 4$ ($n = 5$), compared with 3.2-fold for $\alpha 3\beta 2$ (at 30 μ M ACh; Fig. 2A). We therefore chose to study in detail the action of morantel on $\alpha 3\beta 2$ receptors. We studied rat receptors for consistency with other ongoing studies, but we found that morantel potentiates human $\alpha 3\beta 2$ nAChRs equally well (not shown).

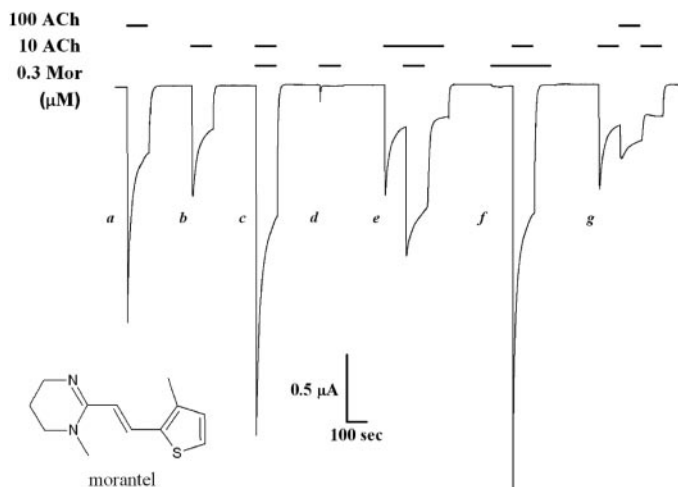


Fig. 1. Morantel does not affect desensitization. A sample continuous current trace for an oocyte expressing $\alpha 3\beta 2$ receptors is shown. Drug applications were for 100 or 300 s when either ACh or morantel was used to “presaturate,” in which case the coapplication was begun after 100 s. The holding potential was -60 mV.

Altered Desensitization Does Not Account for Potentiation. Nicotinic receptors undergo desensitization, a process in which the agonist-evoked current decreases upon

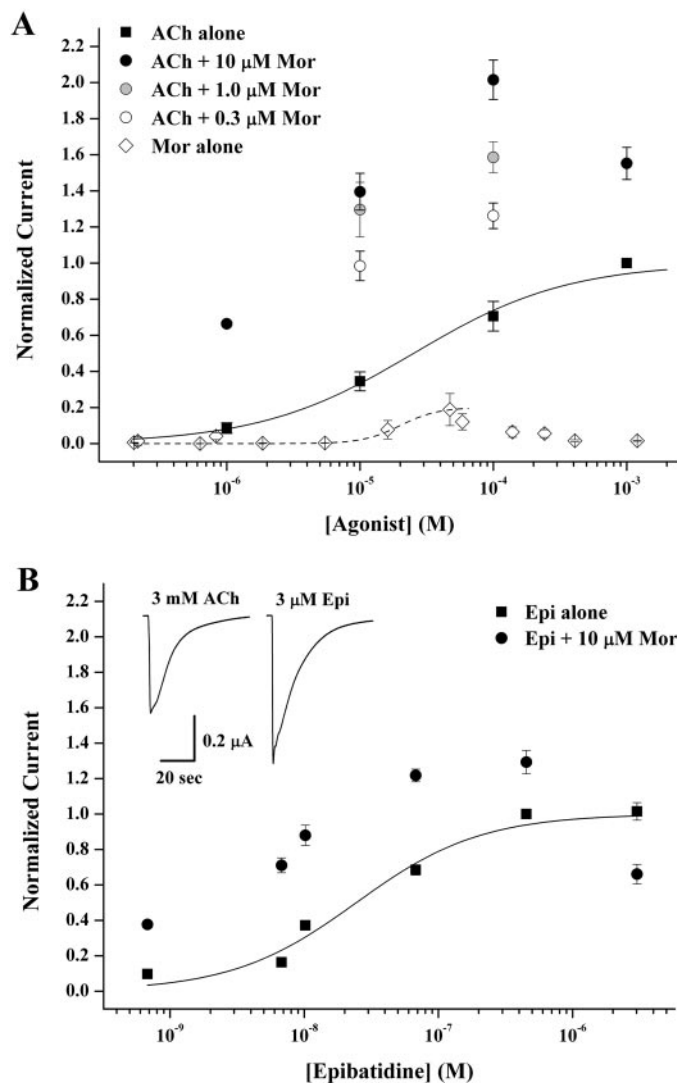


Fig. 2. Morantel potentiates currents at saturating ACh. **A**, oocytes expressing rat $\alpha 3\beta 2$ receptors were challenged with 5- or 10-s applications of ACh or morantel alone as agonist, or as coapplication of ACh and Mor at various concentrations. In one experiment, the peak current responses to increasing ACh concentration alone (■) or with 10 μ M morantel (●) were all normalized to that evoked by 1.0 mM ACh; $n = 4$, two donors. The best fit to the Hill equation is shown as the solid curve through the ACh data, with parameters $EC_{50} = 30 \pm 5$ μ M, $n_H = 0.75 \pm 0.11$. In a separate experiment, oocytes were challenged by coapplication with 0.3 μ M (○) or 1.0 μ M morantel (◐), and the response was normalized to the respective 10 or 100 μ M ACh evoked response. Because in this case 1.0 mM ACh was not used, the current ratios (I_{+Mor}/I_{-Mor}) were corrected for the fractional response elicited by ACh alone, using 0.34 for 10 μ M ACh and 0.71 for 100 μ M ACh; $n = 5$, one donor. In a third experiment, currents elicited by 5-s application of morantel alone at the indicated concentrations were normalized to the response evoked by 100 μ M ACh alone and the data corrected for the fractional response at 100 μ M ACh of 0.71; the best fit to the Hill equation is shown as the dashed curve with $EC_{50} = 20 \pm 2$ μ M, $n_H = 3.1 \pm 1.6$, and fixed $E_{max} = 0.20$. $n = 4$ to 5, two donors. **B**, coapplication experiments, as described in **A**, using epibatidine as the agonist are shown. ■ are epibatidine responses alone, and ● are plus 10 μ M morantel, each normalized to the 0.4 μ M epibatidine response; $n = 5$ to 13, two donors. The best fit to the Hill equation is shown as the solid curve through the epibatidine data, with parameters $EC_{50} = 25 \pm 5$ nM, $n_H = 0.94 \pm 0.17$. The inset shows sample current traces from the same oocyte for maximum responses evoked by a saturating concentration of ACh (left) or epibatidine (right). Values are presented as mean \pm S.E.M.

