The α7 Nicotinic Acetylcholine Receptor Subunit Exists in Two Isoforms that Contribute to Functional Ligand-Gated Ion Channels

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ABSTRACT

Fast synaptic transmission in mammalian autonomic ganglia is mediated primarily by nicotinic receptors, and one of the most abundant nicotinic acetylcholine receptor subtypes in these neurons contains the α7 subunit (α7-nAChRs). Unlike α7-nAChRs expressed in other cells, the predominant α7-nAChR subtype found in rat intracardiac and superior cervical ganglion neurons exhibits a slow rate of desensitization and is reversibly blocked by α-bungarotoxin (αBgt). We report here the identification of an α7 subunit sequence variant in rat autonomic neurons that incorporates a novel 87-base pair cassette exon in the N terminus of the receptor and preserves the reading frame of the transcript. This α7 isoform was detected using reverse transcriptase-polymerase chain reaction techniques in neonatal rat brain and intracardiac and superior cervical ganglion neurons. Immunoblot experiments using a polyclonal antibody directed against the deduced amino acid sequence of the α7-2 insert showed a pattern of expression consistent with α7-2 subunit mRNA distribution. Moreover, the α7-2 subunit could be immunodepleted from protein extracts by solid-phase immunoprecipitation techniques using the anti-α7 monoclonal antibody 319. The α7-2 subunit was shown to form functional homomeric ion channels that were activated by acetylcholine and blocked by α-bungarotoxin when expressed in Xenopus laevis oocytes. This α7 isoform exhibited a slow rate of desensitization, and inhibition of these channels by αBgt reversed rapidly after washout. Taken together, these data indicate that the α7-2 subunit is capable of forming functional αBgt-sensitive acetylcholine receptors that resemble the α7-nAChRs previously identified in rat autonomic neurons. Furthermore, the distribution of the α7-2 isoform is not limited to peripheral neurons.

Nicotinic acetylcholine receptor channels (nAChRs) that contain the α7 gene product (α7-nAChRs) are one of the most abundant types of nicotinic receptors in the vertebrate nervous system. The α7-nAChRs differ from most neuronal nicotinic receptors in that they bind α-bungarotoxin (αBgt) with high affinity and have calcium permeability comparable with glutamatergic N-methyl-D-aspartate receptors (Seguela et al., 1993). The α7-nAChRs modulate various cell processes ranging from synaptic transmission (Zhang et al., 1996) to apoptosis (Berger et al., 1998). In the central nervous system, these receptors seem to be involved in learning and memory (Radcliffe and Dani, 1998) and have been linked to pathophysiological conditions such as schizophrenia (Freedman et al., 1997). Experiments have also shown that the β-amyloid peptide is a ligand for α7-nAChRs (Liu et al., 2001; Dineley et al., 2002), suggesting that α7-nAChR function may be altered during Alzheimer’s disease. Furthermore, the α7-nAChRs participate in important physiological processes in the viscera, such as the regulation of inflammation (Wang et al., 2003) and nicotine-induced nitricergic neurogenic vasodilation (Si and Lee, 2002).

The α7 nicotinic acetylcholine receptor subunit was first cloned from chick brain (Schoepfer et al., 1990). This subunit was later found to form functional homomeric AChRs when expressed in Xenopus laevis oocytes (Seguela et al., 1993) and to contribute to functional nAChRs in native cells (Alkondon and Albuquerque, 1993; Zhang et al., 1994). Although there is strong evidence that native α7-nAChRs are homopentamers (Chen and Patrick, 1997; Drisdel and Green, 2000), the composition and stoichiometry of native α7-nAChRs remains

ABBREVIATIONS: nAChR, nicotinic acetylcholine receptor; α7-nAChR, nicotinic acetylcholine receptor containing the α7 gene product; αBgt, α-bungarotoxin; bp, base pair; RT-PCR, reverse transcriptase-polymerase chain reaction; ACh, acetylcholine; SCG, superior cervical ganglia; PCR, polymerase chain reaction; ICG, intracardiac ganglia; Ab, antibody; mAb, monoclonal antibody.
to be confirmed. For example, the α7 subunit can combine with the β2 subunit to form functional heteropentamers in X. laevis oocytes (Khiroug et al., 2002), and the widespread coexpression of these two subunits in the central nervous system has led investigators to suggest that they may form such heteropentamers in vivo (Azam et al., 2003). In addition, differences exist in the pharmacological and biophysical properties of α7-nAChRs from a variety of cell types, an indication of variability in the structure or subunit composition of α7-nAChRs. For example, whereas α7-nAChRs in rat hippocampal neurons desensitize rapidly and bind αBgt in an irreversible manner (Alkondon and Albuquerque, 1993), α7-nAChRs in mammalian autonomic neurons desensitize slowly and recover rapidly from αBgt blockade (Cuevas and Berg, 1998; Cuevas et al., 2000). More recently, denervated mouse muscle was shown to express a subtype of α7-AChRs that desensitizes slowly and is not blocked by the classic α7-AChR-selective antagonist methyllycaconitine (Tsuneiki et al., 2003).

