Elucidating the Transcriptional Network Underlying Expression of a Neuronal Nicotinic Receptor Gene: A Dissertation

Michael D. Scofield

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ELUCIDATING THE TRANSCRIPTIONAL NETWORK
UNDERLYING EXPRESSION OF A NEURONAL NICOTINIC
RECEPTOR GENE

A Dissertation Presented
By
MICHAEL D. SCOFIELD

Submitted to the Faculty of the
University of Massachusetts Graduate School of Biomedical Sciences, Worcester
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

(September 8th, 2010)

INTERDISCIPLINARY GRADUATE PROGRAM
ELUCIDATING THE TRANSCRIPTIONAL NETWORK UNDERLYING EXPRESSION OF A NICOTINIC RECEPTOR GENE

A Dissertation Presented By

Michael D. Scofield

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Interdisciplinary Graduate Program

September 8, 2010
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my mentors, Paul Gardner and Andrew Tapper, who have provided me with the support and direction needed to set the foundation for an independent career. I would also like to thank all the members of the Gardner / Tapper lab for their support and advice, and also for making our lab a great place to work.

I would like to thank my dissertation committee, Daniel Kilpatrick, Anthony Imbalzano, Haley Melikian and Ann Rittenhouse for devoting their time and effort and also for providing valuable insight and advice. In addition, I would like to thank Robert Maue for serving on my committee and also for coming out from Dartmouth Medical School for my defense.

Finally, I would like to acknowledge my friends and family, especially my wife Deidre Scofield for her continued support and undying interest in my research.
ABSTRACT

Neuronal nicotinic acetylcholine receptors (nAChRs) are involved in a plethora of fundamental biological processes ranging from muscle contraction to the formation of memories. The studies described in this work focus on the transcriptional regulation of the CHRNA4 gene, which encodes the β4 subunit of neuronal nAChRs. We previously identified a regulatory sequence (5´– CCACCCCT –3´), or “CA box”, critical for CHRNA4 promoter activity in vitro. Here I report transcription factor interaction at the CA box along with an in vivo analysis of CA box transcriptional activity. My data indicate that Sp1, Sp3, Sox10 and c-Jun interact with the CHRNA4 CA box in the context of native chromatin. Using an in vivo transgenic approach in mice, I demonstrated that a 2.3-kb fragment of the CHRNA4 promoter region, containing the CA box, is capable of directing cell-type specific expression of a reporter gene to many of the brain regions that endogenously express the CHRNA4 gene. Site-directed mutagenesis was used to test the hypothesis that the CA box is critical for CHRNA4 promoter activity in vivo. Transgenic animals were generated in which LacZ expression is driven by a mutant form of the CA box. Reporter gene expression was not detected in any tissue or cell type at ED18.5. Similarly, I observed dramatically reduced reporter gene expression at PD30 when compared to wild type transgenic animals, indicating that the CA box is an important regulatory feature of the CHRNA4 promoter. ChIP analysis of brain tissue from mutant transgenic animals demonstrated that CA box mutation results in decreased interaction of the transcription factor Sp1 with the CHRNA4 promoter.
I have also investigated transcription factor interaction at the CHRN4 promoter CT box, (5´– ACCCTCCCCTCCCTGTAA – 3´) and demonstrated that hnRNP K interacts with the CHRN4 promoter in an olfactory bulb derived cell line. Surprisingly, siRNA experiments demonstrated that hnRNP K knockdown has no impact on CHRNA5, CHRNA3 or CHRN4 gene expression. Interestingly, knockdown of the transcription factor Purα results in significant decreases in CHRNA5, CHRNA3 and CHRN4 mRNA levels. These data indicate that Purα can act to enhance expression of the clustered CHRNA5, CHRNA3 and CHRN4 genes. Together, these results contribute to a more thorough understanding of the transcriptional regulatory mechanisms underlying expression of the CHRN4 as well as the CHRNA5 and CHRNA3 genes, critical components of cholinergic signal transduction pathways in the nervous system.
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<th>Abbreviation</th>
<th>Term</th>
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<tbody>
<tr>
<td>A3I5</td>
<td>Transcriptional repressor located in the fifth intron of the CHRNA5 gene</td>
</tr>
<tr>
<td>ACh</td>
<td>Acetylcholine</td>
</tr>
<tr>
<td>α-Bgtx</td>
<td>α-bungarotoxin</td>
</tr>
<tr>
<td>AU1B</td>
<td>Alpha-conotoxin derived from the venom of the predatory sea snail <em>Conus aulicus</em></td>
</tr>
<tr>
<td>β2m</td>
<td>Beta-2-microglobulin</td>
</tr>
<tr>
<td>β-gal</td>
<td>Beta-galactosidase</td>
</tr>
<tr>
<td>CA Box</td>
<td>A 5’-CCACCCCT-3’ regulatory element</td>
</tr>
<tr>
<td>ChIP</td>
<td>Chromatin immunoprecipitation</td>
</tr>
<tr>
<td>CHRNB4</td>
<td>Neuronal cholinergic receptor β4 subunit gene</td>
</tr>
<tr>
<td>CHRNA5/A3/B4</td>
<td>The locus that encodes the CHRNA5, CHRNA3 and CHRNB4 genes</td>
</tr>
<tr>
<td>CNR4</td>
<td>Conserved non-coding region #4</td>
</tr>
<tr>
<td>CNS</td>
<td>Central nervous system</td>
</tr>
<tr>
<td>CT Box</td>
<td>A 5’-ACCCTCCCCTCCCCTGTAA-3’ regulatory element</td>
</tr>
<tr>
<td>DRG</td>
<td>Dorsal root ganglia</td>
</tr>
<tr>
<td>ED18.5</td>
<td>Embryonic day 18.5</td>
</tr>
<tr>
<td>ETS</td>
<td>E26 transformation-specific sequence</td>
</tr>
<tr>
<td>GABA</td>
<td>γ-aminobutyric acid</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>---------</td>
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<tr>
<td>GAPDH</td>
<td>Glyceraldehyde 3-phosphate dehydrogenase</td>
</tr>
<tr>
<td>GTP</td>
<td>Guanosine triphosphate</td>
</tr>
<tr>
<td>GWAS</td>
<td>Genome wide association study</td>
</tr>
<tr>
<td>hnRNP K</td>
<td>Heterogeneous nuclear ribonucleoprotein K</td>
</tr>
<tr>
<td>IgG</td>
<td>Immunoglobulin G</td>
</tr>
<tr>
<td>KO</td>
<td>Knock out</td>
</tr>
<tr>
<td>LacZ</td>
<td>Beta-galactosidase</td>
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<tr>
<td>MAR</td>
<td>Matrix attachment region</td>
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<tr>
<td>nAChR</td>
<td>Nicotinic acetylcholine receptor</td>
</tr>
<tr>
<td>NGF</td>
<td>Nerve growth factor</td>
</tr>
<tr>
<td>NLS</td>
<td>Nuclear localization sequence</td>
</tr>
<tr>
<td>NMJ</td>
<td>Neuromuscular junction</td>
</tr>
<tr>
<td>PAC</td>
<td>P1-derived artificial chromosome</td>
</tr>
<tr>
<td>PBS</td>
<td>Phosphate-buffered saline</td>
</tr>
<tr>
<td>PCR</td>
<td>Polymerase chain reaction</td>
</tr>
<tr>
<td>PD30</td>
<td>Postnatal day 30</td>
</tr>
<tr>
<td>PNS</td>
<td>Peripheral nervous system</td>
</tr>
<tr>
<td>qRT-PCR</td>
<td>Real-time quantitative reverse transcription PCR</td>
</tr>
<tr>
<td>SCG</td>
<td>Superior cervical ganglion</td>
</tr>
<tr>
<td>SDS-PAGE</td>
<td>Sodium dodecyl sulfate polyacrylamide gel electrophoresis</td>
</tr>
<tr>
<td>SNP</td>
<td>Single nucleotide polymorphism</td>
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</table>
CHAPTER I: INTRODUCTION

Neuronal communication

The transmission of signals through synapses is an essential component of the neuronal circuits responsible for a wide array of physiological functions including memory formation, reward, reinforcement, perception, and emotion (Leisman and Koch, 2009). The discovery of the synapse would not have been possible without the advancements in staining techniques pioneered by the Italian anatomist Camillo Golgi and later refined by the Spanish anatomist Santiago Ramón y Cajal. Using the “reazione nera” or black reaction, Golgi was able to stain the membranes of neuronal tissue with a silver-chromate precipitate (Golgi, 1873). This technique stained the soma, axon and dendrites of a neuron black allowing anatomists to observe the morphological aspects of neurons in stunning detail. However, due to limitations in the staining procedure, myelinated axons were not stained effectively, making the projections of adjacent neurons difficult to resolve. The limitations of Golgi’s staining technique undoubtedly contributed to his sustained defense of Joseph von Gerlach’s reticular hypothesis (von Gerlach, 1871), a widely accepted theory at the time proposing that the brain consists of a large network of directly interconnected cells. Cajal refined Golgi’s silver-chromate staining and also used brain tissue from younger animals in order to minimize the amount of myelinated axons in the preparation. The resulting drawings of neural tissue (Fig. 1.1) clearly demonstrated that neurons are independent elements and not a network of interconnected filaments (Cajal, 1888, 1894).
Figure 1.1: Chick cerebellum. Shown here is a drawing of neurons in the chick cerebellum done by Ramón y Cajal (Cajal, 1888; Sotelo, 2003).
Cajal’s findings quickly gained the attention of several prominent German anatomists including Wilhelm von Waldeyer and Rudolph Albert von Kölliker, who had both previously been ardent supporters of the reticular hypothesis. Cajal’s work also provided the fundamental basis for the “neuron doctrine” proposed by Waldeyer (Waldeyer, 1891) in a seminal review article combining the observations of several scientists including Albert von Kölliker, Camillo Golgi, Franz Nissl, Auguste Forel, Wilhelm His and Santiago Ramón y Cajal. Specifically, the neuron doctrine refuted the reticular hypothesis by stating that neurons are connected to each other at distinct sites of contact (later defined as synapses) and not through a cytoplasmic continuity. The neuron doctrine also states that the neuron is the structural and functional unit of the nervous system and has three main parts, the dendrites, soma and axon, with conduction taking place in the direction of dendrite to soma, ending in the arborizations of the axon (Waldeyer, 1891).

The synapse

The term “synapse” was derived from “synaptein” a term coined by the British physiologist Charles S. Sherrington. “Synaptein” is a combination of the Greek words "syn-" meaning together, and "haptein" to clasp (Sherrington, 1906). Although first described histologically by Cajal, the synapse would not be fully resolved until the invention of the electron microscope and the subsequent work of George Palade, Eduardo de Robertis and George Bennett (De Robertis and Bennett, 1955). Electron micrographs of the frog sympathetic ganglia and the neuropile of the
earthworm nerve cord showed for the first time, in high magnification, detailed images of the synaptic ultrastructure. These experiments confirmed the seemingly clairvoyant hypotheses regarding the synapse and neuronal communication made by anti-reticularists like His, Nansen, Forel, and Cajal. Neuronal signals are transmitted though two main types of synapses, the electrical synapse and the chemical synapse (Kandel et al., 2000).

Many scientists in the early 20th century assumed that electrical synaptic transmission was the most likely method of neuronal communication. However, proof of the existence of the electrical synapse would not come until the 1950s with the work of Furshpan and Potter, demonstrating functional electrical synapses in the giant neurons of the crayfish (Furshpan and Potter, 1957, 1959). The electrical synapse is a conductive link formed at a 3.5 nm gap between the presynaptic and postsynaptic cell (Bennett and Zukin, 2004). At the electrical synapse, several receptor proteins span the membranes of both cells, effectively connecting the cytosol of the pre- and postsynaptic cells and allowing for the flow of electrical current. Signal transduction through electrical synapses is characterized by rapid conduction of nerve impulses, bi-directional signal transmission, and lack of inhibitory action (Bennett and Zukin, 2004). Despite the incredibly fast rate of transmission, electrical synapses cannot amplify the magnitude of the incoming signal from the presynaptic cell, i.e., the induced response in the postsynaptic cell is always smaller than the original signal from the presynaptic cell (Kandel et al., 2000).
Signal transduction through chemical synapses is the primary mode of neuronal communication and is essential for the function of the neural circuits responsible for perception and thought (Leisman and Koch, 2009). Unlike the electrical synapse, the chemical synapse is unidirectional, can either be inhibitory or excitatory and can amplify the extent of the incoming signal. The chemical synapse has several key features: first, a presynaptic neuron that when activated releases a chemical messenger called a neurotransmitter into the synaptic cleft; second, a physical space of approximately 20 – 40 nm that separates the pre- and postsynaptic cells through which neurotransmitters diffuse; and finally, receptor elements that recognize the neurotransmitters released from the presynaptic cell and initiate signal transduction in the postsynaptic cell (Fig. 1.2) (Kandel et al., 2000).

Concrete evidence for chemical signal transmission was not uncovered until 1921 when the German pharmacologist Otto Loewi performed his famous experiment using a frog heart nerve-muscle preparation (Loewi, 1921). Loewi dissected two beating frog hearts, the first heart with the vagus nerve still attached and the second extracted on its own. He then placed each heart in a saline solution and then electrically stimulated the vagus nerve on the first heart, resulting in a decrease in heart rate. When Loewi applied some of the liquid surrounding the first heart ("Vagusstoff") to the second heart, he also observed a reduction in heart rate.
Figure 1.2: The chemical synapse. Schematic representation of the synapse with the presynaptic nerve cell depicted in blue and the postsynaptic cell depicted in orange. In the presynaptic cell, synaptic vesicles are depicted as yellow circles with neurotransmitters depicted as smaller grey circles, mitochondria are depicted as red rectangles. In the postsynaptic cell, ligand-gated ion channels are depicted as green rectangles with flow of ions through activated channels depicted as red arrows. G-protein coupled receptors are depicted as purple rectangles with the inactive G-protein, shown in pink, bound to GDP and the active G-protein bound to GTP (red) disassociated from the G-protein coupled receptor. The direction of the propagation of the action potential is shown under the presynaptic cell as a lightning bolt and a yellow arrow.
These results indicated that a soluble chemical messenger from the vagus nerve was released upon electrical stimulation and that application of this chemical messenger could slow the heart rate of an un-stimulated heart (Loewi, 1921; Loewi and Navratil, 1926).

Additional evidence supporting chemical neurotransmission was provided by Henry Hallette Dale, who suggested that acetylcholine (ACh) may function as chemical neurotransmitter in 1914 (Dale, 1914; Fishman, 1972). Years later while studying the physiological effects of ergot, a fungus that grows on rye and related plants, Dale discovered that the active component of the ergot fungus could profoundly inhibit heart rate when intravenously injected into an anesthetized cat (Dale, 1953). During his experimentation with ergot, he began to notice that the physiological effects elicited by the unknown alkaloid from the fungus appeared to be identical to those elicited by ACh. These results caused Dale to focus his attention on testing the hypothesis that ACh acts as a chemical neurotransmitter. In a series of experiments performed between 1929 and 1936, he was able to demonstrate that ACh is released at nerve endings following electrical stimulation (Dale, 1935) and that application of ACh to muscle tissue resulted in contraction in the absence of electrical stimulation (Dale et al., 1936). Despite the emerging body of evidence supporting the existence of chemical transmission, many scientists still believed that neuronal communication was mediated by electrical synapses. Bernard Katz provided definitive proof of chemical transmission in a series of experiments using intracellular electrodes to study the neuromuscular junction (NMJ), a specialized
synapse formed between motor neurons and muscle fibers. These experiments demonstrated that the fluctuations in membrane potential observed while recording from the muscle fiber were the result of the random release of synaptic vesicles containing ACh from the motor neuron (Fatt and Katz, 1951). Katz later demonstrated that chemical synaptic transmission at the NMJ was unidirectional and that exogenous application of ACh to the NMJ resulted in muscle contraction, similar to what is observed following electrical stimulation of the motor neuron (Katz, 1969). These data confirmed the hypotheses made years earlier by Loewi and Dale regarding ACh and chemical neurotransmission.

Neurotransmitters and their receptors

Neurotransmitters are defined as endogenous chemical messengers that relay, amplify and modulate neuronal signals (Purves et al., 2008). In order for a molecule to be considered a neurotransmitter it must fulfill four specific criteria: first, the compound is synthesized in the neuron; second, it is present in the presynaptic terminal and is released in amounts that are sufficient to exert a defined response in the postsynaptic cell; third, exogenous application of the substance in question at a reasonable concentration must mimic exactly the action of the endogenously released transmitter; finally, a method of inactivation or clearance must exist to remove the chemical from the synaptic cleft after it is released (Kandel et al., 2000). Neurotransmitters can be divided into three main classes; amino acid neurotransmitters, biogenic amines and neuroactive peptides (Kandel et al., 2000).
The most abundant neurotransmitter in the central nervous system (CNS) is the amino acid neurotransmitter glutamate, which like other amino acid transmitters including glycine, \( \gamma \)-aminobutyric acid (GABA), aspartate and serine, can be synthesized at nerve terminals from non-essential amino acids (Purves et al., 2008). Glutamate is the primary excitatory neurotransmitter in the brain. Neurons that use glutamate as a neurotransmitter are located in a vast array of brain regions. GABA is also predominant in the CNS and plays a mainly inhibitory role in the brain, which is likely a consequence of the fact that GABA is the primary neurotransmitter for inhibitory interneurons (Kandel et al., 2000). Amino acid neurotransmitters like glutamate and GABA are responsible for the majority of fast synaptic transmission in the CNS. Disruption of amino acid neurotransmission may contribute to the development of neurological disorders. Specifically, perturbations of inhibitory signaling mediated by GABA in the brain can result in seizures. Furthermore, disruption of GABA signaling has also been implicated in anxiety disorders, premenstrual dysphoric disorder, and schizophrenia (Wong et al., 2003).

The second class of neurotransmitters is the biogenic amines, which include dopamine, epinephrine, norepinephrine and serotonin. These neurotransmitters are small charged molecules derived from amino acids (Purves et al., 2008). Typically, these neurotransmitters are produced in short biosynthetic pathways that are regulated at a single enzymatic step. Mature neurons that participate in biogenic amine neurotransmission typically only express one type of “controlling enzyme” (Kandel et al., 2000). Disruption of this type of neuronal signaling has been
implicated in several neurological and psychiatric disorders and interestingly, modification of biogenic amine signaling is also the mechanism of action for several drugs of abuse including cocaine and methamphetamine (Deadwyler, 2010; Yamamoto et al., 2010).

Unlike amino acid neurotransmitters and biogenic amines, neuroactive peptides such as insulin, substance P and neuropeptide Y cannot be synthesized at nerve terminals and must instead be derived from secretory proteins that are assembled and processed in the cell body. Once processed, these peptides are loaded into vesicles and transported to nerve terminals where, like the other classes of neurotransmitters, they are released into the synaptic cleft following activation of the presynaptic cell. Neuroactive peptide signaling can result in either excitation or inhibition of target cells. Signaling with these molecules has been implicated in regulation of sensory perception and emotions (Katsouni et al., 2009; Pape et al., 2010).

Neurotransmitters evoke a response in the postsynaptic cell by interacting with members of a diverse group of proteins called neurotransmitter receptors. These proteins are embedded in the postsynaptic membrane and recognize specific neurotransmitter molecules. Once activated by the binding of neurotransmitter, these receptor proteins modify the electrical properties of the postsynaptic cell by either opening or closing ion channels. In this manner, the chemical signal mediated by neurotransmission from the presynaptic cell can be converted back into an electrical
signal in the postsynaptic cell. Molecules that interact with a receptor and initiate functional changes in the physiological properties of the postsynaptic cell are called agonists, whereas those that bind competitively or block the interaction of neurotransmitters with their receptors are called antagonists.

At present, neurotransmitter receptors can be classified into two main superfamilies based on their mechanism of action following the binding of the ligand. The first neurotransmitter receptor superfamily consists of ligand-gated ion channels. Ionotropic receptors allow for the flow of ions through a central pore as a result of the binding of neurotransmitter. The second neurotransmitter receptor superfamily, known as metabotropic receptors, initiates a signal cascade following ligand binding that has a downstream effect on ion permeability. Metabotropic receptors will not be discussed at length in this work. Ligand gated ion channels are typically multimeric structures consisting of two main functional units, an extracellular segment that recognizes the neurotransmitter and a membrane-spanning domain that forms a pore through which ions flow. Upon binding of ligand, the channel protein goes through a conformational change allowing for the flow of ions (Unwin, 1993). Signaling through these types of receptors occurs rapidly and usually only lasts for a few milliseconds (Purves et al., 2008).

The Cys-loop superfamily

The Cys-loop superfamily constitutes a major class of ligand gated ion channels in mammals and comprises both cationic (acetylcholine (ACh) and 5-
hydroxytryptamine (5-HT3) receptors) and anionic (GABA and glycine receptors) channels (Connolly and Wafford, 2004). Mature Cys-loop receptors are pentameric structures assembled with the combination of five subunits arranged around a central pore. These receptors can either be homomeric (assembled with 5 copies of a single subunit protein) or heteromeric (assembled with combinations of several subunits). Subunits in the Cys-loop superfamily have an extracellular amino-terminus, four transmembrane domains with a variable intracellular loop between transmembrane segments three and four and an extracellular carboxyl-terminus (Sine and Engel, 2006). The term "Cys-loop" refers to a characteristic sequence of 13 residues linked by covalently bound cysteines forming a closed loop, located in the extracellular amino terminus of each individual receptor subunit protein (Connolly and Wafford, 2004). Cys-loop receptor subunits are constructed on a modular basis, with the extracellular domain forming the agonist binding sites and the transmembrane domain containing the channel gate, which regulates ion selectivity and pore, through which ions flow (Miller and Smart).

Interestingly, the genes encoding of the Cys-loop receptor superfamily subunits are distributed in two monophyletic groups (Connolly and Wafford, 2004), with the subunits that form anionic channels (e.g., GABA_A, and Glycine,) in the first group and the subunits that form cationic channels (e.g., ACh and 5-HT_3 receptors) in the second. In mammals, sequences of six α, three β, three γ, one δ, three ρ, one ε, one π and one ψ GABA_A receptor subunits have been reported (Barnard et al., 1998) with four isoforms of an α-subunit (α1 – α4) and one variant of a β-subunit (β1)
reported for Glycine channels (Moss and Smart, 2001). A total of 17 ACh receptor subunits ($\alpha$1-10, $\beta$1-4, $\delta$, $\epsilon$ and $\gamma$) have been identified (Albuquerque et al., 2009) whereas just three 5HT$_3$ receptor subunits have been reported (5-HT$_3$A, 5-HT$_3$B and 5-HT$_3$C) (Reeves and Lummis, 2002).

Though not part of the Cys-loop superfamily, an additional class of ionotropic channels gated by the excitatory neurotransmitter glutamate also exists (Kandel et al., 2000). Glutamate receptors include members of the N-methyl-D-aspartate (NMDA), $\alpha$-amino-3-hydroxy-5-methyl-4-isoxazole propionic acid (AMPA) and kainate receptor classes (Madden, 2002). Like the Cys-loop receptors, glutamate receptors can also be homomeric or heteromeric. However, these receptors are assembled into cation-selective tetramers as opposed to the pentameric organization observed in the Cys-loop receptor family. Furthermore, the structure of the individual glutamate receptor subunits also differs from what is observed in the Cys-loop family. Glutamate receptor subunits have an extracellular N-terminus, three transmembrane domains (TM1, TM3 and TM4), a channel lining re-entrant ‘p-loop’ located between TM1 and TM3, and an intracellular C-terminus (Traynelis et al., 2010).

