Subtype-Selective Positive Cooperative Interactions Between Brucine Analogs and Acetylcholine at Muscarinic Receptors: Functional Studies

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ABSTRACT

In radioligand binding studies, it has been reported that brucine, N-chloromethyl brucine, and brucine N-oxide increased the affinity of acetylcholine for M₁, M₃, and M₄ muscarinic receptors, respectively, in a manner consistent with the predictions of the ternary complex allostERIC model. We now demonstrate an equivalent ability of these three allosteric agents to modulate the actions of acetylcholine in functional studies in membranes and in whole cells. The enhancing actions of brucine and brucine N-oxide on acetylcholine (ACh) potency at M₁ and M₄ receptors respectively have been confirmed in guanosine-5'-O-(3-[35S]thio)triphosphate functional assays, in terms of both its affinity and cooperativity with ACh, as those found in binding assays. Neutral cooperativity of N-chloromethyl brucine with ACh on M₄ receptor function was also observed, thereby demonstrating its "absolute subtype selectivity": a lack of action at any concentration at M₂ receptors and an action at M₂ and M₃ receptors. The enhancing action of N-chloromethyl brucine on neurogenically released ACh binding at M₂ receptors was also detected in whole tissue as an increased contraction of the isolated guinea pig ileum to submaximal electrical stimulation. In conclusion, these functional studies confirm that brucine analogs are allosteric enhancers of ACh affinity at certain muscarinic receptor subtypes.

Exogenous receptor ligands can increase receptor function either directly, by causing the receptor to adopt an active conformation, or indirectly, by increasing the efficacy or affinity of the endogenous ligand for its receptor. This indirect (allosteric) mechanism is the molecular basis for the therapeutic actions of benzodiazepine tranquillizers and other ligands that enhance γ-aminobutyric acid actions at γ-aminobutyric acid-gated receptor channels (Macdonald and Olsen, 1994; Costa and Guidotti, 1996). Although allosteric phenomena are relatively common in the superfamily of ion-channel coupled receptors, there is, to our knowledge, no drug that produces its therapeutic action via an allosteric mechanism at G protein-coupled receptors.

The first and most thoroughly studied allosteric site on a G protein-coupled receptor is that on muscarinic acetylcholine (ACh) receptors (for recent reviews, see Birdsall et al., 1995, Tucek and Proksa, 1995, Ellis, 1997, Christopoulos et al., 1998, Holzgrabe and Mohr, 1998); allosterism at adenosine A₁ (Bruns and Fergus, 1990, Kollias-Baker et al., 1994), α₂A-adrenergic (Leppik et al., 1998), and dopamine D₂ receptors (Hoare and Strange, 1996) has also been characterized. The first compound that was shown to interact allosterically at muscarinic receptors was gallamine (Clark and Mitchelson, 1976; Stockton et al., 1983), and it satisfies the equilibrium and kinetic predictions of the ternary complex allosteric model (Fig. 1) in both binding (Stockton et al., 1983) and functional (Ehrlert, 1988; Lazareno and Birdsall, 1995) studies on M₂ receptors. The allosteric site is present on all five muscarinic receptor subtypes (Ellis et al., 1991), and a number of other ligands have been discovered that interact allosterically at muscarinic receptors (for a review, see Lee and El-Fakahany, 1991, Ellis, 1997, Holzgrabe and Mohr, 1998).

According to the ternary complex allosteric model, the ac-

ABBREVIATIONS: ACh, acetylcholine; GTPγS, guanosine-5'-O-(3-thio)triphosphate; CHO, Chinese hamster ovary.
tions of an allosteric agent are defined by two parameters, the affinity of the allosteric ligand, X, for the unoccupied receptor, $K_X$, and its cooperativity with the ligand, A, interacting at the other (primary) binding site, $\alpha$ (Fig. 1). In this figure, positive cooperativity is present if $\alpha > 1$. The value of $\alpha$ is not just a characteristic of the allosteric ligand but is dependent on the nature of the other interacting ligand, as has been shown for gallamine (Stockton et al., 1983) and other allosteric ligands (Lazareno et al., 1998; Lazareno and Birdsell, 1995; Jakubik et al., 1997).

