Structure-Function Studies of Allosteric Agonism at M2 Muscarinic Acetylcholine Receptors

Lauren T. May, Vimesh A. Avlani, Christopher J. Langmead, Hugh J. Herdon, Martyn D. Wood, Patrick M. Sexton, and Arthur Christopoulos

Drug Discovery Biology Laboratory, Department of Pharmacology, Monash University, Clayton, Victoria, Australia (L.T.M., V.A.A., P.M.S., A.C.) and Psychiatry Centre of Excellence for Drug Discovery, GlaxoSmithKline, Harlow, Essex, United Kingdom (C.J.L., H.J.H., M.D.W.)

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ABSTRACT

The M2 muscarinic acetylcholine receptor (mAChR) possesses an increased affinity or proportion of high-affinity sites at the combined EDGE-YT mutation, indicating a different mode of binding to the prototypical modulators. Subsequent functional assays of extracellular signal-regulated kinase (ERK)1/2 phosphorylation and guanosine 5’-[(γ35S)thio]triphosphate ([35S]GTPγS) binding revealed minimal effects of the mutations on the orthosteric agonists acetylcholine (ACh) and pilocarpine but a significant increase in the efficacy of McN-A-343 and potency of 77-LH-28-1. Additional mutagenesis experiments found that these effects were predominantly mediated by Tyr177 and Thr423, rather than the EDGE sequence. Radioligand binding experiments revealed that these effects were predominantly mediated by Tyr177 and Thr423. However, the contribution of these residues to actions of allosteric agonists, as opposed to modulators, is unknown. We created mutant M2 mAChRs in which the charge of the EDGE sequence had been neutralized and each Tyr177 and Thr423 was substituted with alanine. Radioligand binding experiments revealed that these mutations had a profound inhibitory effect on the prototypical modulators gallamine, alcuronium, and heptane-1,7-bis-(dimethyl-3-yl)ammonium bromide (C7/3-phth) but minimal effects on the orthosteric antagonist [3H]methylscopolamine. In contrast, the allosteric agonists 4-[3-chlorophenyl]carbamoyloxy)-2-butynyltrimethylammonium chloride (McN-A-343), 4-n-butyl-1-[4-(2-methylphenyl)-4-oxo-1-butyl] piperidine hydrogen chloride (AC-42), and the novel AC-42 derivative 1-[3-(4-buty1-1-piperidinyl)propyl]-3,4-dihydro-2(1H)-quinolinone (77-LH-28-1) demonstrated an increased affinity or proportion of high-affinity sites at the combined EDGE-YT mutation, indicating a different mode of binding to the prototypical modulators. Subsequent functional assays of extracellular signal-regulated kinase (ERK)1/2 phosphorylation and guanosine 5’-[(γ35S)thio]triphosphate ([35S]GTPγS) binding revealed minimal effects of the mutations on the orthosteric agonists acetylcholine (ACh) and pilocarpine but a significant increase in the efficacy of McN-A-343 and potency of 77-LH-28-1. Additional mutagenesis experiments found that these effects were predominantly mediated by Tyr177 and Thr423, rather than the EDGE sequence. The functional interaction between each of the allosteric agonists and ACh was characterized by high negative cooperativity but was consistent with an increased allosteric agonist affinity at the combined EDGE-YT mutant M2 mAChR. This study has thus revealed a differential role of critical allosteric site residues on the binding and function of allosteric agonists versus allosteric modulators of M2 mAChRs.

Muscarinic acetylcholine receptors (mAChRs) are a group of five family A G protein-coupled receptors (GPCRs) distributed throughout the body (Hulme et al., 1990; Christopoulos, 2007). Drugs targeting mAChRs are currently used in the treatment of chronic obstructive pulmonary disease and urinary incontinence. These receptors also represent potential therapeutic targets for conditions such as Alzheimer’s disease, schizophrenia, and irritable bowel syndrome (Felder et al., 2000; Eglen et al., 2001). To date, however, the widespread development of highly efficacious mAChR therapeutics with acceptable side effect profiles has been limited by a relative lack of ligands with sufficient subtype selectivity (Felder et al., 2000; Eglen et al., 2001).

Allosteric modulation of GPCRs represents a novel therapeutic avenue for overcoming difficulties associated with selective drug targeting (Christopoulos, 2002; May et al., 2007), and may be particularly amenable to mAChRs. Functional and radioligand binding studies have provided evidence for at least two allosteric binding sites on each mAChR subtype (Ellis et al., 1991; Christopoulos et al., 1998; Lazareno et al., 1993).

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ABBREVIATIONS: mAChR, muscarinic acetylcholine receptor; GPCR, G protein-coupled receptor; ATCM, allosteric ternary complex model; McN-A-343, 4-[(N-[3-chlorophenyl]carbamoyloxy)-2-butynyltrimethylammonium chloride; AC-42, 4-n-butyl-1-[4-(2-methylphenyl)-4-oxo-1-butyl] piperidine hydrogen chloride; NMS, N-methylscopolamine; TM, transmembrane domain; 77-LH-28-1, 1-[3-(4-butyl-1-piperidinyl)propyl]-3,4-dihydro-2(1H)-quinolinone; DMEM, Dulbecco’s modified Eagle’s medium; FBS, fetal bovine serum; [35S]GTPγS, guanosine 5’-[(γ35S)thio]triphosphohate; C7/3-phth, heptane-1,7-bis-(dimethyl-3-yl)ammonium bromide; CHO, Chinese hamster ovary; Gpp[NH]p, guanosine 5’-(β,γ-imido)triphosphate; ERK1/2, extracellular signal regulated kinases 1 and 2.
2000), with one of the sites recognized by prototypical mAChR allosteric modulators, such as gallamine, alcuronium, and heptane-1,7-bis(dimethyl-3-phthalimidopropyl)ammonium bromide (C7/3-phth) (Lanzafame et al., 1997). The allosteric interactions mediated by these mAChR modulators are for the most part adequately described by a simple allosteric ternary complex model (ATCM) (Ehler et al., 1988; Lazareno and Birdsall, 1995), with the effects of the modulators largely restricted to either enhancing or inhibiting orthosteric ligand binding affinity; minimal, if any, intrinsic efficacy has been detected for these compounds (but see Zahn et al., 2002).

It is now recognized, however, that some GPCR allosteric ligands have the capacity to affect receptor signaling in the absence of orthosteric agonist (Langmead and Christopoulos, 2006). Such “allosteric agonists” represent an important expansion in the chemical space surrounding allosteric modulators, because they have the potential to modulate orthosteric ligand pharmacology in addition to perturbing cellular signaling in their own right. Two mAChR ligands suggested to act this way are the functionally selective partial agonists McN-A-343 and AC-42 (Fig. 1A). Both compounds have been reported to cause incomplete inhibition of the binding of the orthosteric antagonist [3H]N-methylscopolamine ([3H]NMS) when present at saturating concentrations at rat M2 (McN-A-343) and human M1 (AC-42) mAChRs, as well as retarding [3H]NMS dissociation (Birdsall et al., 1983; Waelbroeck, 1994; Langmead et al., 2006); these phenomena are characteristics of the formation of a ternary complex between the receptor and two concomitantly bound ligands. Despite these observations, it remains to be determined whether the allosteric effects of these agonists are receptor subtype- or species-dependent, what the relationship is between the common allosteric site recognized by prototypical modulators and that recognized by allosteric agonists, and whether both the agonistic and allosteric modulator properties of these latter
compounds are mediated via the same (allosteric) domain on the receptor, or whether they reflect differential interactions with the orthosteric site (agonism) and an allosteric site (modulation).