**Muscle nicotinic receptors**

The concept of a receptor protein responsible for the recognition and transmission of a signal from a neuron to a muscle fiber was first hypothesized in the early 20th century by John Newport Langley (Langley, 1905). Langley developed the idea of a
“receptive substance” from the observation that nicotine, the addictive component of tobacco, caused tonic contraction of denervated muscles in the frog, fowl, and toad, which could be blocked by the poison, curare (Langley, 1909b, a, 1914). From these experiments Langley concluded that the “receptive substance of muscle” received stimuli from the nerve cell, and transferred it to the muscle cell, ultimately resulting in contraction (Maehle, 2004). The muscle type nicotinic acetylcholine receptor (nAChR) was the first ligand-gated ion channel protein to be isolated and purified. Using the electric organ of the eel *Electrophorus*, Jean Pierre Changeux and colleagues were able to isolate the receptor protein in 1970. Purification was achieved by exploiting the receptor’s high affinity for \(\alpha\)-bungarotoxin (\(\alpha\)-Bgtx), a component of the venom of the *Bungaris Multicinctus* snake that competitively and irreversibly binds to the receptor (Changeux et al., 1970). Further experiments demonstrated that the muscle type nicotinic receptor is a membrane spanning allosteric glycoprotein with an approximate molecular weight of 275,000 Da (Weill et al., 1974). Muscle type nicotinic receptors are pentameric structures consisting of five types of polypeptide chains \((\alpha, \beta, \gamma, \delta \text{ and } \varepsilon)\). As discussed above, each muscle nAChR subunit protein contains four putative transmembrane spanning domains deemed M1-M4 (Fig. 1.3 A), with the M2 segment of each subunit in the pentameric receptor contributing to the pore-forming domain of the pentameric receptor (Fig. 1.3 B) (Albuquerque et al., 2009). The individual muscle type nAChR subunits were named in accordance to the speed of their migration in protein gels, with the \(\alpha\) subunit migrating the fastest and the \(\delta\) subunit migrating the slowest (Klett et al., 1973; Karlin, 1974; Heidmann and Changeux, 1978).
Figure 1.3: Muscle-type nAChR subunits and subtypes. (A) Schematic representation of an individual nAChR subunit protein. The amino and carboxy terminals of the protein are labeled N and C, respectively, with the transmembrane segments labeled M1 – M4. (B) Schematic representation of the pentameric muscle-type nAChR, with individual subunits depicted as colored cylinders. (C) Subunit composition of the muscle-type nAChRs during development (left) and in adulthood (right). Individual receptor subunits are represented as colored circles. Diamonds located between adjacent receptor subunits represent ligand-binding sites while pentagons in the center of each pentamer represent the pore region.
Mature muscle nAChR subunits are assembled in the stoichiometric combination of α₂βγδ early in development and α₂βεδ at adulthood (Takai et al., 1985; Mishina et al., 1986) (Fig. 1.3 B, C). Each receptor has two ACh (ligand) binding sites, which are located at the interface of an α and a non-α subunit (Fig. 1.3 C). The receptor itself can occupy three distinct functional states: the resting state, where it has low affinity for agonists and the ion channel is closed; the active state, where agonist occupies the ligand binding sites and the channel is open, allowing for the flow of ions; and finally, the desensitized state, where the channel is closed and the receptor is no longer responsive to ligand (Albuquerque et al., 2009).

Muscle type nAChRs are crucial for the transmission of nerve signals to skeletal muscle and in turn underlie the molecular machinery responsible for the operation of the voluntary and involuntary muscle response (Kandel et al., 2000). Disruption of neuronal communication through muscle type nAChRs can result in neuromuscular disorders that effect muscle control like Myasthenia Gravis. In Myasthenia Gravis the observed decline of the voluntary muscle response is a result of the destruction of muscle type nAChRs at the NMJ caused by an abnormal immune response (Lindstrom, 2000b).

**Neuronal nicotinic acetylcholine receptors**

Evidence for the existence of several functionally distinct classes of nAChRs in neuronal tissue was uncovered during early autoradiography experiments that compared the binding of [³H] – ACh and [³H] – Nicotine to [³H] - α-Bgtx in rodent and
chick brains (Marks and Collins, 1982). These experiments demonstrated that there were nAChRs in nervous tissue and that there appeared to be at least two classes of neuronal nicotinic receptors, those that were sensitive to $\alpha$-Bgtx and those that were not (Marks and Collins, 1982). Norman and colleagues were the first to purify a neuronal nicotinic receptor protein from the chick optic lobe in 1982, using $\alpha$-Bgtx as a ligand (Norman et al., 1982). Whiting and Lindstrom purified the first $\alpha$-Bgtx insensitive receptor from chicken brains in 1986. Purification of the $\alpha$-Bgtx insensitive receptor protein was achieved with affinity chromatography, using a monoclonal antibody that recognizes the muscle-type nAChR protein (Whiting and Lindstrom, 1986). The $\alpha$-Bgtx insensitive receptor purified from chick brain had high affinity for nicotine, was resistant to desensitization and was comprised of two subunits. These results demonstrated the existence of nAChRs in the brain that were pharmacologically and functionally distinct from their muscle-type counterparts.

While performing a low stringency screen of a cDNA library using the muscle-type nAChR subunit $\alpha$, Boulter and colleagues isolated a cDNA clone for a neuronal nAChR subunit (Boulter et al., 1986). These experiments set the stage for the discovery of an entire family of neuronal nAChR subunit genes in rapid succession (Heinemann et al., 1990; Gotti and Clementi, 2004; Gotti et al., 2007; Albuquerque et al., 2009).

The neuronal nAChR gene family

Like the muscle-type receptor subunits, each neuronal nAChR gene encodes a protein consisting of an extracellular N-terminus, four transmembrane segments
(M1-M4), a variable intracellular loop between the M3 and M4 transmembrane segments as well as an extracellular C-terminus (Corringer et al., 2000). Similar to what is observed in the muscle receptors, five neuronal nAChR subunits co-assemble to form ligand-gated channels (Cooper et al., 1991; Brejc et al., 2001). However, the diversity of the neuronal nAChR subunit gene family allows for a vast array of subunit combinations, with the biophysical and pharmacological properties of a given receptor subtype determined by subunit composition (McGehee and Role, 1995). At present, 12 members of the nAChR subunit gene family exist including CHRNA2 – CHRNA10 and CHRNB2 – CHRNB4 (Fig. 1.4) (Dani and Bertrand, 2007b; Albuquerque et al., 2009). The \( \alpha 2 – \alpha 6 \) subunits can form functional receptors in combination with the \( \beta 2 – \beta 4 \) subunits while the \( \alpha 7 – \alpha 10 \) subunits are capable of forming homomeric nAChRs. Two classes of unique heteromeric receptors have been discovered recently, which are assembled with the combination of the \( \alpha 9 \) and \( \alpha 10 \) subunits (Elgoyhen et al., 2001; Lustig et al., 2001) or the \( \alpha 7 \) and \( \beta 2 \) subunits (Liu et al., 2009b). The functional diversity exhibited by the neuronal nAChR family is a consequence, in large part, of the differential expression of the various subunit genes leading to the incorporation of distinct subunits into mature receptors (Albuquerque et al., 2009). Thus, the incorporation of a particular subunit into a mature receptor is controlled, at least in part, by the transcriptional regulation of the nAChR subunit genes.
**Figure 1.4: Neuronal nAChR subtypes.** Schematic representations of homomeric and heteromeric receptor subtypes depicted as groups of colored circles with ligand-binding sites depicted as yellow diamonds and the pore region depicted as an unfilled pentagon. Biophysical characteristics of homomeric and heteromeric nAChR subtypes are provided in the center column with primary regions of expression for specific subtypes listed in the right most column (Leonard and Bertrand, 2001; Wang and Sun, 2005).

<table>
<thead>
<tr>
<th>Subtype</th>
<th>Physiology</th>
<th>Main locations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Homomeric</strong></td>
<td>$\alpha$-BgT sensitive</td>
<td>$\alpha 7$: Limbic system, cortex</td>
</tr>
<tr>
<td></td>
<td>$P_{Ca^{2+}}/P_{Na^+} \approx 10$</td>
<td>$\alpha 8$: Only found in chick</td>
</tr>
<tr>
<td></td>
<td>Nicotine $&gt;$ Cytisine</td>
<td>$\alpha 9$: Cochlea, olfactory bulb</td>
</tr>
<tr>
<td></td>
<td>Rapid desensitization ($t=20$ ms)</td>
<td>$\alpha 10$: Cochlear inner hair cells</td>
</tr>
<tr>
<td>$e.g., \alpha 7$ and $\alpha 8$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Heteromeric</strong></td>
<td>$\alpha$-BgT insensitive</td>
<td>$\alpha 5$: Cortex, monoamine-containing nuclei</td>
</tr>
<tr>
<td></td>
<td>$P_{Ca^{2+}}/P_{Na^+} \approx 1-3$</td>
<td>$\alpha 3\beta 4$: PNS, habenulo-interpeduncular system</td>
</tr>
<tr>
<td>$\beta 2$-containing nAChR:</td>
<td>Nicotine $&gt;$ Cytisine</td>
<td>$\alpha 4\beta 2$: Thalamus, cortex</td>
</tr>
<tr>
<td></td>
<td>Fast desensitization ($t=200$ ms)</td>
<td>$\alpha 6\beta 3$: Monoamine-containing nuclei</td>
</tr>
<tr>
<td>$e.g., \alpha 4\beta 2$ and $\alpha 5\alpha 3\beta 4$</td>
<td></td>
<td>$\alpha 2$: Interpeduncular nucleus</td>
</tr>
<tr>
<td>$\beta 4$-containing nAChR:</td>
<td>Nicotine $&gt;$ Cytisine</td>
<td>Slow desensitization ($t=1.2$ s)</td>
</tr>
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</table>
The function of neuronal nAChRs is determined, in part, by the sub-cellular localization of the receptor. nAChRs are located at the soma, where activation directly contributes to excitability through the influx of sodium and calcium (Pidoplichko et al., 1997), at presynaptic terminals, where they can modulate neurotransmitter release (McGehee et al., 1995), and also at postsynaptic terminals, where they receive signals from cholinergic neurons (Albuquerque et al., 2009). The targeting of nAChRs is regulated by the interaction of cellular trafficking proteins with residues in the intracellular loop between the M3 and M4 transmembrane spanning domains of individual receptor subunit proteins (Dani and Bertrand, 2007b).

Characterization of the biophysical and pharmacological properties of nAChRs was made possible by the use of heterologous expression systems (McGehee and Role, 1995). By injecting nAChR mRNA or cRNA into *Xenopus* oocytes, nAChR subunits can be expressed either independently or in combination with other subunits. These experiments demonstrated that the $\alpha_7$, $\alpha_8$, and $\alpha_9$ subunits are able to form functional homomeric receptors, while other $\alpha$ subunits require the presence of an additional $\beta$ subunit to form functional receptors (Couturier et al., 1990b; Gerzanich et al., 1997). Functional heteromeric nAChRs result from co-expression of CHRNA2 – CHRNA6 with the CHRNA2 – CHRNA4 nAChR subunit genes (Boulter et al., 1987; Wada et al., 1988). When activated by agonist, nAChRs allow for the flow of monovalent and divalent cations eliciting a rapid inward current that desensitizes (Barnard et al., 1982) and is potentiated by calcium ions (Vernino et al., 1992). Most high affinity nAChRs in the CNS contain the $\alpha_4$ and $\beta_2$ subunits while most low
affinity receptors are presumably homomeric α7 receptors (Albuquerque et al., 2009).

*The CHRNA5/A3/B4 gene cluster*

Couturier and colleagues were the first to discover the colocalization of the CHRNA5, CHRNA3 and CHRNB4 genes in the avian genome. Shortly after, a remarkably similar CHRNA5/A3/B4 cluster of homologous genes was discovered in the rat genome by Boulter and colleagues (Boulter et al., 1990). It was later elucidated that the clustering of these three nAChR subunit genes is conserved throughout vertebrates, with similar CHRNA5/A3/B4 clusters found in the mouse (Eng et al., 1991) pig (Tammen, 1998) and human genomes (Fig. 1.5) (Raimondi et al., 1992). To date, no clustered subunit genes analogous to CHRNA5, CHRNA3 and CHRNB4 have been identified in the Xenopus, Zebrafish, Drosophila or C. elegans genomes (Le Novere and Changeux, 1995; Tsunoyama and Gojobori, 1998). The conservation at the CHRNA5/A3/B4 locus paired with the observation that these genes are co-expressed in a variety of cell types and tissues suggests that these subunit genes are coordinately regulated (Gotti et al., 2006; Improgo et al., 2010b). Functional characterization of the promoter regions of each of the three clustered subunit genes revealed that as expected, several transcription factors act to positively influence expression of each of the clustered genes including, Sp1, Sp3, Sox10, and SCIP/Tst-1/Oct-6 (Improgo et al., 2010b).
Figure 1.5: The CHRNA5/A3/B4 gene cluster. Schematic representation of the human CHRNA5/A3/B4 gene cluster. Each gene is drawn to scale with colored boxes representing exons and red boxes representing untranslated regions. Horizontal black lines represent introns while horizontal gray lines represent intragenic regions. Colored arrows indicate the direction of transcription. The 25 stars below the CHRNA5/A3/B4 locus indicate the position of SNPs linked to either to an increased risk of nicotine dependence or lung cancer.
Figure 1.6: Transcriptional regulation of the CHRNA5/A3/B4 locus. Coding regions of the nAChR subunit genes are represented as colored boxes with arrows indicating the direction of transcription. Two transcriptional regulatory elements, the intronic repressor in the fifth intron of CHRNA5 (A3I5) and the 3' enhancer in the CHRNB4 gene, are shown (green and purple boxes, respectively). Horizontal black lines depict the non-coding regions of DNA. Transcription factors that regulate expression of these genes are depicted as colored circles and are touching each other if they directly interact. Circles labeled with a “?” indicate transcription factors whose identities have yet to be identified. In the case of Sp1, multiple binding sites have been identified in each of the nAChR genes, however, for clarity, the sites are represented as a single green circle at each promoter region.
However, it is important to note that the expression patterns of the clustered subunit genes do not completely overlap, indicating that in addition to the coordinate regulation, unique regulatory mechanisms also act to control expression of the individual subunit genes (Fig. 1.6). Nicotinic receptors containing $\alpha_5$, $\alpha_3$, and $\beta_4$ subunits are the most abundant nAChRs expressed in the peripheral nervous system (PNS) (Conroy and Berg, 1995; Improgo et al., 2010b), where they play a crucial role in mediating fast synaptic transmission in autonomic ganglia (Rust et al., 1994; Conroy and Berg, 1995; Flores et al., 1996). They are also expressed centrally (Leonard and Bertrand, 2001; Gotti et al., 2007), particularly in the habenulo-interpeduncular pathway where they are hypothesized to play a role in reward and motivation (Grady et al., 2009).

In *Xenopus* oocytes, co-expression of rat $\alpha_3$ and $\beta_4$ nicotinic receptor subunit cRNA results in functional receptors that are activated by ACh with an EC$_{50}$ of 79-180 µM and a single channel conductance, $\gamma_1$, of 22 pS (McGehee and Role, 1995; Improgo et al., 2010b). Interestingly, the $\alpha_5$ subunit fails to form functional receptors when co-expressed with either the $\beta_4$ or $\beta_2$ subunits alone (Boulter et al., 1987; Couturier et al., 1990a). However, functional channels are formed if $\alpha_5$ is co-expressed with both the $\alpha_4$ and $\beta_2$ subunits (Ramirez-Latorre et al., 1996) or with both the $\alpha_3$ and $\beta_4$ subunits (Wang et al., 1996; Groot-Kormelink et al., 2001). Surprisingly, inclusion of the $\alpha_5$ subunit in the $\alpha_3\beta_4$ receptor has little impact on the ACh/nicotine concentration-response relationship. However, the $\alpha_5\alpha_3\beta_4$ subtype does have an
accelerated rate of desensitization when compared to the $\alpha3\beta4$ receptor (Wang et al., 1996; Wang and Sun, 2005). The $\alpha3\beta4$ subtype has an EC$_{50}$ for ACh that is significantly higher than the $\alpha4\beta2$ subtype, which has an ACh EC$_{50}$ of 0.8 $\mu$M. Cytisine is the most potent agonist at the $\alpha3\beta4$ subtype (EC$_{50}$ of 15 $\mu$M) whereas nicotine is the most potent agonist at the $\alpha4\beta2$ (EC$_{50}$ of 0.13-0.3 $\mu$M) subtype (McGehee and Role, 1995; Improgo et al., 2010b).

It has been shown previously that nAChR subtypes in the brain containing the $\alpha5$, $\alpha3$ and $\beta4$ subunits are involved in the pathogenesis of nicotine-induced seizures (Wang et al., 2002; Kedmi et al., 2004; Salas et al., 2004b) as well as nicotine-induced hypolocomotion (Salas et al., 2004b). Specifically, CHRNB4 knock out (KO) mice exhibit decreased signs of nicotine withdrawal (Salas et al., 2004a) as well as autonomic cardiac and intestinal dysfunction (Wang et al., 2003). CHRNA3 KO mice exhibit poor growth, decreased survival, absence of bladder contractility and widely dilated pupils (Xu et al., 1999b), whereas CHRNA5 KO mice display altered autonomic function and decreased sensitivity to nicotine induced seizures (Salas et al., 2003b). Recently, $\alpha3$- and $\beta4$-containing nAChR subtypes in the habenulo-interpeduncular pathway have been shown to mediate ACh release (Grady et al., 2009).

A series of candidate gene analyses and genome-wide association studies (GWAS) has identified single nucleotide polymorphisms (SNPs) in the chromosomal locus encoding the clustered nAChR subunit genes as risk factors for nicotine
dependence, lung cancer, chronic obstructive pulmonary disease, alcoholism and peripheral arterial disease (Saccone, 2007; Amos, 2008; Berrettini, 2008; Bierut, 2008; Hung et al., 2008; Schlaepfer, 2008; Stevens et al., 2008; Thorgeirsson, 2008; Weiss et al., 2008; Caporaso et al., 2009; Freathy et al., 2009; Saccone et al., 2009; Sasaki et al., 2009; Wang et al., 2009b; Wang et al., 2009a). As a result of the correlation of lung cancer susceptibility with variability in the clustered subunit genes, new attention has been brought to the $\alpha_5\alpha_3\beta_4$ subtype shifting the focus from the more commonly studied $\alpha_7$ and $\alpha_4\beta_2$ subtypes (Sciamanna et al., 1997; Picciotto et al., 1998; Wang et al., 2001; Walters et al., 2006; Breitling et al., 2009; Paleari et al., 2009; Sun et al., 2009).

**Nicotinic receptors and lung cancer**

A variety of evidence exists indicating that nAChRs play a role in lung carcinogenesis (Improgo et al., 2010a). First, nAChRs are expressed in both normal and lung cancer cells with several nAChR subunit genes, including CHRNA5, CHRNA3 and CHRNAB4, overexpressed in lung cancer (Schuller, 1989; Maneckjee and Minna, 1990; Maus et al., 1998; Wang et al., 2001; Song et al., 2003; Lam et al., 2007; Sartelet et al., 2008; Improgo et al., 2010d). In addition, the $\alpha_7$, $\alpha_4\beta_2$, $\alpha_3\beta_2$, and $\alpha_3\beta_4$ nAChR subtypes have been shown to mediate cellular processes involved in the pathogenesis of lung cancer (Schuller, 2009). Activation of these receptors potentiates the development and progression of lung cancer through several different mechanisms.
Activation of nAChRs by either nicotine or ACh can enhance cell proliferation. It has been shown previously that ACh activates signaling pathways vital for growth and differentiation of human epithelial cells (Grando, 2008). Nicotine treatment has been shown to initiate a signal cascade that leads to inactivation of cyclins and cyclin-dependent kinases, disassociation of E2F1 from the retinoblastoma protein, activation of proliferative promoters by E2F1 and entry into S-phase (Dasgupta and Chellappan, 2006; Egleton et al., 2008). Nicotine also upregulates a wide variety of growth factors and their receptors (Sher et al., 1998).

Nicotine can also confer resistance to apoptosis in lung cancer cells (Maneckjee and Minna, 1994). Nicotine's ability to protect cells from apoptosis appears to involve several pathways. One such pathway involves activation of the anti-apoptotic protein B cell lymphoma gene 2 by protein kinase Cα and phospholipase C (Mai et al., 2003). Consistently, nicotine also inactivates the proapoptotic functions of the Bax and Bad proteins (Jin et al., 2004; Xin and Deng, 2005).

Nicotine also functions as a pro-angiogenic agent, activating angiogenesis through the phosphatidylinositol 3-kinase and mitogen-activated protein kinase pathways (Heeschen et al., 2001). Nicotine enhances angiogenesis by promoting endothelial cell migration, proliferation, survival, tube formation, and nitric oxide production (Cooke and Ghebremariam, 2008).
\( \beta 4 \)-containing nicotinic receptors

The \( \beta 4 \) nAChR subunit was initially identified in 1989 (Duvoisin et al., 1989) in a screen of a rat cDNA library. Duvoisin and colleagues were able to demonstrate that in *Xenopus* oocytes, the newly discovered \( \beta 4 \) subunit could form functional channels with the \( \alpha 2 - \alpha 4 \) subunits. A year later the sequence of the CHRN\( \beta 4 \) gene was reported for the first time along with CHRNA5 (Boulter et al., 1990). Subsequent studies on \( \beta 4 \)-containing receptors like \( \alpha 3 \beta 4 \) and \( \alpha 5 \alpha 3 \beta 4 \) revealed that these receptors are insensitive to \( \alpha \)-Bgtx and display a slower time course of desensitization when compared to other receptor subtypes like the \( \alpha 7 \) homomeric receptor (Fig. 1.4) (Couturier et al., 1990a; Role, 1992). Much like the CHRNA5 and CHRNA3 subunit genes, the CHRN\( \beta 4 \) gene is widely expressed in the PNS with a more restricted pattern of expression in the CNS (Gotti and Clementi, 2004). CHRN\( \beta 4 \) expression is relatively high in trigeminal sensory neurons (Flores et al., 1996; Liu et al., 1998) as well as the superior cervical, dorsal root, sphenopalatine and otic ganglia (Mandelzys et al., 1994; Rust et al., 1994; Zoli et al., 1995). CHRN\( \beta 4 \) is also expressed in the adrenal medulla (Di Angelantonio et al., 2003) with lower expression in the retina (Moretti et al., 2004). In the CNS, CHRN\( \beta 4 \) expression is particularly high in the olfactory bulb, pineal gland, medial habenula and interpeduncular nucleus (Dineley-Miller and Patrick, 1992; Winzer-Serhan and Leslie, 1997; Grady et al., 2009) with lower expression in other thalamic nuclei, the cortex, hippocampus, spinal cord, cerebellum and midbrain (Hellstrom-Lindahl et al., 1998; Quik et al., 2000; Azam et al., 2002; Perry et al., 2002; Keiger et al., 2003; Gahring et al., 2004; Turner and Kellar, 2005).
As discussed above, the transcription factors Sp1, Sp3, Sox10 and SCIP/Tst-1/Oct-6 positively impact transcription of the CHRNB4 gene as well as the CHRNA5 and CHRNA3 genes (Fig. 1.6). In addition to these factors, CHRNB4 expression is also positively regulated by c-Jun (Melnikova and Gardner, 2001). Transactivation by Sp1, Sp3, c-Jun and Sox10 is abolished when the Sp-binding site on the CHRNB4 promoter (referred to as a CA box) is mutated. Conversely, synergistic activation of the CHRNB4 promoter is observed when Sp1 is supplied in concert with Sox10, Sp3 or c-Jun (Melnikova et al., 2000b; Melnikova and Gardner, 2001). Co-immunoprecipitation experiments demonstrated that all of these factors physically interact (Melnikova et al., 2000a). These findings suggest the existence of a positively acting multi-subunit transcriptional regulatory complex that assembles on the CHRNB4 promoter (Fig. 1.6). This result is consistent with the hypothesis that Sp1 is critical for transcription from the CHRNB4 promoter and likely nucleates the regulatory complex that drives expression of CHRNB4.