In the case of gallamine, all reported $\alpha$ values are < 1. Subsequently, alcuronium (Tucek et al., 1990) and strychnine (Lazareno and Birdsell, 1995; Proskova and Tucek, 1995) was shown to exhibit positive cooperativity with the antagonist radioligand $[^{3}H]$N-methylscopolamine at one or more subtypes of muscarinic receptor ($\alpha > 1$), although these compounds were still negatively cooperative with ACh. It should be noted that there is a special importance of the value of the cooperativity with ACh in that any therapeutic effect of a drug as an allosteric agent at muscarinic receptors (or any other receptor) is defined by its cooperativity with the endogenous neurotransmitter.

We are interested in compounds that are positively cooperative with ACh at muscarinic receptors and that may be of use in, for example, the treatment of the cognitive deficits in the earlier stages of Alzheimer’s disease. We have discovered that brucine and some analogs (Fig. 2) are allosteric agents at muscarinic receptors and exhibit positive cooperativity at one or more muscarinic receptor subtypes (Birdsell et al., 1997), a result that has been confirmed for brucine itself (Jakubik et al., 1997). These brucine derivatives satisfy the equilibrium and kinetic predictions of the ternary allosteric model in binding studies (Lazareno et al., 1998). In this report, we examine whether the qualitative and quantitative predictions of subtype selectivity and cooperativity, derived from the binding studies of brucine and its analogs, can be observed in a variety of functional studies on muscarinic receptors.

**Experimental Procedures**

**Materials.** Guanosine-5’-O-(3-[$\gamma$-32P]thiotriphosphate ($[^{3}P]GTP\gamma S$) was from DuPont/NEN (Hounslow, Middlesex, UK). [$\gamma$-32P]GTP was from Amersham International (Cardiff, Wales). Saponin, GDP, brucine sulfate, ACh chloride, Fura 2-acetoxymethyl ester, 5,5'-dithiobis(2-nitrobenzoic acid), 9-amino-1,2,3,4-tetrahydroacridine (tacrine), and acetylthiocholine were from Sigma Chemical (Poole, Dorset, UK). N-Chloromethylbrucine chloride was synthesized from the reaction of brucine with dichloromethane.

**Cell Culture and Membrane Preparation.** Chinese hamster ovary (CHO) cells stably expressing cDNA encoding human muscarinic M$_1$–M$_5$ receptors were generously provided by Dr. N. J. Buckley (University College, London). The nomenclature used in this report is that approved by the IUPHAR Committee on Receptor Nomenclature and Drug Classification (Caulfield and Birdsall, 1998). The cells were grown in a minimal essential medium (GIBCO, Grand Island, NY) containing 10% (v/v) newborn calf serum, 50 units/ml penicillin, 50 μg/ml streptomycin, and 2 mM glutamine at 37°C under 5% CO$_2$. Cells were grown to confluence and harvested by scraping in a hypotonic medium (20 mM HEPES, pH 7.4).

Membranes were prepared at 0°C by homogenization with a Polytron followed by centrifugation (40,000 g, 15 min), washed once in 20 mM HEPES plus 0.1 mM EDTA, pH 7.4, and stored at −70°C in the same buffer at protein concentrations of 2 to 5 mg/ml. Protein concentrations were measured with the Bio-Rad reagent using BSA as the standard. The yields of receptor varied from batch to batch but were approximately 5, 1, 7, 2, and 1 pmol/mg total membrane protein for the M$_1$–M$_5$ subtypes, respectively.