Using the M₂ mAChR as a model, prior mutagenesis studies have found that the common allosteric site recognized by classic mAChR modulators comprises the second extracellular loop and the top of the third extracellular loop and the top of transmembrane domain (TM) 7; specifically, the highly acidic 172EDGE175 sequence (Leppik et al., 1994), as well as Tyr₁⁷⁷ and the second extracellular loop, Asn₁⁴⁹ at the junction of the third extracellular loop and TM7, and Thr₁⁴³ near the top of TM7 (Fig. 1B) (Voigtländer et al., 2003; Huang et al., 2005). The conserved Trp₁²² in TM7 has also been implicated in the actions of allosteric modulators of mAChRs (Matsui et al., 1995; Prilla et al., 2006). It is noteworthy that most mutations in these regions that affect allosteric modulator binding have minimal effects on binding of orthosteric ligands.

In contrast to the studies on prototypical modulators, there have been no reports to date on the effect of allosteric site mutations on the actions of allosteric agonists. Thus, the aim of the current study was to investigate the mode of action of Mcn-A-343, AC-42, and a novel AC-42 derivative, 77-LH-TGCATACATTCC-3', reverse, 5'-CTGAAATGAGCTCCTGGCAG-3' (QuikChange Multi; single primer); EDGE175: QNGQ: forward, 5'-GCCAGATCTTGCCACACTTC-3' (QuikChange Multi; single primer); EDGE175: QNGQ + Y177A + T423A; forward, 5'-GGGTTGAGACTGCAGAATCCCCTGACATGCGCCATTGACACTCAATG-3' (QuikChange Multi; single primer); T423A: 5'-GCCAACATTGTGGCCAAATGTTCGCTGCTTTG-3' (QuikChange Multi; single primer); 172EDGE175: QNGQ + Y₁⁷⁷A + T₄²³A; forward, 5'-GGGTTGAGACTGCAGAATCCCCTGACATGCGCCATTGACACTCAATG-3' (QuikChange Multi; single primer). Therefore, these fragments were amplified and subsequently cloned into the pEFS/FRT/V5-DEST vector as described above. Oligonucleotides for site-directed mutagenesis and DNA sequencing were purchased from GeneWorks (Hindmarsh, Australia). The primers used for the site-directed mutagenesis reactions are as follows: wild type (with V5 tag): 5'-CATAGGGGCTACAGAAAAAGGTGGGGC-3' (QuikChange Multi; single primer); 172EDGE175: QNGQ: forward, 5'-GGGTTGAGACTGCAGAATCCCCTGACATGCGCCATTGACACTCAATG-3'; reverse, 5'-CTGAAATGAGCTCCTGGCAG-3' (QuikChange Multi; single primer); T₄₂³A: 5'-GCCAACATTGTGGCCAAATGTTCGCTGCTTTG-3' (QuikChange Multi; single primer); 172EDGE175: QNGQ + Y₁⁷⁷A + T₄²³A; forward, 5'-GGGTTGAGACTGCAGAATCCCCTGACATGCGCCATTGACACTCAATG-3' (QuikChange Multi; single primer). Therefore, these fragments were amplified and subsequently cloned into the pEFS/FRT/V5-DEST vector as described above. Oligonucleotides for site-directed mutagenesis and DNA sequencing were purchased from GeneWorks (Hindmarsh, Australia).
buffer (10 mM HEPES, 0.9% NaCl, 0.2% EDTA, pH 7.4 at room temperature) and centrifuged (300g, 3 min). The pellet was then resuspended in buffer A (10 mM HEPES and 10 mM EDTA, pH 7.4, at 4°C) and homogenized as described above. The homogenate was centrifuged (5000g, 10 min, 4°C), the pellet was discarded, and the supernatant was recentrifuged (30000g, 30 min, 4°C). The pellet was resuspended in buffer B (10 mM HEPES and 0.01 mM EDTA, pH 7.4 at 4°C) and centrifuged (30000g, 30 min, 4°C). The resulting pellet was resuspended in 3 ml of buffer B, the protein content was determined, and aliquots were stored as described above.

**[3H]NMS Inhibition or Potentiation Binding Assays.** Membrane homogenates (25 μg) were incubated in a 1-ml total volume of Tris buffer (50 mM Tris Base, 3 mM MgCl₂, and 0.2 mM EDTA, pH 7.4) containing [3H]NMS (0.5 nM) and a range of concentrations of an allosteric modulator to a 500-fold excess of the modulator to a 500-fold excess of the modulator. In particular, to the first set of tubes, 10 μM atropine or 77-LH-28-1 was added to buffer in the presence or absence of atropine (100 μM), pilocarpine (3 nM–300 μM), or McN-A-343 (3 nM–300 μM) at 30°C for 30 min. After this time, 100 μM of [35S]GTPγS (100 PM) was added and incubation continued for another 30 min at 30°C. Termination of reaction and determination of radioactivity were performed as described above.

**[3H]GTPγS Binding Assay.** Membrane homogenates (15 μg) were equilibrated in a 900-μl total volume of [35S]GTPγS assay buffer (10 mM HEPES, 100 mM NaCl, and 10 mM MgCl₂, pH 7.4, at 30°C) containing 10 μM GDP and a range of concentrations of ace-tylcholine (0.3 nM–100 μM), pilocarpine (3 nM–300 μM), or McN-A-343 (3 nM–300 μM) at 30°C for 30 min. After this time, 100 μM of [35S]GTPγS (100 PM) was added and incubation continued for another 60 min at 30°C. Termination of reaction and determination of radioactivity were performed as described above.

**ERK1/2 Phosphorylation Assay.** Cells were seeded into 96-well plates at a density of 50,000 cells/well. After 4 h, cells were washed twice with PBS and maintained in DMEM containing 20 mM HEPES and 50 μM penicillin-streptomycin for at least 4 h before assaying. Assays investigating the time course of action and concentra-tion-response curves were generated by the addition of ligand for the indicated time periods (200-μl final volume) at 37°C. The time of stimulation for concentration-response curves represents the time of peak response as determined in time course assays. Agonist stimulation of cells (5 min unless otherwise specified) was terminated by the removal of media and the addition of 100 μl of SureFire lysis buffer to each well. The plate was then agitated for 1 to 2 min. A 1:4 (v/v) dilution of lysate/SureFire activation buffer was made in a total volume of 50 μl. A 1:100:120 (v/v/v) dilution of AlphaScreen beads/activated lysate mixture/SureFire reaction buffer in a 11-μl total volume was then transferred to a white opaque 384-well Proxiplate in dimmed light. This plate was then incubated in the dark at 37°C for 1.5 h after which time the fluorescence signal was measured by a Fusion-α plate reader (PerkinElmer Life and Analytical Sciences), using standard AlphaScreen settings. All data were expressed as a percentage of the ERK1/2 phosphorylation mediated after a 6-min exposure to DMEM containing 3% FBS.