Two additional transcription factors have been shown to interact with the CHRNB4 promoter, Purα and heterogeneous nuclear ribonucleoprotein K (hnRNP K) (Du et al., 1997; Du et al., 1998) (Fig. 1.6). These proteins interact with another motif, the CT box, located directly upstream of the CA box. hnRNP K is capable of repressing Sp factor-mediated transactivation of the CHRNB4 promoter (Du et al., 1998) and also physically interacts with Sox10 (Melnikova et al., 2000a). Similar to hnRNP K, Purα is capable of interacting with Sox10 (Melnikova et al., 2000a). Moreover, Purα and hnRNP K themselves physically interact (Melnikova et al., 2000a). These
proteins may participate in the multi-subunit complex described above to modulate expression of the CHRN4 gene in the appropriate cellular context. In vitro binding experiments demonstrated that each factor binds preferentially to the opposing single strand elements of the CT box, suggesting that some local DNA helix unwinding may occur (Krecic and Swanson, 1999). Interestingly, Purα and hnRNP K have been shown to function together to negatively impact transcription of genes in other systems and the same may be occurring at the CHRN4 promoter (Fig. 1.7) (Da Silva et al., 2002).

While the molecular machinery responsible for the incorporation of a particular subunit into a mature nAChR is poorly understood, regulation at the level of transcription undoubtedly plays an important role. The transcriptional regulatory mechanisms controlling expression of the CHRN4 gene are not completely understood, however, and therefore served as the focus of my studies.

I have focused on investigating the transcriptional regulation of the CHRN4 gene both in vitro and in vivo. Specifically, I demonstrated that a set of transcription factors shown previously to enhance CHRN4 promoter activity in vitro are capable of interacting with the CHRN4 promoter in the context of native chromatin using both neuronal-like cell lines and rodent brain tissue. In addition, I have developed a transgenic animal model to investigate the importance of the CHRN4 promoter CA box regulatory element in vivo.
Figure 1.7: Protein-DNA interaction at the CHRN4 promoter CT box.
Nucleotide sequences of the CT and CA box are represented as colored boxes with each base represented as either green (A), pink (T), yellow (C) or blue (G) boxes. The transcription factors hnRNP K (blue) and Purα (green) are depicted as colored shapes interacting with single stranded regions of the CT box shown. Nucleotide sequences that physically interact with either hnRNP K or Purα in vitro have been depicted as colored boxes orientated towards the hnRNP K or Purα proteins. Because hnRNP K and Purα physically interact, they have been depicted here as interlocking shapes.
Using this model system I was able to demonstrate that the CA box regulatory element is critical for CHRNB4 promoter activity *in vivo* and that mutation of this sequence results in decreased interaction of the regulatory factor Sp1 with the CHRNB4 promoter. Finally, I have investigated the role that the transcription factors hnRNP K and Purα play at the CHRNB4 promoter.
CHAPTER II: MATERIALS AND METHODS

Cell culture and differentiation

PC12 cells (Greene and Tischler, 1976) were maintained in Dulbecco’s modified Eagle’s medium (Cellgro) containing 10% fetal bovine serum (GIBCO) and 5% heat inactivated horse serum (GIBCO). PC12 cells were differentiated for 72 hours with nerve growth factor (NGF) (Millipore) as described previously (Hu et al., 1994). OBL21 cells (Ryder et al., 1990) were grown in Dulbecco’s modified Eagle’s medium (Cellgro) containing 10% fetal bovine serum (GIBCO). Neuro 2A cells (Olmsted et al., 1970) were maintained in minimum essential medium (GIBCO) containing 10% fetal bovine serum (GIBCO). SN17 cells (Hammond et al., 1990) were maintained in Dulbecco’s modified Eagle’s medium (Cellgro) containing 10% fetal bovine serum (GIBCO).

ChIP

The ChIP experiment was originally designed to map the location of post-translational modified histone proteins (Kuo and Allis, 1999). This technique has since been adapted to investigate the interaction of transcription factor proteins with a locus or DNA region of interest (Collas, 2010). The ChIP assay allows for the investigation of protein-DNA interaction in the native chromatin environment. This technique provides more physiologically relevant data when compared to electrophoretic mobility shift assays where nuclear extracts are incubated with short-labeled DNA oligonucleotides. In electrophoretic mobility shift assays, DNA is not
associated with histone proteins or organized into higher order chromatin structures. This is a considerable advantage of the ChIP technique, as it is well known that chromatin structure can profoundly impact protein-DNA interaction and transcription (Li et al., 2007).

**ChIP Protocol:** ChIP experiments performed on cells grown in culture were carried out using a modified version of the ChIP protocol provided in the Millipore ChIP assay kit, catalogue #17-295. Cells used for these experiments were grown in 150 cm culture dishes (Corning) to a confluency of ~80%, yielding approximately $10^7$ cells. Proteins were cross-linked to DNA by adding formaldehyde directly to culture medium to a final concentration of 1% and incubating for 10 minutes at 37°C. Cross-linking was then stopped by the addition of glycine to a final concentration of 0.125 M, followed by a 10-minute room temperature incubation. Culture media was aspirated off and cells were then washed twice with ice cold PBS + protease inhibitors (1 µg/ml aprotinin, 1 µg/ml pepstatin A and 1 mM phenylmethylsulfonyl fluoride (Sigma)). Cells were scraped into ice-cold PBS containing protease inhibitors and collected by centrifugation for 4 minutes at 2,000 rpm at 4°C. The resulting pellet was then resuspended again in ice cold PBS containing protease inhibitors and placed on ice. Cell number was determined using a hemocytometer in order to ensure that each individual ChIP was performed using approximately $10^6$ cells as a source of chromatin. Cells were processed in batches of $10^7$ cells, enough for 10 individual ChIP reactions. After quantification and any necessary adjustments, cells were collected again by centrifugation for 4 minutes at 2,000 rpm at 4°C and
supernatant was removed. The resulting pellet was re-suspended in 2 mls SDS lysis buffer (1% SDS, 10 mM EDTA 50 mM Tris-HCL, pH 8.1) with protease inhibitors in a pre-cooled 15 ml conical tube (Fisher). Once in SDS lysis buffer, cells were allowed to incubate on ice for 10 minutes. Cells were then sonicated in the 15 ml conical tube, which was kept in an ice water bath throughout the sonication protocol. The intensity and duration of the sonication was optimized in order to shear chromatin into an average size of 500 base pairs. After sonication, fragmented chromatin was transferred to a pre-cooled microfuge tubes and centrifuged at 13,000 rpm for 10 minutes at 4°C, in order to eliminate cellular debris. The supernatant was carefully removed from the debris pellet and then transferred to a fresh pre-cooled 15 ml conical tube stored on ice. Chromatin was then diluted 10 fold in ChIP dilution buffer (0.01% SDS, 1.1% Triton X-100, 1.2 mM EDTA, 16.7 mM Tris-HCL, pH 8.11, 67 mM NaCl), containing protease inhibitors. At this point, the Input unprecipitated control sample is set aside. Diluted chromatin was pre-cleared by adding 80 µl salmon sperm DNA/protein A-agarose beads (Millipore catalog #16-157C) for each individual ChIP reaction (800 µl was used for a batch of 10 individual ChIPs) and incubating for 30 minutes with rotation at 4°C. After the 30-minute incubation, salmon sperm DNA/protein A-agarose beads were spun down for 2 minutes at 1,500 rpm at 4°C and the cleared supernatant was transferred to a fresh pre-cooled conical tube on ice. Diluted chromatin samples were then aliquoted to pre-cooled siliconized IP tubes (Fisher) kept on ice. Each individual ChIP reaction was performed using 2 ml of diluted chromatin. 5 µg of the desired antibody was then added to each individual ChIP reaction and samples were incubated at 4°C with rotation, overnight.
The following morning, 60 μl of salmon sperm DNA/protein A-agarose beads were added to each IP. ChIP samples were allowed to incubate with salmon sperm DNA/protein A-agarose beads for 1 hour at 4ºC with rotation, in order to allow protein A / antibody / transcription factor / DNA complexes to form. Salmon sperm DNA/protein A-agarose beads were collected by centrifugation at 1000 rpm at 4ºC for 1 minute. Following centrifugation the supernatant was carefully removed and discarded. Protein A / antibody / transcription factor / DNA complexes were washed with 1 ml of a low salt buffer (0.1% SDS, 1% Triton X-100, 2 mM EDTA, 20 mM Tris, pH 8.1, 150 mM NaCl) for 5 minutes at 4ºC with rotation. Salmon sperm DNA/protein A-agarose beads were collected by centrifugation at 1000 rpm at 4ºC for 1 minute and supernatant was carefully removed and discarded. Additional washes were carried out in the same manner for high salt (0.1% SDS, 1% Triton X-100, 2 mM EDTA, 20 mM Tris, pH 8.1, 500 mM NaCl), lithium chloride (1% IGEPAL-CA 630, 1% Deoxycholic acid, 1 mM EDTA, 10 mM Tris, pH 8, 0.25 M LiCl) and TE (10 mM Tris, pH 8, 1 mM EDTA) wash buffers. After the final wash step, beads were collected by centrifugation at 1,000 rpm at 4ºC for 1 minute a final time and supernatant was carefully removed. The salmon sperm DNA/protein A-agarose beads were then eluted by adding 400 μl of elution buffer (0.1 M NaCHO₂, 1% SDS – must be prepared fresh) to each ChIP sample. After briefly vortexing, samples were incubated at room temperature for 30 minutes, with rotation. Salmon sperm DNA/protein A-agarose beads were then collected by centrifugation at 1,000 rpm for 1 minute at room temperature. The resulting supernatant was transferred to freshly labeled tubes and the eluted beads were discarded. 8 μl of 5 M NaCl was added to
each eluted ChIP reaction and samples were incubated at 65°C for 4 hours in order to reverse protein-DNA crosslinking. After the 4-hour incubation at 65°C 40 µl of 10X Proteinase K buffer (2% SDS, 1 M Tris-HCL, pH 8.0, 50 mM EDTA, 2 M NaCl) and 2 µl of a 10 mg/ml proteinase K stock (Sigma) was added to each individual ChIP sample. Samples were then incubated at 45°C for 2 hours in order to digest protein. Following proteinase K treatment, DNA was isolated with phenol:chloroform extraction, followed by ethanol precipitation. The resulting ChIP-derived DNA was then used as template for conventional or quantitative real-time PCR (qRT-PCR).

ChIP experiments using brain tissue as a source of chromatin were performed using a modified version of the protocol discussed above. Rodent brain tissue was ground into a powder using a mortar and pestle (Coors) cooled with liquid nitrogen, on dry ice. Approximately 100 mg of brain tissue was used for each individual ChIP. Once ground to a powder, 1 g of brain tissue (enough for one experiment with 10 individual ChIPs) was triturated in 4 mls PBS with 1% formaldehyde. Cells were incubated in PBS + formaldehyde for 10 minutes in a 37°C water bath. Cross-linking was then stopped by the addition of glycine to a final concentration of 0.125 M, followed by a 10-minute room temperature incubation with rotation. After the 10-minute incubation, tissue slurry was transferred to 2 pre-cooled 2ml dounce homogenizers on ice (Kontes Glass Co.). The brain tissue was homogenized with 10-15 pestle strokes using the “tight” pestle. Cells were then transferred to 2, 2 ml pre-cooled tubes and collected by centrifugation at 1,500 rpm for 5 minutes at 4°C. Supernatant was removed and cells and each pellet was washed in 1 ml ice-cold
PBS containing protease inhibitors. Cells were then collected again by centrifugation at 1,500 rpm for 5 minutes at 4°C and were subsequently washed an additional time. The resulting pellets were resuspended in 1 ml of SDS lysis buffer (1% SDS, 10 mM EDTA 50 mM Tris-HCL, pH 8.1) containing protease inhibitors and then combined to reach a final volume of 2 ml. Brain tissue ChIPs were carried out as described above for the remainder of the procedure.

*Cell lines used in the ChIP assay*

**PC12 Cells:** The rat pheochromocytoma cell line PC12 is a widely used model system for NGF-induced neuronal differentiation (Greene and Tischler, 1976). Upon NGF treatment these cells extend long neurite-like processes and acquire many of the biochemical and physiological properties associated with autonomic neurons (Rogers et al., 1992). NGF treated PC12 cells exhibit increased expression levels of several nAChR subunit genes including the CHRN4 gene (Rogers et al., 1992). PC12 cells treated with NGF were used in the ChIP experiments described below due to the fact that these cells will be actively transcribing the CHRN4 gene. In these cells, it is most likely that the factors that act to control transcription of this gene will be present at the CHRN4 promoter.

**OBL21 Cells:** The OBL21 cell line was produced by retroviral vector-mediated transduction of the avian myc oncogene. Mitotic progenitor cells of postnatal mouse olfactory bulb were infected in order to produce a clonal cell line that exhibits a
stable neuronal phenotype (Ryder et al., 1990). OBL21 cells extend long processes and display growth cones. These cells also express the 150 kD neurofilament protein (a common neuronal marker (Zopf et al., 1987)) as well as voltage-gated potassium channels, but do not express voltage-gated sodium channels (Ryder et al., 1990). OBL21 cells were used in ChIP assays because of their neuronal-like morphology and also due to the fact that the CHNRB4 gene is expressed in the olfactory bulb (Dineley-Miller and Patrick, 1992; Winzer-Serhan and Leslie, 1997).

**Neuro 2A Cells:** The mouse neuroblastoma cell line Neuro 2A was derived from a spontaneously occurring neuroblastoma in an albino mouse strain (Olmsted et al., 1970). These cells produce a microtubular protein, which is believed to play a role in the contractile system giving axoplasmic flow in nerve cells. When cultured these cell rapidly adhere to substrate and extend branching processes, giving them a neuronal-like morphology. Neuro 2A cells were used in ChIP assays because of their neuronal-like morphology and also because they express relatively high levels of several nAChR subunits including the CHRNA5, CHRNA3 and CHRNB4 genes.

*Antibodies used in the ChIP assay*

**Anti-acetyl Histone protein H4 (Millipore – 06-866):** rabbit polyclonal antiserum raised against amino acids 2-19 of *Tetrahymena* histone H4. 5 µl of H4 antibody was used in each H4 ChIP positive control reaction.

**Normal Rabbit IgG:** (Santa Cruz Biotechnology – sc-2027)

**Normal Mouse IgG:** (Santa Cruz Biotechnology – sc-2025)
**Sp1 (PEP 2) X (Santa Cruz Biotechnology – sc-59X):** an affinity purified rabbit polyclonal antibody raised against amino acids 528-546 mapping within an internal region of Sp1 of rat origin.

**Sp3 (D-20) X Santa Cruz Biotechnology – sc-644X) an affinity purified rabbit polyclonal antibody raised against a peptide within the C-terminus of Sp3 of human origin.**

**Sox10 (H-140) X (Santa Cruz Biotechnology – sc-48824X) a rabbit polyclonal antibody raised against amino acids 311-450 mapping near the C-terminus of Sox-10 of human origin.**

**c-Jun (N) X (Santa Cruz Biotechnology – sc-45X):** an affinity purified rabbit polyclonal antibody raised against a peptide within the N-terminus of c-Jun of mouse origin.

**hnRNP K (H-300) (Santa Cruz Biotechnology – sc-25373):** an affinity purified rabbit polyclonal antibody raised against amino acids 1-300 of hnRNP K of human origin.

**Purα (Abcam – Ab79936):** an affinity purified rabbit polyclonal antibody raised against a peptide containing residues 1-100 of Purα of human origin.

**Amplification of ChIP-derived DNA**

**Conventional PCR**

ChIPs performed on cells grown in culture: PC12 cell ChIP-derived DNA was used as template in PCRs with the following primers designed to recognize a segment of the rat CHRN1 promoter containing the CT and CA boxes, 5’-
Neuro 2A and OBL21 ChIP-derived DNA was used as template in PCRs with the following primers designed to recognize a segment of the mouse CHRNBP4 promoter containing the CT and CA boxes 5’- TTGGGTAAGCCAGGCTAAGA-3’, 5’- TTGGGTAAGCCAGGCTAAGA-3’. Both mouse and rat ChIP-derived PCR products were sequenced to confirm the specificity of the PCR reaction. Following amplification, PCR products were electrophoresed through a 2% agarose gel.

Fetal and adult rat brain ChIPs: Rat brain ChIP-derived DNA was used as template in PCRs with the rat primers discussed above, designed to recognize a segment of the rat CHRNBP4 promoter containing the CT and CA boxes, 5’- TAAGCTGCCTCGGGTGAACTAAGA-3’, 5’- TAAGCTGCCTCGGGTGAACTAAGA-3’. Following amplification, PCR products were electrophoresed through a 2% agarose gel.

CA box mutant transgenic brain tissue ChIPs: Each ChIP-derived DNA sample was used in PCR with the rat primers discussed above designed to amplify a segment of the rat mutant transgenic CHRNBP4 promoter, 5’- TAAGCTGCCTCGGGTGAACTAAGA-3’, 5’- TAAGCTGCCTCGGGTGAACTAAGA-3’. The same ChIP-derived DNA was also used as template in a separate set of reactions using the mouse primers discussed above, which are designed to amplify a segment of the endogenous wild type mouse CHRNBP4 promoter, 5’- TTGGGTAAGCCAGGCTAAGA-3’, 5’- TTGGGTAAGCCAGGCTAAGA-3’. Following
amplification, PCR products were electrophoresed through a 2% agarose gel.

Densitometry values for ChIP-DNA derived PCR products were obtained using the Ultra-Violet Products EpiChemi® Darkroom imaging system and UVP analysis software (UVP). Densitometry values obtained for each ChIP reaction were normalized to the corresponding value obtained for the Input control sample, in order correct for differences in starting material. Student’s t-test was used for statistical analysis.

**qRT-PCR**

Quantification of CHRNA4 promoter fragment enrichment in OBL21, PC12 and Neuro 2A ChIP-derived DNA samples was performed using the absolute quantification method (Chini et al., 2007) using SYBR green supermix with ROX (BioRad). Serial dilutions of a plasmid containing a fragment of either the rat (used for PC12 ChIPs) or mouse (used for the OBL21 and Neuro 2A ChIPs) CHRNA4 promoter were used to generate a standard curve for the quantification of the ChIP-derived DNA samples. ChIP-derived DNA from the rat PC12 cell line was amplified using the primers discussed above designed to recognize a segment of the rat CHRNA4 promoter containing the CT and CA boxes, 5’-

TAAGCTGCCTCGGGTGAACTAAGA-3’, 5’-TGTCTGGGGGAACCTGTGGCTAT-3’.

ChIP-derived DNA from the mouse OBL21 and Neuro 2A cells were amplified using the primers discussed above, designed to recognize a segment of the mouse CHRNA4 promoter, 5’- TTGGGTAAGCCAGGCTAAGA-3’, 5’-

GGTCCCGAGACTTTCACAA-3’. Each ChIP-derived DNA sample was run in
triplicate and values obtained for each ChIP were normalized to the value obtained for the Input ChIP positive control (a 2% sample of un-precipitated DNA) in order to control for differences in starting material. Data from these experiments are presented as a percentage of the value obtained for the Input control or % Input.

Construction of the mutant CHRNB4 promoter / lacZ transgene

The 2,346-base pair SacI/HindIII fragment of the rat CHRNB4 gene promoter was excised from the pSGB4SH construct (Bruschweiler-Li et al., 2010) and used as the template for mutagenic PCR. For mutagenesis, the primers were designed to make 3 base pair substitutions in the CA box within the context of the 2.3-kb promoter fragment. After mutagenesis, the resulting fragment was ligated back into the pSG-MAR backbone in order to generate the pSGMutB4SH construct. The SacI/HindIII fragment in the resulting construct was sequenced in order to ensure that only the expected mutations were made (Genewiz, CA) (Fig. 4.3).

Determination of transgene copy number

Transgene copy number of the mutant transgenic lines was determined using absolute quantification-based real-time PCR (Yuan et al., 2007). PCR reactions were performed with primers designed to amplify a fragment of the lacZ coding sequence present in the CHRNB4 promoter / lacZ transgene. The sequence of the upper strand primer was 5’- GATTTCCATGTTGCCACTCGCTTTA-3’ while that of the lower strand primer was 5’- TTCAGCAGCAGCAGACCATTCTTCAA-3’. All PCR reactions were set up in triplicate and included 100 ng of genomic DNA as template.
Three individuals from each founder line were used to determine copy number. Two positive control samples of known copy number (a generous gift from Ricardo Medina, University of Massachusetts Medical School) were used in this analysis. These control samples were isolated from transgenic animals that contain a targeted lacZ coding sequence. One of these animals has 1 copy of the lacZ transgene and the other has 2 copies. The value obtained for the single copy positive control sample was set as 1 in each experiment. This value was used to estimate the copy number for all other samples including the control sample with 2 copies. In order to determine copy number for our 6 mutant CHRNB4 / lacZ transgenic lines, 3 DNA samples from each line were run in qRT-PCR experiments. The quantities derived from the standard curve for each set of 3 animals were averaged and then divided by the value for the 1-copy positive control.

**Generation of transgenic mice**

pSGMutB4SH was digested with NotI to release the mutated CHRNB4 / lacZ transgene. Following agarose gel electrophoresis, the transgene fragment was excised and the DNA was extracted from the gel using a QIAquick Gel Extraction Kit (QIAGEN). The purified DNA was injected into pronuclei followed by implantation into pseudopregnant females. The C57BL/6 x SJL F2 hybrid mouse strain was used for all transgenic experiments. Transgenic founders were identified by PCR. Founders were mated with C57BL/6 x SJL F2 hybrid mice to establish transgenic lines. Adequate measures were taken to minimize pain and discomfort to the animals. All procedures were conducted in accordance with the rules of the
Institutional Animal Care and Use Committee of the University of Massachusetts Medical School.

