Photoaffinity Labeling the Torpedo Nicotinic Acetylcholine Receptor with [3H]Tetracaine, a Nondesensitizing Noncompetitive Antagonist

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Received March 23, 1999; accepted May 18, 1999

ABSTRACT

Tetracaine (N,N-dimethylaminoethyl-4-butylaminobenzoate) and related N,N-dialkylaminoethyl substituted benzoic acid esters have been used to characterize the high-affinity binding site for aromatic amine noncompetitive antagonists in the Torpedo nicotinic acetylcholine receptor (nAChR). [3H]Tetracaine binds at equilibrium to a single site with a Kd value of 0.5 μM in the absence of agonist or presence of α-bungarotoxin and with a Kd value of 30 μM in the presence of agonist (i.e., for nAChR in the desensitized state). Preferential binding to nAChR in the absence of agonist is also seen for N,N-DEAE and N,N-diethylaminopropyl esters, both binding with 10-fold higher affinity in the absence of agonist than in the presence, and for the 4-ethoxybenzoic acid ester of N,N-diethylaminobenzoic acid, but not for the 4-amino benzoate ester (procaine).

Irradiation at 302 nm of nAChR-rich membranes equilibrated with [3H]tetracaine resulted in covalent incorporation with similar efficiency into nAChR α, β, γ, and δ subunits. The pharmacological specificity of nAChR subunit photolabeling as well as its dependence on [3H]tetracaine concentration establish that the observed photolabeling is at the high-affinity [3H]tetracaine-binding site. Within α subunit, ≥95% of specific photolabeling was contained within a 20-kilodalton proteolytic fragment beginning at Ser173 that contains the M1 to M3 hydrophobic segments. With all four subunits contributing to [3H]tetracaine site, the site in the closed channel state of the nAChR is most likely within the central ion channel domain.

The muscle nicotinic acetylcholine receptor (nAChR) consists of four homologous subunits (α2βγδ) arranged pseudo-symmetrically around a central axis that is a cation-selective ion channel. Each subunit has a common primary structure motif: a hydrophilic, extracellular N-terminal half containing amino acids of the agonist-binding sites, followed by three hydrophobic membrane spanning segments (M1–M3), a cytoplasmic domain, a fourth transmembrane segment (M4), and short extracellular C-terminal tail. Affinity labeling studies, site-directed mutagenesis, and low-resolution (9 Å) cryoelectron microscopy provide considerable information about nAChR structure (reviewed in Karlin and Akabas, 1995; Hucho et al., 1996; Unwin, 1998). The two agonist-binding sites, which are located extracellularly at the α-γ and α-δ subunit interfaces, are composed of multiple loops of primary structure from α and γ (or δ) subunits (reviewed in Prince and Sine, 1998). M2 domains from each subunit line the pore of the ion channel (Imoto et al., 1988; Unwin, 1995), with additional contributions from the extracellular ends of the M1 segments (Zhang and Karlin, 1997), whereas M3 and M4 segments are more peripheral and in contact with lipid (Blanton and Cohen, 1994).

Noncompetitive antagonists (NCAs) block the nAChR permeability response without preventing the binding of ACh (acetylcholine). A structurally diverse group of drugs act as NCAs, including many aromatic amines, general anesthetics, fatty acids, steroids, and neuropeptides such as Substance P (reviewed in Arias, 1998). Studies of the binding of the aromatic amines [3H]mepropradifen and [3H]phencyclidine (PCP) or of the spiropropidine [3H]histrionicotoxin ([3H]HTX) to nAChR-rich membranes from Torpedo electric organ establish that each binds with high affinity (K ≈ μM) to one site per nAChR and to additional lower-affinity sites (Heidmann et al., 1983). The high-affinity site is linked allosterically to the ACh site, with most aromatic amines binding at equilibrium with highest affinity in the presence of agonist [i.e., to the desensitized state of the nAChR (Cohen et al., 1985; Arias, 1996; Lurtz and Pedersen, 1999)].

ABBREVIATIONS: nAChR, nicotinic acetylcholine receptor; ACh, acetylcholine; NCA, noncompetitive antagonist; V8 protease, Staphylococcus aureus glutamyl endopeptidase; GSSG, oxidized glutathione; [3H]HTX, [3H]histrionicotoxin; [125I]TID, 3-(trifluoromethyl)-3-(M-[125I])iodophenyl)diazirine; HTX, di-perhydrohistrionicotoxin; H10-HTX, di-decahydro(pentenyli)histrionicotoxin; PAGE, polyacrylamide gel electrophoresis; PCP, phencyclidine; TPS, Torpedo physiological saline.
Affinity-labeling studies have identified homologous residues near the cytoplasmic end of each M2 segment that contribute to the high-affinity binding site in desensitized Torpedo nAChRs for the aromatic amine NCAs \([^{3}H]\)chlorpromazine (Revah et al., 1990) and \([^{3}H]\)trimethylphenylphosphonium (Hucho et al., 1986). Mutational analyses also implicate these amino acids as affinity determinants for the aromatic amine QX-222 (Charnet et al., 1990) and for aliphatic alcohols (Forman, 1997) acting as open channel blockers. However, in each conformational state, there may be distinct, nonoverlapping sites for positively charged NCAs, and different regions within the ion channel may contribute to the binding site for a single ligand in different conformational states. In the desensitized nAChR, \([^{3}H]\)meproafenid mustard reacts with \(\alpha\text{Glu}^{262}\) at the extracellular end of M2 (Pedersen et al., 1992), and based on fluorescence energy transfer, the binding site for etidium is located above the level of the bilayer in the vestibule of the channel (Johnson and Nuss, 1994, but see Lurtz et al., 1997). In the open channel state, \([^{3}H]\)quinacrine azide is photoincorporated into amino acids within \(\alpha\text{M1} (\text{DiPaola et al., 1990})\), and mutations within \(\alpha\text{M1} \) affect quinacrine potency as an NCA but not chlorpromazine (Tamamizu et al., 1995). Photoaffinity labeling studies with 3-(trifluoromethyl)-3-(\(\text{[125}I]\)iodophenyl) diazirine \((^{125}I\text{TID}; \text{White and Cohen, 1992}) \) and \([^{3}H]\)tetracaine itself as an intrinsic photoaffinity reagent for preferential binding to the closed channel state, and we utilized analogs of tetracaine to further define the requirements of the desensitized state of the nAChR (Boyd and Cohen, 1984).