**Data Analysis.** Data sets of total and nonspecific binding obtained from each [3H]NMS saturation binding assay were globally fitted to the following equation using Prism 4.03 (GraphPad Software, San Diego, CA).

\[
Y = \frac{B_{max} \times [A]}{[A] + K_A} + NS \times [A] \tag{1}
\]

where \(Y\) represents radioligand binding, \([A]\) denotes the concentration of radioligand, \(B_{max}\) denotes the maximal density of binding sites, \(K_A\) is the radioligand equilibrium dissociation constant, and \(NS\) is the fraction of nonspecific binding. The hyperbolic term in this equation was not used when fitting the nonspecific binding data, whereas the parameter \(NS\) was shared between both total and nonspecific binding data sets (Motulsky and Christopoulos, 2004).

Agonist inhibition binding data were empirically fitted to either a one-site (eq. 2) or two-site/state (eq. 3) inhibition mass action curve using Prism 4.03:

\[
Y = \frac{Bottom + Top - Bottom}{1 + 10^{X - LogIC_{50}}} \tag{2}
\]

where \(Top\) is the specific binding of the radioligand in the absence of any competing ligand, \(Bottom\) is the specific binding of the radioligand equal to nonspecific binding, \(IC_{50}\) is the concentration of competing ligand that produces radioligand binding halfway between the \(Top\) and \(Bottom\), and \(X\) is the logarithm of the concentration of the competing ligand.

\[
Y = \frac{Bottom + (Top - Bottom)}{1 + 10^{X - LogIC_{50}}} \times \left(\frac{F_H}{1 + 10^{X - LogIC_{50}}} + \frac{1 - F_H}{1 - 10^{X - LogIC_{50}}} \right) \tag{3}
\]
Y, Top, Bottom, and X are as above for eq 2; \( F_H \) denotes the fraction of receptors inhibiting radioligand binding with a potency described by IC_{50,0}, whereas IC_{50,2} represents the inhibitory potency of the remaining fraction of receptors. In all instances, an extra-sum-of-squares (F test) was used to determine whether the data were better described by a one- versus a two-site model.

Dissociation kinetic data all followed a monoexponential decay and were thus fitted to the following equation using Prism 4.03:

\[
B_t = B_0 \times e^{-k_{off} \times t}
\]  
(4)

where \( t \) denotes incubation time, \( B_0 \) denotes specific radioligand binding at time \( t = 0 \), \( B_0 \) denotes the specific radioligand binding at time \( t \) at equilibrium (time \( t \)), and \( k_{off} \) represents the observed radioligand dissociation rate constant. For the two-point dissociation experiments, the effects of the range of concentrations of allosteric modulators were investigated, individual \( k_{off} \) values determined in the presence of modulator were normalized to the control \( k_{off} \) value (absence of modulator) and then plotted as a function of modulator concentration. The EC_{50,0} value from the fit of a three-parameter logistic equation to these data represents the ratio \( K_{D,0} \) in the ATCM (Lazareno and Birdsell, 1995). In the case of the prototypical modulators gallamine, C7/β-phth, and alcuronium, these two-point kinetic concentration response curves were globally (simultaneously) fitted with the corresponding pseudo-equilibrium binding curves (see below), with the parameters \( K_A \) and \( \alpha \) shared between the data sets.

Pseudo-equilibrium binding data were analyzed by Prism 4.03 according to a kinetic ATCM (Lazareno and Birdsell, 1995; Avlani et al., 2004; Lanzafame et al., 2006). This model explicitly incorporates additional kinetic parameters, such as the dissociation rate constant of the radioligand in the absence and presence of allosteric modulator, and fits the binding as a function of incubation time.

\[
B_t = B_{AH} \times [1 - e^{-k_{obs} \times t}] + B_{BH} \times e^{-k_{obs} \times t}
\]  
(5)

where

\[
k_{obs} = k_{off} \times \left( 1 + \frac{[A]}{K_{APP}} \right)
\]  
(6)

\[
k_{off} = \frac{[B] \times k_{off}}{[B]_{off} + k_{off}}
\]  
(7)

\[
B_{AH} = \frac{[R]_A \times [A]/K_{APP}}{1 + [A]/K_{APP}}
\]  
(8)

\[
B_{BH} = \frac{[R]_B \times [A]/50 \times 1/K_A}{1 + [A]/50 \times 1/K_A}
\]  
(9)

Agonist concentration-response curves were fitted to the following three-parameter-logistic equation using Prism 4.03:

\[
Response = Bottom + \frac{(Top - Bottom)}{1 + 10^{(LogEC_{50} - Log(M)}}
\]  
(10)

where Bottom and Top are the lower and upper plateaus, respectively, of the concentration-response curve, \([A]\) is the molar concentration of agonist, and EC_{50,0} is the molar concentration of agonist required to generate a response halfway between the Top and Bottom.

For combination studies, the interaction between ACh and each of the partial allosteric agonists displayed high negative cooperativity (see Results) and therefore was indistinguishable from a competitive interaction. Consequently, ACh concentration response curves in the absence and presence of the partial agonists, McN-A-343, AC-42, and 77-LH-28-1, were adequately fitted to the following operational model for the competitive interaction between an orthosteric full agonist and orthosteric partial agonist, as derived previously by Leff et al. (1999).

\[
E = \frac{E_{max}([A][K_A + \tau[B][EC_{50}])}{[EC_{50} + [B]]^n + ([A][K_A + \tau[B][EC_{50}])}^n
\]  
(11)

where \( E \) is the pharmacological effect, \( E_{max} \) is the maximal possible response, EC_{50} is the molar concentration of the orthosteric full agonist (\( \alpha \)) required to achieve half-maximal response, \( n \) is the Hill slope of the orthosteric full agonist concentration-response curve, and \( K_A \) and \( \tau \) represent the equilibrium dissociation constant and the operational index of efficacy of the partial agonist (B, respectively). This analysis assumes that 1) the value of \( E_{max} \) and \( n \) derived from the orthosteric full agonist concentration-response curve are approximate estimates of system maximal responsiveness and transducer function slope, respectively, and that 2) both agonists use the same transduction machinery and, as such, the Hill slope can be shared across the full and partial agonist concentration-response curves.

All affinity, potency, efficacy, and cooperativity parameters were estimated as logarithms (Christopoulos, 1998). In all instances, results are expressed as mean ± S.E.M. Statistical analyses were performed by a paired \( t \) test or by \( F \) test, as appropriate, using Prism 4.03, and statistical significance was taken as \( p < 0.05 \).

Results

Characterization of the Binding Properties of [\(^{3}H\)]NMS and Prototypical Allosteric Modulators at Wild-Type and Mutant M2 mAChRs. Previous studies indicating a role for the M2 mAChR residues 172EDGE175, Tyr177 and Thr423 in allosteric modulator binding generally used a substitution approach, whereby these amino acids in the M2 mAChR (highest affinity for prototypical modulators) were swapped to corresponding amino acids in the M2 mAChR (lowest affinity for prototypical modulators) to probe the determinants of modulator subtype-selectivity (see Introduction and references therein). In the current study, we created a different set of mutations in these regions. Specifically, we chose to investigate the impact of neutralizing the charge of the EDGE sequence while maintaining the side-chain structure [i.e., QNGQ ("M2-EDGE" mutant), replacing Tyr^{177} and Thr^{423} with alanine ("M2-YT" mutant) and a combination of the EDGE-QNGQ and Y^{177}A, T^{423}A mutations ("M2-EDGE-YT" mutant)]. As expected, saturation binding assays using the orthosteric antagonist [\(^{3}H\)]NMS found no significant effects of any of the mutations on [\(^{3}H\)]NMS binding affinity relative to the wild-type ("M2-WT") receptor (Table 1). Some variations were noted in the maxi-
mal density of binding sites (although all constructs were well expressed), but this was only statistically significant for the M₂-EDGE mutant (Table 1). In dissociation kinetic experiments, no significant differences were found for the dissociation rate of $[^{3}H]$NMS at any of the mutants relative to the wild type (0.29 ± 0.02 min$^{-1}$; $n = 3$). Thus, it can be concluded that the mutations did not significantly perturb the conformation of the orthosteric binding pocket or the access to or egress from that pocket by the radioligand.