**Histochemical analysis of transgenic mice**

Two ages of transgenic mice were studied: ED18.5 and PD30. The embryonic time point was selected due to the fact that it is several days after the initiation of CHRN4 expression (Zoli et al., 1995). The postnatal time point was selected in order to accurately compare the expression patterns of our reporter gene to previous in situ hybridization studies that investigated CHRN4 expression in mice at this time point (Winzer-Serhan and Leslie, 1997). Mice were anesthetized with pentobarbital and perfused transcardially with cold 0.1 M sodium phosphate buffer/2 mM MgCl₂ followed by fixative (cold 4% paraformaldehyde). Tissues were then dissected and post-fixed for 5-6 hours (ED18.5) or 4 hours (PD30). Fixed tissues were transferred to 30% sucrose/2 mM MgCl₂, in 1X PBS and incubated at 4°C overnight. Tissues were embedded in Tissue-Tek (Miles) and quick frozen on dry ice. If not used immediately, the samples were stored at -80°C. Sectioning was done on a Leica CM3050S cryostat at -28°C generating either 14 μm (ED18.5) or 25 μm (PD30) thick sections that were transferred directly onto Superfrost glass slides (Fisher). Slides were air-dried at room temperature, washed with sodium phosphate buffer and then incubated overnight at 37°C with β-gal staining solution (0.1 M NaHPO₄, 0.1 M NaH₂PO₄, 2 mM MgCl₂, 0.1% sodium deoxycholate, 0.02% NP-40, 10 mM K₃(Fe)CN₆, 10 mM K₄(Fe)CN₆, 1 mg/ml X-gal). In order to minimize any variability in the β-Gal staining results, sections from mutant transgenic lines and the
corresponding WT transgenic and non-transgenic lines were stained at the same time and in the same batch of staining solution. Two animals from each transgenic founder line were studied in depth. Following β-gal staining, slides were washed with 1X PBS and incubated in distilled water either for 1 h (ED18.5) or overnight (PD30). Slides were then counter-stained with Neutral Red (1% w/v in 37 mM sodium acetate), dehydrated through a graded series of ethanol solutions (50%, 70%, 90% and 100%) and cleared with xylene. The slides were air-dried overnight at room temperature in a fume hood followed by the application of cover slips. Microscopy was done using a Zeiss Axiovert 200M microscope with a high resolution Retiga 1300R CCD camera and Slidebook image analysis software. Anatomical analysis was done with the aid of the Paxinos and Franklin mouse brain atlas (Franklin and Paxinos, 2001) and the Kaufman atlas of mouse development (Kaufman, 1998).

**Northern blot analysis**

Expression of Sox10 mRNA in the OBL21 cell line was determined by Northern blot analysis as previously described (Fanger et al., 1995) using a radioactively labeled Sox10 cDNA.

**Quantification of gene expression using qRT-PCR**

Quantification of hnRNP K, Purα, CHRNA5, CHRNA3 and CHRNB4 gene expression in OBL21, PC12 and Neuro 2A cells was performed using the -ΔCT relative quantification method (Fernandez et al., 2003) with an ABI 7500 Real Time
PCR System. In these experiments, expression of a gene of interest is expressed relative to the expression level of the housekeeping gene β2-microglobulin (β2M).

Quantification of gene expression in the siRNA experiments was performed using the $2^{-\Delta\Delta CT}$ relative quantification method (Livak and Schmittgen, 2001). In these experiments, β2M was used as the endogenous control to quantify gene expression, while the negative control siRNA treated cells are used as a calibrator. In each set of experiments, total RNA was isolated from cells using the RNeasy kit (Qiagen). cDNAs were generated using the RETROscript kit (Ambion). Each of the three clustered nAChR subunit genes along with hnRNP K, Purα, β2M and glyceraldehyde 3-phosphate dehydrogenase (GAPDH) were amplified using TaqMan® probes (ABI).

**Transient Transfections**

Neuro 2A or SN17 cells were transfected using Lipofectamine 2000 (Invitrogen) according to the manufacturers instructions. Cells were transfected with either the WT or mutant construct and a luciferase expression construct, pGL-Promoter, in which the SV40 promoter drives expression of the firefly luciferase gene. (Promega). These cells were allowed to incubate in transfection medium for 2 days and then harvested and assayed for β-gal (Galacto-Star, Applied Biosystems) and luciferase (Luciferase Assay System, Promega) activities in triplicate using a Lumimark microplate luminometer (Bio-Rad).
To correct for differences in transfection efficiencies between dishes, the β-gal activity in each sample was normalized to the luciferase activity in that same sample. The Student’s t-test was used for statistical analysis.

Silencer select® siRNAs specific for hnRNP K, Purα or a negative control siRNA (ABI) were transfected into Neuro 2A cells at a final concentration of 5 nM. siRNA was delivered to Neuro 2A cells using Lipofectamine 2000 (Invitrogen).

Western blot analysis

Expression of Sox10 protein in OBL21 cells was determined by Western blot analysis as described previously (Scofield et al., 2008). Anti-Sox10 antibody (Santa Cruz Biotechnology - sc-48824) was used at a dilution of 1: 200.

hnRNP K, Purα, nAChR α3, α5, β4, β-Actin and β2M protein levels in siRNA treated Neuro 2A cells were also determined by Western blot analysis. Proteins from siRNA treated cells were separated by sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) then electrophoretically transferred to nitrocellulose membranes. The resulting membranes were probed with anti-hnRNP K, Purα, nAChR α3, α5, β4, β-Actin or β2M antibodies. Signal intensities were measured following chemiluminescent detection. Values for hnRNP K, Purα, nAChR subunits α3 α5 or β4 were normalized to the corresponding value obtained for either β2m or β-Actin, in order to correct for differences in the amount of lysate loaded into each well. In siRNA western experiments, negative control siRNA and either hnRNP
K or Purα siRNA treated cell lysates were run on the same gels in order to more accurately quantify any reduction in protein levels. The anti-nAChR α3 (Santa Cruz Biotechnology – sc5590), anti-nAChR α5 (Abcam – ab41173), anti-nAChR β4 (R&D antibodies – As-5656S), anti-hnRNP K antibody (Santa Cruz Biotechnology - sc-25373) and anti-Purα antibody (Abcam – Ab79936) were used at a dilution of 1:400, whereas the anti-β-Actin antibody (Sigma – A2228), and anti-β2m antibody (Santa Cruz Biotechnology – sc-51509) were used at a dilution of 1:5000. Image acquisition and analysis were performed using a BioRad VersaDoc system and software.
CHAPTER III: PROTEIN-DNA INTERACTION AT THE CHRNA4 PROMOTER CA

Disclaimer: I performed all of the experiments described in this chapter with the exception of the Northern and Western blots shown in Figure 3.3 (OBL21 cells express high levels of Sox10 mRNA and protein), which were performed by Zhongming Mou.

Abstract

nAChR s are involved in a plethora of fundamental biological processes ranging from muscle contraction to the formation of memories. These receptors are pentameric proteins whose subunits are encoded by distinct genes, with the biophysical properties of nAChRs governed by subunit composition. The incorporation of a particular subunit into a mature receptor is governed in part by the cell-type specific transcriptional regulation of each subunit gene. Here, using the ChIP assay, I report the interaction of Sp1, Sp3, Sox10 and c-Jun with the CHRNA4 promoter in neuronal-like cell lines as well as rodent brain tissue. These results are in agreement with previous data from our lab demonstrating that these factors functionally interact with the CHRNA4 promoter in vitro. Taken together, these data strongly suggest that Sp1, Sp3, Sox10 and c-Jun regulate expression of the CHRNA4 subunit gene in the mammalian brain.
Introduction

Neuronal nAChRs play an essential role in an array of physiological processes including learning, memory, and attention (Leonard and Bertrand, 2001; Gotti and Clementi, 2004; Albuquerque et al., 2009). The subunit composition of a particular nAChR is governed, at least in part, by the transcriptional regulation of individual subunit genes. Our laboratory has had a long-standing interest in the transcriptional mechanisms underlying expression of the CHRNA/A3/B4 subunit genes. The three nAChR subunits encoded by these genes makeup the predominant nicotinic receptor subtype expressed in the peripheral nervous system (PNS) (Leonard and Bertrand, 2001). Recently, GWAS studies have linked variability in the CHRNA5/A3/B4 locus to an increased risk of nicotine dependence and lung cancer (Greenbaum and Lerer, 2009; Improgo et al., 2010c).

As only a small subset of neurons in the CNS express the CHRNβ4 gene (Dineley-Miller and Patrick, 1992; Zoli et al., 1995; Gahring et al., 2004) it is likely that receptors including this subunit play an important role in mediating cholinergic signaling in and around these brain regions (Duvoisin et al., 1989; Gahring et al., 2004). Studies done using CHRNβ4 KO animals have demonstrated that the β4 subunit plays a critical role in the molecular mechanism underlying nicotine induced withdrawal (Salas et al., 2004a). Furthermore, blockade of α3β4 nAChRs results in a reduction of opioid and stimulant self-administration, suggesting that nAChRs that contain the β4 subunit may be involved in mediating withdrawal syndromes elicited by other drugs of abuse (Glick et al., 2002).
Gaining a better understanding of the transcriptional regulation of the CHRNB4 gene would contribute not only to a more complete understanding of cholinergic signaling in the brain, but also nicotine addiction and withdrawal. Here, I focus on elucidating the interaction of transcription factors with the CHRNB4 gene promoter in the chromatin environment.

Previous work from our laboratory has identified a 226-base pair segment of DNA in the 5´-flanking region of the CHRNB4 gene capable of driving luciferase expression in a cell type specific manner (Hu et al., 1994; Liu et al., 1999). Deletional analysis led to the identification of a unique regulatory element, referred to as a CA box (Fig. 3.1), located upstream of the CHRNB4 initiator methionine. Interestingly, a C – T mutation of a similar CA box regulatory element located in the β globin gene promoter resulted in a 50% reduction in promoter activity (Kulozik et al., 1991). By introducing similar mutations to the CHRNB4 promoter CA box, we have previously shown that this regulatory element is critical for luciferase expression from the CHRNB4 promoter in neuronal-like cell lines (Hu et al., 1994). Using electrophoretic mobility shift assays we also previously showed that the transcription factors Sp1 (Bigger et al., 1996; Bigger et al., 1997), Sp3 (Bigger et al., 1997), and Sox10 (Liu et al., 1999) bind to the CA box in vitro. In addition, each of these factors is capable of transactivating expression of a luciferase reporter gene driven by the CHRNB4 promoter, as is the transcription factor c-Jun (Bigger et al., 1997; Liu et al., 1999; Melnikova and Gardner, 2001).
Figure 3.1: The CT and CA box regulatory elements of the CHRNA4 gene promoter. The CHRNA4 gene is depicted in green with the arrow inside denoting the direction of transcription. Nucleotide positions of the SacI, FokI, and HindIII sites are shown relative to the major transcription initiation site of the CHRNA4 gene indicated by the bent arrow. The CT and CA boxes are shown in grey and white, respectively with their nucleotide sequences shown below the schematic representation.
Interestingly, transfection of c-Fos had no impact on CHRNB4 promoter activity and there is no consensus AP-1 (c-Jun and c-Fos heterodimer binding site) site in the CHRNB4 promoter. Co-immunoprecipitation studies have demonstrated that Sp1 and Sp3 (Bigger et al., 1997), as well as Sox10 and the Sp factors (Melnikova et al., 2000b; Melnikova et al., 2000a), physically interact. Furthermore, transient transfections have demonstrated that these factors transactivate the CHRNB4 promoter synergistically when co-transfected into neuronal-like cell lines (Bigger et al., 1997; Melnikova et al., 2000b). Similarly, Sp1 and c-Jun also synergistically transactivate the CHRNB4 promoter in transient transfection experiments (Melnikova and Gardner, 2001).

Therefore, I hypothesize that Sp1, Sp3, Sox10 and c-Jun act to enhance expression of the CHRNB4 gene by interacting with the CHRNB4 promoter CA box, in the chromatin environment. To test whether these four regulatory factors interact with the CHRNB4 promoter, in neuronal-like cells as well as in the mammalian brain, ChIP experiments were performed using the PC12 and OBL21 cell lines as well as chromatin isolated from fetal and adult rat brain tissue. These experiments assay for the interaction of Sp1, Sp3, Sox10 and c-Jun with the CHRNB4 promoter in the chromatin environment. Previous Sp1, Sp3 and Sox10 in vitro binding experiments were performed using short DNA oligonucleotides (Bigger et al., 1997; Melnikova et al., 2000b), whereas the ChIP assay is performed using fragmented chromatin where DNA is associated with histone proteins and may be organized into higher order structures.
Results

*Sp1, Sp3 and c-Jun interact with the CHRNB4 promoter in differentiated PC12 cells.*

To investigate whether Sp1, Sp3 and c-Jun interact with the CHRNB4 promoter on cellular chromatin, ChIP assays were performed using differentiated PC12 cells. PCR reactions using ChIP-derived DNA from Sp1, Sp3 and c-Jun immunoprecipitations resulted in the amplification of a 207-base pair fragment of the rat CHRNB4 promoter containing the CA box (Fig. 3.2). The specificity of antibody-transcription factor complexes was demonstrated by negative results in ChIP assays using either normal mouse IgG or no antibody (Fig. 3.2). An additional negative control was performed by substituting water for ChIP-derived DNA at the final PCR step (Fig. 3.2). Immunoprecipitation with an anti-histone protein H4 antibody was performed as a ChIP positive control, which resulted in the amplification of the expected fragment (Fig. 3.2). In addition, a sample of fragmented chromatin prior to immunoprecipitation was used as a positive control (referred to as “Input”), which also amplified the expected 207-base pair product (Fig. 3.2). Taken together, these data indicate that Sp1, Sp3 and c-Jun are present at the endogenous CHRNB4 promoter in NGF-treated PC12 cells.

*Sp1, Sp3, Sox10 and c-Jun interact with the CHRNB4 promoter in the neuronal-like cell line OBL21.*

Our laboratory has previously shown that Sox10 binds to and transactivates the CHRNB4 promoter in neuronal-like cell lines, but not in non-neuronal cell lines (Liu et al., 1999). As PC12 cells do not express Sox10 (data not shown),
Figure 3.2: Differentiated PC12 chromatin immunoprecipitation. ChIP-derived DNA was used as template for PCR reactions designed to amplify a fragment of the rat CHRNB4 promoter containing the CA box. Amplification was observed for both histone H4 (“H4”) and input (“Input”) ChIP positive controls. The expected PCR product was also produced in Sp1, Sp3 and c-Jun reactions (“Sp1”, “Sp3”, “c-Jun”). No amplification was observed when using DNA immunoprecipitated by normal mouse IgG (“IgG”), no antibody (“No Ab”) or in no-template PCR reactions (“No Template”). The arrow indicates the 200-base pair marker in the 100-base pair ladder (“M”). Each ChIP experiment was carried out a minimum of three times.
ChIP analyses were extended to another cell line, the mouse olfactory bulb derived cell line OBL21 (Ryder et al., 1990), which express high levels of Sox10 mRNA and protein (Fig. 3.3 A and B respectively). ChIP experiments with OBL21 cells were carried out as described above for PC12 cells. PCR reactions with ChIP derived DNA from Sp1, Sp3, Sox10 and c-Jun IPs resulted in the amplification of the expected 243-base pair product of the mouse CHRNB4 promoter, containing the CA box (Fig. 3.4, lanes 4-7). Once again, the specificity of antibody-transcription factor complexes was confirmed by the failure of ChIP-derived DNA from mouse IgG and mock immunoprecipitations to produce the CHRNB4 promoter PCR product (Fig. 3.4, lanes 3 and 8). Finally, H4 and Input ChIP positive controls showed strong bands (Fig. 3.4, lanes 2 and 9) and there was no amplification in the no template PCR control (Fig. 3.4, lane 10). These data indicate that Sp1, Sp3, Sox10 and c-Jun interact with the CHRNB4 promoter in OBL21 cells.

Sp1, Sp3, Sox10 and c-Jun interact with the CHRNB4 promoter in fetal and adult rat brain tissue.

In order to assay for the interaction of Sp1, Sp3, Sox10 and c-Jun with the CHRNB4 promoter in the most physiologically relevant setting, ChIP experiments were performed using chromatin derived from rodent brain tissue. PCR reactions using fetal rat brain ChIP-derived DNA as template resulted in the amplification of the expected rat CHRNB4 promoter fragment for Sp1, Sp3, Sox10 and c-Jun ChIPs (Fig. 3.5 A).
Figure 3.3: OBL21 cells express high levels of Sox10 mRNA and protein. (A) Northern blot analysis of OBL21 cells revealed relatively high levels of Sox10 mRNA. Northern analysis was also carried out for β-actin message as a loading control. (B) Western blot analysis was carried out on OBL21 cell lysates and showed abundant levels of Sox10 protein (MW = 68 kDa). Lines on the left of the blot indicate the positions and weights of protein standards.
**Figure 3.4: OBL21 chromatin immunoprecipitation.** ChIP-derived DNA was used as a template for PCR reactions designed to amplify a 243-base pair product of the mouse CHRNB4 promoter. The expected product was observed in PCR reactions for both histone H4 ("H4") and input ("Input") positive controls. Amplification was also observed in Sp1, Sp3, Sox10 and c-Jun immunoprecipitations ("Sp1", "Sp3", "Sox10", "c-Jun"). No amplification was seen in PCR reactions using DNA immunoprecipitated by normal mouse IgG ("IgG"), no antibody ("No Ab") or in no-template PCR reactions ("No Template"). The arrow indicates the 250-base pair marker in the 100-base pair ladder ("M"). Each ChIP experiment was carried out a minimum of three times.
The specificity of antibody-transcription factor complexes in these ChIP experiments was demonstrated by failure of ChIP-derived DNA from mouse IgG and no antibody immunoprecipitations to produce the expected product (Fig. 3.5 A). These experiments indicate that Sp1, Sp3, c-Jun and Sox10 interact with the CHRNB4 promoter, at the CA box, in fetal rat brain.

I hypothesized that Sp1, Sp3, Sox10 and c-Jun would also interact with the CHRNB4 promoter in adult rat brain. In order to test this hypothesis, I performed an additional round of ChIP assays using adult rat brain tissue. These experiments were performed using whole brain tissue as a source of chromatin for ChIP assays. Due to the restricted pattern of CHRNB4 expression, I would expect there to be regional differences in ChIP results. However, conventional microdissection procedures were not suitable for the removal of the very small brain regions where CHRNB4 is highly expressed (e.g., medial habenula and the interpeduncular nucleus). Therefore, whole brain homogenate was used. PCR using ChIP DNA from Sp1, Sp3, Sox10 and c-Jun immunoprecipitations resulted in the amplification of the expected fragment of the rat CHRNB4 promoter (Fig. 3.5 B). No amplification occurred in PCR reactions using DNA derived from mouse IgG and mock immunoprecipitations (Fig. 3.5 B), further suggesting that positive ChIP results are specific to the antibodies used in the immunoprecipitations.
Figure 3.5: Rat brain chromatin immunoprecipitation. (A) Fetal rat brain ChIP-derived DNA was used as template for PCR reactions designed to amplify a segment of the rat CHRNB4 promoter. Histone H4 ("H4") and input ("Input") positive controls produced the expected product. Amplification was also observed for Sp1, Sp3, Sox10 and c-Jun PCR reactions ("Sp1", "Sp3", "Sox10", "c-Jun"). ChIP negative controls, normal mouse IgG ("IgG"), mock immunoprecipitation ("No Ab") and no-template PCR control ("No Template") produced no amplified products. The arrow indicates the 200-base pair marker in the 100-base pair ladder ("M"). (B) Adult rat brain ChIP-derived DNA was used in PCR reactions designed to amplify the rat CHRNB4 promoter. Again, both the histone H4 ("H4") and input ("Input") positive controls produced the expected product. Amplification was also observed for Sp1, Sp3, Sox10 and c-Jun PCR reactions ("Sp1", "Sp3", "Sox10", "c-Jun"). Finally, ChIP negative controls, normal mouse IgG ("IgG"), mock immunoprecipitation ("No Ab") and no-template PCR control ("No Template") produced no amplified products. The arrow indicates the 200-base pair marker in the 100-base pair ladder ("M"). Each ChIP experiment was carried out a minimum of three times.
Discussion

nAChR subunit genes are expressed in a variety of locations in both the PNS and CNS (Gotti et al., 2007; Albuquerque et al., 2009). However, the molecular mechanisms underlying the temporally and spatially specific expression of nAChR subunit genes remain to be completely elucidated. Here I extended our previous in vitro work on protein-DNA interactions that occur at the CHRN4B promoter CA box. In this study, using both cell lines and brain tissue as a chromatin source for ChIP assays, I have shown that Sp1, Sp3, Sox10 and c-Jun interact with the CHRN4B promoter in the chromatin environment. These data confirm and extend our previous results indicating that Sp1, Sp3, Sox10 and c-Jun interact with the CHRN4B promoter in vitro, as it is well known that chromatin structure can profoundly impact protein-DNA interaction (Li et al., 2007).

The positive ChIP results for the transcription factors Sp1 and Sp3 are in agreement with previous data from our lab indicating an interaction between these proteins and the CHRN4B promoter in vitro (Bigger et al., 1997). In addition to those present in the CHRN4B promoter, there are several functionally relevant Sp1 binding sites in the CHRNA3 and CHRNA5 subunit gene promoters (Campos-Caro et al., 1999; Deneris et al., 2000; Valor et al., 2002). Due to the fact that these genes are located in a tight cluster in the mammalian genome, they are likely subject to some level of coordinate regulation. (Boulter et al., 1990; Yang et al., 1997). This coordinate regulation is likely responsible for directing the overlapping expression patterns of the clustered subunits in the mammalian nervous system (Winzer-Serhan and
Leslie, 1997; Albuquerque et al., 2009). It is my hypothesis that the coordinate regulation of these clustered subunits takes place at least in part through the action of Sp factors (Campos-Caro et al., 1999; Liu et al., 1999; Deneris et al., 2000; Valor et al., 2002).

I have also shown here that Sox10 interacts with the CHRNA4 promoter in the chromatin environment, this finding is also corroborated by previous results from our laboratory indicating that the Sox10 protein can interact with and transactivate the CHRNA4 promoter in vitro (Liu et al., 1999; Melnikova et al., 2000b).

There is no consensus c-Jun binding site in the CHRNA4 promoter and the c-Jun protein does not interact with the CHRNA4 promoter using in vitro binding assays. However, c-Jun synergistically transactivates the CHRNA4 promoter when co-transfected with Sp1 (Melnikova and Gardner, 2001). This result is in agreement with the data presented here, demonstrating that c-Jun is associated with the endogenous CHRNA4 promoter in neuronal-like cell lines and in rodent brain tissue. c-Jun is most likely recruited to the CHRNA4 promoter through a protein-protein interaction with Sp1, as mutation of Sp binding sites in the CHRNA4 promoter abrogates transactivation by c-Jun (Melnikova and Gardner, 2001).

By assembling previous data from our lab as well as the ChIP data discussed above, I have generated a model of protein-DNA interaction at the CHRNA4 promoter CA box (Fig. 3.6). Given the high GC content of the CA box, transcription factors in the
Sp family were likely candidates for proteins that may interact with the CHRNA4 promoter. Using electrophoretic mobility shift assays we previously demonstrated that both the Sp1 and Sp3 are capable of interacting with the CHRNA4 promoter CA box *in vitro*. As expected, mutation of the CA box abrogated this interaction (Bigger et al., 1996; Bigger et al., 1997). In addition to their ability to directly interact with the CHRNA4 CA box *in vitro*, both Sp1 and Sp3 are capable of transactivating the CHRNA4 promoter (Bigger et al., 1997). Furthermore, co-immunoprecipitation assays demonstrated that Sp1 and Sp3 directly interact and when these factors are supplied in concert, synergistic transactivation of the CHRNA4 promoter is observed (Bigger et al., 1997). Finally, ChIP assays discussed in this chapter have demonstrated that these factors interact with the CHRNA4 promoter in the chromatin environment, in the mammalian brain (Fig. 3.5). Taken together these data indicate that Sp1 and Sp3 directly interact with the CHRNA4 promoter in order to enhance expression of the CHRNA4 gene. As a result, I have depicted Sp1 and Sp3 contacting the CHRNA4 CA box, as well as each other (Fig. 3.6).

