Potentiation and Inhibition of Neuronal Nicotinic Receptors by Atropine: Competitive and Noncompetitive Effects

RUDI ZWART and HENK P. M. VIJVERBERG
Research Institute of Toxicology, Utrecht University, NL-3508 TD Utrecht, The Netherlands
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SUMMARY
Atropine, the classic muscarinic receptor antagonist, inhibits ion currents mediated by neuronal nicotinic acetylcholine receptors expressed in Xenopus laevis oocytes. At the holding potential of −80 mV, 1 μM atropine inhibits 1 mM acetylcholine-induced inward currents mediated by rat α2β2, α2β4, α3β2, α3β4, α4β2, αβ4, and α7 nicotinic receptors by 12–56%. Inward currents induced with a low agonist concentration are equally inhibited (α3β2, α3β4), less inhibited (α2β4, α7), or potentiated (α4β2, α4β4) by 1 μM atropine. Effects on the more sensitive α4β4 nicotinic receptors were investigated in detail by systematic variation of acetylcholine and atropine concentrations and of membrane potential. At high agonist concentration, atropine inhibits α4β4 nicotinic receptor-mediated ion current in a noncompetitive, voltage-dependent way with IC50 values of 655 nM at −80 mV, and of 4.5 μM at −40 mV. At low agonist concentration, 1 μM atropine potentiates α4β4 nicotinic receptor-mediated ion current. This potentiating effect is surmounted by high concentrations of acetylcholine, indicating a competitive interaction of atropine with the nicotinic receptor, and potentiation is also reversed at high atropine concentrations. Steady state effects of acetylcholine and atropine are accounted for by a model for combined receptor occupation and channel block, in which atropine acts on two distinct sites. The first site is associated with noncompetitive ion channel block. The second site is associated with competitive potentiation, which appears to occur when the agonist recognition sites of the receptor are occupied by acetylcholine and atropine. The apparent affinity of atropine for the agonist recognition sites of the α4β4 nicotinic acetylcholine receptor is estimated to be 29.9 μM.

The neurotransmitter ACh signals through two distinct types of receptors: nAChRs and mAChRs. These two classes of receptors for ACh were already distinguished pharmacologically by Sir Henry Dale in 1914 (1) on the basis of the resemblance of ACh effects with those of naturally occurring plant alkaloids. mAChRs are activated selectively by muscarine and blocked by atropine, and nAChRs are activated selectively by nicotine and blocked by curare (2, 3). This classification found support from biochemical and electrophysiological data, which showed that nicotinic and muscarinic receptors are functionally distinct entities. Molecular cloning has further demonstrated that the primary structure of nicotinic and muscarinic receptor proteins falls into two different gene families, the ligand-gated ion channels and G protein-coupled receptors, respectively (4–6).

Atropine is still widely used to selectively antagonize mAChRs. mAChRs are sensitive to atropine, with IC50 values in the nanomolar concentration range (see Ref. 7). At these concentrations, atropine is believed to have few or no side effects on nAChRs because very high (near-millimolar) concentrations of atropine are required to cause any degree of inhibition of the effects of ACh at end-plate-type nAChRs and neuronal-type nAChRs in autonomic ganglia (8–10).

In recent years, however, a multiplicity of neuronal nAChRs have been identified (for reviews, see Refs. 6 and 11). Known subunits of neuronal nAChRs (α2–9 and β2–4) combine in various compositions to generate pentameric complexes with different functional and pharmacological characteristics. Atropine has been reported to inhibit several types of ligand-gated ion channels. Ion currents mediated by homooligomeric α7, α8, and α9 nAChRs as well as the homooligomeric serotonin type 3 receptor are inhibited with IC50 values in the range of 0.4–7 μM atropine (12–14). Atropine displaces α-bungarotoxin from homooligomeric nAChRs, and noncompetitive interaction of atropine with these receptors has also been suggested (12). However, the mechanism of the inhibition of the nAChR-mediated ion currents by atropine is unresolved. Effects of atropine on heteromeric neuronal nAChRs, which differ from the homooligomeric nAChRs by their insensitivity to α-bungarotoxin (see Refs. 11 and 15), have not been reported.