In contrast, Fig. 2 illustrates the dramatic effects of the mutations on the ability of the prototypical modulators, alcuronium, gallamine, and C$_7$/3-phth to interact with $[^{3}H]$NMS in pseudo-equilibrium binding assays. Also shown are the effects of the modulators on $[^{3}H]$NMS dissociation.

**TABLE 1**

Allosteric model binding parameters for the interaction between the orthosteric antagonist $[^{3}H]$NMS and each of three prototypical allosteric modulators at various M$_2$ mAChR mutants.

Values represent the mean ± S.E.M. from three to eight experiments performed in triplicate. $p_K_B$ is the negative logarithm of the equilibrium dissociation constant. $B_{max}$ is the maximal density of binding sites. Log $a$ is the logarithm of the cooperativity factor governing the allosteric interaction between the modulator and $[^{3}H]$NMS.

<table>
<thead>
<tr>
<th>M$_2$ Receptor Construct</th>
<th>Orthosteric Ligand $[^{3}H]$NMS</th>
<th>Allosteric Modulator</th>
<th>Allosteric Modulator</th>
<th>Allosteric Modulator</th>
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<tbody>
<tr>
<td></td>
<td>$p_K_B$</td>
<td>$B_{max}$</td>
<td>$p_K_B$</td>
<td>Log $a$</td>
</tr>
<tr>
<td>M$_2$-WT</td>
<td>9.20 ± 0.20</td>
<td>2.30 ± 0.30</td>
<td>5.96 ± 0.03</td>
<td>0.61 ± 0.03</td>
</tr>
<tr>
<td>M$_2$-EDGE</td>
<td>9.16 ± 0.36</td>
<td>1.00 ± 0.16*</td>
<td>5.56 ± 0.05*</td>
<td>0.64 ± 0.09</td>
</tr>
<tr>
<td>M$_2$-YT</td>
<td>8.80 ± 0.12</td>
<td>2.93 ± 0.96*</td>
<td>4.64 ± 0.07*</td>
<td>0.10 ± 0.02*</td>
</tr>
<tr>
<td>M$_2$-EDGE-YT</td>
<td>8.77 ± 0.28</td>
<td>3.15 ± 0.15*</td>
<td>4.56 ± 0.05*</td>
<td>-0.18 ± 0.03*</td>
</tr>
</tbody>
</table>

* Significantly different ($P < 0.05$) from the wild-type receptor as determined by one-way analysis of variance.
kinetics. Global analysis of both groups of data to a kinetic ATCM yielded the parameters listed in Table 1. Removing the charge of the EDGE mutation while maintaining the essential side-chain structure significantly reduced the affinity of the allosteric enhancer alcuronium as well as that of the allosteric inhibitors gallamine and C7/3-phth. The M2-YT mutant had an even more profound inhibitory effect on modulator affinity. Not surprisingly, the combination of both sets of modulators had the strongest inhibitory effect on modulator affinity. In some instances, the cooperativity between each modulator and [3H]NMS was also significantly changed (Table 1). The combined effect of reductions in modulator affinity and, in some cases, cooperativity, is manifested in the dissociation kinetic assays, where the potency of the compounds to allosterically retard [3H]NMS dissociation is reduced between 10- and 150-fold (Fig. 2). Despite the reduced potency, however, all modulators were still able to completely prevent [3H]NMS dissociation at high concentrations (Fig. 2).

Effects of Orthosteric and Allosteric Agonists on [3H]NMS Inhibition Binding at the M2-WT and M2-EDGE-YT mAChRs. Given that the combined M2-EDGE-YT mAChR mutant had an even more profound inhibitory effect on modulator affinity, at both the M2-WT and M2-EDGE-YT mAChRs. These experiments were performed in the absence of any guanine nucleotides and, as such, it was expected that they could be influenced by the G protein-coupling status of the receptor. At both the M2-WT and M2-EDGE-YT, nonlinear regression analysis of the ACh curves in conjunction with an extra-sum-of-squares test ($F$ test) indicated that these curves were preferentially described by a single shared value for the fraction of receptors exhibiting high-affinity binding. At the M2-EDGE-YT, ACh had a reduced apparent dissociation constant for the high-affinity, presumably G protein-coupled, form of the receptor; a similar trend was noted for the low-affinity binding site, but this was not statistically significant (Table 2). These results suggest that mutations were chosen for comparison with the M2-WT to investigate the effects on agonist binding. As shown in Fig. 3, the orthosteric agonist ACh, as well as McN-A-343, AC-42, and 77-LH-28-1, caused full inhibition of [3H]NMS (0.5 nM) specific binding at both the M2-WT and M2-EDGE-YT mAChRs.

**Fig. 3.** Effects of the combined M2-EDGE-YT mutations on the ability of mAChR agonists to inhibit the binding of [3H]NMS. Inhibition of 0.5 nM [3H]NMS binding at 37°C by ACh (A), McN-A-343 (B), AC-42 (C), or 77-LH-28-1 (D) at M2-WT ( ) and M2-EDGE-YT ( ) mAChRs in membranes from CHO FlpIn cells. The curves superimposed on the data points represent the best global fit of an empirical one- or two-site mass action binding model, as determined by an $F$ test (see Table 2). In each case, data points represent the mean ± S.E.M. obtained from three experiments conducted in triplicate.

**TABLE 2**

<table>
<thead>
<tr>
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<th>M2-WT</th>
<th>M2-EDGE-YT</th>
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<tbody>
<tr>
<td></td>
<td>$pK_B^{(\text{High})}$</td>
<td>$pK_B^{(\text{Low})}$</td>
</tr>
<tr>
<td>ACh</td>
<td>7.08±0.13</td>
<td>5.61±0.17</td>
</tr>
<tr>
<td>McN-A-343</td>
<td>6.14±0.16</td>
<td>4.89±0.08</td>
</tr>
<tr>
<td>AC-42</td>
<td>5.42±0.06</td>
<td>5.42±0.06</td>
</tr>
<tr>
<td>77-LH-28-1</td>
<td>6.23±0.03</td>
<td>6.23±0.03</td>
</tr>
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* Significantly different ($P < 0.05$) from 1.

* Significantly different ($P < 0.05$) from the corresponding control value within the same treatment group.
within the common allosteric site may actually have a small inhibitory effect on orthosteric agonist binding.