When PC12 cells are differentiated with NGF, CHRNA4 gene expression is increased (Rogers et al., 1992). The signal cascade that results from the recognition of NGF by its receptor causes the phosphorylation and subsequent activation of the c-Jun transcription factor. NGF treatment also causes an increase in c-Jun expression (Greenberg et al., 1986).
Figure 3.6: Assembly of positive-acting factors at the CHRNA4 gene promoter. The coding region of the CHRNA4 gene is represented as a light green box with arrow above the coding region indicating that CHRNA4 expression is turned on. The double stranded nucleotide sequences of two transcriptional regulatory elements, the CT and CA boxes, are also shown. The transcription factor Sox10 is depicted as a yellow colored oval with Sp1, Sp3, and c-Jun depicted as colored squares above the CA box.
Since both CHRNB4 and c-Jun expression are increased during NGF treatment in these cells, c-Jun was an attractive candidate for a possible factor involved in controlling expression of the CHRNB4 gene. As discussed above, electrophoretic mobility shift assays revealed no interaction of c-Jun with the CHRNB4 promoter. This result was not surprising considering that the CHRNB4 promoter contains no c-Jun binding site. Despite the lack of direct interaction with the CHRNB4 promoter in vitro, transient transfection assays revealed that c-Jun is capable of transactivating the CHRNB4 promoter (Melnikova and Gardner, 2001). Using lysates from NGF treated PC12 cells, we have previously shown that Sp1 and c-Jun directly interact (Melnikova and Gardner, 2001). In addition, when the site of Sp factor binding in the CHRNB4 promoter (the CA box) is mutated, c-Jun is no longer capable of transactivating the CHRNB4 promoter (Melnikova and Gardner, 2001). Furthermore, when Sp1 and c-Jun are supplied in concert, synergistic transactivation of the CHRNB4 promoter is observed (Melnikova and Gardner, 2001). These data suggest that c-Jun exerts its positive effect on CHRNB4 gene expression by virtue of its interaction with Sp1. The c-Jun ChIP assays discussed above demonstrate that this factor is also associated with the CHRNB4 promoter in the chromatin environment.

In addition to cross-linking proteins to DNA, formaldehyde is also capable of causing some protein-protein cross-linking as well. This allows for the detection of proteins that are associated with DNA through a protein intermediate. However, formaldehyde cross-linking is not suitable for the detection of large multisubunit protein complexes due to its short 2Å spacer arm length (Orlando, 2000). This phenomenon explains the discrepancy between the positive results for c-Jun in the
ChIP assays discussed above and the negative result in the c-Jun electrophoretic mobility shift assays done previously in our lab (Melnikova and Gardner, 2001). Taken together, these data suggest that c-Jun is present at the CHRNB4 promoter by virtue of its interaction with Sp1, and most likely does not directly interact with DNA. As a result, I have depicted c-Jun contacting Sp1, but not directly interacting with DNA at the CHRNB4 promoter CA box (Fig. 3.6).

Analysis of the CHRNB4 expression patterns during development of the nervous system revealed considerable spatial and temporal overlap with the expression of the Sox10 transcription factor (Zoli et al., 1995; Kuhlbrodt et al., 1998). The co-expression of Sox10 and CHRNB4 in a variety of cell types during development lead to the hypothesis that Sox10 may act to regulate CHRNB4 expression. Electrophoretic mobility shift assays, using a segment of the CHRNB4 promoter containing the CT and CA boxes, demonstrated that Sox10 interacts with the CHRNB4 promoter in vitro. However, competition of Sox10 binding using a CA box mutant probe was not complete, suggesting that Sox10 interacts with the CHRNB4 promoter in a region that overlaps the CA box (Liu et al., 1999). Transient transfection assays revealed that in addition to directly interacting with the CHRNB4 promoter, Sox10 is also capable of transactivating the CHRNB4 promoter in vitro (Liu et al., 1999). Interestingly, co-immunoprecipitation assays revealed that Sox10 is capable of physically interacting with Sp1 and Sp3, and can also synergistically transactivate the CHRNB4 promoter when supplied in concert with either Sp1 or Sp3 (Melnikova et al., 2000b). In the ChIP assays performed on neuronal-like cells as
well as brain tissue I obtained positive results for Sox10, indicating that Sox10 interacts with the CHRNA4 promoter in the chromatin environment. Taken together, these data indicate that Sox10 interacts with the CHRNA4 promoter, as well as the Sp1 and Sp3 transcription factors, in order to enhance expression of the CHRNA4 gene. As a result, I have depicted Sox10 interacting with a region of DNA that encompasses the CA box. Due to the synergy observed with the Sp factors and the their direct physical interaction, Sox10 was depicted contacting the Sp1 and Sp3 proteins, as well as the CHRNA4 promoter DNA sequence (Fig. 3.6).

These experiments have provided insight into the interaction of regulatory factors with the CHRNA4 gene promoter CA box in the chromatin environment, where DNA is associated with histone proteins and may be organized into higher order structures. Using the ChIP assay, I was able to demonstrate these factors are associated with the endogenous CHRNA4 promoter, at the CA box, in neuronal-like cell lines and in rodent brain tissue. Taken together, these data suggest that Sp1, Sp3, c-Jun and Sox10 assemble at the CHRNA4 promoter CA box to enhance transcription of the CHRNA4 gene in the mammalian brain. The majority of the data presented here were published in 2008 (Scofield et al., 2008).

**Limitations and Future Perspectives**

In order to control for extensive formaldehyde cross-linking in CHRNA4 ChIP experiments, additional control PCRs should be preformed on ChIP-derived DNAs. In these control reactions, ChIP-derived DNA would be amplified with primers
designed to recognize the segment of DNA where the transcription factors of interest do not bind. Negative results in these PCRs would indicate that the association of Sp1, Sp3, Sox10 and c-Jun with the CHRNA4 promoter observed in the experiments discussed above is not a result of extensive cross-linking.

In addition to negative sequence controls, ChIP experiments could also be performed with negative control immunoprecipitations. In this additional ChIP negative control, an antibody that recognizes a transcription factor which does not interact with the CHRNA4 promoter is used. For example, in PC12 cells the Sox10 gene is not expressed, thus we would expect negative results in Sox10 PC12 ChIPs. Obtaining negative results in the additional ChIP negative controls would indicate that the positive results obtained in PC12 ChIPs are not due to non-specific antibody-DNA interactions or improper DNA fragmentation.

As an additional layer of control, amplification of ChIP derived DNA could also be performed using positive control PCR primer sets. These primers would be designed to recognize segments of DNA that are known sites of interaction for the transcription factors of interest. Obtaining positive results in these additional ChIP-derived DNA PCRs would further demonstrate that the interaction of Sp1, Sp3, Sox10 and c-Jun with the CHRNA4 promoter is specific and not an artifact of the experimental procedure.
CHAPTER IV: THE CA BOX IS AN ESSENTIAL REGULATORY FEATURE OF THE CHRNB4 PROMOTER

Disclaimer: I performed all experiments described in this chapter with the exception of the generation of the WT transgenic construct and the sectioning and staining of the tissue shown in Figures 4.2 and 4.3 (CHRNB4 promoter activity in ED18.5 transgenic mice and CHRNB4 promoter activity in the CNS of PD30 transgenic mice). Generation of the WT CHRNB4 promoter / lacZ transgenic construct was performed by Lei Bruschweiler Li. The tissues shown in Figures 4.2 and 4.3 were sectioned and stained by Ellen Trang and Sarah Binke, respectively. Finally, injection of DNA and all subsequent steps up to and including the generation of founder animals were performed by the University of Massachusetts Medical School Transgenic Animal Modeling Core for both the WT and mutant transgenic animal lines.

Abstract

GWAS studies have underscored the importance of the clustered neuronal nAChR subunit genes with respect to nicotine dependence as well as lung cancer susceptibility. CHRNB4, which encodes the nAChR β4 subunit, plays a major role in the molecular mechanisms that govern nicotine withdrawal. Thus, elucidating how expression of the CHRNB4 gene is regulated is critical for understanding the pathophysiology of nicotine addiction. We previously identified a CA box regulatory element, (5′– CCACCCCT –3′) critical for CHRNB4 promoter activity in vitro. We
further demonstrated that a 2.3-kb fragment of the CHRNB4 promoter region containing the CA box is capable of directing cell-type specific expression of a reporter gene to a myriad of brain regions that endogenously express the CHRNB4 gene (Bruschweiler-Li et al., 2010). To test the hypothesis that the CA box is critical for CHRNB4 promoter activity in vivo, transgenic animals expressing a mutant form of the CHRNB4 promoter were generated. Reporter gene expression was not detected in any tissue or cell type at embryonic day 18.5 (ED18.5). Similarly, we observed dramatically reduced reporter gene expression at postnatal day 30 (PD30) when compared to wild type transgenic animals. Finally, we demonstrated that CA box mutation results in decreased interaction of the transcription factor Sp1 with the mutant CHRNB4 promoter. Taken together, these results demonstrate that the CA box is critical for CHRNB4 promoter activity in vivo.

**Introduction**

Cholinergic signaling mediated by nAChRs is involved in an array of physiological functions including learning, memory and attention (Albuquerque et al., 2009). Interestingly, substantial alterations in cholinergic signal transduction are observed in numerous neurological disorders including Alzheimer’s disease, schizophrenia, epilepsy and nicotine addiction (Whitehouse et al., 1988; Steinlein et al., 1995; De Fusco et al., 2000; Perry et al., 2001; Isacson et al., 2002; Perl et al., 2003; Teaktong et al., 2003). Thus, further elucidating the molecular mechanisms that act to control expression of the nAChR subunit genes will contribute not only to our
understanding of neuronal development but to a greater understanding of the pathophysiology of several neurological disorders as well.

Neuronal populations in both the CNS and PNS express multiple nAChR subtypes (Goldman et al., 1987; Corriveau and Berg, 1993; Vernallis et al., 1993; Conroy and Berg, 1995; Gotti et al., 1997; Zoli et al., 1998; Genzen et al., 2001). Each distinct nAChR subtype displays unique biophysical and pharmacological properties, which are determined by subunit composition (McGehee and Role, 1995). The specific subunits assembled into a particular receptor subtype is dictated, at least in part, by the cell-type specific transcription of the individual subunit genes (Albuquerque et al., 2009).

Three of the twelve neuronal nAChR subunit genes, those encoding the α5, α3 and β4 subunits, are located in a highly conserved genomic cluster (Boulter et al., 1990). These three receptor subunit genes are co-expressed in a variety of cell types and tissues in the nervous system (Gotti et al., 2006). The co-expression of these three genes is thought to result from the coordinate regulation of the CHRNA5/A3/B4 locus (Albuquerque et al., 2009). As a likely consequence of their co-expression, the α5α3β4 receptor subtype is the predominant nAChR expressed in the PNS where they play a crucial role in mediating fast synaptic transmission in autonomic ganglia (Rust et al., 1994; Conroy and Berg, 1995; Flores et al., 1996). Despite their largely overlapping patterns of expression, there are a small subset of regions where these genes appear to be uniquely regulated (Gotti et al., 2007; Grady et al., 2009). For
example, all three of the clustered nAChR subunit genes are expressed in the hippocampus, habenula and interpeduncular nucleus whereas only CHRNA3 and CHRNA5 are expressed in the ventral tegmental area (Improgo et al., 2010b).

nAChR subunit gene KO mice have proven to be a valuable tool for deciphering the function of specific nAChR subtypes in the nervous system. CHRNB4 KO animals display significantly milder somatic symptoms of nicotine withdrawal (Salas et al., 2004a). These results demonstrate that the β4 subunit plays a major role in the molecular mechanism underlying nicotine dependence. There is also some indication that blockade of α3β4 nAChRs results in a reduction of opioid and stimulant self-administration, suggesting that nAChRs that contain the β4 subunit are involved in mediating withdrawal syndromes elicited by other drugs of abuse (Glick et al., 2002). Thus, elucidating the molecular mechanisms underlying expression of the CHRNB4 gene will improve our understanding of nicotine addiction and withdrawal.

The expression pattern of the CHRNB4 gene has been investigated by several groups, (Dineley-Miller and Patrick, 1992; Zoli et al., 1995; Winzer-Serhan and Leslie, 1997) yet the mechanisms that control its expression are not completely understood. We previously identified an 8-base pair transcriptional regulatory element in the CHRNB4 promoter that is critical for promoter activity in vitro (Bigger et al., 1996). This regulatory element, deemed the CA box due to its nucleotide
composition, is also the binding site for several transcription factors *in vivo* (Scofield et al., 2008).

We recently demonstrated that a 2.3-kb fragment of the CHRN4B promoter region containing the CA box is capable of directing cell-type specific and developmentally regulated expression of a reporter gene *in vivo* (Bruschweiler-Li et al., 2010). In these experiments we used a 2.3-kb fragment of the rat CHRN4B promoter to drive expression of a lacZ reporter gene in transgenic mice. The lacZ reporter gene was placed upstream of a nuclear localization sequence in order to restrict reporter gene expression to the nucleus. This was done in order to more easily compare our data to previous CHRN4B in situ hybridization studies (Fig. 4.1) (Dineley-Miller and Patrick, 1992; Zoli et al., 1995). We also included a matrix attachment region (MAR) in the transgenic construct, which has been shown previously to inhibit position- and copy number-dependent effects on transgene expression (Fig. 4.1) (Phi-Van and Stratling, 1996). In the CHRN4B promoter / lacZ transgenic animals we observed a striking recapitulation of CHRB4 expression patterns at ED18.5. For example, we observed β-gal reactivity in the cortex, spinal cord, intestine and tongue (Fig. 4.2 A, A-D), all regions that endogenously express the CHRN4B gene (Zoli et al., 1995; Winzer-Serhan and Leslie, 1997; Flora et al., 2000b; Glushakov et al., 2004). We also observed a striking recapitulation of CHRN4B expression in the CNS at PD30. β-galactosidase (β-gal) expression was detected in the layer 5 of the frontal cortex, as well as in the piriform cortex, association cortex, and caudate putamen (Fig. 4.3 A-D) (Bruschweiler-Li et al., 2010).
Figure 4.1: WT and mutant CHRNA4 promoter / lacZ transgene architecture. The CHRNA5/A3/B4 gene cluster is depicted as boxes with arrows depicting the direction of transcription. Below the clustered nAChR subunit genes is a schematic of the linearized construct used to generate the transgenic animals. MAR, matrix attachment region; NLS, nuclear localization sequence. Shown below this schematic are the nucleotide sequences of the WT and mutant CA boxes. Mutations made to the CA box in the mutant transgenic construct are shown in red with asterisks above the mutated nucleotides.
Figure 4.2: CHRNB4 promoter activity in ED18.5 transgenic mice. Sagittal sections of WT transgenic line 54 (A - D) and non transgenic (E - H) ED18.5 mouse embryos are shown. These sections were simultaneously stained for β-Gal activity and then counter-stained with neutral red. (A and E) cortex (IZ, intermediate zone; VZ, ventricular zone); (B and F), upper cervical region of the spinal cord; (C and G), mucosa of the small intestine; (D and H) tongue. β-gal staining of the tongue appears to be restricted to or near the longitudinal intrinsic muscle. Arrows in panel D indicate β-gal-expressing cells.
Figure 4.3: CHRNB4 promoter activity in the CNS of PD30 transgenic mice. Coronal sections of WT transgenic line 39 (A - D) and non transgenic (E - H) PD30 mouse brains are shown. These sections were simultaneously stained for β-Gal activity, and then counter-stained with neutral red. (A and E) layer 5 of the cortex (“5”); (B and F) piriform cortex; (C and G) association cortex; (D and H) caudate putamen; Arrows in panels C and D indicate β-Gal-expressing cells.
These brain regions are also areas of endogenous CHRNA4 gene expression (Dineley-Miller and Patrick, 1992; Winzer-Serhan and Leslie, 1997; Gahring et al., 2004). To date, this transgenic model is the only system that accurately recapitulates the endogenous patterns of CHRNA4 during development in the PNS and CNS. Moreover, this transgenic model is also the only system that recapitulates the endogenous expression patterns of CHRNA4 in non-neuronal tissues like the intestine and tongue (Bruschweiler-Li et al., 2010).

In this work, I sought to determine whether the CA box regulatory element within the CHRNA4 promoter region is indeed critical for the temporally and spatially restricted transcriptional activity of the CHRNA4 promoter \textit{in vivo}. In order to test this hypothesis I generated transgenic animals using a transgenic construct with 3 base pair substitutions made to the CA box (Fig. 4.1).

**Results**

\textit{Mutation of the CA box significantly reduces CHRNA4 promoter activity in vitro}

Previously, we showed that mutagenesis of the CA box within the CHRNA4 promoter virtually eliminates promoter activity \textit{in vitro} (Bigger et al., 1996). When both the WT and mutant CHRNA4 promoter transgenic constructs were tested \textit{in vitro}, significantly reduced levels of \(\beta\)-Gal activity were observed in the two neuronal-like cell lines Neuro 2A and SN17 (Fig. 4.4).
Figure 4.4: WT and mutant CHRNB4 promoter activity in vitro. (A) DNA from either the WT (green) or mutant (red) transgenic constructs was transfected into Neuro 2A (left) or SN17 cells (right) along with a luciferase construct in which the SV40 promoter drives expression of the firefly luciferase gene. β-Gal and luciferase activities were measured with a luminometer. β-Gal activity was normalized to luciferase activity in order to correct for differences in transfection efficiencies. The data shown here are an average of 2 independent experiments, error bars represent standard error of the means, n=2. Student’s t-test indicated that CA box mutation significantly decreased the β-gal activity of the mutant transgenic construct in both cell lines, p<0.01 (**). (B) Raw data for the graphs shown above, values reported are relative light units.
These results indicated that the mutant construct was suitable for use in the generation of transgenic animals. A total of 6 CHRNB4 mutant promoter / lacZ founder lines (lines 19, 25, 28, 30, 33, and 83) were generated and analyzed for β-Gal activity at both ED18.5 and PD30. Using a quantitative PCR approach (Bruschweiler-Li et al., 2010), copy number analysis revealed that line 19 has 10 copies, line 25 has 63 copies, line 28 has 69 copies, line 30 has 25 copies, line 33 has 23 copies and line 83 has 37 copies (Fig. 4.5).

CA box mutation eliminates CHRNB4 promoter activity in transgenic animals at ED18.5

In the WT CHRNB4 promoter / lacZ transgenic lines, we observed reporter gene expression in an array of regions of endogenous CHRNB4 gene expression at ED18.5 in both the CNS and PNS, including the spinal cord, intestine, and cortex (Fig. 4.6 A-C) (Zoli et al., 1995; Bruschweiler-Li et al., 2010). In contrast, no reporter gene expression was seen in any of these tissues at ED18.5 in any of the mutant CHRNB4 promoter / lacZ transgenic lines (Fig. 4.6 E-G). CHRNB4 gene expression is observed early during prenatal development in the dorsal root ganglia (DRG) where it co-assembles with the α3 and α5 subunits to form the α5α3β4 nAChR subtype. This receptor subtype has been shown previously to be the predominant subtype expressed in the PNS (Conroy and Berg, 1995) where it plays a role in nicotinic transmission at the synapses of autonomic ganglia (Vernallis et al., 1993). At ED18.5, we observed β-gal expression in the DRG of the WT transgenic lines
Figure 4.5: Copy number of the mutant CA box transgenic lines. Transgene copy number was determined using absolute quantification-based real-time PCR (Yuan et al., 2007) designed to amplify the lacZ sequence in the transgenic construct. A positive control sample from a mouse containing a single copy of a lacZ gene (1 copy +C) was used to normalize values obtained for CA box mutant transgenic lines 19, 25, 28, 30, 33 and 83. An additional positive control isolated from a mouse that has 2 copies of a lacZ transgene was also analyzed (2 copy +C). The data shown here are an average of values obtained for three individual animals from each transgenic line, error bars represent standard error of the means.
Figure 4.6: CHRNB4 promoter activity in ED18.5 WT and mutant transgenic mice. Sagittal sections of WT transgenic line 54 (A - D) and mutant transgenic line 28 (E - H) ED18.5 mouse embryos are shown. These sections were simultaneously stained for β-Gal activity and then counter-stained with neutral red. (A and E) lower lumbar region of the spinal cord; (B and F), mucosa of the small intestine; (C and G) cortex (β-gal-expressing cells are located in the intermediate zone); (D and H) lower lumbar dorsal root ganglion (DRG). Arrows in panels A, C and D indicate β-gal-expressing cells.
(Fig. 4.6 D) at levels that closely resemble what has been reported in previous
CHRNB4 in situ experiments done by Changeux and colleagues (Zoli et al., 1995).
However, no β-gal expression was observed in the DRG of any of the six mutant
transgenic lines (Fig. 4.6 H).

*Mutant transgenic animals express very low levels of β-gal at PD30 in the CNS*

β-Gal activity was observed in PD30 WT transgenic lines in several areas that
endogenously express the CHRB4 gene including the piriform cortex, medial
habenula, and the subiculum (Dineley-Miller and Patrick, 1992; Winzer-Serhan and
Leslie, 1997; Gahring et al., 2004; Bruschweiler-Li et al., 2010) (Fig. 4.7 A-C). Out of
the 6 mutant transgenic founder lines investigated, no β-gal expression was
observed in any region of the brain at PD30 in 4 of these lines, lines 25, 30, 33, and
83 (Table 4.1). The remaining 2 lines, mutant lines 19 and 28, expressed extremely
low levels of the β-gal in a small subset of brain regions (Table 4.1). Interestingly, no
expression of β-gal was observed in the any of the mutant transgenic lines in several
areas of endogenous CHRNB4 expression including the piriform cortex, medial
habenula, or the subiculum (Dineley-Miller and Patrick, 1992; Winzer-Serhan and
Leslie, 1997; Gahring et al., 2004) (Fig. 4.7 E-G). In addition, mutant transgenic lines
19 and 28 displayed fewer β-gal positive cells when compared to the WT transgenic
lines in several areas of endogenous CHRNB4 expression. For example, I observed
a drastically reduced number of β-gal positive cells in the dentate gyrus of mutant
transgenic line 28 when compared to WT transgenic line 39 (Fig. 4.6 D, H) (Table
4.1).
Figure 4.7: CHRNB4 promoter activity in the CNS of PD30 WT and mutant transgenic mice. Coronal sections of WT transgenic line 39 (A - D) and mutant transgenic line 28 (E - H) PD30 mouse brains are shown. These sections were simultaneously stained for β-Gal activity and then counter-stained with neutral red. (A and E) piriform cortex (Pir); (B and F) medial habenula (Mhb); (C and G) subiculum (S); (D and H) hippocampus, cornu ammonis 1 (CA1), dentate gyrus (DG); Arrows in panels A and B indicate β-Gal-expressing cells.
Table 4.1: CHRNB4 promoter activity in the CNS of PD30 WT and mutant transgenic mice.