In this study, we investigated and compared the effects of atropine on various subunit combinations of nAChRs ex-

ABBREVIATIONS: ACh, acetylcholine; mAChR, muscarinic acetylcholine receptor; nAChR, nicotinic acetylcholine receptor; HEPES, 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid.
pressed in *Xenopus laevis* oocytes, and the mechanism of atropine action was investigated in detail on the αβ4 nAChR. Part of this work has appeared in abstract form (16).

**Experimental Procedures**

**Materials.** *X. laevis* were bred and kept in the Hubrecht Laboratory (Utrecht, The Netherlands). Acetylcholine chloride, (−)-nicotine bitartrate, gentamicin, 3-amino-benzoic acid ethyl ester, and collagenase type I were from Sigma Chemical (St. Louis, MO), and atropine sulfate was from Fluka (Buchs, Switzerland). All other salts and HEPES were from Merck (Darmstadt, Germany). cDNAs of nicotinic receptor subunits ligated into the pSm plasmid vector containing the SV40 viral promoter were a kind gift from Dr. J. Patrick (Baylor College of Medicine, Houston, TX).

**Expression in oocytes.** Mature female specimen of *X. laevis* were anesthetized by submersion in 0.1% 3-aminobenzoic acid ethyl ester and ovarian lobes were surgically removed. Oocytes were defolliculated manually after treatment with collagenase type I (1.5 mg/ml calcium-free Barth’s solution) for 1.5 hr at room temperature. Plasmids coding for α and β subunits of neuronal nAChRs, dissolved in distilled water at a 1:1 molar ratio, were co-injected into the nuclei of stages V and VI oocytes within 8 hr after harvesting, using a Drummond microinjector. Approximately 1 ng of each plasmid containing α and β cDNA (2 ng for α7) was injected in a total injection volume of 10–15 nl/oocyte. After injection oocytes were incubated at 19° in modified Barth’s solution containing 88 mM NaCl, 1 mM KCl, 2.4 mM NaHCO₃, 0.3 mM Ca(NO₃)₂, 0.41 mM CaCl₂, 0.82 mM MgSO₄, 15 mM HEPES, and 10 μg/ml gentamicin (pH 7.6 with NaOH). Experiments were performed on oocytes after 2–5 days of incubation.

**Electrophysiology and data analysis.** Oocytes were voltage-clamped using two microelectrodes (0.5–2.5 MΩ) filled with 3 M KCl and a custom-built voltage clamp amplifier with high-voltage output stage according to the methods described by Stühmer (17). The external saline was clamped at ground potential by means of a virtual ground circuit using an Ag/AgCl reference electrode and a Pt/Pt-black current passing electrode. Membrane current was measured with a current-to-voltage converter incorporated in the virtual ground circuit. The membrane potential was held at −80 mV, unless otherwise indicated. All experiments were performed at room temperature (22–24°C).

Oocytes were placed in a silicon tube (i.d. 3 mm), which was continuously perfused with saline solution (115 mM NaCl, 2.5 mM KCl, 1 mM CaCl₂, 10 mM HEPES, pH 7.2, with NaOH) at a rate of 20 ml/min. Aliquots of freshly prepared, concentrated stock solutions of atropine sulfate and acetylcholine chloride in distilled water were added to the saline immediately before the experiments. Drugs were applied by switching between control and drug-containing saline using a servomotor-operated valve. Agonist applications were alternated by 5 min of superfusion with agonist-free saline to allow the receptors to recover completely from desensitization. Membrane currents were low-pass filtered (eight-pole Bessel; −3 dB at 0.3 kHz), digitized (12 bits; 1024 samples/record), and stored on disk for offline computer analysis. Data are expressed as mean ± standard deviation. Results are compared using a two-tailed Student’s t test. Curve fitting was performed by a nonlinear least-squares algorithm (18).

**Results**

**Atropine inhibits neuronal nAChRs.** Superfusion of voltage-clamped oocytes expressing different subunit combinations of neuronal nAChRs with 1 mM ACh evoked typical inward ligand-gated ion currents. The kinetics of the inward currents varied for the different subunit combinations and with some subtypes of nAChR tail currents were observed on washout of the high concentration of the agonist (Fig. 1). To investigate the effects of atropine, oocytes were superfused with saline-containing atropine for ≥4 min, inward currents were evoked by switching the superfusate to saline-containing ACh and the same concentration of atropine, and subsequently, the agonist was washed out by switching back to atropine-containing saline. For all subunit combinations tested, the peak amplitude of the inward current evoked by 1 mM ACh was reduced in the presence of 1 μM atropine. Examples of the inhibitory effects of atropine are shown in Fig. 1A. The degree of inhibition by atropine varied for the different combinations of nAChR subunits. The results for the reduction in the peak amplitude of 1 mM ACh-induced inward currents by 1 μM atropine are summarized in Table 1 for the subtypes of nAChRs that were tested. Atropine in the concentration range of 1 μM to 1 mM did not induce any detectable change in membrane holding current on itself.