**GTP$\gamma$S Assay.** Membranes were suspended in a buffer containing 20 mM HEPES, 100 mM NaCl, and 10 mM MgCl$_2$, pH 7.4, at a protein concentration of 25 to 50 μg/ml. To the membrane suspension on ice was added the appropriate concentration of GDP followed by $[^{35}S]GTP\gamma S$ (final concentration 100 μM). Then, 1-mU aliquots were added to polystyrene tubes (5 ml) containing ACh and additional allosteric ligands as appropriate. Incubations were at 30°C for 30 min. The samples were filtered over glass fiber filters (Whatman GF/B) using a Brandel cell harvester and washed with 2 × 3 ml of water. The filter disks were extracted overnight with 3 ml of scintillation cocktail and counted by liquid scintillation spectrometry at an efficiency of about 95%. Assays were conducted in duplicate, with each set of replicates filtered together. The concentrations of GDP used in these assays were 10$^{-7}$ M for M$_1$ and M$_2$ receptors and 10$^{-6}$ M for M$_4$ and M$_5$ receptors. In some assays, saponin (10 μg/ml) was present. This increases the signal and the signal-to-noise ratio in such assays without substantially affecting the ACh potency (Cohen et al., 1995; Lazareno, 1997).

**GTPase Assay.** Membranes were suspended in a buffer (0.1 ml) containing 20 mM HEPES, 100 mM NaCl, 5 mM MgCl$_2$, and 1 mM ATP, pH 7.4, at a protein concentration of 50 μg/ml. To the membrane suspension was added $[^{35}P]GTP$ (final concentration 10–100 nM). Incubations were at 30°C for 30 min, after which the reaction was stopped by the addition of 0.75 ml of a slurry of 5% charcoal in 20 mM orthophosphoric acid plus 1 mg/ml BSA. After centrifugation (14,000 g, 5 min), an aliquot of the supernatant, containing the released labeled phosphate, was counted for radioactivity. Assays were conducted in duplicate.

**cAMP Assay.** CHO cells expressing M$_4$ receptors were detached from the culture flasks by brief exposure to trypsin/EDTA solution and washed twice with a solution containing 118 mM NaCl, 1.8 mM CaCl$_2$, 2.7 mM KCl, 0.81 mM MgSO$_4$, 1.0 mM NaHPO$_4$, 5.6 mM
glucose, 0.5 mM 3-isobutyl-1-methylxanthine, and 10 mM HEPES (pH 7.4). The cells were suspended in the same medium at a density of 5 \times 10^7 cells/ml. Aliquots of the cell suspension (0.1 ml) were incubated with various concentrations of ACh with or without brucine (100 \mu M) at 37°C for 10 min. The reaction was stopped by adding 1 N HCl (final concentration 0.1 N). cAMP levels in each sample were measured with a cAMP enzyme/immunoassay system (Amersham International) after acetylation of the samples with acetic anhydride. Assays were conducted in triplicate.

**Ca^{2+} Assay.** CHO cells expressing M1 receptors were detached from the culture flask by brief exposure with trypsin/EDTA solution and loaded with Fura-2 acetoxymethyl ester (5 \mu M) at 37°C for 30 min in 10 ml of alpha-minimal essential medium containing 10% newborn calf serum. Fura-2-loaded cells were washed twice with 10 ml of Ca^{2+}-free Locke’s solution by centrifugation. The cells were suspended in a small volume of Ca^{2+}-free Locke’s solution and kept on ice. An aliquot of the cells was incubated in 2 ml of Locke’s solution containing 2.3 mM Ca^{2+} at 37°C, and the fluorescence at 510 nm, which results from the excitation at 340 and 380 nm, was recorded with a fluorescence spectrophotometer (F-2000; Hitachi). Ca^{2+} concentrations were calculated automatically. The magnitude of the Ca^{2+} signal produced by a given concentration ACh slowly decreased (typically by 50–70%) over the 3-h time course of an experiment. Therefore, the response to 3 \mu M ACh, a concentration producing a maximal signal, was measured every four or five trials, and the magnitude of the responses produced by different concentrations of ACh was normalized to the interpolated maximal response at the time of measurement to give the dose-response curves of the type shown in Fig. 4B. In general, the effects of any given submaximal concentration of ACh were measured at least two times within an experiment.