continued exposure to agonist (Giniatullin et al., 2005). We therefore asked whether morantel potentiates by inhibiting desensitization of $\alpha 3\beta 2$ nAChRs. As seen in the multiple responses from the same oocyte (Fig. 1), the current response decays during continued exposure to agonist for 100 to 300 s, and this decay occurs even in the presence of morantel. The time course of desensitization is best fitted with two exponential terms. As indicated in Table 1 for experiments using 10 μ M ACh and 0.3 μ M Mor (as in Fig. 1), the fitted relative areas and time constants are unchanged in the presence of morantel ($p > 0.2$ for each paired comparison). In addition, the extent of desensitization ($I_{\text{plateau}}/I_{\text{peak}}$) is the same in both cases: 0.32 ± 0.02 for the ACh control and 0.34 ± 0.03 with morantel ($n = 7$). The data in Fig. 1 and Table 1 are from a comprehensive study of desensitization that included four pairs of ACh and morantel concentrations (10 and 100 μ M ACh, 0.3 and 1.0 μ M Mor) and the saturating concentration of 1 mM ACh alone. Across all these conditions, the mean time constants for desensitization ranged from 5 to 10 s and 30 to 100 s for the two exponential terms and are in general agreement with other studies of desensitization in neuronal nAChRs (e.g., Fenster et al., 1997). Although we cannot exclude a minor contribution of enhanced slow desensitization to the potentiation of $\alpha 3\beta 2$ receptors by morantel, this clearly does not account for the manyfold enhancement of macroscopic currents.

The design of the prolonged agonist exposure experiments (Fig. 1) also reveals additional features of morantel potentiation of $\alpha 3\beta 2$ receptors. First, as indicated in the fifth response (Fig. 1, e), morantel can potentiate receptors even after significant decay of the initial peak response. Second, exposure to morantel for 100 s before applying ACh (sixth response; Fig. 1, f) results in a peak response that is larger than for the standard simultaneous coapplication (Fig. 1, response c). For example, in experiments with 10 μ M ACh and 0.3 μ M Mor as in Fig. 1, the "Mor presaturation" response (Fig. 1, i.e., response f) was 25% larger than that elicited by the standard coapplication ($p < 0.01$; $n = 5$). This result suggests that even the macroscopic recordings harbor a kinetic component of morantel potentiation, a full understanding of which requires further study. Most importantly, the experiment in Fig. 1 demonstrates that the responses are robust and that desensitization is readily reversible upon washout. In more than 50 min of recording, the peak current elicited by 10 μ M ACh remains the same (Fig. 1, responses b, e, and g), even after repeated cycles of desensitization and recovery. These observations held true for all experiments of this study using the following combinations of ligand concentrations: 0.3 μ M Mor, 10 μ M ACh [$n = 10$, two donors]; 0.3 μ M Mor, 100 μ M ACh [$n = 11$, two donors]; 1.0 μ M Mor, 10 μ M ACh [$n = 11$, two donors]; 1.0 μ M Mor, 100 μ M ACh [$n = 9$, three donors].

TABLE 1

Sample current decay parameters

Values represent means \pm S.E.M.; $n = 7$ for each measurement. In this experiment, the control was 10 μ M ACh and the coapplication was 10 μ M ACh + 0.3 μ M Mor, delivered in the standard manner (see response c in Fig. 1). Both challenges were for 100 s.

	A1	τ_1	A2	τ_2
		s		s
Control	0.36 ± 0.06	7 ± 2	0.64 ± 0.06	37 ± 4
Coapplication	0.39 ± 0.03	9 ± 2	0.61 ± 0.03	43 ± 5

Morantel Enhances Responses Even at Saturating Concentrations of ACh. To understand morantel potentiation quantitatively, we further explored this enhancement as a function of agonist and modulator concentrations. Figure 2A shows that coapplication of 10 μ M morantel enhances the response to a wide range of ACh concentrations, including the saturating concentration of 1.0 mM, to which all these responses are normalized. Thus, a saturating concentration of ACh alone elicits only a nominal maximum response of $\alpha 3\beta 2$ receptors. A shift in potency also accompanies the morantel effect; in the presence of 10 μ M morantel, the EC_{50} is 5 μ M, a 6-fold decrease relative to ACh alone. Potentiation also depends on the concentration of morantel. For example, in the series 0.3, 1.0, and 10 μ M morantel coapplied with 100 μ M ACh; the currents are 1.3, 1.6, and 2.0 relative to the response evoked by 1.0 mM ACh alone (Fig. 2A).

Morantel, like levamisole and pyrantel, is a potent agonist at nematode muscle-type nAChRs (Martin, 1997). We therefore studied currents from rat neuronal $\alpha 3\beta 2$ receptors elicited by morantel alone. Representative traces for morantel-evoked currents are shown in Fig. 1 (response d and the first 100 s of f) and again in Fig. 5A. The full concentration-response relationship is shown in Fig. 2A (\diamond). The mean maximum response is only ~ 0.2 relative to the ACh maximum. Note that the response decreases at morantel concentrations above 50 μ M; such currents (not shown) display the "rebound" upon washout of the drug that is characteristic of open channel block (e.g., Levandoski et al., 2003). Excluding responses to morantel concentrations above 50 μ M, the data can be fitted by the Hill equation, giving $EC_{50} = 20 \pm 2$ μ M, $n_H = 3.1 \pm 1.6$ (for a fixed $E_{\text{max}} = 0.20$). These measurements show that morantel is a weak partial agonist of $\alpha 3\beta 2$ receptors.

Morantel also potentiates responses evoked by epibatidine, as shown in Fig. 2B. As observed with ACh, the enhancement occurs even at saturating concentrations of epibatidine. However, the relative degree of potentiation is smaller; this dependence of potentiation on the choice of agonist was also observed with levamisole (Levandowski et al., 2003). In side-by-side measurements (e.g., inset of Fig. 2B), we determined that epibatidine is $50 \pm 5\%$ more efficacious than ACh on these receptors ($n = 21$ total, three donors), in agreement with the reduced potentiation by morantel. That ACh and epibatidine responses are both potentiated by morantel at saturating concentrations but to differing degrees suggests an effect on channel gating.