A number of experiments were performed to exclude the possibility that atropine exerted its effects on ACh-induced ion currents via endogenous mAChRs, which are supposed to be present in *X. laevis* oocytes (19, 20). In oocytes expressing αβ4 nAChR, the ion current evoked by the selective nAChR agonist (−)-nicotine was inhibited by 1 μM atropine to 41.7 ± 4.5% (three oocytes), and the ACh-induced ion current was inhibited to 41.3 ± 5.0% (four oocytes). Inhibition of the
atropine, which was evoked after fusion of 100 nAChRs, changes in membrane current had been injected with nAChR subunit cDNAs but did not respond to ACh. In these oocytes, as well as in oocytes that nAChRs in the oocytes did not play a role in the atropine effects observed. In addition, at least three uninjected oocytes were investigated in detail in oocytes expressing α4β4 nAChRs. These results demonstrate that inhibition of nAChR-mediated ion currents by atropine is voltage dependent, suggesting that atropine acts by blocking the nAChR channel. Further evidence for open channel block by atropine came from experiments in which atropine was coapplied with ACh (Fig. 3B). The application of 10 μM atropine did not induce a change in membrane holding current on its own. The application of 10 μM ACh to oocytes expressing α4β4 nAChRs and voltage-clamped at −100 mV induced a virtually non-desensitizing inward current. On removal of ACh, the current returned to the base-line level. The coapplication of 10 μM ACh with 10 μM atropine induced an inward current that was much smaller than the current elicited by ACh alone. In addition, the current evoked by the coapplication decayed toward a steady level, and a transient increase in membrane

### TABLE 1

<table>
<thead>
<tr>
<th>αnAChR</th>
<th>1 μM ACh response</th>
<th>1 μM ACh response</th>
</tr>
</thead>
<tbody>
<tr>
<td>α2β2</td>
<td>85.9 ± 7.8 (6)</td>
<td>N.D.³, ²</td>
</tr>
<tr>
<td>α2β4</td>
<td>51.0 ± 3.0 (6)</td>
<td>93.5 ± 2.8 (6)</td>
</tr>
<tr>
<td>α3β2</td>
<td>85.9 ± 3.7 (10)</td>
<td>91.0 ± 4.6 (6)</td>
</tr>
<tr>
<td>α3β4</td>
<td>87.5 ± 4.7 (6)</td>
<td>88.3 ± 4.3 (6)²</td>
</tr>
<tr>
<td>α4β2</td>
<td>74.1 ± 7.2 (7)</td>
<td>140.5 ± 4.9 (6)</td>
</tr>
<tr>
<td>α4β4</td>
<td>43.5 ± 4.5 (6)²</td>
<td>170.3 ± 10.2 (6)</td>
</tr>
<tr>
<td>α7</td>
<td>53.3 ± 4.8 (6)</td>
<td>81.9 ± 3.5 (4)²</td>
</tr>
</tbody>
</table>

¹ Students’ t test probability of the hypothesis that the effect of atropine on responses evoked by high agonist concentration (left column) equals the effect on responses evoked by low agonist concentration (right column).

² Not determined because large numbers of receptors were not expressed.

³ Inward currents induced with 10 μM ACh.

ACh-induced ion current does not differ significantly from inhibition of nicotine-induced current by atropine (t test; p = 0.91; Fig. 1B). This indicates that block of putative endogenous mAChRs in the oocytes did not play a role in the atropine effects observed. In addition, at least three uninjected oocytes from every batch of oocytes used were tested for responses to ACh. In these oocytes, as well as in oocytes that had been injected with nAChR subunit cDNAs but did not express functional nAChRs, changes in membrane current were never induced by superfusion with 100 μM ACh at the holding potentials of −80 and −20 mV. The results indicate that endogenous mAChRs, if present in the oocytes used in this study, did not mediate electrophysiological responses and did not interfere with nAChR-mediated ion currents. It is concluded that atropine interacts directly with the nAChR. Because the α4β4 nAChR was one of the more sensitive subunit combinations (see Table 1), the mechanism of action of atropine has been investigated in detail in oocytes expressing these receptors.