<table>
<thead>
<tr>
<th>Founder Line:</th>
<th>Wild type Transgenic</th>
<th>Mutant CA Box Transgenic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30  39  54  447</td>
<td>19  25  28  30  33  83</td>
</tr>
<tr>
<td><strong>Brain Region</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Pir) Piriform Cortex</td>
<td>++  +++  ++++  ++++</td>
<td>-  -  -  -  -  -  -</td>
</tr>
<tr>
<td>(Cpu) Caudate Putamen</td>
<td>+  +  ++  ++</td>
<td>-  -  -  -  -  -  -</td>
</tr>
<tr>
<td>(Mhb) Medial Habenula</td>
<td>-  +++  ++  +</td>
<td>-  -  -  -  -  -  -</td>
</tr>
<tr>
<td>(DG) Dentate Gyrus</td>
<td>++  ++++  ++  ++</td>
<td>+  -  +  -  -  -  -</td>
</tr>
<tr>
<td>(S) Subiculum</td>
<td>-  +++  ++++  +</td>
<td>-  -  -  -  -  -  -</td>
</tr>
<tr>
<td>(Cb) Cerebellum</td>
<td>-  -  -  -</td>
<td>-  -  -  -  -  -  -</td>
</tr>
<tr>
<td>(SN) Substantia Nigra</td>
<td>-  -  -  -</td>
<td>-  -  -  -  -  -  -</td>
</tr>
<tr>
<td>(IPn) Interpeduncular Nucleus</td>
<td>-  -  -  -</td>
<td>-  -  -  -  -  -  -</td>
</tr>
<tr>
<td><strong>Transgene Copy Number</strong></td>
<td>7  26  12  10</td>
<td>10  62  69  25  23  37</td>
</tr>
</tbody>
</table>

Expression levels were scored as follows: -, no expression; +, low level; ++, intermediate level; ++++, high level; ++++, very high level.
Consistent with our previous observations at ED18.5, β-gal expression was detected in the DRG of 4 WT transgenic lines at PD30 while no expression of β-gal was detected in the DRG in any of the 6 mutant transgenic lines (Fig. 4.8). In the WT transgenic animals, there are higher numbers of lacZ positive cells in the DRG of ED18.5 transgenic animals (Fig. 4.6, D) when compared to PD30 WT transgenic animals (Fig. 4.8, A). This result is in agreement with previous in situ hybridization studies demonstrating that DRG expression of CHRNA4 is highest early during development (Zoli et al., 1995; Winzer-Serhan and Leslie, 1997). Taken together, these data suggest that the CA box regulatory element plays a critical role in directing CHRNA4 promoter activity in vivo.

CA box mutation results in decreased levels of Sp1 association with the CHRNA4 promoter in vivo

We previously demonstrated that, in addition to virtually eliminating promoter activity, mutation of the CHRNA4 promoter CA box substantially reduced binding and transactivation by the transcription factor Sp1 in vitro (Bigger et al., 1996; Bigger et al., 1997). In order to test the hypothesis that CA box mutation results in reduced association of the Sp1 transcription factor with the CHRNA4 promoter in vivo, brain tissue from mutant CHRNA4 promoter / lacZ transgenic line 28 was used as a source of chromatin for ChIP assays. Using these animals I can assay for the interaction of Sp1 with the endogenous mouse CHRNA4 promoter or the transgenic rat CA box mutant CHRNA4 promoter.
Figure 4.8: CHRNA4 promoter activity in the DRG of PD30 transgenic mice. Sections of WT transgenic line 54 (left) and mutant transgenic line 28 (right) PD30 DRG are shown. These sections were simultaneously stained for β-Gal activity and then counter-stained with neutral red. Arrows in panel A indicate β-Gal-expressing cells.
ChIP-derived DNA from the mutant transgenic brain tissue experiments was used as template in PCR reactions with primers that recognize either the endogenous mouse CHRNB4 promoter region containing the CA box, or the corresponding segment of the rat transgenic promoter containing the mutant CA box. Consistent with our previous work (Scofield et al., 2008), PCR using Sp1 ChIP-derived DNA as template resulted in amplification of the endogenous mouse CHRNB4 promoter to levels that were approximately 3-fold higher than controls (Fig. 4.9, black bars), indicating an interaction of Sp1 with the endogenous CHRNB4 promoter. Conversely, PCR reactions using the same Sp1 ChIP-derived DNA as template did not result in amplification of the mutant transgenic CHRNB4 promoter above background levels (Fig. 4.9, white bars), indicating that there was no or significantly reduced interaction between Sp1 and the mutant CHRNB4 promoter. The H4 ChIP positive control is performed using an antibody directed against acetylated histone protein H4. Acetylation of the H4 protein is highly associated with actively transcribed genes (Hebbes et al., 1988; Jeppesen and Turner, 1993). As the mutant CA box CHRNB4 promoter is significantly less active, this may be a possible explanation for the differences in the endogenous (black) and transgenic (white) H4 ChIPs.

Discussion

The biophysical diversity of nAChRs is a result of the large variety of subunit combinations that can assemble into functional receptors (Gotti et al., 2006).
Figure 4.9: CA box mutation results in decreased association of Sp1 with the CHRNA4 promoter. (A) ChIP experiments were performed using brain tissue from mutant CHRNA4 promoter / lacZ transgenic line 28. Transgenic brain ChIP-derived DNA was used as template for PCR designed to amplify either the WT endogenous mouse CHRNA4 promoter (black bars), or the CA box mutant transgenic rat CHRNA4 promoter (white bars). (H4) anti-acetylated histone protein H4; (IgG) normal rabbit IgG; (Sp1) Transcription factor Sp1; (No Ab) Mock IP. The data shown here are an average of 4 independent experiments, expressed as percent Input. Student’s t-test statistical analysis indicated a significant difference between the Sp1 ChIPs and the WT IgG and mock ChIP controls, p <0.01 (**). Student’s t-test statistical analysis was also performed on the transgenic mutant CHRNA4 promoter values (white bars) and indicated no significant difference between Sp1 ChIPs and the IgG and mock ChIP controls at the mutant CHRNA4 promoter. Error bars represent standard error of the means, n=4. (B) Representative agarose gels for either the endogenous wild type CHRNA4 promoter PCR (left) or the mutant transgenic CHRNA4 promoter PCR (right).
While the exact molecular mechanisms controlling the incorporation of a particular subunit into a mature receptor are not completely understood, regulation at the level of transcription plays a critical role. Consistent with this hypothesis, the CHRNA5, CHRNA3, and CHRNB4 genes are co-expressed in a variety of cell types in the PNS where the α5α3β4 receptor subtype is the predominant nicotinic receptor subtype expressed (Rust et al., 1994; Conroy and Berg, 1995). The co-expression of these subunits is likely the result of coordinate regulation of the CHRNA5/A3/B4 locus by shared transcriptional regulatory features, an example of which is the positive regulation of these three genes by the transcription factor Sp1 (Yang et al., 1995; Bigger et al., 1997; Campos-Caro et al., 1999; Improgo et al., 2010b). Data from our lab as well as from others indicate that Sp1 likely acts in concert with cell-type specific regulatory factors (e.g., Nuclear transcription factor Y and Paired mesoderm homeobox protein 2A) in order to direct expression of the clustered subunit genes to the appropriate cell types (Campos-Caro et al., 1999; Melnikova et al., 2000b; Valor et al., 2002; Benfante et al., 2007; Scofield et al., 2008).

Several groups, including our own, have intensively studied the transcriptional regulatory mechanisms that act to control expression of these three subunit genes. These studies have uncovered several regulatory elements (discussed below) that are involved in directing cell-type specific expression of the clustered nAChR subunit genes. In these studies, I have used mutant CHRNB4 promoter transgenic mice to demonstrate that the CA box is a critical mediator of CHRNB4 promoter activity in vivo. Mutation of the CA box resulted in absent or substantially decreased
expression of the β-gal in an array of brain regions where β-gal expression is observed in the WT CHRN4 promoter / lacZ transgenic lines (Bruschweiler-Li et al., 2010) and CHRN4 is endogenously expressed (Winzer-Serhan and Leslie, 1997; Gahring et al., 2004). Taken together, these results demonstrate that the CA box is crucial for CHRN4 promoter activity in vivo.

Previous studies done by Deneris and colleagues have uncovered additional transcriptional regulatory elements that influence expression of the CHRN4 gene. One such element, deemed the conserved non-coding region #4 (CNR4), is located approximately 30-kb upstream of the CHRN4 gene (Fig. 4.10, A) (Xu et al., 2006). CNR4 appears to contain regulatory information needed to direct expression of the CHRN4 gene to the pineal gland and interpeduncular nucleus (Xu et al., 1999a), two areas of endogenous CHRN4 gene expression where we do not see β-gal expression in the WT (Bruschweiler-Li et al., 2010) or mutant CHRN4 promoter / lacZ transgenic lines. Additional experiments done by Deneris and colleagues demonstrated that CNR4 is critical for the coordinate expression of the CHRN4 and CHRNA3 genes in the pineal gland as well as in the superior cervical ganglion. Based on its high degree of conservation and its distal location from the genes it acts to regulate, CNR4 is thought to function as a locus control region-like regulatory domain (Xu et al., 2006). In addition to CNR4, Deneris and colleagues have also characterized a transcriptional enhancer element located in the CHRN4 3´-untranslated region (called the β43´ enhancer) (Fig. 4.10, A).
Figure 4.10: Positive and negative regulation of the CHRNA5/A3/B4 locus. (A and B) Coding regions of the clustered subunits are represented as colored boxes with arrows that indicate the direction of transcription. Four transcriptional regulatory elements are depicted in this figure: A3I5 (green box), the β4 3’ enhancer (purple), the Sacl – HindIII fragment of the CHRNB4 promoter region (dark grey box), and the distal CNR4 regulatory region (white box). The boundaries of the latter two regions are labeled relative to the transcriptional start site of the CHRNB4 gene. Green arrows in A denote positive regulatory effects in a neuronal context whereas red lines in B indicate negative transcriptional regulation occurring in non-neuronal cells.
Interestingly, mutation of several E26 transformation-specific sequence (ETS) factor binding sites in the enhancer can severely diminish expression of the CHRNA5, CHRNA3 and CHRNB4 genes in the adrenal gland (Xu et al., 2006) (Fig. 4.10, A). Furthermore, mutation of ETS binding sites within the β43’ enhancer also diminished expression of these genes in the superior cervical ganglion (Xu et al., 2006). Apart from the positive regulatory elements described above, we have previously shown that there is a transcriptional repressor element present in the fifth intron of the CHRNA5 gene (A3I5) (Fuentes Medel and Gardner, 2007) (Fig. 4.10, B). The A3I5 repressor is capable of inhibiting transcription from CHRNA3 and CHRNB4 gene promoters in an orientation- and position-independent manor. Interestingly, repression of transcription by A3I5 was cell-type specific, only occurring in cells with little or no expression of the clustered nAChR subunit genes (Fuentes Medel and Gardner, 2007). It is clear from these data that several transcriptional regulatory elements located around the clustered subunit genes act in concert to provide the necessary regulatory information to drive expression of the required subunits in the appropriate cell type (Yang et al., 1997; Francis and Deneris, 2002; Xu et al., 2006; Fuentes Medel and Gardner, 2007; Bruschweiler-Li et al., 2010).

ChIP experiments done on mutant transgenic brain tissue demonstrated a reduced interaction of Sp1 with the mutant CA box CHRNB4 promoter (Fig. 4.9). To date, Sp1 is the only factor that has been investigated using CA box mutant transgenic brain tissue. These data are in agreement with previous studies from our lab indicating that CA box mutation abrogates Sp factor binding and transactivation of
the CHRNA4 promoter *in vitro* (Bigger et al., 1996; Bigger et al., 1997). Because the 
CHRNA4 promoter lacks a TATA box, Sp1 could play a crucial role in tethering the 
basal transcription machinery to the CHRNA4 promoter, as it does at other TATA-
less promoters (Pugh and Tjian, 1991). The lack of Sp1 interaction with the mutant 
CA promoter provides a plausible molecular mechanism for the severely reduced 
CHRNA4 promoter activity observed in the CA box mutant CHRNA4 promoter / lacZ 
transgenic lines. CA box mutation may also impede the transactivation ability of 
additional transcriptional regulatory factors that associate with the CHRNA4 
promoter by virtue of protein-protein interactions with Sp1 (Melnikova et al., 2000a; 
Scofield et al., 2008). This is likely the case for transcription factor c-Jun, which 
physically interacts with Sp1 and is capable of activating transcription from the 
CHRNA4 promoter *in vitro*, despite the fact that the CHRNA4 promoter lacks a c-Jun 
binding site. At the WT CHRNA4 promoter, Sp1 and c-Jun synergistically activate 
transcription, however, when the CA box is mutated, the CHRNA4 promoter is no 
longer responsive to either Sp1 or c-Jun (Melnikova and Gardner, 2001). In addition, 
the transcription factor Sox10 also synergistically transactivates the CHRNA4 
promoter when supplied in concert with Sp1 (Melnikova et al., 2000b). Similar to 
what is observed with c-Jun, CA box mutation also dramatically reduces Sox10’s 
ability to activate transcription from the CHRNA4 promoter (Liu et al., 1999). From 
these data it appears that Sp1 may act to nucleate a complex of positive-acting 
transcription factors needed for cell-type specific expression for the CHRNA4 gene 
*in vivo*. However, additional experimentation is required to test the hypothesis that
Sp1 binding is upstream of the binding of the other factors shown previously to interact with the CHRNB4 promoter CA box \textit{in vivo}.

In conclusion, these results demonstrate that the CA box is a key determinant of CHRNB4 promoter activity at ED18.5 and PD30 in the PNS and CNS. Furthermore, these data also indicate that Sp1 plays a critical role in directing the positive transcriptional regulatory effect of the CA box \textit{in vivo}. Positive regulation of the CHRNB4 promoter by Sp1 at the CA box is a crucial aspect of the intricate regulatory cascade that ensures accurate expression of the CHRNB4 gene, allowing nAChRs containing the $\beta_4$ subunit to participate in both normal physiological processes (Dani and Bertrand, 2007a; Albuquerque et al., 2009), as well as tobacco-related pathological conditions (Salas et al., 2004a; Salas et al., 2009).

These studies provide insight into the protein-DNA interactions that govern expression of the CHRNB4 gene in the mammalian brain. Furthermore, these data indicate that the CA box is an essential regulatory element in the CHRNB4 promoter, and that mutation of this element reduces promoter activity as well as the interaction of the transcription factor Sp1 with the CHRNB4 promoter \textit{in vivo}.

**Limitations and Future Perspectives**

Although there was no CHRNB4 promoter activity in the mutant transgenic animals at ED18.5, it remains unclear if the CA box is involved in directing basal promoter activity or if it governs the developmentally and temporally regulated expression of
the CHRNB4 gene. Due to the dramatically reduced promoter activity observed in the mutant transgenic animals, it is most likely that the CA box and its interaction with Sp1 is critical for basal activity of the CHRNB4 promoter. This hypothesis is consistent with findings from other groups demonstrating that regulation by Sp1 is essential for the basal activity of other TATA-less promoters (Botella et al., 2001; Kim et al., 2010; Yu et al., 2010). Future studies should focus on testing this hypothesis by investigating the association of RNA polymerase II and the general transcription factors with the wild type and mutant CA box CHRNB4 promoter. These experiments would provide insight into the molecular mechanism behind the reduction of transcriptional activity observed at the mutant CA box CHRNB4 promoter.

In order to further elucidate how CA box mutation impacts transcription factor occupancy at the CHRNB4 promoter, additional Sp3, Sox10 and c-Jun ChIP assays should be performed using mutant transgenic animal brain tissue. These experiments could test the hypothesis that CA box mutation impacts the interaction of Sp3, Sox10 and c-Jun with the CHRNB4 promoter, in the mammalian brain. I would expect the additional ChIP assays to demonstrate little to no interaction of Sp3, Sox10 and c-Jun with the mutant promoter as CA box mutation abrogates transactivation of the CHRNB4 promoter by these factors in vitro (Bigger et al., 1997; Melnikova et al., 2000b; Melnikova and Gardner, 2001).
In the work discussed above we used a conventional transgenic approach to investigate WT and mutant CHRNB4 promoter activity *in vivo*. The integration site of the CHRNB4 promoter reporter construct and the number of transgene integration events are not controlled. As discussed above, we included a MAR element in our transgenic constructs to control for integration position-dependent effects as well as variability in levels of transgene expression (Phi-Van and Stratling, 1996). Due to the fact that we observed very similar results in mutant transgenic lines 19 and 28, which had the largest difference in copy number (Fig. 4.5), I was not concerned that the copy number was impacting the results.

The hypothesis that the CA box is critical for activity of the CHRNB4 promoter *in vivo* could also be investigated with CHRNB4 promoter CA box mutant knock in transgenic mice. Through the use of homologous recombination techniques, mice could be generated with the mutations discussed above made to the endogenous CHRNB4 promoter CA box. Transgenic mice generated with this technique would not be subject to the complications of transgene integration site or number of transgene integrations. Using these animals, future experiments would be able to focus on the impact that CA box mutation has on endogenous CHRNB4 gene expression. I would expect that, as observed *in vitro* and in the transgenic animals discussed above, CHRNB4 promoter activity would be severely diminished in the mutant CA box knock in animals. As a result, these mice would likely express the CHRNB4 gene at very low levels, if at all. When using mutant CA box knock in animals in behavioral assays it is most likely that these animals would display
characteristics similar to the CHRNA4 KO animals. Thusly, I would expect that the mutant CA box knock in animals would have an altered anxiety related-response (Salas et al., 2003a), be less sensitive to nicotine induced seizures (Salas et al., 2004b), and display an overall reduction in the somatic symptoms of nicotine withdrawal (Salas et al., 2004a). These experiments would be able to test the hypothesis that CA box mutation causes a functionally relevant decline in CHRNA4 gene expression. If I were running the laboratory I would make the CA box knock in mouse as it would be the most elegant way to determine the relevance of CA box mutation in vivo, and would allow me to test the hypothesis that CA box mutation results in a decline in CHRNA4 expression that ultimately affects behavior.

Additional gene expression analysis assays could be performed using the knock in mice to test the hypothesis that the reduced expression of CHRNA4 results in an augmented nAChR subtype expression profile. Because mutant CA box knock in mice would likely have extremely low levels of CHRNA4 gene expression, they may also have reduced expression of α3 subunit mRNA, much like CHRNA4 KO mice (Salas et al., 2004b). I could test this hypothesis by comparing the ability of an α3β4 receptor specific antagonist to block nicotine-induced whole cell currents in WT, CHRNA4 KO and mutant CA box knock in animals. In these experiments, the efficacy of the α3β4 receptor selective conotoxin AU1B to block nicotine induced whole cell currents in neurons of WT animals would be compared to what is observed in CHRNA4 KO and mutant CA box knock in animals (Azam and McIntosh, 2009). Neurons in the habenulo-interpeduncular pathway would be
selected for recording as they express high levels of the CHRNA3 and CHRNA4 genes (Salas et al., 2009). As a result of diminished CHRNA4 and subsequently CHRNA3 gene expression, there would be fewer $\alpha_3\beta_4$ receptors and subsequently a less potent inhibition of nicotine induced currents by AU1B in the CHRNA4 KO and mutant CA box knock in animals. These results would demonstrate that CA box mutation causes a functionally relevant decline in CHRNA4 gene expression, resulting in fewer functional $\beta_4$-containing receptors.
CHAPTER V: DISCUSSION

Signal transmission through nAChRs is essential for the function of the nervous system, with cholinergic signaling involved in the molecular mechanisms underlying learning, memory formation and attention (Albuquerque et al., 2009). In order to perform specific biological functions, physiologically diverse neuronal nAChR subtypes are expressed in unique patterns throughout the mammalian brain (Gotti et al., 2007; Albuquerque et al., 2009). By precisely controlling the expression of the individual nAChR subunit genes, highly specialized neurons can produce the required nAChR subtypes needed in order to perform specific biological functions. Thus, elucidating the underpinnings of the transcriptional regulation of the nAChR subunit genes is essential for gaining a thorough understanding of neuronal cholinergic signaling.

Three of the twelve genes that encode neuronal nicotinic receptor subunits, CHRNA5, CHRNA3, and CHRNB4, are located in a tight genomic cluster, suggesting that they are subject to some level of coordinate regulation (Boulter et al., 1990; Improgo et al., 2010b). The $\alpha_5\alpha_3\beta_4$ subtype is the most prevalent nAChR expressed in the PNS (Conroy and Berg, 1995). In the CNS, receptors that contain these subunits play a central role in mediating ACh release in the habenulo-interpeduncular pathway (Quick et al., 1999; Grady et al., 2009). Recently, independent studies from several laboratories have shown that genetic variability at the CHRNA5/A3/B4 locus can be linked not only to an increased risk of nicotine
dependence, but also to an increased risk of lung cancer (Greenbaum and Lerer, 2009). Taken together, these findings highlight the importance of the α5α3β4 nAChR subtype with respect to susceptibility to tobacco addiction and tobacco related disease. Hence, the α5α3β4 nAChR may play an important role in the molecular mechanisms that govern tobacco addiction, adding an additional component to the more commonly studied α4β2 and α7 receptor subtypes implicated in the pathophysiology of tobacco related disease (Picciotto et al., 1998; Schuller et al., 2000; Wang et al., 2001; Tapper et al., 2004; Kuryatov et al., 2005; Walters et al., 2006). In this work, I have focused on the transcriptional regulation of the CHRNA4 gene, which has been shown previously to be critical for nicotine withdrawal symptoms in mice (Salas et al., 2004a).

Transcription factor interaction with the CHRNA4 promoter CA box

The data presented in Chapter III confirm and extend previous data from our lab indicating that Sp1, Sp3, and Sox10 interact with the CHRNA4 promoter at the CA box region in vitro by demonstrating that these proteins also interact with the CHRNA4 promoter in the chromatin environment (Bigger et al., 1997; Melnikova et al., 2000b). I have also shown that c-Jun interacts with the CHRNA4 promoter in the chromatin environment (Scofield et al., 2008), which is consistent with previous data from our lab demonstrating that c-Jun is capable of transactivating the CHRNA4 promoter in vitro (Melnikova and Gardner, 2001). In combination, these data strongly suggest that Sp1, Sp3, Sox10 and c-Jun functionally interact with the CHRNA4
promoter, at the CA box, to promote transcription of the CHRNB4 gene in the mammalian brain.

My data on protein-DNA interaction at the CHRNB4 promoter contribute to a more thorough understanding of the molecular mechanisms that control expression of the CHRNB4 gene. These data can be compiled with additional results from our lab as well as the Deneris, Criado and Fornasari groups, to present a detailed description of the transcriptional regulatory mechanisms that control expression of the CHRNA5, CHRNA3 and CHRNB4 genes (Fig. 4.9). From the data presented in both Chapters III and IV, it is most likely that the association of Sp1 with the CHRNB4 promoter CA box aids in the recruitment of additional positive-acting co-factors, including Sp3, Sox10 and c-Jun, which ultimately enhance transcription of the CHRNB4 gene. Similar to the CHRNB4 gene promoter, the CHRNA5 and CHRNA3 promoters also lack TATA boxes (Boulter et al., 1990) and contain several functional Sp1 binding sites (Yang et al., 1995; Campos-Caro et al., 1999; Flora et al., 2000a; Terzano et al., 2000; Campos-Caro et al., 2001), indicating that Sp1 may play a crucial role in regulating expression of the CHRNA5 and CHRNA3 genes as well.

**Transgenic Animal Models**

Transgenic animals were first used to study the transcriptional regulatory mechanisms of nAChR subunit genes by Changeux and colleagues. The Changeux group used a 1.163-kb segment of the β2 promoter to drive expression of lacZ in transgenic mice (Bessis et al., 1995). These experiments demonstrated that the β2
promoter confers neuron-specific expression of β-gal in a pattern that closely resembles endogenous β2 gene expression. In addition, Changeux and colleagues demonstrated that the 1.163-kb β2 promoter fragment used in the transgenic construct contains both positive and negative regulatory elements, a hallmark of neuronal gene promoters (Bessis et al., 1995).