1979), and it stabilizes the resting state rather than the absence of agonist than in the presence (Blanchard et al., 1999), we identify the homologous amino acids in the M2 domain between resting and desensitized states. However, the TID site in the closed channel appears distinct from the binding site for PCP because PCP does not inhibit \([^{125}I]\)TID photoincorporation and TID does not inhibit \([^{3}H]\)PCP binding (White et al., 1991).

Tetracaine (dimethylaminoethyl-\(p\)-butylaminobenzoate) is an unusual aromatic amine NCA because it is 100-fold more potent as an inhibitor of \([^{3}H]\)HTX binding \((K = 1 \mu M)\) in the absence of agonist than in the presence (Blanchard et al., 1979), and it stabilizes the resting state rather than the desensitized state of the nAChR (Boyd and Cohen, 1984). Here, we characterize the binding properties of several structural analogs of tetracaine to further define the requirements for preferential binding to the closed channel state, and we use \([^{3}H]\)tetracaine itself as an intrinsic photoaffinity reagent to define the structure of its high-affinity binding site in the nAChR in the absence of agonist. \([^{3}H]\)Tetracaine is specifically photoincorporated with similar efficiency into each nAChR subunit. In the following report (Gallagher and Cohen, 1999), we identify the homologous amino acids in the M2 segment of each subunit that contribute to this high-affinity \([^{3}H]\)tetracaine site.

**Experimental Procedures**

**Materials.** \([\text{ring-3,5-}^{3}H]\)Tetracaine (\([^{3}H]\)tetracaine, 36 Ci/mmole) and \([^{3}H]\)HTX (60 Ci/mmole) were prepared at New England Nuclear Research Products (Boston, MA) by tritium gas catalytic reduction of 3,5-dibromotetracaine and \(dl\)-decahydro(pentenyl)histrionicotinonic acid (H\(_{10}\)-HTX), respectively. For binding experiments, \([^{3}H]\)tetracaine was purified to \(>95\% \) by silica thin-layer chromatography (5:4:1 cyclohexane/chloroform/diethylethylamine; \(R_{f} = 0.17\)). When stored in ethanol, \([^{3}H]\)tetracaine decomposed at \(-10\% \) per month, forming tritiated degradation products that did not partition into nAChR-rich membranes or bind to glass filters. Also, these degradation products did not appear to photoincorporate into nAChR-rich membranes because the same \([^{3}H]\)tetracaine photolabeling patterns were seen with \([^{3}H]\)tetracaine of 95 or 50\% radiochemical purity (not shown).

H\(_{10}\)-HTX and \(dl\)-perhydrohistrionicotinonic acid (H\(_{2}\)-HTX) were kindly provided by Dr. Y. Kishi (Harvard University, Cambridge, MA). Proudifen was obtained from SmithKline Beecham (Philadelphia, PA). Piperoxane was obtained from Eli Lilly (Indianapolis, IN). Tetracaine, promazine, carbamylcholine chloride, \(dl\)-tubocurarine chloride, oxidized glutathione (GSSG), and endoglycosidase H were obtained from Sigma Chemical Co. (St. Louis, MO). \(\alpha\)-Bungarotoxin was purchased from Bio toxins Inc. (St. Cloud, FL). FCPC was obtained from Alltech Associates. Staphylococcus aureus V8 protease (V8 protease) was obtained from ICN Biochemicals (Costa Mesa, CA).

The \(2\)-diethylaminophenyl- and \(3\)-diethylamino)propyl esters of \(p\)-butylaminobenzoic acid were synthesized by coupling with diisopropylcarbodiimide using chemicals from Aldrich Chemical (Milwaukee, WI). For synthesis of the DEAE ester, 2 g (0.01 mol) of 4-(\(butyloxy)benzoic acid, 1.8 ml (0.011 mol) of diisopropylcarbodiimide, and 0.2 g (0.0013 mol) of 4-pyryridoinopropionyline were stirred for 5 min at room temperature in 10 ml of methylene chloride, and then 3 equivalents (6 ml) of \(NN\)-diethylthalamolamine were added and allowed to react overnight. After removal of methylene chloride under vacuum, the residue was suspended in anhydrous ether, with the insoluble diisopropyl urea removed by filtration. The filtrate was washed with \(5\% \) NaHCO\(_3\), and then centrifuged in a Beckman Airfuge at \(100,000 \times g\) at \(4^\circ C\). quaintification of the high-affinity \([^{3}H]\)tetracaine sites compared with the concentration of \([^{3}H]\)ACh sites measured simultaneously with the same membranes. For studies with \([^{3}H]\)ACh, membrane suspensions pretreated with 0.3 mM diisopropylphosphofluoridate to inhibit cholinesterase activity. \([^{3}H]\)Tetracaine was diluted isotopeically with \(H_2\)-HTX to produce a final radiochemical specific activity of 2 Ci/mmole for binding assays.