**Mechanism of inhibition of α4β4 nAChR-mediated ion currents by atropine.** The concentration-dependent effects of atropine on α4β4 nAChRs were investigated in oocytes superfused with various concentrations of atropine. On the first response to 100 μM ACh in the presence of atropine, which was evoked after ~5 min of superfusion with atropine-containing saline, the inhibitory effect on the peak amplitude of α4β4 nAChR-mediated current had reached a steady level. Examples of inward currents evoked by superfusion of 100 μM ACh in the absence and presence of various concentrations of atropine and the concentration-effect curve for reduction in the peak amplitude of the α4β4 nAChR-mediated inward current by atropine are shown in Fig. 2A. The inhibition curve fitted to the data yielded estimates for the IC50 values of atropine of 655 ± 35 μM and for the slope factor of −0.92 ± 0.04. The inhibitory effects of atropine were reversed completely within 5 min of washing, which was also the interval maintained between subsequent agonist applications (Fig. 1).

Concentration-effect curves of ACh were obtained from oocytes expressing α4β4 nAChRs in the absence and presence of atropine. An example of responses evoked by superfusion of 1–1000 μM ACh in the absence and presence of 1 μM atropine recorded from a single oocyte is shown in Fig. 2B. For three oocytes, peak inward current amplitudes were normalized to those of control inward currents evoked by 1 mM ACh in the same oocyte and data obtained in the absence and in the presence of 1 μM atropine were plotted against agonist concentration. Fitting concentration-effect curves to the data obtained from these experiments yielded estimates of EC50, slope factor, and Emax of 13.8 ± 0.7 μM ACh, 1.2 ± 0.1, and 110 ± 2% in the control situation and 8.5 ± 0.8 μM ACh, 1.0 ± 0.1, and 51 ± 1%, respectively, in the presence of 1 μM atropine (Fig. 2B). The data measured at the highest agonist concentration were excluded from the curve-fitting procedure because this high concentration of ACh caused a reduction of the peak amplitude of the ACh-induced inward current. The concentration-effect curves show that in the presence of 1 μM atropine, the inward currents induced by concentrations of >10 μM ACh were inhibited to the same extent. At the agonist concentrations of ≥3 μM, no inhibition of ACh-induced current responses by 1 μM atropine was observed. Instead, at 1 μM ACh, the amplitude of the inward current was enhanced in the presence of atropine to 189 ± 35% (three oocytes) of the control values. The effect of atropine on the concentration-effect curve of ACh (i.e., a marked reduction in Emax and no large shift in EC50 value) indicates that atropine exerts its inhibition via a noncompetitive mechanism. A small but significant change in the EC50 value and slope factor of the concentration-effect curve for ACh is most likely due to the potentiation of α4β4 nAChR-mediated ion currents by atropine at low agonist concentration. This potentiation effect of atropine has been investigated separately (see below).

Effects of membrane potential were investigated to obtain an indication of the mechanism underlying the inhibitory effect of atropine. In the absence of extracellular atropine, the amplitude of the 100 μM ACh-induced current decreased at less negative holding potentials (Fig. 3A), and ACh-induced ion currents were not observed on application of 100 μM ACh at positive holding potentials (not shown). In the presence of atropine, the ACh-induced inward current was markedly reduced at strongly hyperpolarized membrane potentials, and smaller inhibitory effects were observed at more depolarized membrane potentials. The current-voltage relationships of 100 μM ACh-induced ion currents in the absence and presence of 1 and 10 μM atropine are depicted in Fig. 3A. These results demonstrate that inhibition of nAChR-mediated ion currents by atropine is voltage dependent, suggesting that atropine acts by blocking the nAChR channel. Further evidence for open channel block by atropine came from experiments in which atropine was coapplied with ACh (Fig. 3B). The application of 10 μM atropine did not induce a change in membrane holding current on its own. The application of 10 μM ACh to oocytes expressing α4β4 nAChRs and voltage-clamped at −100 mV induced a virtually non-desensitizing inward current. On removal of ACh, the current returned to the base-line level. The coapplication of 10 μM ACh with 10 μM atropine induced an inward current that was much smaller than the current elicited by ACh alone.
current ("tail current") was observed on removal of ACh and atropine by washing. High concentrations of nAChR agonists also cause an acceleration of current decay and a tail current on removal of the agonist (e.g., see Fig. 1A); these phenomena are generally attributed to the onset and reversal of open channel block (21–26). To determine whether atropine or ACh induced the tail current, an additional response was evoked by coapplication of ACh and atropine, but ACh was removed in the continued presence of atropine (Fig. 3B). The absence of a tail current under these experimental circumstances demonstrates that atropine is the agent causing the tail current. The voltage dependence of the blocking effect of atropine is depicted in Fig. 3C. The data obtained from three oocytes exposed to 10 μM atropine were fitted by a Boltzmann curve for voltage-dependent block, and the current-voltage relationships in the presence of atropine (Fig. 3A) were fitted by the same equation. The IC₅₀ values for atropine at 0 mV and for the slope yielding best fit of the data in Fig. 3, A and C, were 21.2 μM and 38.7, respectively. It is concluded that the inhibition of ion current induced by a high concentration of agonist at strongly negative membrane potential is due to noncompetitive ion channel block by atropine.