Cuevas and Berg (1998) proposed that the heterogeneity in α7-nAChRs might be caused by cell-dependent expression of α7 subunit isoforms. This theory was supported by the observation that splice variants of the α7 subunit are detected in human brain and leukocytes (Gault et al., 1998; Villiger et al., 2002). However, most of these α7 isoforms contain a premature stop codon (Gault et al., 1998) or form a truncated subunit that is not activated by acetylcholine (Villiger et al., 2002). Although various other ligand-gated ion channels such as 5-hydroxytryptamine-3 and GABA receptors express functional splice variants with distinct properties (Bruss et al., 2002), this type of diversity has been less forthcoming in nicotinic acetylcholine receptors.

In the current study, we present the first evidence for a functional splice variant of a nicotinic receptor subunit that contributes to a distinctive channel. The α7-2 isoform of the α7 nicotinic receptor subunit contains an 87-base pair insert (Cuevas and Berg, 1998; Cuevas and Berg, 2002). Total RNA was isolated from rat intracardiac ganglia and associated tissue, superior cervical ganglia (SCG), nodosal ganglia and brain (RNeasy; QIAGEN GmbH, Hilden, Germany). Primers specific for the α7 gene product (α7-P1) were designed to span an intron to discriminate between genomic DNA and cDNA. Table 1 lists the sequences of the primers used in this study and the predicted size for the products. For single-cell RT-PCR experiments, intracardiac neurons were dissociated from 4- to 7-day-old neonatal rats, and cytoplasm was extracted from isolated neurons as described previously (Zhang and Cuevas, 2002). All procedures were done in accordance with the regulations of the University of South Florida Institutional Animal Care and Use Committee. Negative controls for these experiments included the use of water as template for the RT-PCR and the suctioning of extracellular solution to control for cytoplasmic contamination in the single-cell RT-PCR reactions. PCR products were gel-purified using a QIAEX II Gel Purification kit (QIAGEN) and sequenced by the Molecular Biology Core Facility at the H. Lee Moffitt Cancer Center and Research Institute (University of South Florida, Tampa, FL).

Table 1 lists the sequences of the primers used in this study and the predicted size for the products. For single-cell RT-PCR experiments, one selective for both isoforms and a second that specifically amplifies α7-2 transcripts, and a reverse primer that recognizes both α7 splice variants. This primer combination was used to overcome preferential amplification of the smaller α7-1 transcripts, which would occur if only a single primer pair, such as α7-P1 was used. The ability of this primer pair to properly detect the relative abundance of α7-1 and α7-2 transcripts was assessed by using various ratios of α7-1 and α7-2-pCIneo plasmids (1:10 to 10:1) and was linear over the range tested.

### Materials and Methods

**RT-PCR.** The expression of α7 nicotinic receptor subunit splice variants in central and peripheral neurons was examined using RT-PCR techniques similar to those reported previously (Zhang and Cuevas, 2002). Total RNA was isolated from rat intracardiac ganglia and associated tissue, superior cervical ganglia (SCG), nodosal ganglia and brain (RNeasy; QIAGEN GmbH, Hilden, Germany). Primers specific for the α7 gene product (α7-P1) were designed to span an intron to discriminate between genomic DNA and cDNA. Table 1 lists the sequences of the primers used in this study and the predicted size for the products. For single-cell RT-PCR experiments, intracardiac neurons were dissociated from 4- to 7-day-old neonatal rats, and cytoplasm was extracted from isolated neurons as described previously (Zhang and Cuevas, 2002). All procedures were done in accordance with the regulations of the University of South Florida Institutional Animal Care and Use Committee. Negative controls for these experiments included the use of water as template for the RT-PCR and the suctioning of extracellular solution to control for cytoplasmic contamination in the single-cell RT-PCR reactions. PCR products were gel-purified using a QIAEX II Gel Purification kit (QIAGEN) and sequenced by the Molecular Biology Core Facility at the H. Lee Moffitt Cancer Center and Research Institute (University of South Florida, Tampa, FL).