**Smooth Muscle Preparation.** The experiments were performed on 5-cm strips of male guinea pig ileum suspended in Tyrode’s solution and bubbled with 95% O2 and 5% CO2. The bath (60 ml) was kept at 37°C. The preparation was coaxially stimulated by rectan-

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**Fig. 3.** Enhancement by brucine of ACh potency at M1 receptors in assays of function in membranes. A, brucine (100 \mu M) increased the potency of ACh to stimulate [35S]GTPyS to G proteins in M1-CHO cell membranes. In this experiment, the EC_{50} value for ACh decreased from 2.8 \mu M (■) to 0.9 \mu M (□) without significantly affecting the basal response or maximal stimulation. B, enhancement of ACh-stimulated [35S]GTPyS binding by brucine in pertussis toxin-treated M1-CHO cell membranes in the presence of saponin. In the control membranes, the potency of ACh in the presence (●) of brucine (10^{-4} M) was enhanced 2.1-fold relative to the absence of brucine (○) without changing the Hill slope of the dose-response curve (0.7). The effect of pertussis toxin treatment was to increase ACh potency 8-fold in both the presence (□) and absence (○) of brucine (10^{-4} M) such that brucine retained the same enhancing action. The Hill slope of the dose-response curves for the pertussis toxin-treated membranes increased to 1.0. This result was reproduced in two other experiments conducted in the presence and absence of saponin (mean enhancement, 1.8 ± 0.2; n = 3).

**Fig. 4.** Dose-response curves for the potentiation by brucine of ACh whole-cell M1 muscarinic receptor responses. A, brucine (10^{-4} M) enhanced the potency of ACh to increase cAMP accumulation in M1-CHO cells by 2.6-fold. B, dose-response curves generated from the data shown in Fig. 5 and additional data from the same experiment, normalized to the response to 10^{-6} M ACh alone, show that brucine (100 \mu M) produced a 3.0-fold increase in ACh potency. 
gular current pulses (0.1 Hz, 1-ms duration, 1.0–1.5 V), conditions chosen to generate a submaximal contraction. After an established contraction was obtained, compounds were added cumulatively at intervals of 3 min.

**Acetylcholinesterase Assay.** The isolated guinea pig ileum was homogenized in a pH 8 phosphate buffer (2:1 w/v), diluted 200-fold in the same buffer, and filtered through a 0.45-μm filter. The filtrate was incubated with N-chloromethyl brucine (2–600 μM) or tacrine (3 μM) and acetylthiocholine (90 μM) for 30 min at 37°C. Thiocholine was assayed spectrophotometrically at 412 nm using 5,5'-dithio-bis(2-nitrobenzoic acid). (Ellman et al., 1961)

**Data Analysis.** Data were fitted using equations derived previously from the ternary allosteric complex model (Lazareno et al., 1995, 1998) and nonlinear regression analysis using the fitting procedure in SigmaPlot (SPSS, Ekrath, Germany). This procedure allows the use of two or more independent variables (e.g., the concentration of two drugs). Unless otherwise stated, the results are presented as mean ± S.E.M. (n represents the number of independent experiments). The enhancement by brucine and its analogs of ACh potency in the (paired) functional assays was assessed by a single-tailed paired-sample t test. All the enhancements in potency reported here were significant at the 1% level except for one set of experiments, where P < .05.

### Results

**Allosteric Enhancement of M1 Receptor Function in Membranes and Whole Cells.** We reported previously that in binding studies, brucine exhibits a 1.6 ± 0.1-fold positive cooperativity with ACh at M1 receptors (Lazareno et al., 1998). The positive cooperativity at M1 receptors has been confirmed in [35S]GTPγS functional assays in membranes where the ability of an agonist (in these experiments, ACh) to increase the rate of binding of [35S]GTPγS to G proteins was measured under the same ionic conditions as the binding studies (Lazareno et al., 1993, Lazareno and Birdsall, 1993). In the experiment shown in Fig. 3A, ACh stimulated the binding of [35S]GTPγS with an EC50 value of 2.8 μM. In the presence of brucine (10−4 M), the ACh potency increased 3-fold to 0.9 μM. As illustrated here, neither the basal level of [35S]GTPγS binding nor the maximal level of stimulation was changed significantly by the presence of brucine. The threshold concentration of brucine for observing an enhancement of ACh potency was about 30 μM (data not shown). We have observed in experiments with strychnine (Lazareno et al.,