Several groups have used transgenic model systems to investigate the function of regulatory elements the control expression of the CHRNA5/A3/B4 genes. For example, the intragenic region between the CHRNA3 gene and the CHRNA3 promoter region, was used to drive expression of lacZ in transgenic mice by the Deneris group (Yang et al., 1997). In these animals, reporter gene expression resembled expression of the CHRNA3 gene, with β-gal reactivity restricted to the olfactory bulb, medial habenula, locus coeruleus and medial geniculate. However, no reporter gene expression was observed in the PNS, indicating that the regulatory information that directs expression of the CHRNA5 and CHRNA3 genes to PNS tissues is not contained in this segment of DNA. However, additional analysis of the β43` enhancer region indicated that this regulatory element is capable of directing neuron-specific expression.

In these experiments, Deneris and colleagues used a construct where the β43` enhancer was placed upstream of the SV40 viral promoter and a luciferase reporter gene. The resulting construct was then electroporated in a variety of cell lines,
having the highest activity in neuronal-like PC12 cells (McDonough and Deneris, 1997). In an extension of this analysis Deneris and colleagues transfected the β43’ enhancer / reporter construct into dissociated rat sympathetic ganglia cultures, which contain nAChR-positive neurons as well as nAChR-negative non-neuronal cells. These experiments demonstrated that the β43’ enhancer confers neuron-specific activity, as 90% of neurons transfected with the enhancer construct were positive for the luciferase and cells transfected with a control construct lacking the β43’ enhancer displayed a significant reduction in neuron-specific expression (McDonough et al., 2000). One possible explanation for the lack of PNS expression of the reporter gene in the transgenic animals discussed above could be the differences between the experimental methods used to investigate the activity of the β43’ enhancer. It is possible copy number- and the integration position-dependent factors may have impacted the ability of the transgenic construct to direct expression to neurons in the PNS. Moreover, neuron-specific expression in vivo may require additional regulatory elements not present in the transgenic construct used by the Deneris group.

Using a P1-derived artificial chromosome (PAC) containing 132 kb of DNA, including the entire rat CHRNA5/A3/B4 locus, the Deneris group generated an additional set of transgenic mice that express the rat CHRNA5, CHRNA3 and CHRNB4 genes under direction of transcriptional regulatory information included in the 132-kb PAC construct. These animals express the CHRNA5, CHRNA3 and CHRNB4 transgenes in a variety of regions where they are endogenously expressed including the SCG,
pineal gland, adrenal gland and trigeminal ganglia (Xu et al., 2006). In this model system, mutation of several ETS factor binding sites in the β43’ enhancer eliminated expression of all three rat nAChR transgenes in the adrenal gland. These data indicate that the ETS sites in the β43’ enhancer are required for expression of the CHRNA5, CHRNA3 and CHRN8 genes in the adrenal gland in vivo (Xu et al., 2006).

The Deneris group has also investigated several regions of non-coding DNA upstream of the CHRN4 gene that are phylogenetically conserved, with 70% identity across the human, mouse and rat sequences (Xu et al., 2006). As discussed in Chapter IV, when the CNR4 region is deleted from the PAC construct, the resulting transgenic animals do not express the rat CHRNA3 or CHRN4 transgenes in the pineal gland, indicating that CNR4 is required for expression of the CHRNA3 and CHRN4 genes in the pineal gland in vivo (Xu et al., 2006). As an extension of this analysis, an additional set of transgenic animals was generated with a transgenic construct with CNR4 placed upstream of a luciferase reporter gene. This CNR4 / reporter transgenic model demonstrated that the 599-bp CNR4 segment of DNA is capable of directing expression of β-gal to the medial habenula, interpeduncular nucleus, inferior colliculus, adrenal gland, pineal gland, and the SCG (Xu et al., 2006), all regions of endogenous CHRN4 gene expression (Dineley-Miller and Patrick, 1992; Winzer-Serhan and Leslie, 1997; Gahring et al., 2004).
We have shown previously that a 2.3-kb segment of the CHRNB4 promoter, containing the CA box, is capable of directing expression of β-gal to a variety of tissues and cell types that endogenously express the CHRNB4 gene at ED18.5 and PD30, in the CNS and PNS (Bruschweiler-Li et al., 2010). At ED18.5, we observed β-gal expression in WT transgenic animals in the cerebral cortex, piriform cortex, and medial habenula. We also observed β-gal expression in the cervical, thoracic and lumbar root ganglia, as well as the spinal cord (Bruschweiler-Li et al., 2010). This pattern of β-gal expression closely resembles the endogenous patterns of CHRNB4 gene expression in the PNS and CNS (Dineley-Miller and Patrick, 1992; Zoli et al., 1995; Winzer-Serhan and Leslie, 1997; Gahring et al., 2004). As discussed in Chapter IV, we did not observe β-gal expression in the pineal gland, this is likely due to the fact that our transgenic construct does not contain the CNR4 regulatory element which has been shown to be required for CHRNB4 promoter activity in this region (Xu et al., 2006).

At PD30, we observed β-gal expression in WT transgenic animals in the piriform cortex, dentate gyrus, medial habenula, subiculum and inferior colliculus (Scofield et al., 2008), all regions of endogenous CHRNB4 gene expression (Dineley-Miller and Patrick, 1992; Winzer-Serhan and Leslie, 1997; Gahring et al., 2004). As indicated in Chapter IV, we did not observe expression of β-gal in the interpeduncular nucleus in our transgenic mice (Bruschweiler-Li et al., 2010), a region where the CHRNB4 gene is known to be highly expressed (Dineley-Miller and Patrick, 1992; Winzer-Serhan and Leslie, 1997; Gahring et al., 2004). This is likely due to the fact that that our
transgenic construct did not include CNR4, which has been shown by the Deneris group to be required for reporter gene expression in the interpeduncular nucleus (Xu et al., 2006).

It is interesting to note that the CHRNβ4-CHRNα3 intragenic region, the CNR4 region and the 2.3-kb region of the CHRNβ4 promoter used by our lab are all capable of directing expression of a reporter gene to the medial habenula. The amount of redundant regulatory information responsible for gene expression in this region suggests that receptors containing the α5, α3 and β4 subunits play an important role in mediating cholinergic signaling in this region. This hypothesis is supported by recent findings indicating that nAChRs containing the α3 and β4 subunits are responsible for ACh release in the habenulo-interpeduncular pathway (Grady et al., 2009), and also that nAChRs in this region are necessary for nicotine withdrawal in mice (Salas et al., 2009).

While a significant amount of redundant regulatory sequences exist at the CHRNA5/A3/B4 locus, unique regulatory elements responsible for directing gene expression to very specific regions also exist. As discussed above, the Deneris group has shown that mutation of the β43´ enhancer abrogates expression of the CHRNA5, CHRNA3 and CHRNβ4 transgenes in the adrenal gland, while deletion of CNR4 abrogates expression of CHRNA3 and CHRNβ4 subunit genes in the pineal gland (Xu et al., 2006). In WT transgenic animals, we do not observe expression of β-gal in either the pineal or adrenal gland. This is most likely due to the fact that the
transgenic construct used does not contain the β43´ enhancer or CNR4. Moreover, the data presented by the Deneris group indicate that the β43´ enhancer and the CNR4 regions are required for directing expression to the adrenal and pineal gland, respectively.

Interestingly, our CHRNB4 promoter / reporter transgenic construct is the first to direct reporter gene expression to the subiculum and piriform cortex at ED18.5 and PD30 (Bruschweiler-Li et al., 2010), both regions where the CHRNB4 gene is endogenously expressed (Dineley-Miller and Patrick, 1992; Zoli et al., 1995; Winzer-Serhan and Leslie, 1997; Gahring et al., 2004). Additional studies would be required to determine if the regulatory information contained in the SacI – HindIII fragment of the CHRNB4 promoter is necessary for gene expression in the subiculum and piriform cortex, or if other regulatory elements can also direct expression to these brain regions.

Another advantage of our CHRNB4 promoter / reporter transgenic model is the recapitulation the expression pattern of the CHRNB4 gene in the PNS during development. Not only do we observe reporter gene expression in PNS ganglia where CHRNB4 is known to be highly expressed (Rust et al., 1994), we also observe promoter activity in non-neuronal tissues, like the intestine and tongue (Fig. 4.2 C and D), (Bruschweiler-Li et al., 2010). These results are consistent with previous in situ experiments demonstrating that CHRNB4 message is present in these regions (Zoli et al., 1995; Winzer-Serhan and Leslie, 1997; Flora et al., 2000b;
Glushakov et al., 2004). Our lab is also the first to use transgenic animal models to investigate CHRNB4 promoter activity during development; the studies done by the Deneris and colleagues were performed on adult animals (Yang et al., 1997; Xu et al., 2006).

In order to directly assess the importance of the CA box regulatory element in the CHRNB4 promoter, I generated an additional set of CHRNB4 promoter / reporter transgenic animals with expression of the lacZ gene driven by a mutant CA box CHRNB4 promoter. These experiments demonstrated that mutation of the CA box results in absent or severely reduced reporter gene expression in nearly all areas where expression is observed in the WT transgenic animals and where the CHRNB4 gene is endogenously expressed (Fig. 4.5, 4.6 and Table 4.1). This drastic reduction of CHRNB4 promoter activity was observed in CA box mutant transgenic animals at ED18.5 and at PD30, in the CNS and PNS. These data strongly suggest that the CA box is an essential regulatory feature of the CHRNB4 promoter and is required for CHRNB4 promoter activity in vivo, which is consistent with previous data from our lab demonstrating that CA box mutation drastically reduces CHRNB4 promoter activity in vitro (Bigger et al., 1996).

I have also demonstrated that mutation of the CHRNB4 promoter CA box results in a significant decrease in the interaction of Sp1 with the CHRNB4 promoter in brain tissue (Fig. 4.9). These results are in agreement with previous data from our lab demonstrating that mutation of the CA box eliminates transactivation of the CHRNB4
promoter by Sp1 *in vitro* (Bigger et al., 1997). Taken together, these data strongly suggest that the loss of promoter activity that results from CA box mutation is a consequence of decreased interaction of Sp1 with the mutant CHRN B4 promoter. These findings advance the current understanding of the transcriptional regulation of the CHRN B4 gene by identifying a critical regulatory element in the CHRN B4 promoter and also by demonstrating that regulation of the CHRN B4 promoter by Sp1 is necessary for promoter activity *in vivo*.

By assembling multiple regulatory elements into one construct expression one could design a targeting construct that would more accurately mirror expression of the endogenous CHRN B4 gene. Using this more comprehensive transgenic construct, one could selectively express any gene of interest in CHRN B4 expressing cells. For example, it would be interesting to use a construct like this to drive expression of a modified diphtheria toxin, in order to selectively eliminate CHRN B4 expressing neurons and the neuronal circuits that they are located in (Miyoshi and Fishell, 2006; Wang et al., 2006). Using this transgenic model one could test the hypothesis that CHRN B4-expressing neurons are critical for nicotine withdrawal or withdrawal syndromes elicited by other drugs of abuse. Given that antagonism of α3β4-containing receptors in the habenulo-interpeduncular pathway has been shown to reduce opioid and stimulant self administration in rats (Glick et al., 2002), I would expect that animals with selective death of CHRN B4-expressing neurons would display an alteration in self administration or reinstatement of drug use following a drug-paired cue during abstinence, when compared to wild type littermates. It has
been shown previously that chronic use of several drugs of abuse, including methamphetamine, cocaine and nicotine, results in atrophy of neurons in the habenulo-interpeduncular circuit, suggesting that the death of these neurons may contribute to addiction-associated behaviors (Ellison, 2002).

Another possibility would be to use the combined regulatory elements to drive expression of the CRE recombinase gene. These mice could be crossed with genetically engineered mice with loxP sites flanking a gene of interest. Using this experimental design, one could eliminate expression of a particular gene, selectively in CHRN4-expressing cells. This system could be used to eliminate tyrosine hydroxylase expression, and subsequently dopamine neurotransmission, in neurons that express the CHRN4 gene. These mice could be used to determine if dopamine signaling, in specific neurons, is involved in nicotine addiction and withdrawal. In this manner, one could selectively inactivate modes of neurotransmission in CHRN4-expressing neurons by targeting key enzymes in their biosynthetic pathways. Similar results could be achieved by using the comprehensive construct to direct expression of shRNA designed to recognize a gene of interest. This method may be more efficient as it would not require crossing CRE transgenic mice to loxP mice, and would still effectively eliminate expression of the target gene in CHRN4-expressing cells.
Summary

Overall, the work presented here provides insight into the molecular mechanisms that control expression of the CHRNB4 gene. These findings contribute to a growing body of work describing the underpinnings of the transcriptional regulation of the clustered neuronal nAChR subunit genes CHRNA5, CHRNA3 and CHRNB4. Here I have shown that a multicomponent regulatory complex assembles at the CHRNB4 promoter CA box, in the context of native chromatin, to drive expression of the CHRNB4 gene in the mammalian brain. Moreover, this CA box regulatory element is critical for CHRNB4 promoter activity \textit{in vivo}. Mutation of this region results in a severe decrease in promoter activity as well as a decreased association of the transcription factor Sp1 with the CHRNB4 promoter in the mammalian brain. Taken together these results indicate that Sp1, Sp3, Sox10 and c-Jun interact with the CA box to enhance expression of the CHRNB4 in the mammalian brain.
APPENDIX I: PROTEIN-DNA INTERACTION AT THE CHRN B4 PROMOTER CT BOX

Abstract

Our laboratory has had a long-standing interest in the transcriptional mechanisms underlying expression of the CHRNA5, CHRNA3, and CHRN B4 genes, which are located in a tight genomic cluster. Two proteins, heterogeneous nuclear ribonucleoprotein K (hnRNP K) and Purα were purified by virtue of their ability to interact with the CHRN B4 promoter CT box in vitro. Here I analyze the ability of Purα and hnRNP K to interact with the CHRN B4 promoter in the context of native chromatin using a ChIP approach. These experiments demonstrated that hnRNP K physically interacts with the CHRN B4 promoter in OBL21 cells but not in Neuro 2A or PC12 cells. In contrast, I obtained negative Purα ChIP results in OBL21, Neuro 2A and PC12 cells. Using the Neuro 2A cell line, I knocked down expression of either Purα or hnRNP K and measured CHRNA5, CHRNA3 and CHRN B4 gene expression with quantitative RT-PCR. I found that in Neuro 2A cells, hnRNP K knockdown had no impact on expression levels of the CHRNA5, CHRNA3 and CHRN B4 genes despite a significant reduction in both hnRNP K message and protein. Conversely, Purα knockdown resulted in decreased levels of Purα, CHRNA5, CHRNA3 and CHRN B4 gene expression. Subsequent analysis of protein levels in siRNA treated cells revealed that Purα knockdown results in a substantial reduction of Purα, α3, and α5 protein levels, while an increase in β4 protein levels was detected.
Introduction

Regulation of gene expression at the level of transcription is crucial for both the control of normal cellular processes and for neuronal differentiation. By regulating which genes are transcribed, individual cells can produce specific proteins required to perform unique cellular functions, allowing for the existence of a vast array of highly specialized cells. The production of mRNA is carried out by RNA polymerase II and a set of general transcription factors (Fuda et al., 2009). These factors act to regulate RNA polymerase II’s binding, enzymatic activity, and eventual disassociation from the DNA template (Fuda et al., 2009; Selth et al., 2010; Weake and Workman, 2010). An additional set of transcription factors act to enhance or repress transcription by influencing the recruitment of RNA polymerase II to specific genes. These transcription factors are sequence-specific DNA-binding proteins that recognize stretches of DNA called transcriptional regulatory elements (Pan et al., 2010). Regulatory elements are usually located in non-coding stretches of DNA and can be positioned either in close proximity or far distally from the genes they act to regulate (Bulger and Groudine, 2010). Thus, gene expression can be precisely controlled through the interaction of transcription factors with transcriptional regulatory elements. By expressing a particular program of transcription factors, individual cell types can precisely control gene expression, allowing these cells to perform distinct functions.

We previously identified a 19-base pair transcriptional regulatory element in the CHRNA4 promoter referred to as the CT box, because of its nucleotide composition
(Hu et al., 1995). We have also shown previously that mutation of this element results in a substantial reduction of CHRN4 promoter activity in the neuronal-like cell line SN17 (Hu et al., 1995). In addition, we demonstrated, using \textit{in vitro} binding assays, that the CT box specifically interacts with DNA-binding proteins from rat brain nuclear extracts (Hu et al., 1995). Using affinity chromatography, two proteins were isolated by virtue of their affinities for the CHRN4 promoter CT box. Subsequent peptide sequencing revealed the identity of the two CT box-interacting proteins to be Purine rich element binding protein A (Pur\(\alpha\)) (Du et al., 1997) and heterogeneous nuclear ribonucleoprotein K (hnRNP K) (Du et al., 1998).

The Pur\(\alpha\) protein is a single polypeptide of approximately 40 kDa that interacts specifically with purine-rich motifs (Bergemann and Johnson, 1992). Pur\(\alpha\) is one of four Pur proteins in the Pur gene family, which consists of Pur\(\alpha\), Pur\(\beta\) and two isoforms of Pur\(\gamma\) (Gallia et al., 2000). Pur\(\alpha\) can positively or negatively impact transcription of target genes and is also capable of interacting with both single-stranded DNA and RNA (Gallia et al., 2000). In addition, Pur\(\alpha\) possesses DNA helicase activity (Wortman et al., 2005) and plays a role in several physiological processes including transcription, translation, and cell growth (Gallia et al., 2000). At the CHRN4 promoter, Pur\(\alpha\) interacts preferentially with the single-stranded 3´ – GGGAGGGGAGGGGA – 5´ sequence located on the minus strand of DNA at the CT box (Fig. 1.7).
hnRNP K is a 65kDa member of the ribonucleoprotein complex of heterogeneous nuclear RNA in mammalian cells (Bomsztyk et al., 1997). hnRNP K binds tenaciously to pyrimidine rich sequences (Matunis et al., 1992) and can also either activate or inhibit transcription of target genes (Bomsztyk et al., 2004). Like Purα, hnRNP K is capable of interacting with both single-stranded DNA and RNA, yet it has higher affinity for single-stranded DNA (Tomonaga and Levens, 1995). hnRNP K plays a role in chromatin remodeling, transcription, RNA editing, and repression of translation (Bomsztyk et al., 2004). At the CHRNB4 promoter, hnRNP K interacts with the single-stranded 5′ – CCCTCCCCTCCCCT – 3′ sequence located on the plus strand of the CT box. We have shown previously that hnRNP K can inhibit Sp factor binding to the CHRNB4 promoter in vitro as well as Sp factor-mediated transactivation of the CHRNB4 promoter drosophila SL2 cells (Du et al., 1998). We have also shown by in vitro co-immunoprecipitation that Purα and hnRNP K physically interact (Melnikova et al., 2000a).

Given the negative transcriptional role that hnRNP K plays at the CHRNB4 promoter and the cooperative down-regulation of transcription in other systems by Purα and hnRNP K (Da Silva et al., 2002; Wang et al., 2008), I hypothesize that hnRNP K and Purα act to repress expression of the CHRNB4 gene. Based on the previous data from our lab discussed above, I have constructed the following model of hnRNP K and Purα mediated repression of CHRNB4 gene expression (Fig. A1.1).
Figure A1.1: Model of hnRNP K and Purα-mediated repression of CHRNB4 gene expression

The coding region of the CHRNB4 gene is represented as a light green box with the red X indicating that CHRNB4 expression is turned off. The double stranded nucleotide sequences of two transcriptional regulatory elements, the CT and CA boxes, are also shown. Transcription factors hnRNP K and Purα are depicted as red and pink colored ovals, contacting each other and separating the DNA strands at the CT box. Sp1 and Sp3 are depicted as colored squares above the CA box and cannot associate with the CHRNB4 promoter (depicted as red lines) as a result of strand separation by hnRNP K and Purα. Sox10 and c-Jun are depicted as a yellow oval and an orange square respectively and also do not interact with the CHRNB4 promoter.
Results

OBL21 cells express high levels of hnRNP K and Purα mRNA and low levels of CHRNA5, CHRNA3 and CHRNB4 mRNA.

Several observations led to development of the hypothesis that hnRNP K and Purα act to negatively impact transcription from the CHRNB4 promoter: first, hnRNP K and Purα have higher affinity for the single stranded elements of the CT box (Du et al., 1997; Du et al., 1998); second, both hnRNP K and Purα have the ability to unwind the DNA duplex (Bomsztyk et al., 2004; Wortman et al., 2005); third, hnRNP K was previously shown to inhibit Sp factor binding and transactivation of the CHRNB4 promoter (Du et al., 1998); finally, these factors have been shown to cooperatively inhibit expression of other target genes (Da Silva et al., 2002; Wang et al., 2008). I began my analysis by investigating the expression levels of the Purα, hnRNP K, CHRNA5, CHRNA3 and CHRNB4 in the mouse olfactory bulb derived cell line OBL21. qRT-PCR analysis of OBL21 cells revealed that the clustered nAChR subunit gene mRNAs are expressed at low levels while hnRNP K and Purα mRNA are expressed at high levels. The correlation of high levels of hnRNP K and Purα expression with low levels of CHRNB4 expression is consistent with the hypothesis that hnRNP K and Purα act in concert to repress transcription of the CHRNB4 gene (Fig. A1.2). Similar to what was observed for CHRNB4, CHRNA5 and CHRNA3 mRNA was also minimally expressed in OBL21 cells.
Figure A1.2: Expression levels of hnRNP K, Purα, CHRNA5, CHRNA3 and CHRNDB4 in OBL21 cells. The mouse olfactory bulb derived cell line OBL21 is shown in the bright field image on the left. mRNA levels of CHRNA3 (green), CHRNA5 (blue), CHRNDB4 (red), hnRNP K (light green) and Purα (orange) are expressed relative to the housekeeping gene β2M. Error bars represent standard error of the means, n=3.
**hnRNP K interacts with the CHRNB4 promoter in OBL21 cells**

In order to determine if hnRNP K and Purα interact with the CHRNB4 promoter in cells that express low levels of CHRNB4 mRNA, I performed ChIP assays using the OBL21 cell line (Fig. A1.3). Sox10 ChIP experiments were performed in this cell line as a positive control due to the fact that the interaction of Sox10 with the CHRNB4 promoter has been well characterized both *in vitro* (Liu et al., 1999) and in the context of native chromatin (Scofield et al., 2008). In these experiments, enrichment of the CHRNB4 promoter fragment in the Sox10 and hnRNP K ChIPs was significantly higher than that observed in the IgG and No Ab ChIP negative controls, indicating an interaction of Sox10 and hnRNP K with the CHRNB4 promoter in these cells. Enrichment of the CHRNB4 promoter fragment in the Purα ChIPs was no higher than what was observed in the IgG and No Ab ChIP negative controls, indicating a negative ChIP result for Purα at the CHRNB4 promoter in these cells. These data suggest that hnRNP K is present at the CHRNB4 promoter in OBL21 cells, however additional experimentation is required to determine if Purα is not. Further experimentation would be able to determine if the negative Purα ChIP result from the use of an antibody not suited for the ChIP assay. Additionally, using the same ChIP-derived DNA, a set of separate positive control PCRs could be performed with primers designed to amplify a segment of DNA shown previously to be a site of Purα interaction. Data obtained from these experiments would aid in deciphering if Purα truly does not interact with the CHRNB4 promoter in OBL21 cells, or if the negative results obtained were an artifact of the experimental procedure.
Figure A1.3: hnRNP K and Sox10 interact with the CHRNB4 promoter in OBL21 cells. OBL21 cells were used in ChIP experiments to investigate hnRNP K and Purα interactions with the CHRNB4 promoter in the context of native chromatin. Sox10 ChIPs were performed as a positive control. OBL21 ChIP-derived DNA was quantified using absolute quantification-based real time PCR. Data from three individual ChIP experiments were pooled and analyzed for statistical significance using the Student’s t-test. Both hnRNP K and Sox10 values differed significantly when compared to the IgG negative control, whereas Purα did not (***, p value <0.001). Error bars represent standard error of the means, n=3.
Both differentiated and undifferentiated PC12 cells express high levels of hnRNP K and intermediate levels of Purα

The treatment of the neuronal-like rat pheochromocytoma cell line PC12 with NGF is a well-established model of neuronal differentiation in vitro (Greene and Tischler, 1976; Henderson et al., 1994; Hu et al., 1994; Leppa et al., 1998). Following the application of NGF, PC12 cells extend neurite-like processes, change their program of gene expression and become electrically excitable (Greene and Tischler, 1976). Interestingly, CHRNB4 is among the genes upregulated in response to NGF (Henderson et al., 1994). Thus, PC12 cells provide a system where expression of the CHRNB4 gene can be enhanced in vitro. I first measured expression levels of hnRNP K and Purα in both differentiated and undifferentiated PC12 cells to determine whether these genes are expressed in PC12 cells. qRT-PCR analysis revealed that both hnRNP K and Purα are expressed in undifferentiated and differentiated PC12 cells (Fig. A1.4). hnRNP K expression is approximately 4-fold higher than Purα in both cases. No difference in expression levels of hnRNP K or Purα mRNA were observed when comparing undifferentiated and differentiated PC12 cells (Fig. A1.4).