**Genomic DNA Extraction and PCR Amplification.** Genomic DNA was isolated from the livers of 7-day-old neonatal rats using the Wizard Genomic DNA Purification Kit (Promega, Madison, WI). Rats were killed by decapitation for these experiments. Primers pairs

### TABLE 1

Sequence of oligonucleotide primers used in this study, and the predicted size for the individual products

<table>
<thead>
<tr>
<th>Name</th>
<th>Sequence</th>
<th>Nucleotide Numbers</th>
<th>Product Size</th>
<th>bp</th>
</tr>
</thead>
<tbody>
<tr>
<td>α7-P1</td>
<td>Forward GTACGAGGAGCTGGCAAGAATTCAACC</td>
<td>109–137</td>
<td>740(α7-2)</td>
<td>740</td>
</tr>
<tr>
<td></td>
<td>Reverse GAGCTGAAATGAGTACACAAGG</td>
<td>740–761</td>
<td>653(α7-1)</td>
<td>740</td>
</tr>
<tr>
<td>α7-P2</td>
<td>Forward GGAGTAAAGATGGTTGGTTCCAG</td>
<td>308–332</td>
<td>91(α7-2)</td>
<td>308</td>
</tr>
<tr>
<td></td>
<td>Reverse CCTGAGCAAATGGCAACTGACACC</td>
<td>375–398</td>
<td>122(α7-2)</td>
<td>375</td>
</tr>
<tr>
<td>α7-P3</td>
<td>Forward AGTTGACATTGACAGAGATGTCGC</td>
<td>381–404</td>
<td>122(α7-2)</td>
<td>381</td>
</tr>
<tr>
<td></td>
<td>Reverse CAAAATGACGTTGGGAACTGAC</td>
<td>394–415</td>
<td>122(α7-2)</td>
<td>394</td>
</tr>
<tr>
<td>α7-P4</td>
<td>Forward GGGCTGAGTGGCTATGGGCAACAG</td>
<td>375–398</td>
<td>474(α7-2)</td>
<td>375</td>
</tr>
<tr>
<td></td>
<td>Reverse GGGCTGAAATGAGTACACAAGG</td>
<td>740–761</td>
<td>468(α7-2)</td>
<td>740</td>
</tr>
<tr>
<td>α7-P5</td>
<td>Forward GTACGAGGAGCTGGCAAGAATTCAACC</td>
<td>109–137</td>
<td>740(α7-1)</td>
<td>740</td>
</tr>
<tr>
<td></td>
<td>Forward AGTTGACATTGACAGAGATGTCGC</td>
<td>381–404</td>
<td>653(α7-1)</td>
<td>381</td>
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<td>740–761</td>
<td>653(α7-1)</td>
<td>740</td>
</tr>
</tbody>
</table>
were designed to detect the presence of introns flanking the putative exon 4a of the rat α7 gene. One primer pair, α7-P2, consisted of a sense primer located in exon 4 and an antisense primer that was specific for the α7-2 variant. A second primer pair, α7-P3, consisted of a sense primer specific for the α7-2 insert and an antisense primer specific for exon 5. Genomic DNA was amplified by PCR in 50-μl reactions containing 1X PCR buffer, 2.0 mM MgCl₂, 0.2 mM each dNTP, 0.2 μM each primer, and 1.25 units of HotStarTaq polymerase (QIAGEN). A negative control that lacked template DNA was also included. PCR products were electrophoresed through a 1% Tris/borate/EDTA agarose gel, stained with ethidium bromide, and visualized through UV illumination.

**Immunoblot Analysis.** Whole brains and SCG were dissected from 10- to 14-day-old neonatal rats, and intracardiac ganglia (ICG) were dissected from postnatal day 1 to 5 rats. For brain and intracardiac ganglia dissections, animals were killed by decapitation, and they were killed by CO₂ asphyxiation for SCG dissections. Tissues were homogenized in a 2: Triton X-100 extraction buffer containing 50 mM sodium phosphate, pH 7.4, and the following protease inhibitors: 0.4 mM iodoacetamide, 5 mM benzamidine, 5 μg/ml phosphoramidomycin, 10 μg/ml soybean trypsin inhibitor, 10 μg/ml leupeptin, 20 μg/ml pepstatin A, 5 mM EDTA, 5 mM EGTA, 2 μg/ml aprotinin, and 1 mM phenylmethylsulfonyl fluoride; they were then incubated for 1 h at 4°C before centrifuging. Homogenates were sedimented at 15,000 rpm for 15 min at 4°C, and the supernatant was centrifuged at 33,000 rpm for 1 h at 4°C. The supernatant containing the detergent extracts was collected and stored at −20°C before experiments.

Protein concentrations of the detergent extracts were determined using the Bio-Rad Protein Assay 1 (Bio-Rad, Hercules, CA). For immunodepletion, AChRIs were immunomutated to microtiter wells in a manner described previously for solid-phase immunoprecipitations (Conroy and Berg, 1995; Cuevas et al., 2000). Equal amounts of extract were incubated overnight with constant agitation at 4°C in wells containing a 1:1000 dilution of the antibody-coated microtiter wells and for 1 h at 4°C before centrifuging. Homogenates were sedimented at 15,000 rpm for 15 min at 4°C, and the supernatant was centrifuged at 33,000 rpm for 1 h at 4°C. The supernatant containing the detergent extracts was collected and stored at −20°C before experiments.