![Fig. 5. Allosteric enhancement by brucine of a whole-cell M1 Ca2+ response to ACh. ACh (10−8 to 10−6 M) produced a dose-dependent increase in intracellular Ca2+ concentration levels in M1-CHO cells (A–C). The responses to 10−8 and 10−7 M ACh are significantly potentiated by 10−4 M brucine (D and E), whereas a much smaller effect on the response to 10−6 M ACh is observed (F). The potentiation, however, was not dependent on the order of addition of brucine and ACh (G), and the intracellular Ca2+ concentration elevation in the presence and absence of brucine was completely blocked by the muscarinic antagonist 3-quinuclidinyl benzilate (1 μM) (H). These results are from a single representative experiment that was repeated three times.](image-url)
and in some experiments with brucine (10⁻⁴ M and higher concentrations) that the basal and maximal levels of binding were affected. This can have the apparent effect of increasing ACh potency; the results of such experiments were not included in the data analysis. The mean enhancement of ACh potency by 10⁻⁴ M brucine in experiments where basal and maximal levels of binding were unaffected was 2.1 ± 0.4-fold (n = 4).

We have observed elsewhere that pertussis toxin treatment of cells generates membranes in which basal activity in GTPase and [⁴⁰]GTPγS assays of function is reduced and the potency of ACh is increased up to 10-fold (Lazareno et al., 1993, Lazareno, 1997). Although a reduction in basal activity was not observed with the brucine analogs, it was considered that there was a slight chance that the observed enhancement of ACh potency by brucine is not an allosteric effect but an artifact mediated by an effect on Gαo proteins or a change in the G protein-coupling selectivity of M₁ receptors. [⁴⁰]GTPγS assays were therefore performed on membranes of M₁-CHO cells treated with pertussis toxin (30 ng/ml) for 18 h before harvesting the membranes. These conditions were known from preliminary experiments to block essentially all Gαo protein function. These [⁴⁰]GTPγS assays were carried out in the presence of saponin to enhance the signal-to-noise ratio. In the control membranes, the ACh dose-response curve had a Hill slope of about 0.7 and its potency was essentially neutral with ACh in binding studies on M₄ receptors. (Lazareno et al., 1998). This is mirrored in functional studies by a 2.8 ± 0.1-fold increase in ACh potency at M₄ receptors by 10⁻³ M brucine N-oxide in a GTPase assay of function (Fig. 6). In measures of ACh-stimulated GTPγS binding at M₄ receptors, the EC₅₀ value for ACh is about 2 to 3 × 10⁻⁷ M (Lazareno et al., 1993; Lazareno and Birdsall, 1993); significant enhancements of the actions of a submaximal single concentration ACh (10⁻⁷ M) were observed using 3 × 10⁻⁴ or 10⁻³ M brucine N-oxide. These were equivalent to 1.5- to 2.9-fold (range, n = 10) increases in potency. In analogous experiments to those illustrated in Fig. 3A, 3 × 10⁻⁴ M brucine N-oxide increased ACh potency at M₄ receptors by 1.9 ± 0.3-fold (n = 2, data not shown).

In binding studies, brucine N-oxide is positively cooperative with ACh at M₃ receptors, neutral at M₁ receptors, and weakly negatively cooperative at M₂ receptors (Lazareno et al., 1998). This qualitative profile was also observed in [⁴⁰]GTPγS functional studies on these subtypes (data not shown).