Potentiation of nAChR-mediated ion currents by atropine. Under the conditions used so far, potentiation by atropine was observed only for the α₄β₄ nAChR-mediated ion current evoked by a low concentration of ACh at −80 mV. Under the same experimental conditions, α₄β₂ nAChR-mediated ion current was also potentiated, whereas ion currents mediated by other heteromeric subunit combinations were slightly inhibited by 1 μM atropine (Table 1). Table 1 shows that α₄β₄ was the more strongly affected subtype of nAChR. Because the inhibition of α₄β₄ nAChRs by atropine depends...
on holding potential (Fig. 3), the membrane potential was varied to improve experimental conditions for investigation of the potentiating effect of atropine on α4β4 nAChRs. This was done for the effect of a relatively high concentration of 10 μM atropine on responses evoked with the low concentration of 1 μM ACh, for which the potentiation was initially observed (see Fig. 2B). Atropine was applied during apparent steady state responses to 1 μM ACh, so the onset and reversal of the effects of atropine could be observed during a single agonist response. Fig. 4, A and B, shows that at membrane potentials in the range of −30 to −70 mV, the ACh-induced ion current is potentiated by 10 μM atropine. The potentiating effect of atropine, relative to the size of ACh-induced ion current, was largest at the more depolarized membrane potential. At more hyperpolarized membrane potentials, the potentiating effect was reduced and became transient, and only inhibition was observed at the holding potential of −100 mV. This indicates that atropine causes a combination of potentiating and blocking effects. At the more negative membrane potentials, the potentiation is counteracted by inhibition that becomes stronger and more rapid. The tail current on washing out of atropine reflects a mixture of reversal of ion channel block and change in the balance between potentiating and inhibitory effects of atropine, which are caused by the rapid dilution of atropine. The complex nature of these tail currents and the rapid kinetics of the current transients at the onset of the effect of atropine at the more negative membrane potentials preclude the use of these parameters to quantify the potentiating effect of atropine. However, the large amplitude of the tail current indicates that potentiation is not suppressed at the more negative membrane potentials. Measurement of the net, steady effects of atropine at the various holding potentials showed that potentiation and inhibition are approximately equal at holding potentials between −80 and −90 mV. Potentiation predominates at more depolarized holding potentials, and inhibition predominates at more hyperpolarized holding potentials (Fig. 4B). Atropine potentiates the ion current induced by the low concentration of 0.3 μM (-)-nicotine similarly to its potentiation of the 1 μM ACh-induced ion current (Fig. 4C). This result confirms that like the inhibitory effect, potentiation is not mediated by mAChR and shows that potentiation may also occur with nicotinic agonists other than ACh.

At the optimized membrane potential of −40 mV, the concentration-effect curve of ACh was determined. The results in Fig. 5A show that the response amplitude was reduced at ACh concentrations of >1 mM, indicating channel block by ACh. The data from three oocytes were fitted by dual concentration-effect curves for activation and block by ACh. The mean IC50 value obtained from the fitted curves was 4.2 ± 1.5 μM, the mean slope factor for activation was 1.12 ± 0.29, the mean Emax was 103 ± 3%, and the mean IC50 was estimated to be 54.7 ± 22 mM with a fixed value of −1 for the slope factor for inhibition. A number of oocytes injected with α4 and β4 cDNAs did not respond to superfusion with 1 mM ACh, indicating that even this high concentration of ACh does not activate other than nAChR-mediated ion current in oocytes. Channel block by atropine at −40 mV was determined from responses evoked by 1 mM ACh. The concentration-effect curve of atropine (Fig. 5B) reflects mainly noncompetitive block at a high ACh concentration. The IC50 value of atropine at −40 mV amounts to 4.5 ± 0.6 μM, and the slope factor is −0.96 ± 0.04 (three oocytes). The IC50 value estimated from the inhibition curve is close to the value of 4.1 μM.
predicted from the results on the voltage dependence of ion channel block (Fig. 3).