To test the hypothesis that rat intracardiac neurons express splice variants of the α7 gene product, intrinsic cardiac neurons were studied using RT-PCR techniques. Oligonucleotide primers (α7-P1) (Table 1) were designed to amplify a 653-bp region corresponding to nucleotide positions 109 to 761 of the Rattus norvegicus nicotinic acetylcholine receptor α7 subunit mRNA (accession number L31619). This region is known to encode the extracellular domain containing both the β3G and competitive agonist binding sites (Brejc et al., 2001). Several products with sizes ranging from 400 to 750 bp were detectable over the course of these experiments (Fig. 1A) (n > 10). Cloning and sequencing of the products indicated that several of these products represented splice variants of the α7 gene.

The conventional α7 gene product (α7-1) (Fig. 1A) is composed of 10 exons, with the first transmembrane domain encoded in exon 7 (Fig. 1B). Three of the α7 splice variants detected in intrinsic cardiac neurons were the result of deletions of all or parts of exons 3 to 6 (Fig. 1C). All of these splice variants resulted in a frame shift and contained a premature stop codon before the region encoding the competitive agonist-binding site. The fourth splice variant (α7-2) (Fig. 1A) contains an 87-bp insert between the regions encoded by exons 4 and 5 (Fig. 1C). Figure 2 shows the sequence of the insert contributing to α7-2 and flanking regions aligned to the conventional α7 gene product (accession number 7-P2, consisted of a sense primer specific for the α7-2 variant. A second primer pair, α7-P3, consisted of a sense primer specific for the α7-2 insert and an antisense primer specific for exon 5. Genomic DNA was amplified by PCR in 50-μl reactions containing 1X PCR buffer, 2.0 mM MgCl₂, 0.2 mM each dNTP, 0.2 μM each primer, and 1.25 units of HotStarTaq polymerase (QIAGEN). A negative control that lacked template DNA was also included. PCR products were electrophoresed through a 1% Tris/borate/EDTA agarose gel, stained with ethidium bromide, and visualized through UV illumination.

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To determine whether the 87-bp insert represents a shift in the donor or acceptor sites of exon 4 and/or exon 5, respectively, rat genomic DNA was probed using primers specific for the insert and flanking sequences (a7-P2 and a7-P3) (Table 1). Primer pair a7-P2 has a forward primer specific for exon 4 and a reverse primer specific for the a7-2 insert, whereas primer pair a7-P3 has a forward primer specific for the insert and a reverse primer specific for exon 5. With primer set, a7-P2, a 505-bp product, was detected that when sequenced included sequentially 5’ to 3’, exon 4, a putative 413-bp intron, and the a7-2 insert (Fig. 3). This genomic sequence aligned to the a7-2 splice variant cDNA sequence is shown in Fig. 4. Consistent with an intron, the 413-bp section contains consensus donor and acceptor sequences at the 5’ and 3’ ends, respectively (Fig. 4). Amplification of genomic DNA using primers a7-P3, specific for the a7-2 insert and the 3’ flanking exon 5, failed to yield any product even though these primers could readily amplify cDNA encoding the a7-2 splice variant (Fig. 4) (cDNA, a7-P3). Intron 4 in the rat a7 gene is known to be >25,000 bp (National Center for Biotechnology Information, Entrez Rat Genome, National Library of Medicine, Bethesda, MD), and such a large product would not have been detected by our methods, thus explaining the lack of product in our genomic DNA PCR reaction. Taken together, these data suggest that the a7-2 splice variant is produced via the incorporation of a novel exon, exon 4a, and the a7 gene. Experiments were also conducted to determine whether any other sequence variations in the a7 gene product are linked with the exon 4a cassette insert. RT-PCR analysis of intrinsic cardiac neuron RNA extracts using primers specific for the insert and regions upstream and downstream of the splice (exons 1–10) failed to detect any other sequence variations (n = 20; data not shown).

In silico investigation using the NCBI Blast website (http://www.ncbi.nlm.nih.gov/BLAST/) has detected exon 4A in the sequence of *R. norvegicus* chromosome 1 whole genome shotgun supercontig. The sequence (6197390–6197476) is located within the region of intron 4 of the neuronal nicotinic acetylcholine receptor a7 (Chrna7) and is 413 bases downstream from the 3’ end of exon 4 (6197890) of the a7 subunit. An 87-base sequence (31346–31432) with 85% homology to the rat exon4A was also found in the mouse genome (chromosome 7) and mapped to intron 4 of the mouse a7 subunit exactly 415 bases downstream from the 3’ end of exon 4 (30932). Conservation of the sequence and position of the a7-2 sequence in the rodent genome suggests that this isoform is not particular to the rat.