\([^{3}H]\)HTX and \([^{3}H]\)tetracaine binding were also determined by a centrifugation assay using glass-fiber filters (2.5 cm, No. 32; Schleicher & Schuell, Keene, NH) that had been pretreated with an organosilane (1.0% Prosil; Lancaster Synthesis, Windham, NH). Membrane aliquots (typically 100–200 \(\mu l\)) were applied to the filters in the absence of vacuum to achieve a uniform spread of the suspension over the
filter surface; then, vacuum was applied, and the filter was washed with 5 ml of TAP at 4°C.

**Photoaffinity Labeling of nAChR-Rich Membranes with [3H]Tetracaine.** Membrane suspensions (30 µl, 1.5–1.8 mg protein/ml) in TPS were equilibrated at room temperature with [3H]tetracaine (4 Ci/mmol) and cholinergic ligands and then irradiated for 30 min with a 302-nm lamp (Spectrolite EB-280C, 1150 µW/cm²) at a distance of 12 cm as described (Pedersen and Cohen, 1990). Unless indicated otherwise, suspensions also included 50 mM GSSG as an aqueous photochemical scavenger. The 96-well microtiter plate containing the samples was placed in a water bath during photolysis, so the temperature increased <2°C during 30 min of irradiation. After photolysis, samples were usually prepared for SDS-polyacrylamide gel electrophoresis (PAGE) by the direct addition of 10 µl of 4× sample loading buffer to reaction mixtures. To quantify the dependence of [3H] incorporation as a function of [3H]tetracaine, after photolysis the reaction mixtures were centrifuged, with the supernatants assayed to determine free [3H]tetracaine, and the pellets dissolved in sample loading buffer. In preliminary experiments, the efficiency of [3H]tetracaine photoincorporation into nAChR-rich membranes was found to be 10 times higher for the 302-nm lamp than for lamps of 254 or 365 nm of similar radiant flux density (not shown).

**Gel Electrophoresis.** Polypeptides were resolved by SDS-PAGE on 8% acrylamide gels with a modified Laemmli buffer system (White and Cohen, 1988), and the incorporation of [3H]tetracaine was determined by fluorography or quantified by scintillation counting of gel slices as described previously (Middleton and Cohen, 1991). Proteolytic mapping of the [3H]tetracaine-labeled α subunit with S. aureus V8 protease was performed according to the procedure of Cleveland et al. (1977) as described by White and Cohen (1988). Membrane suspensions (540-µg aliquots) were photolabeled with [3H]tetracaine and then electrophoresed on an 8% acrylamide gel. After a brief staining with Coomassie brilliant blue and destaining, the band containing the subunit was excised and transferred to the filter surface; then, vacuum was applied, and the filter was washed with 5 ml of TAP at 4°C.

**TABLE 1**

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<th>Compound</th>
<th>R&lt;sub&gt;1&lt;/sub&gt;</th>
<th>R&lt;sub&gt;2&lt;/sub&gt;</th>
<th>Inhibition of [3H]HTX Binding K&lt;sub&gt;I&lt;/sub&gt;</th>
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<th>+ Carb</th>
<th>+dTC</th>
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<td>-CH&lt;sub&gt;2&lt;/sub&gt;CH&lt;sub&gt;2&lt;/sub&gt;N(CH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
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B is the bound [3H]tetracaine (or cpm incorporated), A is the maximum specific binding (or cpm incorporated), K<sub>I</sub> is the dissociation constant (or apparent dissociation constant, K<sub>dTC</sub>). L is the measured free [3H]tetracaine concentration, and m is the slope of nonspecific binding (or labeling), which was usually determined in parallel experiments performed in the presence of excess nonradioactive tetracaine or H<sub>10</sub>-HTX. For labeling experiments, the measured free [3H] cpm was adjusted to account for the ~50% radioimpurities known to be present in the [3H]tetracaine used for photolabeling.

The concentration dependence of the inhibition of reversible binding of [3H]HTX or [3H]tetracaine and of [3H]tetracaine photolabeling of nAChR subunits was fit to a function \( B = A/[1 + (I/K_I)] + NSP \), where B is the [3H] cpm bound (or incorporated) in the presence of inhibitor at a total concentration, f; A is the specific [3H] cpm bound (or incorporated) in the absence of inhibitor; K<sub>I</sub> is the apparent inhibitor dissociation constant; n is the Hill coefficient, and NSP is the observed nonspecific binding or labeling, which was not treated as an adjustable parameter. The parameter n<sub>H</sub> was treated as adjustable only if inhibition curves deviated from a single-site model (n<sub>H</sub> = 1). Under the assay conditions used, with the concentration of free [3H]HTX or [3H]tetracaine much less than their K<sub>I</sub> value, K<sub>I</sub> will be close to the inhibitor equilibrium dissociation constant when n<sub>H</sub> = 1 and the total inhibitor concentration is a good approximation of the free concentration.

**Results**

**Inhibition of [3H]HTX Binding by Tetracaine Analogs.** Because tetracaine’s preferential binding to the closed channel state of the nAChR appeared unusual for aromatic amine NCAs, we first examined other benzoic acid esters as inhibitors of [3H]HTX binding to identify structural features responsible for tetracaine’s binding properties (Table 1). All drugs at high concentrations completely inhibited specific binding of [3H]HTX, with the concentration dependence of inhibition for each drug consistent with competition at a single site. With the exception of procaine (V), all bound with highest affinity in the absence of agonist. For the esters of p-butylaminobenzoic acid, replacement of the dimethylaminoethyl of tetracaine (I) by DEAE (II) resulted in a ~6-fold increase in binding affinity in both the absence and presence
of agonist. Comparison of procaine (V) with compound II established that aliphatic substitution at the aryl nitrogen increased affinity for the closed channel conformation by 4000-fold but by only 300-fold for the desensitized conformation. However, high-affinity binding in the absence of agonist did not depend uniquely on the butyramino group because the p-ethoxybenzoic acid ester (IV) also bound preferentially to the resting state \( K_r = 1.6 \, \mu M \), and piperocaine (VI), an unsubstituted benzoic acid ester, was bound with 50-fold higher affinity in the absence of agonist. Thus, selective, high-affinity binding in the absence of agonist appeared to be the rule for many simple benzoic acid esters, with procaine a notable exception.