In contrast, global nonlinear regression analysis of the McN-A-343 binding curves in conjunction with an F test indicated that the data were best described by sharing both the high- and low-affinity dissociation constants of the two sites, but not the fraction of receptors exhibiting high affinity, which was found to be significantly increased at the M₂-EDGE-YT mAChR (Table 2). For AC-42, the inhibition of [³H]NMS specific binding at both the wild-type and mutant receptor yielded Hill slopes that were not significantly different from 1, but the apparent equilibrium dissociation constant of AC-42 was modestly, but significantly (p < 0.05), increased at the M₂-EDGE-YT mAChR (Table 2). It is noteworthy that the inhibition of [³H]NMS binding by 77-LH-28-1 preferentially fitted to a one-site model at the M₂-WT but a two-site binding model at the M₂-EDGE-YT mAChR (Table 2). Together, these results suggest that, in the absence of guanine nucleotides, the affinity of ACh seems to be slightly reduced, whereas McN-A-343, AC-42, and 77-LH-28-1 trend either toward an increased affinity or increased fraction of receptors exhibiting high affinity at the M₂-EDGE-YT mAChR.

Effects of McN-A-343, AC-42, and 77-LH-28-1 on [³H]NMS Dissociation Kinetics at the M₂-WT and M₂-EDGE-YT mAChRs. To more directly probe the ability of McN-A-343, AC-42, and 77-LH-28-1 to allosterically modulate orthosteric ligand binding, the effect of these compounds on the rate of orthosteric radioligand dissociation was investigated. These experiments were all performed in the presence of 100 μM Gpp(NH)p to reduce receptor-G protein coupling and thus simplify the interpretation of the data. At the M₂-WT mAChR, the presence of McN-A-343 (300 μM; 0.17 ± 0.02 min⁻¹) and 77-LH-28-1 (100 μM; 0.15 ± 0.02 min⁻¹), but not AC-42 (100 μM; 0.22 ± 0.02 min⁻¹), significantly (p < 0.05) retarded the dissociation rate of [³H]NMS (Fig. 4A). These findings suggest that McN-A-343 and 77-LH-28-1 can bind simultaneously with [³H]NMS to the M₂ mAChR to allosterically alter [³H]NMS dissociation. At the M₂-EDGE-YT mAChR, 77-LH-28-1 (100 μM; 0.13 ± 0.06 min⁻¹ versus 0.23 ± 0.02 min⁻¹ for the wild-type) retained the ability to significantly retard [³H]NMS dissociation; a trend was noted for McN-A-343 (0.17 ± 0.02 min⁻¹) as well, but this was not statistically significant at the concentration used (Fig. 4B). To more rigorously investigate the latter, the entire concentration-response relationship of McN-A-343 inhibition of [³H]NMS dissociation kinetics was determined at both the wild-type and mutant mAChRs. At the M₂-WT, McN-A-343 caused virtually complete inhibition of [³H]NMS dissociation (Fig. 4C) and the pEC₅₀ was determined as 3.23 ± 0.05 (n = 4). In contrast, at the M₂-EDGE-YT mAChR, McN-A-343 was unable to cause complete inhibition of [³H]NMS dissociation kinetics and only had a small, albeit significant (p < 0.05), reduction in potency (pEC₅₀ = 2.98 ± 0.05; n = 4; Fig. 4C). This is in contrast to the effects on the prototypical modulators (Fig. 2), which were characterized by substantial reductions in allosteric potency but not maximal effect.

Quantification of the Allosteric Binding Properties of McN-A-343 at the M₂-WT and M₂-EDGE-YT mAChRs. The potency of McN-A-343 to retard the dissociation of [³H]NMS in the kinetic assay reflects the combined effects of both modulator affinity (Kᵦ) and cooperativity with the radioligand (α). To obtain individual estimates of the parameters, a different type of experiment is required. Because of the high negative cooperativity between [³H]NMS and McN-A-343 (Fig. 3B), we exploited the ability of McN-A-343 to slow [³H]NMS dissociation kinetics and to mediate a kinetic artifact in pseudo-equilibrium binding assays with reduced incubation times (20 min). These assays generate two curves, with the only variable between them being whether or not incubation was initiated by the addition of "free" (non-pre-equilibrated) receptor or radioligand-bound (pre-equilibrated) receptor (see Materials and Methods). To ensure that orthosteric ligands do not mediate similar kinetic artifacts, these assays were initially performed using the classic orthosteric antagonist atropine. As shown in Fig. 5A for the M₂-WT mAChR, atropine yielded the expected behavior of a simple competitive orthosteric antagonist, causing complete inhibition of [³H]NMS-specific binding irrespective of the order of ligand-receptor exposure. Nonlinear regression revealed that both curves preferentially fitted to a monophasic isotherm with a Hill slope not significantly different from 1.

Fig. 4. Allosteric agonists can retard the dissociation rate of [³H]NMS from the M₂ mAChR. [³H]NMS dissociation determined in the absence (○) or presence of 300 μM McN-A-343 (●), 100 μM AC-42 (□), and 77-LH-28-1 (▲) at 37°C to M₂-WT (A) or M₂-EDGE-YT (B) mAChRs in membranes from CHO FlpIn cells. C, full concentration-response relationship of the effect of McN-A-343 on the dissociation rate of [³H]NMS at 37°C from the M₂-WT (●) and M₂-EDGE-YT (○) mAChRs. Data represent the mean ± S.E.M. obtained from three to five experiments conducted in duplicate.

For McN-A-343, AC-42, and 77-LH-28-1 on [³H]NMS dissociation kinetics at the M₂-WT and M₂-EDGE-YT mAChRs.
one. When the Hill slope was constrained to one, the estimated $pK_A$ values for atropine were $8.54 \pm 0.03$ and $8.47 \pm 0.07$ for non–pre-equilibrated and pre-equilibrated receptors, respectively ($n = 3$). In contrast, high concentrations of McN-A-343 [in the presence of 100 $\mu$M Gpp(NH)p], caused strikingly divergent effects on the approach of $[^{3}H]$NMS to equilibrium at both the $M_2$-WT (Fig. 5B) and the $M_2$-EDGE-YT (Fig. 5C) mAChRs, clearly indicating a stabilization of a ternary complex between receptor, radioligand, and high concentrations of McN-A-343 that leads to either an overestimation (pre-equilibration) or underestimation (no pre-equilibration) of the level of specific binding over the short assay time period relative to what would be obtained if the system were at equilibrium. A kinetic ATCM, which accounts for additional parameters such as the incubation time and the dissociation rates of $[^{3}H]$NMS from the modulator unoccupied and occupied receptor, was globally fitted to the curves to derive values of $pK_B$ and $\alpha$. Compared with the $M_2$ wild-type mAChR, the affinity of McN-A-343 for the $M_2$-EDGE-YT mAChR had significantly increased negative cooperativity ($\alpha = -1.40 \pm 0.14$ and $-2.37 \pm 0.05$ for the $M_2$ WT and $M_2$-EDGE-YT mAChRs, respectively; $n = 3$) and a trend toward increased affinity ($pK_B$ of 4.70 $\pm 0.17$ and $5.10 \pm 0.01$ for the $M_2$-WT and $M_2$-EDGE-YT mAChRs, respectively; $n = 3$).