Given that a7 subunits have been detected in non-neuronal cells, it seemed prudent to test for the expression of a7-2 at the single-cell level. Intrinsic cardiac neurons were isolated and probed for a7-2 expression using single-cell RT-PCR techniques similar to those reported previously (Zhang and Cuevas, 2002). To facilitate the detection of the a7-2 splice variant, a set of primers (a7-P4) (Table 1) was designed with the forward primer specific for the a7-2 isoform. A product of the predicted size for a7-2 was detected in five of seven intracellular neurons tested (Fig. 5A), which is similar to numbers reported previously in intrinsic cardiac neurons for the a7 subunit using single-cell RT-PCR (Poth et al., 1997).
Cloning and sequencing of these PCR products confirmed that they represented the α7-2 subunit.

Experiments were conducted to test for the presence of α7-2 subunit mRNA in the central nervous system and in other peripheral neurons, to determine whether expression of this subunit is limited to intracardiac ganglia. Figure 5B shows the results of a representative RT-PCR experiment using primers α7-P4 on RNA extracts from neonatal rat intracardiac, superior cervical, and nodose ganglia and brain. The α7-2 transcripts were detected in both the central nervous system and in other autonomic ganglia, suggesting that expression of this transcript is not a phenomenon exclusively associated with intrinsic cardiac neurons. To compare the relative abundance of α7-1 and α7-2 isoform transcripts in the central nervous system and in peripheral ganglia, we performed RT-PCR using multiplexed α7- and α7-2–specific primers (α7-P5) (Table 1). Bands for both the α7-1 and α7-2 were detected in all tissues tested but were not observed in two of five experiments on RNA extracts from nodose ganglia (Fig. 5C). An analysis of the intensity of the α7-2 band relative to that of the α7-1 band for these tissues is shown in Fig. 5D. The α7-1 isoform was 4- to 5-fold more abundant than the α7-2 isoform in the brain, superior cervical ganglion, and intracardiac ganglion but showed 10-fold higher expression in the nodose ganglion (Fig. 5D). A control using a 1:1 mixture of α7-1- and α7-2–pcDNA plasmids exhibited a relative intensity of 1.04 ± 0.1209 (α7-2:α7-1), indicating equivalent detection sensitivities for each isoform using this quantitative method.

To determine whether transcripts encoding the α7-2 isoform are translated in central and peripheral neurons, rat brain and intracardiac and superior cervical ganglia were examined for α7-2 subunit protein expression. Protein extracts from the respective tissues were analyzed by probing immunoblots with the α7-2–specific polyclonal antibody Ab 87 (Fig. 6A). A band of the predicted size for the α7-2 protein (~58 kDa) may be readily detected in protein extracts from all tissues. To confirm that this band represents the α7-2 product, immunodepletions were performed using the anti-α7 monoclonal antibody mAb 319 that binds to the large intracellular loop between transmembrane domains 3 and 4 of the α7-1 subunit (Schoepfer et al., 1990). The amino acid sequence of the α7-2 subunit peptide is expected to be identical with that of α7-1 in this region, and thus mAb 319 should immunoprecipitate both α7-1–and α7-2–containing AChRs. Immunoblot experiments were then conducted on mock-depleted and immunodepleted extracts using the anti-α7-2 polyclonal antibody Ab 87. A band of the size predicted for the α7-2 monomer (~58 kDa) was readily detectable in immunoblots of mock-depleted extracts of all three tissues (Fig. 6B). However, the levels of this product were greatly reduced in extracts immunodepleted of α7 subunits with mAb 319 (Fig. 6B). This observation confirms the expression of α7-2 in peripheral and central tissues and verifies that Ab 87 is specific for α7-2.

The ability of the α7-2 subunit to form functional homeric ligand-gated ion channels was examined in X. laevis oocytes using two-electrode voltage-clamp experiments. Figure 7A shows a family of current traces evoked by ACh at the indicated concentrations from an oocyte injected with cRNA generated from the in vitro transcription of α7-1 (top traces).

**Fig. 2.** Sequence of the α7-2 splice variation of the α7 gene. Sequence of insert contributing to the α7-2 variant and flanking regions as amplified by primers α7-P1, aligned to the α7-1 isoform (RATNARAD). Matching sequence is shown in white text and black background. Sequence numbering is based on the α7-1 isoform (accession number L31619). The deduced amino acid sequence is also provided.