**Equilibrium Binding of \[^3H\]Tetracaine.** The equilibrium binding of \[^3H\]tetracaine to nAChR-rich membranes in TPS at 4°C was determined by centrifugation and filtration assays (Fig. 1A). For \[^3H\]tetracaine concentrations to 4 \, \mu M, in each assay the total binding was well fit by a hyperbolic binding function with a linear, nonspecific component. The nonspecific binding calculated from the fit of the total binding function was approximately the same as that measured in the presence of 50 \, \mu M nonradioactive tetracaine. \[^3H\]Tetracaine bound to the same number of high-affinity sites in both assays, with the ratio of sites determined by filtration and centrifugation equal to 1.2 ± 0.2 in three experiments. The same value of the dissociation constant was determined by centrifugation \( (K_{eq} = 0.5 ± 0.1 \, \mu M) \) and filtration \( (K_{eq} = 0.6 ± 0.1 \, \mu M) \). The nonspecific binding determined by filtration, with a brief (5 s) wash, was only 20% that determined by centrifugation. The partition coefficient, determined as the ratio of the nonspecifically bound to the free tetracaine concentration normalized to the membrane protein concentration, was 0.08 ± 0.02 \,(mg/ml)^{-1} \) by centrifugation and 0.014 ± 0.005 by filtration. Thus, in the absence of agonist, specific \[^3H\]tetracaine binding to the nAChR-rich membranes was characterized by a single \( K_{eq} \), and a filtration assay can be used to quantify equilibrium binding of \[^3H\]tetracaine to its high-affinity site.

The filtration assay was used to examine the effects of an agonist (carbamylcholine) and competitive antagonists (\( \alpha \)-bungarotoxin and \( d \)-tubocurarine) on the binding to nAChR-rich membranes of \[^3H\]tetracaine at concentrations to 20 \, \mu M (Fig. 1B). None of the ligands altered the nonspecific binding determined in the presence of 100 \, \mu M tetracaine (not shown), and \[^3H\]tetracaine was bound with similar affinity \( (K_{eq} = 0.5 ± 0.1 \, \mu M) \) and to the same number of sites \( (\text{ratio} = 1.1 ± 0.2, n = 19) \) in the absence and presence of \( \alpha \)-bungarotoxin. Partial desensitization of the nAChR with \( d \)-tubocurarine resulted in \[^3H\]tetracaine binding to the same number of sites but with a \( K_{eq} \) value of 1.1 ± 0.6 \, \mu M \( (n = 23) \). In the presence of carbamylcholine, which converts nAChRs fully to the desensitized state, \[^3H\]tetracaine binding affinity was decreased dramatically, with only ~80% of the expected tetracaine-binding sites occupied at 20 \, \mu M \[^3H\]tetracaine. When the data were fit using the site concentration determined in the presence of \( \alpha \)-bungarotoxin or \( d \)-tubocurarine, \( K_{eq} \) was 29 ± 7 \, \mu M \( (n = 4) \).

To determine the number of \[^3H\]tetracaine-binding sites per nAChR, \[^3H\]tetracaine binding was measured in parallel with binding assays of \[^3H\]HTX (in the presence of 100 \, \mu M carbamylcholine) and \[^3H\]ACh. The ratio of \[^3H\]tetracaine sites to \[^3H\]ACh sites was 0.43 ± 0.07 \( (n = 19) \), and the ratio of \[^3H\]HTX to \[^3H\]ACh sites was 0.5 ± 0.1. Thus, \[^3H\]tetracaine and \[^3H\]HTX each bound to the same number of sites, and this number was half the number of \[^3H\]ACh sites.

**Inhibition of \[^3H\]Tetracaine Binding by NCAs.** The desensitizing NCAs PCP, meproaddifen, proadifen, and \( H_1 \)-HTX were examined as inhibitors of the equilibrium binding of \[^3H\]tetracaine at 4°C in the absence of other cholinergic ligands or in the presence of either \( \alpha \)-bungarotoxin or \( d \)-tubocurarine (Fig. 2). Although HTX binds with similar affinity \( (K_{eq} = 0.3 \, \mu M) \) in the absence or presence of agonist at 20°C (Blanchard et al., 1979), at 4°C it binds with high affinity \( (K_{eq} = 0.3 \, \mu M) \) in the presence of agonist but only weakly \( (K_{eq} = 8 \, \mu M) \) in the absence (Cohen et al., 1985). The four NCAs inhibited \[^3H\]tetracaine binding in a concentra-
tion-dependent manner, with high concentrations inhibiting \[^{[H]}\text{tetracaine}\] binding by the same extent as 100 \(\mu M\) tetracaine. \(K_i\) values for inhibition of \[^{[H]}\text{tetracaine}\] binding were 6- to 10-fold lower in the presence of \(d\)-tubocurarine than in its absence, consistent with the preferential binding of these NCAs to desensitized nAChR (Heidmann et al., 1983; Cohen et al., 1985). The concentration dependence of inhibition by \(H_{10\text{-HTX}}\) (Fig. 2A) and PCP (Fig. 2B) was well fit by Hill coefficients of 1 in both the absence and presence of \(d\)-tubocurarine or \(\alpha\)-bungarotoxin, consistent with simple competitive inhibition of \[^{[H]}\text{tetracaine}\] binding. For proadifen (Fig. 2C), the Hill coefficients for inhibition were unitary except in the presence of \(\alpha\)-bungarotoxin \((n_H = 1.6)\). For meproadifen (Fig. 2D), the dose dependence of inhibition was characterized by \(n_H = 1\) in the presence of \(d\)-tubocurarine but by \(n_H = 1.5\) in the absence of ACh site ligand and by \(n_H = 1.8\) in the presence of \(\alpha\)-bungarotoxin.