**Effects of Allosteric Site Mutations on Agonist Functional Properties.** For initial functional experiments, the time course of ERK1/2 phosphorylation in response to orthosteric and allosteric agonists was determined in nontransfected, $M_2$-WT and $M_2$-EDGE-YT CHO-FlpIn cells. In addition to ACh, the partial agonist, pilocarpine, was included in these studies as a second well characterized orthosteric agonist. None of the ligands tested mediated a significant level of ERK1/2 phosphorylation in nontransfected CHO-FlpIn cells at any time points measured (data not shown). At both the $M_2$-WT and $M_2$-EDGE-YT mAChRs, ACh and pilocarpine mediated a robust stimulation, whereas AC-42 and 77-LH-28-1 mediated a very modest stimulation, of ERK1/2 phosphorylation (Fig. 6). Interestingly, the level of ERK1/2 phosphorylation mediated by McN-A-343 was markedly different at the $M_2$-WT and $M_2$-EDGE-YT mAChRs, with McN-A-343 causing only modest stimulation at $M_2$-WT mAChRs (Fig. 6A) but equivalent stimulation at the $M_2$-EDGE-YT mAChR to that obtained by ACh (Fig. 6B). The time to the peak ERK1/2 phosphorylation was then chosen as the stimulation period for subsequent experiments aimed at characterizing orthosteric and allosteric concentration-response profiles at $M_2$-WT and $M_2$-EDGE-YT mAChRs. The orthosteric agonists, ACh and pilocarpine, mediated a robust stimulation of ERK1/2 phosphorylation at both $M_2$-WT and $M_2$-EDGE-YT mAChRs. The orthosteric agonists, ACh and pilocarpine, mediated a robust stimulation of ERK1/2 phosphorylation at both $M_2$-WT and $M_2$-EDGE-YT mAChRs (Fig. 7A, 7B). Estimates of ACh potency and maximal response were not significantly different between the two receptors (Table 3). However, the maximal response elicited by pilocarpine was modestly but significantly ($p < 0.05$) increased at the $M_2$-EDGE-YT mAChR (Table 3); this likely reflects the slightly higher expression of the $M_2$-EDGE-YT mAChR compared with the $M_2$-WT receptor (Table 1). At the $M_2$-WT receptor, McN-A-343 and 77-LH-28-1 were weak partial agonists with respect to stimulation of ERK1/2 phosphorylation whereas AC-42 had minimal activity (Fig. 7A; Table 3). Interestingly, at the $M_2$-EDGE-YT mAChR, the efficacy of McN-A-343 was profoundly and significantly increased such that at this receptor it behaved as a full agonist (Fig. 7B; Table 3). Given the modest effect noted on pilocarpine maximal response, the

![Fig. 5. McN-A-343 can cause kinetic binding artifacts on $[^{3}H]$NMS pseudo-equilibrium binding. $M_2$ mAChRs were either pre-equilibrated with $[^{3}H]$NMS before addition of unlabeled inhibitor (○) or exposed simultaneously to a high concentration of $[^{3}H]$NMS and inhibitor before dilution and incubation for an additional 20 min (●) at 37°C. Effects of atropine at $M_2$-WT mAChRs (A), McN-A-343 at $M_2$-WT mAChRs (B), and McN-A-343 at $M_2$-EDGE-YT mAChRs (C) in membranes from CHO FlpIn cells. Curves superimposed on the data represent the best global fit of a monophasic inhibition mass action curve (A) or a kinetic ATCM with the following parameter values: $K_a$ = 9.20; $K_B$ = 4.70 ± 0.17; $\alpha = -1.40 \pm 0.14$; $k_{off}$ = 0.29 min$^{-1}$; $k_{off}$ = 0.002 min$^{-1}$ (B); $K_B$ = 8.77; $K_a$ = 5.10 ± 0.01; $\alpha = -2.37 \pm 0.05$; $k_{off}$ = 0.23 min$^{-1}$; $k_{off}$ = 0.04 min$^{-1}$ (C). Values not associated with standard errors were determined in separate experiments and fixed as constants in the current analysis. In each case, data points represent the mean ± S.E.M. obtained from three experiments performed in triplicate.
substantial increase in the efficacy of McN-A-343 is unlikely to simply reflect increased receptor expression. At the M2-EDGE-YT mAChR, AC-42 maintained minimal activity whereas 77-LH-28-1 had a significantly increased potency (Fig. 7B; Table 3); because the latter compound remained a partial agonist, this increase in potency suggests an increase in affinity of 77-LH-28-1 at the mutant receptor. Thus, the functional results support the binding data in suggesting that mutations within the common allosteric site increase the affinity or efficacy of the allosteric agonists McN-A-343 and 77-LH-28-1.

To ensure that the functional effects of the receptor mutations were not influenced by any potential nonequilibrium artifacts associated with the ERK1/2 phosphorylation assay, a second assay measuring ligand mediated [35S]GTPγS binding to activated G proteins was performed with the ligands pre-equilibrated before addition of the radiolabel. In this assay, ACh was a full agonist and pilocarpine a partial agonist at both the M2-WT and M2-EDGE-YT mAChRs (Fig. 7C, 7D). Similar to the ERK1/2 phosphorylation assays, McN-A-343 caused partial stimulation of [35S]GTPγS binding at the M2-WT mAChR but was practically indistinguish-

Fig. 6. Time course of M2 mAChR-mediated ERK1/2 phosphorylation. Effects of ACh (1 μM, ●), pilocarpine (100 μM, ▲), McN-A-343 (100 μM, ○), AC-42 (100 μM, □), and 77-LH-28-1 (100 μM, ■) on ERK1/2 phosphorylation at 37°C in CHO FlpIn cells stably expressing M2-WT (A) or M2-EDGE-YT mAChRs (B). Data points represent the mean ± S.E.M. obtained from three to six experiments conducted in duplicate, apart from pilocarpine, which is the mean from one experiment conducted in duplicate.

Fig. 7. Concordance between effects of M2 mAChR mutation on allosteric agonism at two different signaling pathways. A and B, concentration-response curves to ACh (5-min stimulation, ●), pilocarpine (8-min stimulation, ▲), McN-A-343 (5-min stimulation, ○), AC-42 (8-min stimulation, □), and 77-LH-28-1 (8-min stimulation, ■) mediated ERK1/2 phosphorylation at 37°C in CHO FlpIn cells stably expressing the M2-WT (A) or M2-EDGE-YT mAChRs (B). Data points represent the mean ± S.E.M. obtained from 6 to 12 experiments conducted in duplicate. C and D, concentration-response curves to ACh (●), pilocarpine (▲), and McN-A-343 (○)-mediated stimulation of [35S]GTPγS binding to activated G proteins in FlpInCHO cell membranes stably expressing the M2 wild-type (C) and M2-EDGE-YT (D) mAChRs at 30°C. Data points represent individual means obtained from two experiments conducted in duplicate.