**Fig. 3.** Identification of a novel exon in the α7 gene. PCR amplification of genomic extracts from rat liver (1 and 2) using α7-2 subunit-specific primers α7-P2 and α7-P3, respectively. Amplification of α7-2 cDNA (cDNA) using both the α7-2 P2 and α7-P3 primers. Right arrow, the predicted product size for α7-P3 amplification of α7-2 cDNA. Larger product represents the product amplified by the forward primer of α7-P2 and the reverse primer of α7-P3. The 500-bp marker of a 100-bp standard ladder is indicated. Negative control (Neg. Cont.) represents a PCR reaction using H2O.
or α7-2 (bottom traces) DNA templates. A plot of the mean concentration-response relationship for ACh activation of α7-2 homopentamers is shown in Fig. 7B (n = 5). A fit of the data using the Hill equation indicates that the α7-2–nAChRs were half-maximally activated by 80 μM ACh and that maximal activation occurs by 1 mM ACh. In contrast, in oocytes injected with α7-1 cRNA, ACh-evoked currents were half-maximally activated at 248 μM ACh, with maximal activation by 3 mM ACh (Fig. 7B) (n = 5). The Hill coefficients were 1.0 and 1.3 for α7-2 and α7-1, respectively. These data indicate that the α7-2 subunit is capable of forming functional AChRs in X. laevis oocytes. Moreover, α7-2–nAChRs are markedly more sensitive to ACh than α7-1–nAChRs.

One of the distinct characteristics of α7-nAChRs is their high affinity for αBgt. To determine whether sensitivity to αBgt is preserved in α7-2–nAChR, ACh-evoked currents

![Fig. 4. Sequence of intron separating exons 4 and 4a. Sequence of the α7 gene product aligned to the α7-2 isoform (α7-2). Sequence numbering for the α7-2 is derived from that provided for α7-2 in Fig. 2, while the sequence numbering for the α7 gene corresponds to that of the R. norvegicus Chrna7 gene. Matching sequence is shown in white text and black background. Consensus donor (gt) and acceptor (ag) sites are shown in italics and with gray background.](https://www.aspetjournals.org/doi/10.1093/molbrain/mxu048)

![Fig. 5. The α7-2 splice variant is found in brain and in both sympathetic and parasympathetic neurons. A, RT-PCR amplification of cytoplasmic extract from a single isolated intrinsic cardiac neuron (ICG) with the α7-P4 primers. The negative control reaction was conducted using a sample of extracellular solution collected near the cell shown here. B, RT-PCR amplification of RNA extracts from rat brain and ICG, SCG, and nodose ganglia using the α7-2 subunit-specific primers α7-P4. C, RT-PCR using the α7-P5 primers on the indicated tissues. D, bar graph of the mean intensity (± S.E.M.) for the α7-2 product relative to that of the product of the α7-1 isoform obtained for each tissue (n = 5 for each tissue) and for a PCR amplification of a 1:1 mixture of α7-1– and α7-2–pCIneo plasmids. Arrows, the predicted size for the α7-2 (475 bp, A and B; 468 bp, C) and α7-1 (653, C only) isoforms. Standards, 100-bp ladder; the 500-bp marker is indicated.](https://www.aspetjournals.org/doi/10.1093/molbrain/mxu048)
were recorded from oocytes injected with α7-2 cRNA in the absence and presence of toxin. Figure 8A shows a family of transient currents evoked by application of 100 μM ACh (in calcium-physiological salt solution) onto a single oocyte voltage-clamped at a membrane potential of −70 mV. αBgt (50 nM) significantly (P < 0.05) attenuated the ACh-evoked response, and in four similar experiments, 50 nM αBgt inhibited the peak ACh-evoked current by 93 ± 3% (Fig. 8B). The inhibition by toxin was rapidly reversible, and after a 10-min wash, the ACh-evoked current recovered to near control levels (Fig. 8B). In contrast, in oocytes injected with α7-1 cRNA, αBgt block of ACh-evoked currents did not appreciably reverse over a similar time interval (data not shown). Thus, the α7-2 subunit contributes to αBgt-sensitive nAChRs, but there is a significant difference in the αBgt binding properties of α7-1– and α7-2–nAChRs subtypes.

A distinguishing attribute of α7-1 containing receptors is their rapid rate of desensitization. Figure 8C shows superimposed ACh-evoked current traces recorded from X. laevis oocytes injected with α7-1 and α7-2 cRNA. Unlike α7-1 homopentamers, α7-2–AChRs exhibited a slow rate of desensitization. In five similar experiments, the currents mediated by α7-1–AChRs decayed to 3.3 ± 0.6% of the peak response after 2.5 s of agonist application (Fig. 8D). However, the currents mediated by α7-2–AChRs exhibited a significantly (p < 0.01) slower rate of decay and were 83.3 ± 3.2% of the peak response after 2.5 s of agonist application (Fig. 8D).