Single-Channel Behavior Reveals the Potentiation Mechanism. Because reduced desensitization does not explain the potentiating effect of morantel on $\alpha 3\beta 2$ receptors, we recorded single-channel currents from cell-free, outside-out patches containing these receptors. After forming the patch and setting the membrane potential to -60 mV, we recorded current for 3 to 4 min in the absence of agonist and morantel and observed no unitary currents (not shown). Upon adding 10 μ M ACh to the bath, unitary currents appeared as mainly brief, single-current pulses or occasionally as groups of closely spaced pulses, flanked by long (>10 ms) closed times (Fig. 3A, top). Addition of morantel to the patch greatly increased the frequency of channel openings, and many of the openings occurred in bursts of several openings in quick succession (Fig. 3A, bottom).

The substantial increase in opening frequency is clear from

the display of the entire experiment, shown in Fig. 3B, which plots the activity in 10-s intervals against recording time. Both the ACh-alone and ACh-plus-Mor recordings are 300 s long (exclusive of the first and last closed times); in the presence of ACh alone, there are 445 openings (total duration, 180 ms), whereas after morantel addition, there are 1518 openings (total duration 1123 ms). It is noteworthy that in agreement with the small macroscopic currents evoked by morantel alone, the increased frequency of single-channel

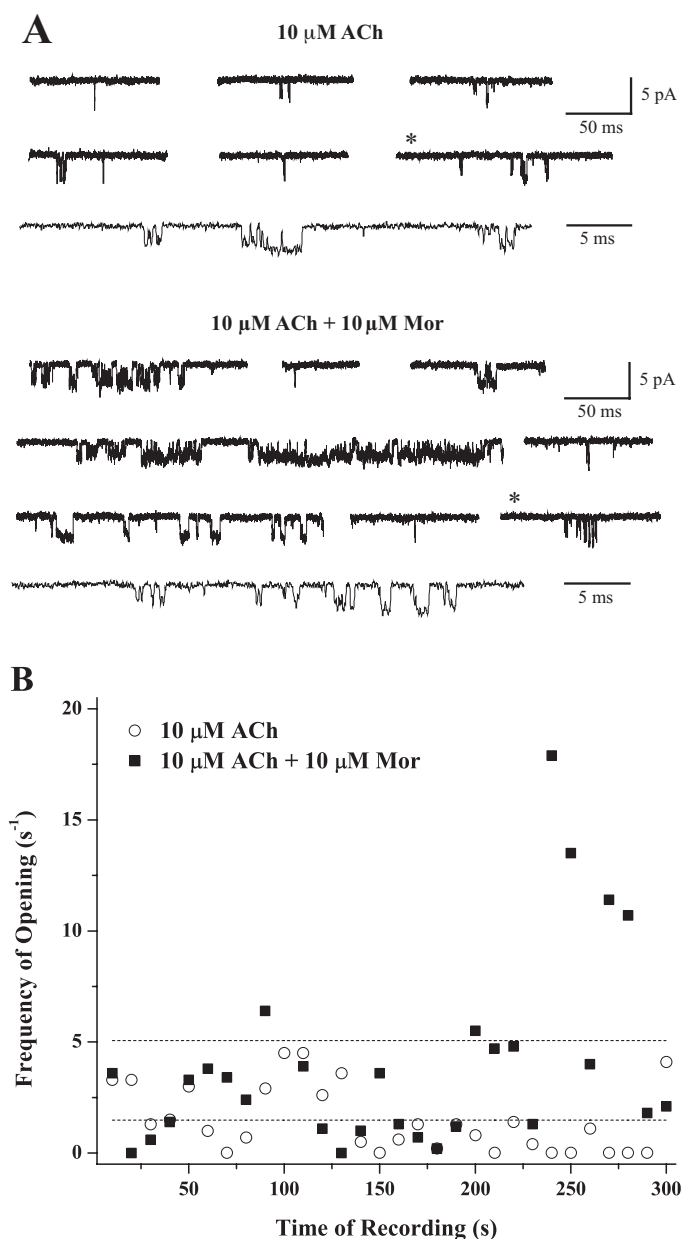


Fig. 3. Morantel increases the frequency of single-channel openings. A, representative single-channel current traces are shown from an experiment using 10 μM ACh alone (top) and with 10 μM morantel added (bottom) to the same outside-out patch held at -60 mV. Traces are not continuous; filtering was at 5 kHz. Downward deflections are the brief openings. The trace marked with * in each set is shown at the higher time resolution as the bottom trace in each set. B, the frequency of channel openings, calculated as averages in 10-s bins to approximate an “instantaneous” measure, is plotted for each entire 300-s recording for the experiment shown in A. The dashed lines indicate the overall average frequencies of 1.5 s^{-1} for ACh alone and 5.1 s^{-1} in the presence of morantel.

openings is not due to a new population of events evoked solely by morantel; in control experiments with 10 μM morantel in the cell-attached configuration ($n = 5$) or applied to outside-out patches in the absence of ACh ($n = 5$), opening frequency was less than 5 per minute.

The increase in single-channel activity upon addition of morantel for all experiments in this study is summarized in Table 2. We quantified potentiation at the single-channel level by taking the ratio $[(\text{ACh} + \text{Mor})/(\text{ACh control})]$ of the total open-state time for a given recording, normalized to the total recording time. The resulting potentiation of single-channel currents is consistent with potentiation of both peak and integrated macroscopic currents (Figs. 1 and 2). For example, 10 μM morantel potentiates single-channel currents elicited by 1.0 μM ACh by a factor of 4, compared with the 6-fold potentiation of peak macroscopic currents. Similar potentiation of ACh-evoked single-channel currents is observed when the ratio of the number of openings per unit time is calculated (not shown). The ratio of macroscopic currents after 100 s of coapplication of 10 μM ACh and 1.0 μM morantel, a condition perhaps more similar to the single-channel experiment is 3.1 ± 0.2 ($n = 11$). The analysis presented here and below is based on 14 patches total. We also observed increased single-channel activity upon addition of morantel to 16 other patches over the four combinations of ACh and morantel concentrations, but we did not analyze these experiments further because of the low frequency of ACh-evoked events (fewer than ~ 100 openings in 5 min of recording).