TABLE 3
Estimated potency (pEC₅₀) and maximal agonist effect (Eₐ₅₀) of mAChR agonists at mediating ERK1/2 phosphorylation

<table>
<thead>
<tr>
<th></th>
<th>M2-WT</th>
<th>M2-EDGE-YT</th>
<th>M2-EDGE</th>
<th>M2-YT</th>
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<tbody>
<tr>
<td>Acetylcholine</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>pEC₅₀</td>
<td>7.52 ± 0.12</td>
<td>7.38 ± 0.12</td>
<td>7.64 ± 0.10</td>
<td>7.50 ± 0.09</td>
</tr>
<tr>
<td>Eₐ₅₀</td>
<td>90.8 ± 6.1</td>
<td>105.3 ± 4.3</td>
<td>77.1 ± 6.1</td>
<td>89.3 ± 5.6</td>
</tr>
<tr>
<td>Pilocarpine</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>pEC₅₀</td>
<td>6.16 ± 0.24</td>
<td>5.66 ± 0.06</td>
<td>N.P.</td>
<td>N.P.</td>
</tr>
<tr>
<td>Eₐ₅₀</td>
<td>80.2 ± 5.6</td>
<td>108.3 ± 2.4*</td>
<td>N.P.</td>
<td>N.P.</td>
</tr>
<tr>
<td>McN-A-343</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>pEC₅₀</td>
<td>5.35 ± 0.05</td>
<td>5.53 ± 0.12</td>
<td>5.10 ± 0.12</td>
<td>5.38 ± 0.11</td>
</tr>
<tr>
<td>Eₐ₅₀</td>
<td>18.0 ± 4.1</td>
<td>97.1 ± 4.3*</td>
<td>32.8 ± 8.1</td>
<td>68.0 ± 9.5*</td>
</tr>
<tr>
<td>AC-42</td>
<td></td>
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<tr>
<td>pEC₅₀</td>
<td>N.D.</td>
<td>N.D.</td>
<td>N.D.</td>
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<tr>
<td>Eₐ₅₀</td>
<td>N.D.</td>
<td>N.D.</td>
<td>N.D.</td>
<td>N.D.</td>
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<tr>
<td>77-LH-28-1</td>
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<td></td>
</tr>
<tr>
<td>pEC₅₀</td>
<td>5.87 ± 0.05</td>
<td>6.98 ± 0.15*</td>
<td>5.83 ± 0.53</td>
<td>6.78 ± 0.13*</td>
</tr>
<tr>
<td>Eₐ₅₀</td>
<td>16.8 ± 2.2</td>
<td>27.9 ± 4.7</td>
<td>13.4 ± 2.6</td>
<td>18.2 ± 3.0</td>
</tr>
</tbody>
</table>

N.D., value could not be accurately determined because of the very modest level of ERK1/2 phosphorylation; N.P., not performed
* Significantly different (p < 0.05) from the corresponding control value within the same treatment group.
able from a full agonist at the M₂-EDGE-YT mAChR (Fig. 7C, 7D).

Finally, to determine which epitopes are primarily involved in mediating the effects of the combined M₂-EDGE-YT mutations, ERK1/2 phosphorylation assays were repeated using M₂-EDGE and M₂-YT mAChRs. At both receptors, ACh mediated a robust stimulation of ERK1/2 phosphorylation with no significant difference in potency or efficacy compared with the M₂-WT mAChR (Fig. 8 and Table 3). At the M₂-EDGE mAChR, the potency and efficacy of McN-A-343, AC-42 and 77-LH-28-1 were not significantly different from the M₂-WT mAChR (Fig. 8A and Table 3). However, the efficacy of McN-A-343 and the potency of 77-LH-28-1 were significantly increased at the M₂-YT mAChR, similar to the M₂-EDGE-YT mAChR (Fig. 8B and Table 3), suggesting that it is the two alanine substitutions that account for the majority of the effect. AC-42 had minimal activity at both the M₂-EDGE and M₂-YT mAChRs (Fig. 8).

Functional Interaction Studies between ACh and Allosteric Agonists at the M₂-WT and M₂-EDGE-YT mAChRs. In addition to gaining insight into the nature of the allosteric interaction, investigating the effect of allosteric modulators on orthosteric agonists can provide estimates of modulator affinity and, under appropriate conditions, cooperativity. McN-A-343, AC-42 and 77-LH-28-1 all mediated a parallel rightward shift in ACh-mediated ERK1/2 phosphorylation with no depression in the maximal response at either the M₂-WT (Fig. 9) or the M₂-EDGE-YT mAChR (Fig. 10; AC-42 and 77-LH-28-1 only); the interaction between McN-A-343 and ACh at the M₂-EDGE-YT mAChR was not investigated due to McN-A-343 acting as a full agonist at this receptor. Global fitting of the data sets to an operational model of competitive antagonism yielded Schild slopes that were not significantly different from 1 (Table 4), indicating that the interactions were characterized by very high negative cooperativity such that they were indistinguishable from a competitive (orthosteric) interaction. Therefore the data were re-fitted to the operational model with the Schild slope constrained to unity. The resulting pKᵦ estimates (Table 4) show that 77-LH-28-1 had a significantly increased affinity for the M₂-EDGE+YT mAChR, which agrees with the increased potency observed for 77-LH-28-1 in ERK1/2 phosphorylation concentration-response assays at the same mutant.

Discussion

We have found that the agonist McN-A-343 and the novel agonist 77-LH-28-1 have an allosteric mechanism of action at the human M₂ mAChR. A similar mechanism of action of AC-42 at the human M₂ mAChR could not be confirmed. Although we cannot yet conclude whether these agonists mediate all their effects via the allosteric site or whether they interact with both orthosteric and allosteric sites, the unique sensitivity of each of the compounds investigated to mutations within the common allosteric site on the M₂ mAChR strongly suggests that all these agonists have a different mode of binding compared with orthosteric ligands, such as ACh and pilocarpine, as well as prototypical mAChR modulators, such as gallamine, alcuronium, and C₇₃-phth. The enhanced activities of McN-A-343 and 77-LH-28-1 at mutant mAChRs that display reduced potencies for prototypical modulators was mediated mainly by the "common allosteric site" residues Tyr1⁷⁷ and Thr4⁴⁵ rather than 1⁷⁹EDGE1⁷⁵. To our knowledge, this is the first study investigating the effects of allosteric-site mutations on allosteric agonists of a family A GPCR.

Our finding that removal of the charge on 1⁷⁹EDGE1⁷⁵ and substitution of Tyr1⁷⁷ and Thr4⁴⁵ with alanine led to a reduction in the potency of prototypical allosteric ligands (Fig. 2) is in agreement with previous studies (Leppik et al., 1994; Gnagey et al., 1999; Buller et al., 2002; Voigtlander et al., 2003; Huang et al., 2005) and confirms that these residues are vital to the binding of modulators structurally related to classic neuromuscular blockers and alkane-bis-onium compounds (Birdsall and Lazareno, 2005). In contrast, binding assays revealed no reduction in the potency of McN-A-343, AC-42, and 77-LH-28-1 to mediate complete inhibition of [³⁵S]GTPγS binding at both the M₂-WT and M₂-EDGE-YT mAChRs (Fig. 3). This finding suggested either that the agonists interacted competitively with [³⁵S]GTPγS, or that they interacted allosterically but with very high negative cooperativity. Previous studies of AC-42 and related compounds at M₁ mAChRs found similar evidence for high negative cooperativity with [³⁵S]GTPγS (Spalding et al., 2002, 2006; Langmead et al., 2006), as well as differential effects of orthosteric site mutations on these compounds compared with the orthosteric agonist carbachol (Spalding et al., 2002, 2006; Sur et al., 2003). In the current study, dissociation kinetic experiments provided conclusive evidence for an allosteric interaction at the human M₂ mAChR by McN-A-343 and 77-LH-28-1, but highlighted significant differences between the effects of allosteric-site mutations on allosteric agonist versus modulator binding. In particular, mutation of the key EDGE-YT residues in the common allosteric site caused approximately 10- to 150-fold reductions in the potency of prototypical modulators to retard [³⁵S]GTPγS dissociation (Fig. 3) but did not affect the ability of the modulators to completely retard radioligand dissociation. In contrast, the same mutations caused only a modest reduction in the potency of McN-A-343 and AC-42 at the human M₂ mAChR.
A-343 (approximately 1.8 fold), but led to a significant reduction in its maximal effect on radioligand dissociation rate (Fig. 4C).