To further optimize experimental conditions with respect to potentiation, the relation between the effect of 10 μM atropine and ACh concentration was investigated at the holding potential of −40 mV. The results of these experiments (Fig. 6) show that potentiation occurs only at low agonist concentration. The 1 μM ACh-induced inward current

Fig. 4. Effect of membrane potential on the balance between potentiation and inhibition of α4β4 nAChR-mediated ion current by atropine. A, Effects of 10 μM atropine on 1 μM ACh-induced ion current recorded at membrane potentials ranging from −30 to −100 mV, as indicated. Bars, application of ACh and atropine. The inhibitory effects of atropine are enhanced at more negative membrane potentials, whereas the large tail currents observed on removal of atropine indicate that potentiation occurs at the more negative holding potentials as well. Similar results were obtained from an additional four oocytes. B, Steady state effects of 10 μM atropine on 1 μM ACh-induced ion current measured at different membrane potentials demonstrate that atropine potentiates the ACh-induced inward currents at membrane potentials of ≤−80 mV. At membrane potentials of ≤−90 mV, the effect of atropine is reversed into inhibition. Data points, mean ± standard deviation (bars) values for five oocytes. C, Similar potentiation of 1 μM ACh- and 0.3 μM (-)-nicotine-induced ion currents by 10 μM atropine at −40 mV membrane potential.

Fig. 5. A, Concentration-effect curve of ACh at −40 mV membrane potential. Peak amplitudes of inward currents evoked by a wide range of ACh concentrations were normalized to the peak amplitude of the 1 mM ACh-induced inward current. Mean ± standard deviation values for three oocytes are plotted against ACh concentration. Concentration-effect curves for activation and inhibition by ACh were fitted to the data of individual experiments according to the equation: $E = E_{\text{max}} / \left(1 + (E_{C50}/[\text{ACh}])^{n}\right) \left(1/(1 + [\text{ACh}]/IC_{50})\right)$. Solid line, mean concentration-effect curve with $E_{C50} = 42.2$ μM ACh, $n = 1.12$, $E_{\text{max}} = 102.8\%$, and $IC_{50} = 54.7$ μM (i.e., the calculated mean values of the parameters estimated from the three experiments). Dashed line, mean concentration-effect curve obtained by fitting the same data with the two-site receptor occupation model as presented in legend to Fig. 8 (eq. 2), including channel block by ACh: $E = E_{\text{max}}/[c_A/(1 + c_A)^2] \left(1/(1 + [\text{ACh}]/ IC_{50})\right)$ (see Discussion). B, Concentration-effect curve of atropine for the inhibition of 1 mM ACh-induced ion current at −40 mV. Inward current amplitudes in the presence of atropine were normalized to those of control inward currents induced with 1 mM ACh. Data points, mean ± standard deviation values for three oocytes. Line, mean concentration-effect curve calculated from the parameters estimated from fitting inhibition curves according to $E = 100/(1 + (IC_{50}/[\text{atropine}])^n)$ to the data for the three experiments. The mean IC_{50} value and $n$ were 4.5 μM atropine and −0.96, respectively. Dashed line, predicted by the model presented in legend to Fig. 8 (eq. 3).
was potentiated by 10 μM atropine, whereas in the same oocytes inward currents induced by 10 μM to 1 mM ACh were inhibited by 10 μM atropine. Despite the pronounced inhibitory effect of 10 μM atropine, current transients were never observed at the onset and reversal of the atropine effects during 100 μM ACh-induced ion currents, measured at the holding potential of −40 mV. Atropine potentiates the ACh-induced inward current only at the 1 μM ACh concentration. At ACh concentrations of ≥10 μM, the effect of atropine is reversed into inhibition. Data points, mean ± standard deviation (bars) values for three oocytes. At 1 mM ACh, the mean ± standard deviation is smaller than the symbol. Dashed line, predicted by the model presented in legend to Fig. 8 (eq. 3) (see Discussion).