For the patch in Fig. 3, the unitary current amplitude was 2.06 ± 0.33 pA at -60 mV, and the slope conductance was 12 pS both in the absence and presence of morantel. This observation, true of all our experiments, immediately excludes the possibility that morantel potentiates by increasing the unitary channel conductance.

As noted above, the bursting character of these channels changes upon addition of morantel. Closed time distributions for the representative experiment in Fig. 3 are shown in Fig. 4A. Not surprisingly, given the greater frequency of openings per unit time (Fig. 3B), the closed time distribution shifts toward shorter times in the presence of morantel. Moreover, the relative weights of the fitted exponential components also change, resulting in a greater proportion of the two briefest components of closings, indicating a greater number of openings within bursts (successive openings flanked by closings briefer than a specified critical time) when morantel is present. Relative areas and time constants for the brief closed-time components for all outside-out patch experiments are summarized in Table 3. Although means are tabulated for convenience, in all cases our statistical analysis is a paired comparison t test. The time constant of the second-briefest component (τ_2) decreases approximately 5-fold with either 1.0 or 10 μM morantel, dropping from ~ 10 ms with ACh alone to ~ 2 ms ($p = 0.001$). However, the increase in the summed areas of the two brief components is only significant with 10 μM morantel added ($p = 0.05$).

Changes in the bursts of channel openings mediated by morantel are even more pronounced (Fig. 4B). Bursts are defined to include all openings separated by closures shorter than a specified critical time, which is taken as the point of intersection of the two intermediate closed time components (e.g., $t_{\text{critical}} = 3$ ms for the ACh + Mor case in Fig. 4A, arrow).

Morantel Is a Noncompetitive Ligand. Morantel dramatically enhances agonist-evoked currents, even at concentrations that should yield low saturation of morantel binding. However, the site of morantel binding to the $\alpha 3 \beta 2$ receptor remains unknown. To address the question of where morantel binds, we studied inhibition of morantel-evoked currents

Discussion

That morantel prevents entry into a very rapidly desensitizing state is, however, a formal possibility. A desensitization step with a half-time for onset as long as 0.2 s would be nearly complete, and therefore undetectable, during the 1- to 2-s rise times of our macroscopic currents. The novel compound PNU-120596 (Hurst et al., 2005), which potentiates $\alpha 7$ receptors by decreasing the rate of entry into a desensitized

-Fold potentiation was calculated as the total open time (normalized to total recording time) in the presence of morantel divided by the ACh-alone control recording for outside-out patch experiments. Values represent means \pm S.E.M. for *n* replicates indicated in parentheses.

	Macroscopic					
	Single-Channel Currents		Integrated Areas			
	1 μ M Mor	10 μ M Mor	1 μ M Mor	10 μ M Mor	1 μ M Mor	10 μ M Mor
1 μ M ACh	3.1 \pm 0.6 (3)	4.1 \pm 1.2 (4)	N.D.	6.0 \pm 1.3 (5)	N.D.	8.2 \pm 1.1 (5)
10 μ M ACh	7.9 \pm 2.4 (3)	9.2 \pm 2.2 (4)	3.0 \pm 0.3 (16)	3.8 \pm 0.6 (5)	3.4 \pm 0.3 (5)	3.6 \pm 0.3 (5)

N.D., not determined.

state, provides a precedent for such a mechanism. However, given our observation of enhanced single-channel activity, appealing to fast desensitization to explain the morantel effect is unnecessary.

Morantel potentiation might be explained by enhancement of ligand binding, channel gating, or both. Unlike the mech-

anistic understanding possible for muscle-type nAChRs (e.g., Sine et al., 1990; Zhang et al., 1995; Ohno et al., 1996), detailed kinetic modeling of binding and gating steps has proven difficult for neuronal nAChRs (e.g., Mathie et al., 1991; Papke and Heinemann, 1991). Figure 4A demonstrates that our recordings display at least four closed states and two open states. This kinetic complexity does not allow for analysis according to the classic linear binding-gating scheme (Colquhoun and Sakmann, 1985; Colquhoun and Ogden, 1988), for which, in the limit of low agonist concentration, only two closed states and one open state are expected. Such kinetic complexity, previously observed with neuronal nAChRs (e.g., Mathie et al., 1991), might arise from exceeding the limit of low agonist concentration, especially when morantel is added, or from channels of different subunit stoichiometry in the same patch. Nonetheless, we can use this simple model as a starting point to understand changes in kinetics caused by morantel.

The simplest interpretation of our data is that channel gating improves, direct evidence for which is seen in the number of openings per burst increasing in the presence of morantel (Figs. 3 and 4, Table 4). For a simple linear mechanism, the number of openings per burst is defined by $1 + \beta/k_{-2}$, where β is the channel opening rate and k_{-2} is the rate of dissociation of one molecule of agonist (Colquhoun and Sakmann, 1985). An increase in channel opening rate, a decrease in agonist dissociation rate, or both would increase the number of openings per burst. Consideration of our single-channel and macroscopic current measurements together allows us to distinguish between morantel effects on binding versus gating. We find that morantel increases macroscopic currents evoked by a saturating concentration of ACh by approximately 2-fold (Fig. 2A). In the limit of high ACh concentration, k_{-2} becomes kinetically insignificant, because any agonist dis-