**Photoincorporation of \[^{[H]}\text{Tetracaine}\]** into nAChR-Rich Membranes. To determine whether \[^{[H]}\text{tetracaine}\] could be specifically photoincorporated into its high-affinity binding site, nAChR-rich membranes were equilibrated with 5 \(\mu M\) \[^{[H]}\text{tetracaine}\] and then irradiated at 302 nm for 30 min in the presence or absence of the NCA \(H_{10\text{-HTX}}\) (30 \(\mu M\)). When the proteins were resolved by SDS-PAGE and the gel was processed for fluorography, it was seen (Fig. 3, lanes 2 and 3) that \(H_{10\text{-HTX}}\) decreased \[^{[H]}\text{tetracaine}\] incorporation not only in the nAChR subunits but also into another protein of the nicotinic postsynaptic membrane \([\text{rapsyn}/43 \text{ kDa}]\) and into polypeptides of contaminating membrane fragments such as the \(\alpha\) subunit of the \(Na^+\)-K\(^+\)-ATPase (90 kDa; White and Cohen, 1988). Photoincorporation into nonreceptor polypeptides was also decreased by the agonist carbachol, which allosterically inhibits \[^{[H]}\text{tetracaine}\] binding (Figs. 6 and 8). It was improbable that HTX and carbachol actually inhibited \[^{[H]}\text{tetracaine}\] binding to specific sites on the \(Na^+\)-K\(^+\)-ATPase. A more likely explanation was that a reactive \[^{[H]}\text{tetracaine}\] intermediate generated primarily when \[^{[H]}\text{tetracaine}\] was bound to its high-affinity site in the nAChR could dissociate from its NCA site and then react with other membrane proteins. This pseudospecific photoincorporation should be sensitive to aqueous compounds that could quench the free reactive species.

GSSG was examined as a potential aqueous scavenger, and indeed high concentrations (50 \(mM\)) were effective in dramatically reducing the pseudospecific \[^{[H]}\text{tetracaine}\] photoincorporation into nonreceptor polypeptides (Fig. 3, lanes 4-7). With 50 \(mM\) GSSG, the \(H_{10\text{-HTX}}\)-sensitive labeling was primarily associated with the four nAChR subunits. There also remained specific photolabeling of an nAChR subunit proteolytic fragment, which appears as a band migrating with slightly greater mobility than the \(\alpha\) subunit (Pedersen and Cohen, 1990), as well as of bands migrating between the \(\alpha\) and \(\beta\) subunits in a gel region known to contain proteolytic fragments of nAChR \(\gamma\) and \(\delta\) subunits (Pedersen and Cohen, 1990).

The effects of GSSG at concentrations up to 100 \(mM\) on specific and nonspecific \[^{[H]}\text{tetracaine}\] photoincorporation into nAChR subunits and nonreceptor polypeptides were quantified by analyzing \(^3\text{H}\text{ incorporation}\) in gel slices excised from stained gels (Fig. 4). For nAChR subunits and nonreceptor polypeptides, the effects of GSSG were most pronounced at concentrations up to 10 \(mM\). For nAChR subunits, the \[^{[H]}\text{tetracaine}\] photolabeling inhibitable by \(H_{10\text{-HTX}}\) (the difference between \(^3\text{H}\text{ incorporation}\) for samples labeled in the absence and presence of HTX) was essentially constant at GSSG concentrations of >10 \(mM\). In the presence of 50 \(mM\) GSSG, the \(H_{10\text{-HTX}}\)-sensitive \(^3\text{H}\text{ incorporation}\) into the nAChR \(\alpha\), \(\beta\), \(\gamma\), and \(\delta\) subunits was 792, 730, 301, and 715 cpm, respectively, with only 21 and 54 cpm in the non-receptor polypeptides.

**Fig. 2.** Inhibition of \[^{[H]}\text{tetracaine}\] binding to nAChR-rich membranes by NCAs. nAChR-rich membranes (0.2 \(\mu M\) tetracaine sites) were preincubated at 4°C for 30 min without competitive antagonist (O), with 50 \(\mu M\) \(d\)-tubocurarine (A), or with \(\alpha\)-bungarotoxin (B, 4 \(\mu M\), 90 min) before the addition of 10 \(nM\) \[^{[H]}\text{tetracaine}\]. Aliquots were immediately mixed at multiplicity of 1 unless noted. For \(H_{10\text{-HTX}}\) (A): in the absence of cholinergic ligands, \(K_i\) was 0.5 \(M\), and \(K_i\) was 2.2 \(M\), with \(d\)-tubocurarine \((6 \pm 1 \mu M) = 0.5 \pm 0.04 \mu M\), \((+\text{Btx}) = 18 \pm 3 \mu M\), and \(n_H = 1.6 \pm 0.1\). For proadifen (C): \(K_i\) was 7 \pm 1 \(\mu M\), \(n_H = 1.5 \pm 0.2\); \(K_i\) was 0.9 \pm 0.1 \(\mu M\), \(n_H = 1\); and \(K_i\) was 56 \pm 4 \(\mu M\), \(n_H = 1.8 \pm 0.2\).
receptor polypeptides of 37 kDa (calelectrin) and 90 kDa (Na\(^+\),K\(^+\)-ATPase \(\alpha\) subunit), respectively. GSSG reduced the pseudospecific incorporation into nonreceptor polypeptides by \(\sim85\%\), and all subsequent experiments included 50 mM GSSG in the reaction mixture.