The relation between potentiation of α4β4 nAChR-mediated current and atropine concentration has been investi-
resulting bell-shaped concentration-effect curve shows potentiation in the range of 0.3–10 μM atropine and inhibition at ≥30 μM atropine. The mechanisms to account for the potentiating and inhibitory effects of atropine are discussed.

**Discussion**

The results demonstrate that neuronal nAChR-mediated ion currents are modulated by the classic mAChR antagonist atropine. At hyperpolarized membrane potential and high agonist concentration, atropine always inhibits the ACh-induced inward current. The degree of this inhibition varies for the different nAChR subunit combinations but cannot be related to a specific α or β receptor subunit. At low agonist concentration, the inhibitory effect of atropine is significantly reduced for most subtypes of nAChR that we investigated, and unexpectedly, atropine potentiates ion current mediated by α4 subunit-containing nAChR (Table 1). Detailed investigation of atropine effects on the more sensitive α4β4 nAChR demonstrates that the potentiating effect differs from the inhibitory effect in being more pronounced at low agonist concentration and at depolarized membrane potential. Ion currents and indirect effects mediated by endogenous mAChRs were not observed in the present experiments. The absence of endogenous mAChRs, which has also been reported in other oocyte studies (13, 27–30), is possibly due to the collagenase treatment and defolliculation of the oocytes (20).

**Inhibition.** The inhibition of ion currents evoked by high concentrations of ACh in oocytes expressing the more sensitive α4β4 nAChR by atropine was found to be noncompetitive (Fig. 2B). The reduction in ion current amplitude by atropine was voltage dependent and associated with an acceleration of inward current decay and a transient tail current on removal of atropine (Figs. 3 and 4). From these results, it is concluded that the noncompetitive inhibitory effect of atropine on nAChRs is caused by the occlusion of open ion channels. IC_{50} values of atropine for blocking ion currents induced by high concentrations of ACh at −80 and −40 mV of 0.96 and 4.1 μM, respectively, are predicted on the basis of the data in Fig. 3C. These predicted values are close to the observed IC_{50} values of 0.66 μM (Fig. 2A) and 4.5 μM (Fig. 5B) atropine at the respective membrane potentials. This indicates that the noncompetitive effect of atropine is adequately accounted for by voltage-dependent ion channel block.

Table 1 shows that α4β4, α2β4, and α7 nAChRs have a similar high sensitivity to block by atropine. Other data available on the sensitivity of neuronal nAChRs to inhibition by atropine are restricted to homo-oligomeric nAChRs. The IC_{50} value of 125 μM atropine for the inhibition of human α7 nAChRs as determined from responses evoked with 30 μM nicotine at a holding potential of −60 mV (31) suggests that the human α7 is less sensitive than the rat α7 nAChR (Table 1). Reported IC_{50} values of atropine for inhibition of rat α9 nAChRs (1.3 μM; ref. 13) and of chicken α7 (7.1 μM) and α8 (0.4 μM; ref. 12) nAChRs have been obtained under conditions less favorable for ion channel block (i.e., low agonist concentrations were used at moderately hyperpolarized membrane potentials). The data in Table 1 show that the inhibitory effects of atropine are significantly reduced at low agonist concentration, except for the effect on α3β4 nAChR. This suggests that potentiation, which is clearly observed for α4β2 and α4β4 nAChR, may occur at other subtypes of nAChR as well but to a lesser degree.