Discussion

The principal finding reported here is the discovery of a novel α7 nicotinic receptor subunit isoform that forms functional α-Bungarotoxin–sensitive homeric receptors with unique biophysical and pharmacological properties when expressed in X. laevis oocytes. The α7-2 isoform contributes to homomeric nAChRs that desensitize slowly, bind αBgt in a rapidly reversible manner, and have a higher affinity for ACh than α7-1–nAChRs. This isoform is produced by the incorporation of a novel cassette exon, exon 4a, near the N terminus of the receptor. Transcripts encoding this splice
variant were detected in both central and peripheral neurons and were found to constitute ~20% of the total number of α7 transcripts in these tissues. Moreover, immunoblot analysis indicated the expression of the α7-2 subunit protein in the same tissues.

The existence of two functional α7 splice variants may resolve some of the long-standing controversy surrounding the structure and function of receptors containing the α7 nicotinic receptor subunit. Although several reports support the coassembly of α7 with other subunits expressed in mammals, such as α5, β2, and β3 (Girod et al., 1999; Khiroug et al., 2002), various studies using subunit-specific antibodies failed to detect the presence of non-α7 subunits in native α7-nAChRs (Schoepfer et al., 1990; Vernallis et al., 1993; Chen and Patrick, 1997; Drisdel and Green, 2000). In addition, the conventional α7 gene product, α7-1, forms functional homomeric channels when expressed in exogenous systems such as X. laevis oocytes and SH-EP1 cells (Couturier et al., 1990; Seguela et al., 1993; Peng et al., 1999). Although the pharmacological and electrophysiological properties of these channels were nearly identical with those of native α7-nAChRs studied in various cell types, such as rat hippocampal neurons (Alkondon and Albuquerque, 1993) and chick ciliary neurons (Zhang et al., 1994), some differences have been noted between heterologously expressed homomeric and native α7-nAChRs (Anand et al., 1993). Furthermore, electrophysiological studies in other cell types have suggested the presence of heterogeneous populations of α7-nAChRs exhibiting distinct pharmacological and biophysical properties. For example, in rat superior cervical ganglion neurons, two distinct α7-nAChR types were detected (Cuevas et al., 2000). Type I α7-nAChRs in SCG neurons desensitize rapidly, are activated by choline, and are blocked by αBgt in an irreversible manner, whereas type II α7-nAChRs desensitize slowly, are insensitive to choline and bind αBgt in a rapidly reversible manner (Cuevas et al., 2000). Likewise, it has been proposed that chick sympathetic neurons express multiple α7-nAChR subtypes, with the α7-7-α antagonist methyllycaconitine discriminating between the different α7-nAChR subtypes (Yu and Role, 1998). Moreover, the observation that a sequence with 85% homology to exon 4A is also found in intron 4 of the mouse α7 subunit gene, coupled with our detection of α7-2 protein in mouse brain in preliminary studies (McCleary et al., 2002), predicts that the α7-2 subunit is probably expressed in other species.

The hypothesis that the α7 subunit exists in multiple isoforms that contribute to α7-nAChRs subtypes was first proposed by Cuevas and Berg (1998). Such α7 receptor isoforms would permit functional diversity while being consistent with studies that suggest that the α7 subunit does not combine with other nAChR subunit species. Splice variations of ligand-gated ion channels such as 5-hydroxytryptamine-3 (Bruss et al., 2000) and GABA-A (Quinlan et al., 2000) can form functional channels and affect the pharmacological

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**Fig. 8.** α7-2-nAChRs bind α-bungarotoxin reversibly and desensitize more slowly than α7-1-nAChRs. A, ACh-evoked (100 μM) currents recorded from a voltage-clamped oocyte (–70 mV) injected with α7-2 cRNA in the absence (Control), presence of 50 nM αBgt (+αBgt), or after washout (Wash) of the toxin for the indicated time. B, bar graph of relative peak current evoked at –70 mV by 100 μM ACh in the absence (Control), presence of 50 nM αBgt (+αBgt), and after 10-min washout of toxin (Wash). Currents are normalized to control (n = 4). *, significant difference (P < 0.05). C, superimposed ACh-evoked (1 nM, 5 s) current traces recorded from oocytes injected with either α7-1 or α7-2 cRNA. Currents were scaled by normalizing each current to peak response (I/Imax) to facilitate comparison of kinetics. D, mean relative current amplitude observed after a 2.5-s application of 1 mM ACh (–70 mV) in oocytes injected with either α7-1 or α7-2 cRNA. Currents were normalized to peak amplitude; n = 5 for both conditions; *, significant difference (P < 0.01).
and/or biophysical properties of the channels. However, no splice variations of nicotinic acetylcholine subunits have been identified previously to contribute to AChRs with distinct characteristics. This lack of sequence variants of nicotinic receptors is surprising, given that most genes encoding AChR subunits contain between 5 and 10 exons, and thus numerous splice possibilities exist. Reports indicate that the α4 subunit exists in two isoforms, but when these respective isoforms are incorporated into functional channels containing the β2 subunit, they are indistinguishable on the basis of their pharmacology and biophysics (Connolly et al., 1992).