Allosteric Enhancement of M₃ Receptor Function in Membranes by N-Chloromethyl Brucine and Its Actions on Other Subtypes. N-Chloromethyl brucine exhibits a different selectivity from that of brucine and brucine N-oxide. It enhances the binding of ACh 3.3-fold at M₃ receptors but not at the other subtypes, being very slightly negatively cooperative at M₁, strongly negative at M₂ receptors, and essentially neutrally cooperative at M₄ receptors (Lazareno et al., 1998).

Because the observed magnitude of positive cooperativity and the range of values of cooperativity between the subtypes in binding studies is larger than observed for the other two compounds, detailed dose-response curves were generated for the effects of N-chloromethyl brucine on ACh-stimulated [⁴⁰]GTPγS binding to membranes of M₁-M₄ transfected cells (Fig. 7). N-Chloromethyl brucine did not affect the basal or maximal responses or the slope of the ACh dose-response curves. The shifts of the curves are shown in the insets. No significant dose-dependent shifts in the dose-response curves at M₁ and M₄ receptors were observed (range of pEC₅₀ val-
ues, 5.80–5.97 and 6.80–6.97 at M₁ and M₄ receptors, respectively). The results at M₂ and M₃ receptors illustrate clearly the qualitatively different effects of chloromethylbrucine at these subtypes. Increasing concentrations of N-chloromethylbrucine progressively shift the ACh dose-response curve for M₂ receptors to the right of the control (dashed) curve, whereas the M₄ curve moves to the left as ACh becomes more potent. Furthermore, these data are capable of being analyzed by the allosteric model, with the curves in Fig. 7 being the fits derived from nonlinear regression analysis. The calculated cooperativities with ACh in this experiment were 0.02 and 4.6 at M₂ and M₃ receptors, respectively. There is a good agreement between the affinities of N-chloromethylbrucine and its cooperativities with ACh at M₂ and M₃ receptors, as determined by analyses of the binding and functional data by the allosteric model (Table 1).

The enhancing actions of N-chloromethylbrucine were also examined in a M₃ whole tissue preparation, the isolated guinea pig ileum. N-Chloromethylbrucine (20–200 μM) produced a 1.8- to 2.6-fold increase in the submaximal contractions produced by a low concentration (2 × 10⁻¹⁰ M) of ACh (n = 4, data not shown) but had no effect on the maximal contractions generated using higher concentrations of ACh (2 × 10⁻⁷ to 2 × 10⁻⁶ M). It was also possible to observe a dose-dependent potentiation by N-chloromethylbrucine (2–200 μM) of the electrically stimulated contraction of isolated strips of guinea pig ileum, a whole tissue response mediated via ACh release and M₃ receptor activation (Fig. 8). The threshold concentration of N-chloromethylbrucine for the potentiation of the submaximal stimuli was 2 to 10 μM and a more than 3-fold enhancement was observed at 200 μM. The potentiation was similar to that shown by eserine (4–400 nM, data not shown) but was not caused by acetylcholinesterase inhibition because N-chloromethylbrucine (2–600 μM) did not inhibit the acetylcholinesterase in homogenates of guinea pig ileum: the enzyme activity was 104 ± 4% (n = 15) of the control value, whereas in the presence of tacrine (10⁻⁶ M), a positive control, the residual activity was 3 ± 1%.(n = 3). The electrically stimulated responses in this tissue were abolished by atropine (300 nM) but were unaffected by the nicotinic antagonist hexamethonium (40 μM). N-Chloromethylbrucine (2–200 μM) failed to affect the electrically stimulated contractions in the rat phrenic nerve preparation that are mediated via nicotinic receptors: these contractions were potentiated by eserine (400 nM). The potentiation by N-chloromethylbrucine of the field-stimulated contractions might reflect a presynaptic inhibition of ACh affinity at an M₂ autoreceptor rather than a postsynaptic enhancement of M₃.