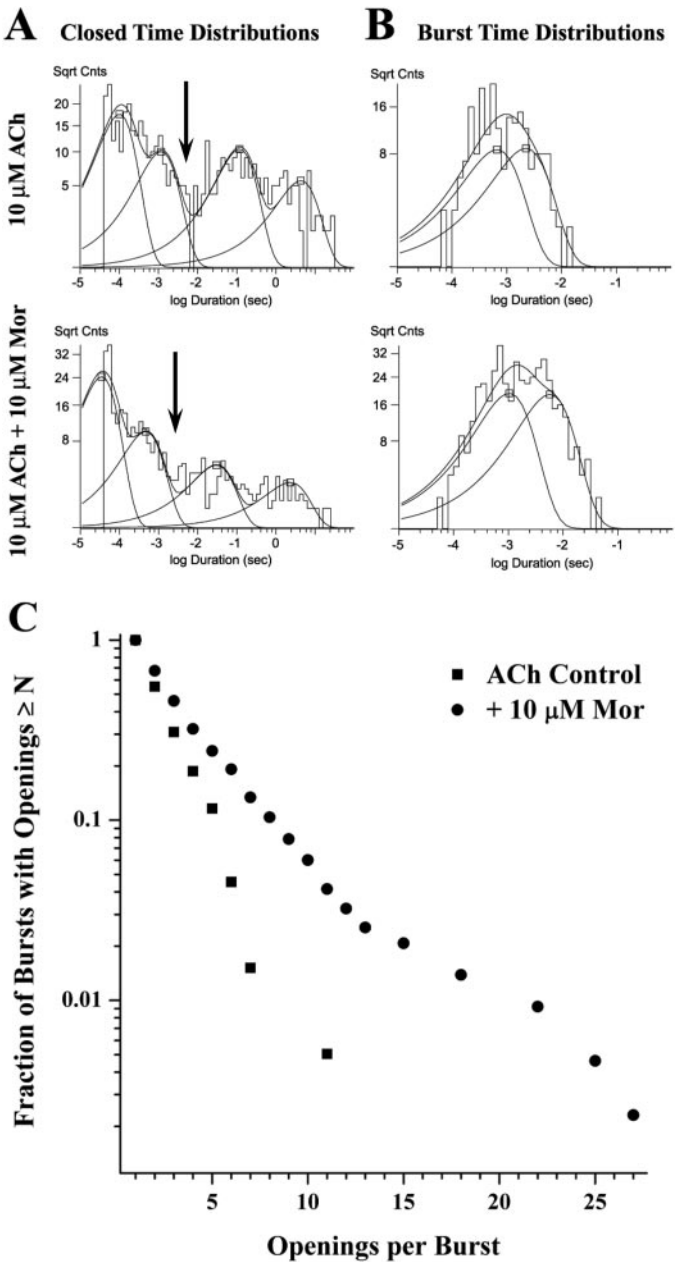


Fig. 4. Morantel increases the bursting behavior of single-channel openings. A, the closed time histograms for the experiment shown in Fig. 3 are given for ACh alone (top) and with morantel (bottom). The four-component fits were as follows (relative area, τ in ms), for 10 μ M ACh alone: 0.385, 0.112; 0.234, 1.12; 0.247, 110; 0.135, 4230; and with 10 μ M Mor: 0.543, 0.052; 0.248, 0.664; 0.128, 47.6; 0.08, 1610. B, the burst time histograms for this same patch are given for ACh alone (top) and with morantel (bottom). The two-component fits were as follows (relative area, τ in ms), for 10 μ M ACh alone: 0.48, 0.669; 0.52, 2.17; and with 10 μ M Mor: 0.57, 1.23; 0.43, 6.37. The arrows in A indicate $t_{\text{critical}} = 3.0$ ms, defining the burst (see Materials and Methods). The ordinate in A and B is the square root of counts per bin. C, the distributions of the number of openings per burst for the two conditions in the experiment are plotted to indicate the difference in bursting character.

TABLE 3
Characteristics of brief closed states
Values represent means \pm S.E.M. for n replicates indicated in parentheses. The quantity A1 + A2 (unitless) is the combined fractional area of the two briefest closed components.

	Control	+ 1 μ M Mor	+ 10 μ M Mor
A1 + A2			
1 μ M ACh	0.49 \pm 0.04 (8)	0.45 \pm 0.11 (4)	0.60 \pm 0.10 (4)*
10 μ M ACh	0.47 \pm 0.05 (7)	0.36 \pm 0.04 (3)	0.59 \pm 0.09 (4)*
τ_1 (ms)			
1 μ M ACh	0.19 \pm 0.04 (8)	0.10 \pm 0.02 (4)*	0.19 \pm 0.04 (4)
10 μ M ACh	0.18 \pm 0.04 (7)	0.09 \pm 0.02 (3)*	0.13 \pm 0.03 (4)
τ_2 (ms)			
1 μ M ACh	10.0 \pm 4.0 (8)	2.1 \pm 0.2 (4)*	2.5 \pm 0.5 (4)*
10 μ M ACh	14.0 \pm 3.8 (7)	1.5 \pm 0.5 (3)*	1.4 \pm 0.5 (4)*

* Significant difference from control in paired t test ($P < 0.05$).

TABLE 4
Burst characteristics
Values represent means \pm S.E.M. for n replicates indicated in parentheses.

	Control	+ 1 μ M Mor	+ 10 μ M Mor
A2			
1 μ M ACh	0.28 \pm 0.03 (8)	0.35 \pm 0.11 (4)	0.36 \pm 0.05 (4)*
10 μ M ACh	0.23 \pm 0.06 (7)	0.23 \pm 0.01 (3)	0.44 \pm 0.03 (4)*
τ_2 (ms)			
1 μ M ACh	3.9 \pm 1.3 (8)	3.6 \pm 1.2 (4)	9.6 \pm 4.4 (4)*
10 μ M ACh	2.9 \pm 0.9 (6)	2.1 \pm 0.3 (3)	8.1 \pm 1.5 (3)*
Openings per burst			
1 μ M ACh	1.7 \pm 0.2 (8)	2.1 \pm 0.6 (4)	3.1 \pm 0.9 (4)*
10 μ M ACh	1.4 \pm 0.1 (7)	1.5 \pm 0.1 (3)	2.6 \pm 0.4 (4)*

* Significant difference from control in paired t test ($P < 0.05$).

sociation event is immediately followed by reassociation, and only the channel gating equilibrium constant, β/α , determines the peak current. The decrease in channel closing rate constant ($\alpha = 1/\tau_{\text{open}}$) in the presence of morantel is modest (70% average over all experiments). Therefore, the potentiation of macroscopic currents seen at saturating ACh concentrations most likely arises from an increased channel opening rate constant.

The probability of channel opening at saturating agonist concentration is given by $P_{\text{open, max}} = \beta/(\alpha + \beta)$ (Colquhoun and Ogden, 1988). Because morantel enhances macroscopic currents even at a saturating concentration of ACh, our data suggest that $\alpha 3\beta 2$ receptors have inherently low gating efficacy, as suggested by Papke and Heinemann (1991). Our observation that morantel enhances epibatidine-evoked cur-

rents to a lesser degree than ACh suggests epibatidine is more efficacious than ACh, in agreement with our finding (Fig. 2B).