\[^{3}H\]Tetracaine photoincorporation into nAChR subunits was quantified by measuring \(^{3}H\) incorporation as a function of free \[^{3}H\]tetracaine concentration (Fig. 5). The nonspecific labeling of each nAChR subunit in the presence of 50 \(\mu\)M \(\text{H}_{10}\)-HTX increased linearly with free tetracaine (Fig. 5, open symbols), and for each subunit, the total \(^{3}H\) incorporation (Fig. 5, filled symbols) was well fit by a simple hyperbolic binding function plus a linear, nonspecific component. For each subunit, \(K_{AP}\) was \(\sim1.4\) \(\mu\)M, a value close to the \(K_{eq}\) value of 0.5 \(\mu\)M determined directly for the reversible, equilibrium binding of \[^{3}H\]tetracaine (Fig. 1A) and well below the affinity of \[^{3}H\]tetracaine for the agonist site (\(K_{A}\) \(\sim800\) \(\mu\)M; Blanchard et al., 1979). For the conditions of photolabeling used, the maximum specific cpm incorporated was equivalent to labeling of 0.6, 1.1, 0.9, and 1.0% of the \(\alpha\), \(\beta\), \(\gamma\), and \(\delta\) subunits, respectively, which was increased by 50 to 75% when the time of irradiation was increased from 30 to 60 min (not shown).

**Effects of Cholinergic Ligands on \[^{3}H\]Tetracaine Photoincorporation into nAChR-Rich Membranes.**

\[^{3}H\]Tetracaine photoincorporation was examined in the presence of agonists, competitive antagonists, and NCAs (Fig. 6) for comparison with the known pharmacology of \[^{3}H\]tetracaine binding to the NCA site. The NCAs proadifen, PCP, and \(\text{H}_{10}\)-HTX each inhibited the photoincorporation of \[^{3}H\]tetracaine into all four nAChR subunits (Fig. 6, lanes 2 versus 3–5). PCP was the least potent, consistent with its relative potency as an inhibitor of \[^{3}H\]tetracaine equilibrium binding in the absence of agonist (Fig. 2). \[^{3}H\]Tetracaine photoincorporation into the nAChR subunits was not inhibited by excess \(\alpha\)-bungarotoxin (Fig. 6, lanes 2 versus 9 and 16), and the three NCAs still inhibited subunit photolabeling in the presence of \(\alpha\)-bungarotoxin (lanes 6–8). Carbamylcholine (10 and 300 \(\mu\)M) reduced \[^{3}H\]tetracaine incorporation into all four nAChR subunits by 70 to 80% (Fig. 6, lanes 2 versus 17 and 18, and counting of excised gel bands), but this inhibition was not seen when \(\alpha\)-bungarotoxin was present, preventing carbamylcholine from binding to the agonist site (lanes 14 and 15). Although \(\delta\)-tubocurarine at 2 \(\mu\)M had little effect on \[^{3}H\]tetracaine photoincorporation (lane 13), \(\delta\)-tubocurarine at 50 \(\mu\)M reduced labeling by 25 to 40% (lane 12), an inhibition not seen in the presence of \(\alpha\)-bungarotoxin (lane 10). Thus, the inhibition of \[^{3}H\]tetracaine photolabeling by the NCAs was consistent with a competitive inhibition of...
high-affinity [3H]tetracaine binding, whereas the inhibition of photolabeling by carbamylcholine and d-tubocurarine resulted from the allosteric inhibition of [3H]tetracaine binding when the nAChR was desensitized by drugs binding to the agonist site.

The concentration dependence for the inhibition of [3H]tetracaine photolabeling of nAChR subunits by H10-HTX (Fig. 7) and carbamylcholine (Fig. 8) was determined by quantification of [H] incorporation in gel slices. For H10-HTX, the inhibition data for each subunit were well fit by a single-site inhibition function with IC50 values ranging from 3 to 4 µM and maximal inhibition of 81, 94, 65, and 93% for the α, β, γ, and δ subunits, respectively. The observed IC50 values exceeded the directly measured Keq value of 0.3 µM at 20°C (Heidmann et al., 1983), but they were consistent with that value for the assay conditions used: 1) the site concentration (1.3 µM) exceeds the Keq value for H10-HTX, 2) a significant percentage of the H10-HTX is bound nonspecifically [partition coefficient = 0.3 (mg/ml)−1], and 3) the free concentration of [3H]tetracaine was greater than its Keq value. For the known nAChR concentration, the approximate free [3H]tetracaine concentration, and the known partition coefficient for H10-HTX, the observed IC50 value leads to a calculated dis-

**Fig. 5.** Concentration dependence of [3H]tetracaine incorporation into the nAChR subunits. nAChR-rich membranes (53 µg) were suspended in 30 µl of TPS (2.7 µM ACh sites)/50 mM GSSG with various concentrations of [3H]tetracaine, in the absence (solid) or presence (open) of 50 µM H10-HTX. Membrane suspensions were irradiated at 302 nm, and the [3H]tetracaine incorporation into the α (▲), β (●), γ (○), and δ (▲) subunits determined as described in Experimental Procedures. Free [3H]tetracaine was measured as supernatant [H] cpm after centrifugation of irradiated samples. Lines represent nonlinear least-squares fits to the data as described in Experimental Procedures, with Kd values of 1.3 ± 0.3, 1.3 ± 0.3, 1.3 ± 0.3, and 1.5 ± 0.3 µM for the α, β, γ, and δ subunits, respectively. The maximum specific incorporation was 1610, 1370, 1270, and 1520 cpm for the α, β, γ, and δ subunits, respectively.