![Fig. 7. Allosteric modulation by N-chloromethylbrucine of ACh-stimulated [³²S]GTPγS binding at M₁–M₄ receptors.](attachment:Fig7.png)

At M₁ and M₄ receptors, there was no dose-dependent change in the pEC₅₀ value of ACh within the experiment illustrated here, and in additional experiments, the mean pEC₅₀ values at the two subtypes was 5.87 ± 0.09 and 6.90 ± 0.09 (mean ± range/2, n = 5). At M₂ and M₃ receptors, the lines represent the simultaneous fits of the data to the ternary allosteric model. The basal and maximal responses were constrained to be the same for a given subtype. For M₂ and M₃ receptors, respectively, the calculated values of the pEC₅₀ for ACh in the absence of allosteric ligand were 7.20 and 5.29; the slopes of the ACh dose-response curves were 0.81 and 0.87; the log affinities of N-chloromethylbrucine were 4.30 and 3.86; and the cooperativity with ACh was 0.02 and 4.6. The averaged values from five experiments are summarized in Table 1. At M₂ and M₃ receptors, 10 μg/ml saponin was present in the assays. *Insets*, fold changes in the EC₅₀ values as a function of log[N-chloromethylbrucine].
receptors. However, in contrast to N-chloromethyl brucine, the M₂-selective antagonist methoctramine (1.4 nM to 4 μM) did not enhance the contractions at any of these concentrations (n = 4, data not shown), but some inhibition was observed at concentrations of methoctramine above 40 nM. The enhancement in Fig. 8 therefore probably is not a presynaptic effect but is due to N-chloromethyl brucine acting as an allosteric enhancer at postsynaptic M₃ receptors.

**Discussion**

We examined the allosteric actions of brucine and two derivatives, brucine N-oxide and N-chloromethyl brucine, in several functional assays on a number of muscarinic receptor subtypes. These compounds were chosen from a range of brucine and strychnine derivatives (Birdsall et al., 1997, Lazareno et al., 1998, Gharagozloo et al., 1999) because of their ability to selectively enhance the binding of ACh to different muscarinic receptor subtypes; furthermore, the allosteric effects of these compounds in binding studies satisfied the equilibrium and kinetic predictions of the allosteric ternary complex model (Fig. 1) (Lazareno et al., 1995, 1998).

We have demonstrated that in a variety of membrane and whole-cell assays of muscarinic receptor function, brucine, N-chloromethyl brucine, and brucine N-oxide are allosteric enhancers at M₁, M₄, and M₆ receptors, respectively. In general, the compounds do not affect either the basal activity or function in the presence of maximally effective concentrations of ACh (Figs. 3, A and B, 4, A and B, 6, and 7). Only the actions of submaximal concentrations of ACh are affected. This illustrates the prediction of the simple allosteric model that an allosteric drug will have no pharmacological action unless the endogenous ligand for the receptor is present.

As a consequence, we find no evidence in our functional studies reported here (or elsewhere, e.g., Lazareno et al., 1995, Ehlert, 1988) that the allosteric agents, including galamine and strychnine and the brucine analogs, activate muscarinic receptors. This is in contrast to the results reported by Jakubik et al. (1996), but we have not carried out the same assays of function.

Brucine analogs and most other reported allosteric agents (but not all, such as obidoxime; Ellis and Seidenberg, 1992) slow down the association and dissociation kinetics of [³H]N-methylscopolamine such that occupancy of the allosteric site precludes access or egress of the antagonist from the binding site. However, we find no evidence that under our experimental conditions, ACh access to its binding site is blocked by these agents; this would result in the brucine analogs slowing the both the onset and offset of the ACh responses. Our results are in accord with the less pronounced maximal slow-

**TABLE 1**

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<th>Subtype</th>
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⁵⁺ The binding data are from Lazareno et al. (1998).