Morantel also decreases the EC_{50} for ACh-evoked macroscopic currents by 6-fold (Fig. 2A). This increased potency can be explained by enhanced channel gating (Colquhoun, 1998), which at the single-channel level manifests as an increased frequency of openings and increased bursting character (Fig. 3, Table 2). Our observations do not exclude the possibility that the rate of agonist association increases, or dissociation decreases, in the presence of morantel.

Physostigmine and galantamine are noncompetitive potentiators of several nAChR subtypes (e.g., Pereira et al., 1993; Akk and Steinbach, 2005), but single-channel studies have not examined enhanced activation by both agonist and modulator, probably because these compounds evoke appreciable single-channel currents on their own. The benzodiazepine diazepam increases the frequency of GABA_A receptor single-channel openings with agonist present, but does not increase the duration of any of three observed classes of openings (Rogers et al., 1994). Although benzodiazepines enhance agonist binding and shift the dose-response curves leftward, they do not increase the maximum response at saturating concentrations of GABA, so whether they enhance agonist binding or channel gating remains unresolved (Hevers and Lüddens, 1998). Downing et al. (2005) showed that benzodiazepines enhance GABA_A receptor responses to saturating concentrations of *partial* agonists, accompanied by decreased EC_{50} and increased cooperativity. These findings can be reconciled if GABA is a very efficacious agonist alone, with $P_{\text{open, max}}$ approaching unity, which would mask enhancement of channel gating by benzodiazepines at the single-channel level. Instead, improved channel gating would cause a shift to higher potency (Colquhoun, 1998). In this light, morantel, which increases the frequency of openings *and* the degree of bursting, shifts the agonist potency and increases macroscopic currents at saturating agonist concentrations, because in $\alpha 3\beta 2$ receptors, ACh and epibatidine are not fully efficacious. Thus, benzodiazepines and positive allosteric modulators of nAChRs may operate by a common mechanism.

On the Nature of the Morantel Binding Site. Our understanding of potentiation mechanisms is incomplete without knowing binding site locations. Two main observations from this study suggest morantel does not bind to the canonical ACh binding sites. First, low concentrations of morantel ($\leq 10 \mu\text{M}$, which elicit less than 30% of the maximum response when morantel is applied alone) increase currents evoked by otherwise saturating concentrations of ACh (Fig. 2A). If morantel potentiated by occupying one of the two canonical binding sites while the other was bound with ACh (see Smulders et al., 2005), potentiation would be eliminated at saturating ACh concentrations, contrary to our finding.

More importantly, we tested directly whether morantel competed with DH β E binding, and found that it does not (Fig. 5). In these experiments, ACh and DH β E are competitive at $\alpha 3\beta 2$ receptors, in agreement with previous work (e.g., Harvey and Luetje, 1996), because increasing the ACh concentration surmounts the DH β E inhibition, but increasing the morantel concentration does not.

Our results indicate that morantel is a noncompetitive allosteric modulator. Given the diversity of structures of

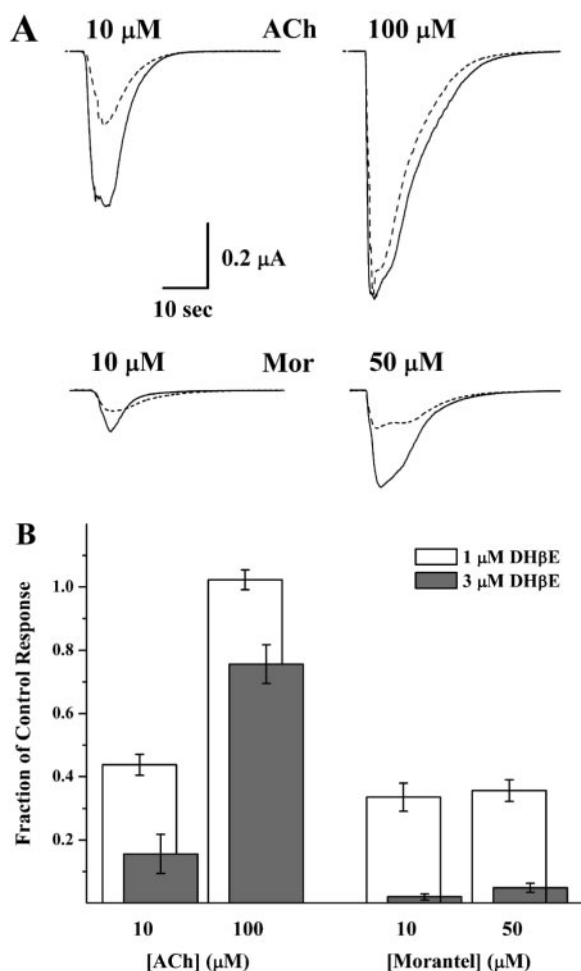


Fig. 5. DH β E inhibits morantel-evoked currents noncompetitively. **A**, currents, all from the same $\alpha 3\beta 2$ -expressing oocyte, evoked by ACh or morantel (solid traces) are overlaid with their pairs, the currents evoked by coapplication of the same concentration and 1.0 μM dihydro- β -erythroidine (DH β E; dashed traces). All applications were 5 s. **B**, collated data of the type shown in **A** are plotted to indicate the degree of inhibition by DH β E [i.e., the fraction of control current remaining upon coapplication with DH β E ($I_{\text{+DH}\beta\text{E}}/I_{\text{agonist alone}}$)]. The open bars are inhibition by 1.0 μM DH β E ($n = 5$, one donor) and the solid bars are inhibition by 3.0 μM DH β E ($n = 8$, one donor, different from the 1 μM experiment). For both experiments, all 8 challenges were given to the entire set of oocytes. The choices of 10 and 50 μM morantel were constrained by the need to have measurable responses both in the absence and presence of DH β E and to avoid the self-inhibition at concentrations $>50 \mu\text{M}$ (see Figure 2A). This 5-fold range constitutes the same relative change in evoked response as the 10-fold range for ACh.