**Mechanism of action of atropine and other drugs.**

Previously, potentiation and inhibition of nAChR-mediated ion currents in PC12 cells have been reported for the cholinesterase inhibitor 1-methyl-galanthamine (33). Like atropine, cholinesterase inhibitors inhibit nAChR-mediated ion currents by open channel block, but a noncompetitive mechanism is thought to be involved in potentiation by 1-methyl-galanthamine as well (26, 34). The action of atropine more strongly resembles that of curare-like drugs, which also cause a combination of potentiating and inhibitory effects on nAChRs. The striking similarities between the actions of atropine and curare-like drugs are that both potentiate the nAChR-mediated ion current only in the presence of low concentrations of agonist and that neither (+)-tubocurarine (22) nor atropine (Fig. 3B) causes direct agonist effects on neuronal nAChRs expressed in X. laevis oocytes. However, curare-like drugs appear to be weak partial agonists on fetal, end-plate-type nAChRs expressed in quail fibroblasts (35), and (+)-tubocurarine activates unitary currents in bovine chromaffin cells (36). The presently found dependence of the potentiation by atropine on agonist concentration (Fig. 6) is consistent with models previously proposed (22, 35) in which the simultaneous occupation of one agonist recognition site with an agonist molecule and of a second agonist recognition site with the “blocking drug” induces ion channel activation. The concentration-dependent potentiation and inhibition of neuronal nAChRs by atropine (Fig. 7) have been evaluated...
using the equilibrium receptor occupation model of Cachelin and Rust (22). The model assumes that (i) the neuronal nAChR contains two identical agonist recognition sites, (ii) these sites must be occupied by ACh molecules or by one ACh and one atropine molecule to produce an activatable state of the receptor, and (iii) ligand binding kinetics are rapid. The original model was extended to incorporate noncompetitive ion channel block by atropine, resulting in eight distinctly occupied states (Fig. 8). The data of Fig. 7 were closely fitted by the steady state occupation/block function derived (see legend to Fig. 8A). The apparent affinity \( K_1 \) of ACh for the agonist recognition site was estimated by fitting a model for two-site receptor occupation and ion channel block by ACh to the concentration-effect data in Fig. 5A (dashed line). The mean of the estimated \( K_1 \) values was 16.9 ± 9.4 μM (three oocytes). The \( K_1 \) value of 16.9 μM ACh and the \( K_b \) value of 4.5 μM for noncompetitive channel block at −40 mV by atropine (Fig. 5B) were entered in the model as constants, and the apparent affinity of atropine for the agonist recognition site \( (K_a) \) and the efficacy factor \( f \) were estimated by nonlinear regression. The values obtained for \( K_a \) and \( f \) were 29.9 ± 0.7 μM and 0.75 ± 0.09, respectively. Subsequently, all these parameter estimates were used to simulate the results obtained in Figs. 5B and 6B (dashed lines). With the same set of estimated parameters, the effects of ACh concentration on the concentration-effect curve of atropine were also simulated by the model. This simulation clearly demonstrates the bell-shaped potentiation/inhibition curves at low concentrations of ACh and atropine and the monophasic inhibition curves at higher concentrations of ACh (Fig. 8B).

The various effects of atropine on nAChR-mediated ion current are accounted for by the equilibrium receptor occupation model combined with ion channel block. The difference in the affinities of atropine for the agonist recognition site \( (K_a = 29.9 \mu M) \) and ion channel block \( (K_b = 4.5 \mu M) \) indicates that channel block by atropine will always be the predominant inhibitory effect at membrane potentials more negative than −40 mV. In the presence of an excess of ACh, atropine will cause ion channel block only (AARB; see legend to Fig. 8). This is consistent with the low IC\(_{50}\) value of atropine and the moderate slope of the inhibition curves obtained at high concentrations of ACh (Figs. 2A and 5B) compared with the higher IC\(_{50}\) value of atropine and the steep slope of inhibition of 1 μM ACh-induced current (Fig. 7B). These features are also predicted by the model illustrated in Fig. 8B.

**General implications of the findings.** The sensitivity of various subtypes of neuronal nAChRs to atropine complicates the interpretation of results obtained in many studies of neuronal nAChRs expressed in oocytes, in which micromolar concentrations of atropine were routinely added to the extracellular solutions to block putative endogenous mAChRs (see Fig. 2B). Results of studies of more complex systems, such as brain slices, in which atropine is used as a tool to discriminate between mAChR- and nAChR-mediated effects should also be treated with caution. Adverse potentiating or inhibitory effects may be more or less pronounced depending on nAChR subtype, cell membrane potential, and agonist concentration. Because mAChRs have affinities to atropine that are several orders of magnitude higher (7) than those of the more sensitive subtypes of nAChR, low therapeutic doses of atropine should not interfere with nAChR function. However, whether potentiating effects of atropine on neuronal nAChRs in the central nervous system are involved in the excitatory symptoms associated with overt toxic
doses of atropine (37) remains to be determined. At concentrations as low as 0.1 μM, which are frequently used in experiments to antagonize mAChRs, direct effects of atropine on the functioning of several subtypes of neuronal nAChRs cannot be ignored.

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