Fig. 8. A, N-Chloromethyl brucine, in a dose-dependent manner, enhanced the field-stimulated contractions of isolated guinea pig ileum strips. The contractions were inhibited by atropine (30 nM). B, histogram of the percentage enhancement of contraction produced in four independent experiments of the type illustrated in A. Data are expressed as mean ± S.E.M.
to fit simultaneously sets of ACh dose-response curves in the presence of several concentrations of allosteric agent to the allosteric ternary complex model and to obtain well-defined estimates of $K_x$ and $\alpha$. In the case of N-chloromethyl brucine, however, it was possible to demonstrate clearly that its positive and negative allosteric effects on ACh-stimulated GTP-$\gamma$S binding, mediated via $M_3$ and $M_4$ receptors respectively, were well fitted by the simple allosteric model (Fig. 7). Furthermore, the parameters defining the allosteric action in binding and function were in good agreement (Table 1). These findings illustrate that it is possible to have a compound exhibiting the opposite pharmacological actions of an allosteric enhancer ($\alpha = 3$–4) and inhibitor ($\alpha = 0.02$–0.09), a ratio of about 60, at two closely related receptor subtypes.

A further and, paradoxically, possibly more important feature of the functional studies depicted in Fig. 7 is the immeasurably small effects of up to 300 $\mu M$ N-chloromethyl brucine on ACh function at $M_1$ and $M_2$ receptors. This is true despite the fact that 10 to 300 $\mu M$ N-chloromethyl brucine has dramatic slowing effects on the dissociation rate constant of $[3H]N$-methylscopolamine from these receptor subtypes (as well as from $M_2$ and $M_3$ receptors) (Lazareno et al., 1998). The lack of effect on ACh function is entirely compatible with the fact that in radioligand binding studies, N-chloromethyl brucine exhibits neutral cooperativity with ACh at $M_3$ receptors ($\alpha = 1.0 \pm 0.1$) and only very slight negative cooperativity with ACh at $M_1$ receptors (Lazareno et al., 1998).

This result illustrates the importance of neutral cooperativity in pharmacological selectivity. Despite the fact that N-chloromethyl brucine is binding to $M_4$ receptors at the same concentrations as it is producing its enhancing actions at $M_3$ receptors and its allosteric inhibitory actions at $M_2$ receptors, it has no action at $M_4$ receptors. We used the term “absolute subtype selectivity” for a positive (or negative) cooperative action at one subtype and the lack of pharmacological action associated with neutral cooperativity at another subtype (Birdsell et al., 1997; Lazareno et al., 1998). Such selectivity is not available to agonists and competitive antagonists, where affinity and/or efficacy is the determinant of relative subtype selectivity. In the case of allosteric agents, both affinity and cooperativity are independent parameters that determine pharmacological action and selectivity.

Finally, we extended our study to the demonstration of allosteric enhancement of muscarinic receptor function in a whole tissue. Again, we chose N-chloromethyl brucine as the allosteric enhancer at $M_3$ receptors because of its large positive cooperativity with ACh. The tissue model was the guinea pig ileum strip in which electrical stimulation causes the release of ACh and the consequent contraction of smooth muscle via stimulation of $M_3$ receptors. It was possible to demonstrate a potentiation by N-chloromethyl brucine of contractions elicited by submaximal (but not maximal) electrical stimulation or exogenous ACh application (Fig. 8). Appropriate controls eliminated any contribution to the contractile response or the actions of N-chloromethyl brucine by nictinic ACh receptors, presynaptic $M_2$ inhibitory autoreceptors, or acetylcholinesterase inhibition.

These results suggest the feasibility that a selective allosteric enhancer, acting at a specific muscarinic subtype, could enhance subnormally functioning cholinergic synapses in the central nervous system while having less or no action at normally functioning synapses. The existence of a regional cholinergic deficit in the earlier stages of Alzheimer’s disease and the association of muscarinic receptors with memory and cognition suggest one possible therapeutic area for muscarinic allosteric enhancers.

**Note Added in Proof.** It has been reported recently that brucine modulates the action of synthetic agonists on $[3H]ACh$ release in rat striatal slices by an action at $M_4$ receptors (Dolezal V and Tucek S (1998) *Br J Pharmacol* **124:**1213–1218).

References


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