subunit interfaces and modulators, competitive or noncompetitive binding sites for nAChR modulators are formal possibilities. However, noncompetitive modulation has been demonstrated in many systems (e.g., Maelicke and Albuquerque, 2000; Levandoski et al., 2003; Broad et al., 2006). Likewise, SEP-174559 inhibits rat $\alpha 3 \beta 4$ noncompetitively, but without the voltage dependence expected for a channel blocker (Fleck, 2002), which was also observed for clozapine block of $\alpha 7$ receptors (Singhal et al., 2007). We are intrigued by the possibility that disparate ligands act through a common *type* of binding site. We previously hypothesized that levamisole potentiates nAChRs by binding to alternate, noncanonical subunit interfaces based on the conclusion that it does not compete with agonist and on the logical parallel to the benzodiazepine modulators of GABA_A receptors (Levandowski et al., 2003). This idea is further supported by the demonstration that zinc potentiates nAChRs by binding to alternate subunit interfaces and increasing burst duration (Hsiao et al., 2006, 2008), and indirectly by the demonstration that noncompetitive inhibitors bind to subunit interfaces in ACh-binding protein (Hansen and Taylor, 2007). We are pursuing the hypothesis that morantel binds to the noncanonical α/β interface of $\alpha 3 \beta 2$ receptors using chemical modification of cysteines substituted in these regions.

Implications of this Work. Morantel potentiation at saturating ACh or epibatidine concentrations clearly demonstrates that these are partial agonists on $\alpha 3 \beta 2$ receptors, a fact not fully appreciated previously. More work is needed to understand mechanisms of nAChR allosteric potentiators and their binding sites, as well as their partial agonist behavior. If morantel or positive modulators generally bind to alternate interfaces, we must re-examine how such compounds activate nAChRs on their own (e.g., Hogg and Bertrand, 2007), because this challenges the concept that channel gating is activated solely by agonist binding to canonical sites. Given the great promise for drug discovery (Maelicke and Albuquerque, 2000), more low-efficacy nicotinic ligands that potentiate agonist responses are needed, and alternate subunit interfaces offer new possibilities for the design of subtype-specific drugs.

Acknowledgments

M.M.L. thanks the members of the Sine lab for their generosity and support, especially Dr. Won Yong Lee for advice and sharing the rig.