In addition to the dissociation kinetic assays, our pseudo-equilibrium binding assays also provided evidence for an allosteric mode of interaction by McN-A-343, as well as yielding estimates of the affinity of McN-A-343 for the allosteric site and its cooperativity with [3H]NMS. With the caveat that the $pK_B$ and Log $a$ values obtained from these assays are derived from a model that assumes McNA-A-343 does not interact with the orthosteric site, the resulting estimates suggested that although there was no significant difference in the affinity of McNA-A-343 for the mutant M2 mAChR relative to the wild type, the modulator had significantly higher negative cooperativity with [3H]NMS at the M2-

**TABLE 4**

Operational model $pK_B$ and Schild slope estimates for McN-A-343, AC-42, and 77-LH-28-1 at the M2-WT and M2-EDGE-YT mAChRs from interaction studies with ACh in assays of ERK1/2 phosphorylation

<table>
<thead>
<tr>
<th>M2-WT</th>
<th>M2-EDGE-YT</th>
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<tbody>
<tr>
<td></td>
<td>$pK_B$</td>
</tr>
<tr>
<td>McN-A-343</td>
<td>4.69 ± 0.10</td>
</tr>
<tr>
<td>AC-42</td>
<td>5.86 ± 0.11</td>
</tr>
<tr>
<td>77-LH-28-1</td>
<td>5.95 ± 0.15</td>
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N.P., not performed.

* Significantly different ($P < 0.05$) from the corresponding control value at the same receptor.
EDGE-YT mAChR, consistent with a change in the mode of McN-A-343 binding. Taken together, the dissociation kinetic and pseudoequilibrium binding studies suggest that the EDGE175-QNGQ + Y177A + T423A mutations alter the binding of McN-A-343 and 77-LH-28-1 to the receptor in a manner that is different from classic (nonagonistic) modulators. It is likely that the allosteric agonists use different epitopes on the M2 mAChR compared with the prototypical modulators, but it remains to be determined whether their binding site(s) overlap at all with the common allosteric site or whether the effects determined in the current study are mediated via indirect conformational changes transmitted between distinct allosteric sites.

Another interesting finding from the initial [3H]NMS inhibition binding, assays conducted in the absence of Gpp(NH)p, was the effect of the combined allosteric-site mutation EDGE+YT on agonist affinity estimates. ACh, like many full agonists, displayed two apparent dissociation constants when competing with [3H]NMS; the effect of the allosteric-site mutations was to reduce the potency of ACh somewhat, but McN-A-343, 77-LH-28-1, and AC-42 all trended toward either a higher affinity or an increase in the proportion of receptors demonstrating high-affinity binding. At the moment, it remains difficult to interpret the mechanistic basis of multiple agonist affinity states in competition binding studies, although in most instances it is assumed to reflect the G protein-coupling status to some extent (Christopoulos and El-Fakahany, 1999). If so, the findings from these types of binding assay indicated that mutation of the common allosteric site on the M2 mAChR may actually increase the efficacy and/or potency of allosteric agonists, a hypothesis that could be directly tested in functional assays.

In experiments measuring M2 mAChR-mediated ERK1/2 phosphorylation, both ACh and pilocarpine mediated a robust response, with potencies that were not significantly different between the M2-WT and M2-EDGE-YT receptors. Different results were obtained with McN-A-343, 77-LH-28-1, and AC-42, however, supporting the hypothesis that the binding mode of these agonists is unlikely to be the same as that of classic orthosteric ligands. The finding that McN-A-343, 77-LH-28-1, and AC-42 mediate minimal or no stimulation of ERK1/2 phosphorylation at the M2-WT mAChR is consistent with the high functional selectivity of these compounds for the M2 mAChR (Mitchelson, 1988; Spalding et al., 2002; C. J. Langmead, C. Bock-Zeigler, C. L. Branch, J. T. Brown, K. A. Buchanan, C. H. Davies, I. T. Forbes, V. A. H. Fry, J. J. Hagan, H. J. Herdon, et al., manuscript in preparation). At the M2-EDGE-YT mAChR, the trend toward a modestly increased maximal response observed for pilocarpine, AC-42, and 77-LH-28-1 is likely to be a consequence of the slightly increased expression of the M2-EDGE-YT mAChR (Table 1) as opposed to an enhanced intrinsic efficacy of each of the ligands. The most significant changes observed at the M2-EDGE-YT mAChR were an increase of more than 5-fold in the maximal response (efficacy) of McN-A-343, such that at the mutant mAChR, it was a full agonist, and an increase of more than 10-fold in the potency of 77-LH-28-1; because the latter remained a partial agonist, the change in its potency must reflect a significant increase in its affinity for the M2-EDGE-YT. These effects are qualitatively consistent with effects noted in the binding assays and are not assay-specific, because a similar profile was noted for McN-A-343 relative to ACh and pilocarpine in assays of [35S]GTP\(\gamma\)S binding to activated G proteins. Together, these results suggest that the conformation of the M2-EDGE-YT mAChR, although having minimal effects on the function of orthosteric agonists, can have a profound effect on the efficacy (McN-A-343) or affinity (77-LH-28-1) of allosteric agonists. They also suggest that differences may exist between the binding/activation modes of McN-A-343 on the one hand and 77-LH-28-1 on the other. Experiments focusing on additional mutants, namely M2 EDGE175- versus M2 YT, found that the latter alanine substitutions are likely to mediate the bulk of the observed effects on the allosteric agonists (Fig. 8).

Given that McN-A-343 and 77-LH-28-1 had an allosteric mechanism of action, it was also important to investigate the propensity for functional interaction between these compounds and the endogenous ligand ACh. In all instances, McN-A-343, 77-LH-28-1, and AC-42 displayed high negative cooperativity (\(\alpha\) approaches 0 in the ATCM) with ACh at the M2-WT and, as such, were fitted to a competitive (orthosteric) model describing the interaction of a partial agonist against a full agonist (Leff et al., 1993); this model is equivalent to the ATCM when \(\alpha = 0\). As expected, the affinity of 77-LH-28-1 as an antagonist of ACh-mediated responses was significantly increased at the M2-EDGE-YT mAChR. It is noteworthy that the affinity of AC-42 was only slightly increased, suggesting perhaps subtle differences in its binding mode relative to 77-LH-28-1. Unfortunately, the full agonism of McN-A-343 at the mutant receptor precluded the use of this agonist in similar interaction studies.

In conclusion, we have shown that McN-A-343 and 77-LH-28-1 exhibit both allosteric modulation and agonism at the human M2 mAChR. In addition, we identified strikingly different effects that EDGE175-QNGQ, Y177A, and T423A allosteric-site mutations have on allosteric agonist compared with prototypical M2 mAChR modulators, such as gallamine, alcuronium, and C\(_2\)-3-phth. The growing list of allosteric modulators that possess intrinsic efficacy in their own right suggests that GPCRs may be activated from different regions within the receptor in addition to the orthosteric binding site. Given the potentially greater sequence diversity for receptor regions located outside the endogenous ligand-binding site, such allosteric agonists represent a new and exciting avenue for therapeutic intervention.

References