**Fig. 6.** Effects of cholinergic ligands on [3H]tetracaine incorporation into nAChR-rich membranes. nAChR-rich membranes (53 µg) were suspended in TPS (2.7 µM)/50 mM GSSG for preincubation (60 min) in the absence (lanes 2–5, 12, 13, and 17) or presence (lanes 6–11 and 14–16) of α-bungarotoxin (10 µM) and the following cholinergic ligands: lane 2, no further additions; lane 3, 30 µM H10-HTX; lane 4, 50 µM PCP; and lane 5, 100 µM proadifen. Lanes 6 to 11, 10 µM α-bungarotoxin with 30 µM H10-HTX (lane 6), 50 µM PCP (lane 7), 100 µM proadifen (lane 8), no other drug (lane 9), 50 µM d-tubocurarine (lane 10), and 2 µM d-tubocurarine (lane 11). Lane 12, 50 µM d-tubocurarine; lane 13, 2 µM d-tubocurarine; lane 14, 10 µM α-bungarotoxin with 300 µM carbamylcholine (lane 14), 10 µM carbamylcholine (lane 15), and no other drug (lane 16). Lane 17, 300 µM carbamylcholine; lane 18, 10 µM carbamylcholine. [3H]Tetracaine was added, the samples were irradiated at 302 nm, and the polypeptides were resolved by SDS-PAGE as described in Experimental Procedures. Coomassie blue stain of a gel lane (lane 1) and the fluorograph (lanes 2–17) exposed for 2 weeks are shown.

**Fig. 7.** Inhibition of [3H]tetracaine photoincorporation into nAChR-rich membranes by H10-HTX. nAChR-rich membranes (53 µg) were suspended in 30 µl of TPS (2.7 µM ACh sites) with 2 µM [3H]tetracaine/50 mM GSSG and various concentrations of H10-HTX. After irradiation, membrane polypeptides were fractionated by SDS-PAGE. The nAChR polypeptides were fractionated by SDS-PAGE. The nAChR subunits determined as described in Experimental Procedures. The [3H]tetracaine was added, the samples were irradiated at 302 nm, and the polypeptides were resolved by SDS-PAGE as described in Experimental Procedures. Coomassie blue stain of a gel lane (lane 1) and the fluorograph (lanes 2–17) exposed for 2 weeks are shown.
Japan, Nihon University) and the molecular weight standards were bovine albumin (66 kDa), egg albumin (45 kDa), glyceraldehyde-3-phosphate dehydrogenase (36 kDa), carbonic anhydrase (29 kDa), trypsinogen (24 kDa), trypsin inhibitor (20 kDa), and cytochrome c (13 kDa). Based on counting of excised gel slices, in the presence of 50 mM GSSG the incorporation into αV8-20 in the absence and presence of HTX was 3433 and 622 cpm, respectively, whereas incorporation in αV8-18 was 68 and 30 cpm: in αV8-10, 154 and 75 cpm: and in αV8-4, 33 and 27 cpm. After α subunit deglycosylation with endoglycosidase H, incorporation in αV8-20 was 3574 and 664 cpm. In the absence of GSSG, incorporation in αV8-18, αV8-10, and αV8-4 each <2% that of αV8-20.

The principal effect of 50 mM GSSG was to reduce the nonspecific incorporation into αV8-20 by 80%, whereas the specific labeling was not decreased at all. In contrast, H$_{10}$-HTX-sensitive labeling of αV8-18, αV8-10, and αV8-4 was reduced by 78, 69, and 97%, respectively.

Discussion

The study presented here concerns the nature of the binding site for amine NCAs that bind selectively to the αnACHR in the absence of agonist (i.e., to the closed channel state of the αnACHR). In contrast to the selectivity for the desensitized state seen for most bulky amine NCAs containing fused aromatic rings or multiple aromatic or aliphatic rings, we found that most N$_\text{a}$-substituted ethanalamine esters of benzoic acid actually bind selectively in the absence of agonist (Table 1). With the exception of procaine, which binds weakly and with similar affinity in the absence and presence of agonist, 4-butylamino and 4-ethoxybenzoate esters bind preferentially to the resting state, as does piperoxane, an unsubstituted benzoate. The selectivity of tetracaine for the resting
state results from contributions both from the 4-butylamino substitution and from the presence of the N,N-dimethyl rather than N,N-diethyl. With reference to procaine (compound V, Table 1), the 4-butylamino substitution (compound II) enhanced binding to the resting state by 10-fold more than to the desensitized state, with the further methyl replacements in tetracaine (compound I) weakening binding to the desensitized state by slightly more than to the resting state. In addition to the phenolic acid esters, at least one phenylactic acid ester of N,N-diethylanilinoethanol binds preferentially in the absence of agonist (Cohen et al., 1986). Although proadifen (the ester of 2,2-diphenylpropionic acid) bound with 10-fold higher affinity to the desensitized state and adiphenine (the ester of diphenylactic acid) bound with similar affinity (Kt = 4 μM) in the presence or absence of agonist, butethemate (the 2-phenylbutyryl ester) bound with 8-fold higher affinity to the resting state. The only other drug known to have high resting state selectivity is amobarbital, which binds with 500-fold higher affinity to the resting state, whereas other barbiturates bind preferentially to the desensitized or open channel states (Cohen et al., 1986; de Armendi et al., 1993).