References

- Akk G and Steinbach JH (2005) Galantamine activates muscle-type nicotinic acetylcholine receptors without binding to the acetylcholine-binding site. *J Neurosci* **25**:1992–2001.
- Berrettini WH and Lerman CE (2005) Pharmacotherapy and pharmacogenetics of nicotine dependence. *Am J Psychiatry* **162**:1441–1451.
- Brejck K, van Dijk WJ, Klaassen RV, Schuurmans M, van Der Oost J, Smit AB, and Sixma TK (2001) Crystal structure of an ACh-binding protein reveals the ligand-binding domain of nicotinic receptors. *Nature* **411**:269–276.
- Broad LM, Zwart R, Pearson KH, Lee M, Wallace L, McPhie GI, Emkey R, Hollinshead SP, Dell CP, Baker SR, et al. (2006) Identification and pharmacological profile of a new class of selective nicotinic acetylcholine receptor potentiators. *J Pharmacol Exp Ther* **318**:1108–1117.
- Cachelin AB and Rust G (1994) Unusual pharmacology of (+)-tubocurarine with rat neuronal nicotinic acetylcholine receptors containing $\beta 4$ subunits. *Mol Pharmacol* **46**:1168–1174.
- 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.
- Colquhoun D and Ogden DC (1988) Activation of ion channel in the frog end-plate by high concentrations of acetylcholine. *J Physiol Lond* **395**:131–159.
- Colquhoun D and Sakmann B (1985) Fast events in single-channel currents activated by acetylcholine and its analogues at the frog muscle end-plate. *J Physiol Lond* **369**:501–557.
- Colquhoun D and Sigworth B (1985) Fitting and statistical analysis of single channel records. In: *Single Channel Recording* (Sakmann B, Neher E, eds), pp 191–264, Plenum Publishing, New York.
- Cooper JC, Gutbrod O, Witzemann V, and Methfessel C (1996) Pharmacology of the nicotinic acetylcholine receptor from fetal rat muscle expressed in *Xenopus* oocytes. *Eur J Pharmacol* **309**:287–298.
- Downing SS, Lee YT, Farb DH, and Gibbs TT (2005) Benzodiazepine modulation of partial agonist efficacy and spontaneously active GABA_A receptors supports an allosteric model of modulation. *Br J Pharmacol* **145**:894–906.
- Fenster CP, Rains MF, Noerager B, Quick MW, and Lester RA (1997) Influence of subunit composition on desensitization of neuronal acetylcholine receptors at low concentrations of nicotine. *J Neurosci* **17**:5747–5759.
- Ferreri F, Agbokou C, and Gauthier S (2006) Cognitive dysfunctions in schizophrenia: potential benefits of cholinesterase inhibitor adjunctive therapy. *J Psychiatry Neurosci* **31**:369–376.
- Fleck MW (2002) Molecular actions of (S)-desmethylozoplicone (SEP-174559), an anxiolytic metabolite of zopiclone. *J Pharmacol Exp Ther* **302**:612–618.
- Giniatullin R, Nistri A, and Yakel JL (2005) Desensitization of nicotinic ACh receptors: shaping cholinergic signaling. *Trends Neurosci* **28**:371–378.
- Hansen SB and Taylor P (2007) Galanthamine and non-competitive inhibitor binding to ACh-binding protein: Evidence for a binding site on non-a-subunit interfaces of heteromeric neuronal nicotinic receptors. *J Mol Biol* **369**:895–901.
- Harvey SC and Luetje CW (1996) Determinants of competitive antagonist sensitivity on neuronal nicotinic receptor beta subunits. *J Neurosci* **16**:3798–3806.
- Hevers W and Lüddens H (1998) The diversity of GABA_A receptors. *Mol Neurobiol* **18**:35–86.
- Hogg RC and Bertrand D (2007) Partial agonists as therapeutic agents at neuronal nicotinic acetylcholine receptors. *Biochem Pharmacol* **73**:459–468.
- Hsiao B, Mihalak KB, Repicky SE, Everhart D, Mederos AH, Malhotra A, and Luetje CW (2006) Determinants of zinc potentiation on $\alpha 4$ neuronal nicotinic receptors. *Mol Pharmacol* **69**:27–36.
- Hsiao B, Mihalak KB, Magleby KL, and Luetje CW (2008) Zinc potentiates neuronal nicotinic receptors by increasing burst duration. *J Neurophysiol* **99**:999–1007.
- Hurst RS, Hajós M, Raggenbass M, Wall TM, Higdon NR, Lawson JA, Rutherford-Root KL, Berkenpas MB, Hoffman WE, Piotrowski DW, et al. (2005) A novel allosteric modulator of the $\alpha 7$ neuronal nicotinic acetylcholine receptor: in vitro and in vivo characterization. *J Neurosci* **25**:4396–4405.
- Lee WY and Sine SM (2004) Invariant aspartic acid in muscle nicotinic receptor contributes selectively to the kinetics of agonist binding. *J Gen Physiol* **124**:555–567.
- Lee WY and Sine SM (2005) Principal pathway coupling agonist binding to channel gating in nicotinic receptors. *Nature* **438**:243–247.
- Levandowski MM, Piket B, and Chang J (2003) The anthelmintic levamisole is an allosteric modulator of human neuronal nicotinic acetylcholine receptors. *Eur J Pharmacol* **471**:9–20.
- Lyford LK, Sproul AD, Eddins D, McLaughlin JT, and Rosenberg RL (2003) Agonist-induced conformational changes in the extracellular domain of $\alpha 7$ nicotinic acetylcholine receptors. *Mol Pharmacol* **64**:650–658.
- Maelicke A and Albuquerque EX (2000) Allosteric modulation of nicotinic acetylcholine receptors as a treatment strategy for Alzheimer's disease. *Eur J Pharmacol* **393**:165–170.
- Martin RJ (1997) Modes of action of anthelmintic drugs. *Vet J* **154**:11–34.
- Mathie A, Cull-Candy SG, and Colquhoun D (1991) Conductance and kinetic properties of single nicotinic acetylcholine receptor channels in rat sympathetic neurones. *J Physiol* **439**:717–750.
- Mitra A, Bailey TD, and Auerbach AL (2004) Structural dynamics of the M4 transmembrane segment of during acetylcholine receptor gating. *Structure* **12**:1909–1918.
- Ohno K, Wang HL, Milone M, Bren N, Brengman JM, Nakano S, Quiram P, Pruitt JN, Sine SM, and Engel AG (1996) Congenital myasthenic syndrome caused by decreased agonist binding affinity due to a mutation in the acetylcholine receptor epsilon subunit. *Neuron* **17**:157–170.
- Papke RL and Heinemann SF (1991) The role of the $\beta 4$ -subunit in determining the kinetic properties of rat neuronal nicotinic acetylcholine $\alpha 3$ -receptors. *J Physiol* **440**:95–112.
- Pereira EF, Reinhardt-Maelicke S, Schratzenholz A, Maelicke A, and Albuquerque EX (1993) Identification and functional characterization of a new agonist site on nicotinic acetylcholine receptors of cultured hippocampal neurons. *J Pharmacol Exp Ther* **265**:1474–1491.
- Pereira EF, Alkondon M, Reinhardt S, Maelicke A, Peng X, Lindstrom J, Whiting P, and Albuquerque EX (1994) Physostigmine and galanthamine: probes for a novel binding site on the $\alpha 4 \beta 2$ subtype of neuronal nicotinic acetylcholine receptors stably expressed in fibroblast cells. *J Pharmacol Exp Ther* **270**:768–778.
- Rang HP (1981) Drugs and ionic channels: mechanisms and implications. *Postgrad Med J* **57** (Suppl 1):89–97.
- Rayes D, De Rosa MJ, Bartos M, and Bouzat C (2004) Molecular basis of the differential sensitivity of nematode and mammalian muscle to the anthelmintic agent levamisole. *J Biol Chem* **279**:36372–36381.
- Rogers CJ, Twyman RE, and Macdonald RL (1994) Benzodiazepine and β -carboline regulation of single GABA_A receptor channels of mouse spinal neurones in culture. *J Physiol* **475**:69–82.
- Schrattenholz A, Pereira EF, Roth U, Weber KH, Albuquerque EX, and Maelicke A (1996) Agonist responses of neuronal nicotinic acetylcholine receptors are potentiated by a novel class of allosterically acting ligands. *Mol Pharmacol* **49**:1–6.

- Sine SM (2002) The nicotinic receptor ligand binding domain. *J Neurobiol* **53**:431–446.
- Sine SM, Claudio T, and Sigworth FJ (1990) Activation of *Torpedo* acetylcholine receptors expressed in mouse fibroblasts: single-channel current kinetics reveal distinct agonist binding affinities. *J Gen Physiol* **96**:395–437.
- Singhal SK, Zhang L, Morales M, and Oz M (2007) Antipsychotic clozapine inhibits the function of $\alpha 7$ -nicotinic acetylcholine receptors. *Neuropharmacology* **52**:387–394.
- Smulders CJ, Zwart R, Bermudez I, van Kleef RG, Groot-Kormelink PJ, and Vijverberg HP (2005) Cholinergic drugs potentiate human nicotinic $\alpha 4 \beta 2$ acetylcholine receptors by a competitive mechanism. *Eur J Pharmacol* **509**:97–108.
- Unwin N (2005) Refined structure of the nicotinic acetylcholine receptor at 4 Å resolution. *J Mol Biol* **346**:967–989.

- Zhang Y, Chen J, and Auerbach A (1995) Activation of recombinant mouse acetylcholine receptors by acetylcholine, carbamylcholine and tetraethylammonium. *J Physiol* **486**:189–206.
- Zwart R, van Kleef RG, Gotti C, Smulders CJ, and Vijverberg HP (2000) Competitive potentiation of acetylcholine effects on neuronal nicotinic receptors by acetylcholinesterase-inhibiting drugs. *J Neurochem* **75**:2492–2500.
- Zwart R and Vijverberg HP (2000) Potentiation and inhibition of neuronal $\alpha 3 \beta 4$ nicotinic acetylcholine receptors by choline. *Eur J Biochem* **393**:209–214.

Address correspondence to: Mark M. Levandoski, Department of Chemistry, Box 805, Grinnell College, Grinnell, IA 50112. E-mail: levandos@grinnell.edu