The α1 subunit has also been shown to exist in multiple sequence variants, but only one of these isoforms assembles functional ACh receptors (Newland et al., 1995). Previous studies have identified several splice variants of the α7 in human brain; all but one of these splice variants contained a premature stop codon (Gault et al., 1998). In bovine chromaffin cells, a splice variant of the α7 subunit has also been detected, in which the exon that codes for the M2 transmembrane domain is deleted (Garcia-Guzman et al., 1995). This splice variant does not yield functional channels when expressed in X. laevis oocytes, but it inhibits the expression of α7-1 homomers when cojected with the full-length isoform. An α7 isoform with an additional exon, which arises from alternative splicing of intron 9, has also been reported in the mouse (Saragoza et al., 2003). This mRNA yields a truncated form of the α7 peptide and acts as a dominant-negative when cotransfected with the α7-1 subunit in human embryonic kidney 293T (Saragoza et al., 2003). It remains to be determined whether the α7 splice variants detected here, which contain a premature stop codon, can regulate expression of the α7-1 and α7-2 isoforms in a similar manner. None of the previously reported α7 isoforms were detected in rat neurons in the present study.

The N-terminal location of the insert within the α7-2 subunit suggests close proximity to the ACh-binding pocket. This theory is in part supported by the crystal structure of the molluscan acetylcholine-binding protein (Brejc et al., 2001). This protein is a homolog of the amino-terminal ligand-binding domain of the α7-1 subunit and thus provides insight into the putative structure of this domain. From the crystalline structure, it was determined that three principal loops (A–C) and three complimentary loops (D–F) compose the α7 acetylcholine-binding site (Brejc et al., 2001). Exon 4a is inserted between the regions that encode principal loop A and complimentary loop E. It is thus quite likely that this insertion results in significant changes to the ACh and αBgt binding domains. This hypothesis is supported by our observation that α7–2-nAChRs have higher affinity for ACh and bind αBgt in a rapidly reversible manner compared with α7–1-nAChRs.

From the results of electrophysiological studies presented here, it is probable that the α7-2 subunit contributes to the type II α7-nAChRs of mammalian autonomic neurons (Cuevas and Berg, 1998; Cuevas et al., 2000). This species of α7-nAChRs binds αBgt with high affinity and in a rapidly reversible manner. Both type II α7–nAChRs and α7–2–nAChRs are blocked by >90% by 50 nM αBgt, and this inhibition is reversed within 10 min of toxin washout (Cuevas and Berg, 1998; Cuevas et al., 2000). A second distinguishing characteristic of type II α7-nAChRs in autonomic neurons is their slow rate of desensitization. The rate of desensitization of type I α7-nAChRs, which are probably α7–1–nAChRs, is 10-fold faster than that of type II α7–nAChRs (Cuevas et al., 2000). Data shown here indicate that α7–1–nAChRs expressed in oocytes desensitize faster than α7–2–nAChRs, further supporting the theory that the α7–2 subunit contributes to type II α7–nAChR. Given that type II α7-nAChRs mediate ~50% of whole-cell nicotinic responses in intracardiac and superior cervical ganglion neurons (Cuevas et al., 2000), α7–2–nAChRs may represent a significant population of AChRs in peripheral neurons. It is interesting to note that one of the few characteristics associated with α7-null mice is dysfunction of the autonomic nervous system (Franceschini et al., 2000). The α7-knockout mouse was generated by a deletion of exons 8 to 10 of the α7 gene (Orr-Urtreger et al., 1997), which are shared by both the α7-1 and α7-2 subunits. Thus, this dysfunction may be in part caused by the loss of the α7–2–nAChR subtype in the neurons. Consistent with an important role for α7-AChRs in regulation of the cardiovascular system is the observation that the effects of nicotine on the heart are in part caused by activation of α7 receptors in autonomic neurons (Ji et al., 2002).

In conclusion, our study presents the first evidence for acetylcholine receptor functional diversity resulting from transcriptional modifications. The finding of a novel α7 nicotinic receptor subunit isoform, α7-2, may help explain the multiplicity of α7-nAChR function. The α7-2 isoform contributes to AChRs with pharmacological and biophysical properties distinct from those of α7–1–nAChRs and closely resembling those of α7–nAChRs found in intrinsic cardiac neurons and type II α7–nAChRs of superior cervical ganglion neurons (Cuevas and Berg, 1998; Cuevas et al., 2000). The presence of α7-2 transcripts and protein in peripheral and central neurons suggests that this receptor subunit may contribute to cell-to-cell signaling in both branches of the nervous system. Acknowledgments

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