In the absence of agonist, [3H]tetracaine was bound at equilibrium with high affinity (Keq = 0.5 μM) to one site per nAChR monomer, and [3H]tetracaine bound with the same high affinity when ACh sites were occupied with high affinity when ACh sites were occupied with [3H]ACh sites in the nAChR-rich membranes. Because [3H]tetracaine (up to 20 μM) binds to additional low-affinity sites in the nAChR-rich membranes. [3H]Tetracaine bound to the same number of high-affinity sites as [3H]H10-HTX, and as seen previously for [3H]PCP and [3H]H10-HTX (Heidmann et al., 1983), this number was half the number of [3H]ACh sites in the nAChR-rich membranes. Because [3H]ACh binds to two sites per nAChR (Neubig and Cohen, 1979), these NCAs each bind with high affinity to one site per nAChR.

HTX, PCP, proadifen, and meproadifen each completely inhibited the specific [3H]tetracaine binding to nAChR-rich membranes in the absence as well as in the presence of the competitive antagonists d-tubocurarine and α-bungarotoxin. For HTX and PCP, in each condition the concentration dependence of inhibition was well fit by a simple, single-site model (nH = 1). In the presence of d-tubocurarine, the concentration dependence of inhibition by meproadifen or proadifen was also consistent with competition at a single site (nH = 1). However, at higher concentrations (>10 μM) of these drugs necessary to inhibit [3H]tetracaine binding in either the presence of α-bungarotoxin or the absence of other agonist or competitive antagonists, the inhibition curves were characterized by Hill coefficients between 1.5 and 2.0. The steep concentration dependence seen in the presence of α-bungarotoxin suggests that high concentrations of meproadifen and proadifen desensitize the nAChR by a mechanism unrelated to their binding to the high-affinity NCA site or to the ACh sites (Heidmann et al., 1983; Boyd and Cohen, 1984). Of the four NCAs studied, meproadifen binds with highest affinity to the ACh site (Keq = 50 μM; Heidmann et al., 1983), so in the absence of α-bungarotoxin or d-tubocurarine, it may also inhibit [3H]tetracaine binding by binding to the agonist site and desensitizing the nAChR.

To characterize the structure of the aromatic amine NCA site in the closed channel state of the nAChR, we tested whether [3H]tetracaine itself could be used as a photoaffinity probe. Irradiation of nAChR-rich membranes equilibrated with [3H]tetracaine resulted in covalent incorporation into membrane polypeptides. However, the observed photolabeling in the absence of aqueous scavenger was surprising, with photoincorporation into all polypeptides in the membrane suspensions inhibited by the presence of the NCA H10-HTX (Figs. 3 and 4) or the agonist carbamylcholine, drugs that inhibit [3H]tetracaine binding to its high-affinity site in the nAChR. Because the H10-HTX-sensitive [3H]tetracaine incorporation into polypeptides other than the nAChR subunits was reduced by at least 85% in the presence of the aqueous scavenger GSSG (50 mM), this labeling probably occurred after photoactivated [3H]tetracaine dissociated from its nAChR binding site. GSSG was also an effective aqueous scavenger of the nonspecific photolabeling by [3H]d-tubocurarine (Pedersen and Cohen, 1990) and [3H]nicotinic (Middleton and Cohen, 1991). However, the specific component of [3H]tetracaine labeling was insensitive to GSSG concentrations to 50 mM, whereas for the photolabeling at the agonist site, concentrations of GSSG of more than 1 mM inhibited the specific as well as the nonspecific components. Thus, it appears that the [3H]tetracaine binding site in the closed channel state of the nAChR is substantially more protected from the aqueous environment than the ACh site. Another difference between the photolabeling by [3H]tetracaine and that by [3H]d-tubocurarine or [3H]nicotinic is the wavelength dependence, with tetracaine photoincorporation more efficient for irradiation above 300 nm, whereas the other drugs required irradiation below 300 nm. Because tetracaine’s long wavelength absorption maximum is 300 nm in benzene and 310 nm in water, it is tetracaine and not the nAChR that is photoactivated.

In the presence of 50 mM GSSG, nearly all [3H]tetracaine photoincorporation sensitive to H10-HTX was restricted to the four nAChR subunits. The specific photolabeling of the four subunits resulted from activation of [3H]tetracaine bound to its high-affinity NCA site, as evidenced by the dependence of this specific photolabeling on free [3H]tetracaine concentration (Fig. 5) and the concentration dependence of inhibition by H10-HTX (Fig. 7) or carbamylcholine (Fig. 8). Also, as expected from the equilibrium binding data, the subunit photolabeling was inhibitable by other aromatic amine NCAs but not by α-bungarotoxin (Fig. 6). Thus, [3H]tetracaine bound to its single high-affinity binding site in the nAChR in the absence of agonist is photoincorporated into all four subunits with similar efficiency, which indicates that the binding site is located within the central ion channel domain at the interface of all five subunits. Within α subunit, the amino acids specifically labeled by [3H]tetracaine are restricted to a 20-kDa fragment containing the M1–M3 hydrophobic segments. As described in Gallagher and Cohen (1999), amino acids from the M2 segments of each subunit are specifically photolabeled by [3H]tetracaine, and the binding site for [3H]tetracaine in the closed state of the ion channel overlaps and extends beyond the binding site for [125I]TID in the M2 ion channel domain (White and Cohen, 1992).
Acknowledgments

We thank Dr. Wu Schyong Liu for synthesis of the p-butylaminobenzoic acid esters and Drs. Benjamin White and Steen Pedersen for helpful suggestions during the course of these experiments.

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