Neither hnRNP K nor Purα interacts with the CHRNB4 promoter in undifferentiated or differentiated PC12 cells

I expected that if hnRNP K or Purα were involved in transcriptionally repressing CHRNB4 gene expression in PC12 cells, I would observe a reduction in hnRNP K or Purα association with the CHRNB4 promoter following NGF treatment.
Figure A1.4: hnRNP K and Purα mRNA expression levels in undifferentiated and differentiated PC12 cells. Bright field images of the rat pheochromocytoma cell line PC12 +/- NGF are shown on the left. hnRNP K (light green) and Purα (orange) gene expression levels are depicted in the right panel relative to the house keeping gene β2M. Error bars represent standard error of the means, n=3.
In order to test this hypothesis, I performed hnRNP K and Purα ChIP assays in undifferentiated and differentiated PC12 cells. In these experiments, enrichment of the CHRNA4 promoter fragment in the hnRNP K and Purα ChIPs was no higher than that of the IgG and No Ab ChIP negative controls, in both undifferentiated and differentiated PC12 cells (Fig. A1.5). These data suggest that hnRNP K and Purα do not interact with the CHRNA4 promoter in PC12 cells. However, due to the large amount of variability and the low n, additional PC12 ChIP experiments need to be performed in order to confirm these results. As discussed above, additional positive control PCRs of ChIP-derived DNA would also aid in deciphering if hnRNP K and Purα truly do not interact with the CHRNA4 promoter in differentiated and undifferentiated PC12 cells.

*Neuro 2A cells express high levels of hnRNP K, Purα, CHRNA3 and CHRNA4 mRNAs, while CHRNA5 mRNA is expressed at an intermediate level.*

In order to extend our analysis into an additional neuronal-like cell line, I investigated the expression levels of the Purα, hnRNP K, CHRNA5, CHRNA3 and CHRNA4 genes in the mouse neuronal-like cell line Neuro 2A (Olmsted et al., 1970). In Neuro 2A cells, expression of hnRNP K is approximately double what is observed for Purα (Fig. A1.6). In addition, the CHRNA3 and CHRNA4 genes are also highly expressed, with CHRNA5 mRNA expressed at an intermediate level (Fig. A1.6). According to the current model I am testing (Fig. A1.1), in Neuro 2A cells I would expect that hnRNP K and Purα do not interact with the CHRNA4 promoter, given that the CHRNA4 gene is highly expressed.
Figure A1.5: hnRNP K and Purα do not interact with the CHRNB4 promoter in PC12 cells. PC12 cells were used in ChIP experiments to investigate hnRNP K and Purα interactions with the CHRNB4 promoter in undifferentiated and differentiated PC12 cells. PC12 ChIP-derived DNA was quantified using absolute quantification-based real time PCR. Data from two individual ChIP experiments for either undifferentiated or differentiated PC12 cells were pooled and analyzed for statistical significance using the Student’s t-test. Statistical analysis of both undifferentiated and differentiated PC12 cell ChIP experiments revealed no significant differences between ChIP controls and hnRNP K or Purα. Error bars represent standard error of the means, n=2.
Figure A1.6: expression levels of hnRNP K, Purα, CHRNA5, CHRNA3 and CHRNB4 in Neuro 2A cells. The mouse neuroblastoma derived cell line Neuro 2A is shown in the bright field image on the left. mRNA levels of CHRNA3 (green), CHRNA5 (blue), and CHRNB4 (red) subunits, as well as hnRNP K (light green) and Purα (orange) are expressed relative to the housekeeping gene β2M. Error bars represent standard error of the means, n=3.
hnRNP K and Purα do not interact with the CHRNB4 promoter in Neuro 2A cells

In order to test the hypothesis that hnRNP K and Purα do not interact with the CHRNB4 promoter in cells that express high levels of the CHRNB4 gene, ChIP assays were performed using Neuro 2A cells. Enrichment of the CHRNB4 promoter fragment in the hnRNP K and Purα ChIPs was no higher than background levels observed in the IgG and No Ab ChIP negative controls. These results suggest that hnRNP K and Purα do not interact with the CHRNB4 promoter in Neuro 2A cells (Fig. A1.7). As the results for both hnRNP K and Purα were negative in Neuro 2A ChIP experiments, additional positive control PCRs of Neuro 2A ChIP-derived DNA could also be performed in order to confirm that hnRNP K and Purα do not interact with the CHRNB4 promoter in these cells.

Knockdown of hnRNP K in Neuro 2A cells has no effect on expression of the CHRNA5, CHRNA3 and CHRNB4 genes

In order to assess the possible transcriptional regulatory role that hnRNP K plays at the CHRNA5/A3/B4 locus, siRNA experiments were performed in Neuro 2A cells. In these experiments, expression of hnRNP K, GAPDH, CHRNA5, CHRNA3 and CHRNB4 genes were measured in negative siRNA and hnRNP K siRNA treated cells. In Neuro 2A cells, transfection of hnRNP K specific siRNA resulted in a decrease in hnRNP K message levels of 69.5% ± 1.7% (Fig. A1.8). When comparing negative siRNA treated and hnRNP K siRNA treated cells using the Student’s t-test, no significant changes in CHRNB4 gene expression were observed, p = 0.93 (Fig. A1.8).
Figure A1.7: hnRNP K and Purα do not interact with the CHRNA4 promoter in Neuro 2A cells. Neuro 2A cells were used in ChIP experiments to investigate hnRNP K and Purα interactions with the CHRNA4 promoter in the chromatin environment. Neuro 2A ChIP-derived DNA was quantified using absolute quantification-based real-time PCR. Data from two individual ChIP experiments were pooled and analyzed for statistical significance using the Student’s t-test. Statistical analysis revealed that neither hnRNP K nor Purα values differed significantly when compared to the IgG or mock IP ChIP negative controls. Error bars represent standard error of the means, n=2.
Figure A1.8: hnRNP K knockdown has no impact on CHRNA3, CHRNA5 and CHRNB4 gene expression in Neuro 2A cells. Gene expression data for hnRNP K, CHRNA3, CHRNA5, CHRNB4 and GAPDH in cells treated with negative control siRNA (red), or hnRNP K siRNA (blue). Data from two individual siRNA experiments were pooled and analyzed for statistical significance using the Student’s t-test. hnRNP K expression in knockdown cells differed significantly when compared to the negative control siRNA treated cells. ***, p value <0.001. GAPDH expression in knockdown cells did not differ significantly when compared to the negative control siRNA treated cells, p value >0.05. Error bars represent standard error of the means, n=2.
In addition, there were no significant changes in mRNA levels of the other clustered nAChR subunit genes CHRNA5 and CHRNA3, \( p = 0.27 \) and \( 0.089 \) respectively. The expression of a housekeeping gene GAPDH was measured as a negative control. When comparing negative siRNA treated and hnRNP K siRNA treated cells, there was also no significant change in GAPDH gene expression, \( p = 0.1499 \).

In order to demonstrate that hnRNP K siRNA treatment of Neuro 2A cells resulted in reduction of both hnRNP K message and protein levels, Western blot analysis of siRNA treated cells was performed. As expected, these results demonstrate that a 69.5\% \pm 1.7\% reduction of hnRNP K message results in a significant decrease in hnRNP K protein levels (Fig. A1.9). These data indicate that hnRNP K knockdown was successful and that reduction of hnRNP K message and protein levels has no impact on the expression levels of the CHRNA5, CHRNA3 and CHRNB4 genes. Taken together, these data suggest that hnRNP K does not regulate expression of the CHRNA5, CHRNA3 and CHRNB4 genes in Neuro 2A cells. As there was a significant decrease in both hnRNP K message and protein levels, I would expect that a hnRNP K function is reduced in siRNA treated cells. I could further test this hypothesis by performing additional positive controls in future hnRNP K siRNA experiments. By measuring expression of a gene shown previously to be regulated by hnRNP K in negative and hnRNP K siRNA treated cells, I would be able to further test the hypothesis that a 70\% reduction in hnRNP K message results in a loss of hnRNP K function.
Figure A1.9: hnRNP K knockdown results in a significant decrease in hnRNP K protein levels in Neuro 2A cells. Lysates from hnRNP K and negative control siRNA treated Neuro 2A cells were separated using SDS-PAGE in duplicate. Following electrophoresis, proteins were transferred to a nitrocellulose membrane and probed with anti-hnRNP K or anti-β-Actin antibodies. hnRNP K and β-Actin band intensities were quantified using the VersaDoc gel imaging system and software. hnRNP K band intensity in hnRNP K and negative siRNA treated cells are expressed normalized to the corresponding β-Actin band intensities. Data were analyzed for statistical analysis using the Student’s t-test, * indicates a p value <0.05. Error bars represent standard error of the means, n=2.
Knockdown of Purα in Neuro 2A cells results in decreased expression of CHRNA5, CHRNA3 and CHRN4 mRNA

In order to investigate the functional role that Purα plays at the CHRN4 promoter, siRNA experiments were performed in Neuro 2A cells. Expression of Purα, CHRNA5, CHRNA3, CHRN4 and GAPDH were measured in both negative siRNA and Purα siRNA treated cells. Transfection of Purα siRNA resulted in a decrease in Purα message levels of 68% ± 12% (Fig. A1.10). Surprisingly, when comparing negative siRNA treated and Purα siRNA treated cells, significant reductions in CHRNA5, CHRNA3 and CHRN4 mRNA levels were observed. CHRNA3 gene expression was reduced by 51.5% ± 10.7%, CHRNA5 gene expression was reduced by 36.54% ± 7.7% and CHRN4 gene expression was reduced by 26.8% ± 9.7% (Fig. A1.10). As described above, expression of a housekeeping gene GAPDH was also measured as a negative control. When comparing negative siRNA treated and Purα siRNA treated cells, no significant change in GAPDH expression was observed. These data indicate that knockdown of Purα does not result in a non-specific reduction in gene expression. It appears that in Neuro 2A cells, Purα positively regulates expression of the CHRNA5, CHRNA3 and CHRN4 genes.

In order to verify that Purα knock down results in a reduction in Purα protein levels, Western blot analysis was performed. In these experiments, Purα siRNA treated cells had significantly lower levels of Purα protein when compared to negative control siRNA treated cells (Fig. A1.11).
Figure A1.10: Purα knockdown results in significant decreases in CHRNA3, CHRNA5 and CHRN4 gene expression in Neuro 2A cells. Gene expression data for Purα, CHRNA3, CHRNA5, CHRN4 and GAPDH in cells treated with negative control siRNA (red), or Purα siRNA (green). Data from four individual siRNA experiments were pooled and analyzed for statistical significance using the Student’s t-test. Purα expression in knockdown cells differed significantly when compared to the negative control siRNA treated cells, as did expression of the CHRNA3, CHRNA5 and CHRN4 genes. ***, p value <0.001; **, p value <0.01; *, p value <0.05. Error bars represent standard error of the means, n=4.
Figure A1.11: Purα knockdown results in a significant decrease in Purα protein levels in Neuro 2A cells

Lysates from Purα and negative control siRNA treated Neuro 2A cells were electrophoresed through a 10% SDS polyacrylamide gel in duplicate. Separated proteins were transferred to a nitrocellulose membrane and probed with anti-Purα or anti-β2M antibodies. Purα and β2M band intensities were quantified using the VersaDoc gel imaging system and software. Purα band intensity in Purα and negative siRNA treated cells is expressed normalized to the corresponding β2M band intensities. Data were analyzed for statistical analysis using the Student’s t-test, * indicates a p value <0.05. Error bars represent standard error of the means, n=2.
These data suggest that reduction of Purα message, and subsequently Purα protein levels, results in decreased expression of the CHRNA5, CHRNA3 and CHRNB4 genes. Despite the observed reduction in Purα protein levels following siRNA treatment, detection of Purα protein should be optimized further in order more robustly quantify the reduction of Purα protein levels following siRNA treatment. Additionally, Purα Western blot experiments of siRNA treated cells could also be performed in parallel using a mouse monoclonal anti-Purα antibody generated by Johnson and colleagues, shown to be suitable for Western blot analysis (Liu et al., 2005).

In order to test the hypothesis that reduction of CHRNA5, CHRNA3 and CHRNB4 mRNA results in a corresponding reduction at the protein level, additional Western blot experiments were performed using siRNA treated cells. In these experiments, Neuro 2A cells were treated with either negative control or Purα siRNA then harvested and split into two aliquots. The first set of cells was used for gene expression analysis (Fig. A1.12, A) while the second set of cells was used for Western blot analysis (Fig. A1.12, B). qRT-PCR analysis of Purα siRNA treated cells indicated a 78.2% ± 10.2% reduction of Purα gene expression, a 60.3% ± 2% reduction of CHRNA3 gene expression, a 37.9% ± 10% reduction of CHRNA5 gene expression and a 34.9% ± 10% reduction in CHRNB4 gene expression, consistent with the experiment presented in Fig. A1.10. Importantly, Purα siRNA treatment did not impact levels of GAPDH gene expression (Fig. A1.12 A).
Figure A1.12: Purα knockdown results in reduced nAChR subunit α3, and α5 protein levels in Neuro 2A cells. (A) Gene expression data for Purα, CHRNA3, CHRNA5, CHRNA4 and GAPDH in cells treated with negative control siRNA (red), or Purα siRNA (green). Error bars represent standard error of the means obtained from triplicate measurements of a single experiment, n=1. (B) Lysates from Purα and negative control siRNA treated Neuro 2A cells were analyzed as described for Fig. A1.11. Purα, nAChR α3, α5 and β4 subunits, and β2M band intensities were quantified using the VersaDoc gel imaging system and software.
Western blot analysis of Purα siRNA treated Neuro 2A cells indicated reduced levels of the Purα, nAChR α3 and α5 proteins while an increase in nAChR β4 subunit protein was observed (Fig. A1.12 B). This result is difficult to interpret given that a reduction in α5 protein was observed, yet the decrease in CHRNA5 message is almost identical to what was observed for CHRN4. It is possible, however, that the detection of nAChR α5, α3, and β4 protein levels was not accurate due to limitations of the commercially available anti-nAChR antibodies. These concerns were brought to light in a paper published around the time I was performing these experiments. In this study, immunoreactivity observed during Western blot analysis of nAChR protein was identical when using lysates from either wild type mice, or the corresponding nAChR subunit KO mice (Moser et al., 2007). Among the antibodies shown to be non-specific were the anti-nAChR α3 and β4 subunit antibodies used in the experiments discussed above (Fig. A1.12). These data suggest that the antibodies used may not be suitable for Western blot analysis (Moser et al., 2007). The specificity of the anti-nAChR α5 subunit antibody used in Figure A1.12 has yet to be tested using α5 KO animals.

Other groups have had some success measuring nAChR subunit protein levels using custom made antibodies (Lindstrom, 2000a; Kuryatov et al., 2005; Tumkosit et al., 2006). Future nAChR β4 Western blot analysis could be performed using antibodies developed by other groups, such as the monoclonal anti-β4 antibody MAb 337 (Liu et al., 2009a) or the polyclonal anti-β4 antibody 4886 (Zhou et al., 2001).
Discussion

In order to test the hypothesis that hnRNP K and Purα negatively regulate CHRNB4 gene expression, I first examined expression levels of the CHRNA5, CHRNA3 and CHRNB4 genes, as well as hnRNP K and Purα, in several cell lines. This analysis revealed high expression of hnRNP K and Purα in all cell lines tested including OBL21, PC12 -/+ NGF and Neuro 2A cells. Expression of CHRNA5, CHRNA3 and CHRNB4 genes was low in OBL21 cells and higher in PC12 -/+ NGF and Neuro 2A cells. In OBL21 cells, where expression of the CHRNB4 gene is low, I observed an interaction of hnRNP K with the CHRNB4 promoter (Fig. A1.2). In undifferentiated and differentiated PC12 cells (Fig. A1.4) as well as Neuro 2A cells (Fig. A1.6), where expression of the CHRNB4 gene is higher, I see no interaction of hnRNP K with the CHRNB4 promoter. These data are in agreement with the hypothesis that hnRNP K negatively regulates expression of the CHRNB4 gene. siRNA mediated knockdown of hnRNP K had no impact on expression levels of the CHRNB4 mRNA or the other clustered nAChR subunits CHRNA5 and CHRNA3 in Neuro 2A cells (Fig. A1.8). As these genes are expressed at high levels in Neuro 2A cells (Fig. A1.6), this finding is also consistent with our previous hypothesis. From these data it appears that, at least in Neuro 2A cells, hnRNP K does not regulate expression of the CHRNA5, CHRNA3 and CHRNB4 genes.

Due to its ability to directly interact with hnRNP K and its ability to interact with the opposing strand of the CT box in vitro, we previously hypothesized that Purα acts in concert with hnRNP K to negatively regulate expression of the CHRNB4 gene (Fig.
A1.1) (Du et al., 1997; Du et al., 1998). Surprisingly, I obtained negative results in Purα ChIP assays in each of the cell lines investigated. However, further experimentation is required to determine if the negative Purα ChIP data (Figures A1.3, A1.5 and A1.7) are the result of a lack of interaction between Purα and the CHRN4 promoter in the chromatin environment (where DNA is associated with histone proteins and may be organized into higher order chromatin structures) or the result of the use of an anti-Purα antibody that is not suitable for the ChIP assay. This issue could be addressed by using additional anti-Purα antibodies, and also by performing additional ChIP positive control PCRs.

Interestingly, Purα knockdown experiments in Neuro 2A cells revealed that a 68% ± 12% reduction of Purα message resulted in decreased CHRNA5, CHRNA3 and CHRN4 mRNA levels (Fig. A1.12). Furthermore, the reduction in clustered nAChR subunit gene expression was not a result of a general dampening of transcription, as GADPH mRNA levels were unchanged during Purα knockdown. In an attempt to extend the analysis of Purα’s regulation of the clustered subunit genes in Neuro 2A cells, Western blot analysis was performed on negative and Purα siRNA treated cells. These data suggest that the reduction of nAChR CHRNA3 and CHRNA5 message observed during Purα knockdown results in reduced levels of the α3 and α5 proteins. Conversely, I detected an increase in β4 protein levels despite the reduction in message observed following Purα siRNA treatment (Fig. A1.12). Further experimentation is required in order to determine to what extent, if any, Purα
knockdown impacts α5, α3 and β4 nAChR subunit protein levels. As discussed above, these experiments should be performed using antibodies whose specificity has been verified using the corresponding nAChR KO animals.

Contrary to our previous hypothesis these data indicate that, at least in Neuro 2A cells, Purα acts to promote transcription of the CHRNB4 gene. Positive regulation of CHRNB4 gene expression by Purα may be achieved through an interaction with Sp1. A similar interaction between Purα and Sp1 has been shown to occur at the myelin basic protein (MBP) gene promoter (Tretiakova et al., 1999). In this system, both Sp1 and Purα interact with the MBP promoter at overlapping regions of DNA, similar to what is observed at the CHRNB4 promoter CT / CA region (Bigger et al., 1997; Du et al., 1997). At the MBP promoter, binding of Sp1 results in increased recruitment of Purα. Furthermore, overexpression of both factors results in synergistic activation of the MBP gene promoter (Tretiakova et al., 1999). If we consider that Purα is not a repressor and acts to positively influence expression of the CHRNB4 gene, the reduction of CHRNB4 gene expression following Purα knockdown could be explained by the dampening of the cooperative effects of Purα and Sp1 at the CHRNB4 gene promoter. Due to the fact that Sp1 also positively regulates expression of the CHRNA5 and CHRNA3 subunit genes (Campos-Caro et al., 1999; Benfante et al., 2007), inhibition of Purα - Sp1 interactions could also explain the reduction in CHRNA5 and CHRNA3 mRNA observed in the Neuro 2A Purα siRNA experiments (Fig. A1.10).
We have also shown previously that Purα directly interacts with the transcription factor Sox10 (Melnikova et al., 2000a). This finding is of particular significance in light of the fact that Sox10 positively regulates expression of each of the three clustered nAChR subunit genes (Melnikova et al., 2000b; Improgo et al., 2010b) and interacts with the CHRNβ4 promoter both in vitro (Liu et al., 1999) and in the context of native chromatin (Scofield et al., 2008). Despite the direct physical interaction, to date no functional interaction between Sox10 and Purα has been reported.

These findings advance the current understanding of the transcriptional regulation of the CHRNβ4 gene by detailing the interaction of hnRNP K and Purα with the CHRNβ4 promoter in several neuronal-like cell lines with varying levels of CHRNA3/A5/B4 gene expression. These studies demonstrate that in Neuro 2A cells, Purα acts to enhance transcription of the CHRNA5, CHRNA3 and CHRNβ4 genes, providing an alternate hypothesis for the role that Purα plays at the CHRNβ4 promoter, and providing the first evidence for positive regulation of nAChR subunit genes by Purα. Given its interaction with factors that positively influence CHRNβ4 promoter activity and its positive regulation of CHRNβ4 gene expression in Neuro 2A cells, I hypothesize that Purα participates in a multi-subunit transcriptional regulatory complex that acts to positively influence transcription of the CHRNβ4 gene (Fig. A1.13). This hypothesis could be tested further with experimentation aimed at discovering protein-protein interactions between Purα and additional transcription factors that act to regulate expression of the CHRNβ4 gene.
Figure A1.13: Revised model of positive-acting factors at the CHRNA4 gene promoter. The coding region of the CHRNA4 gene is represented as a light green box with arrow above the coding region indicating that CHRNA4 expression is turned on. The double stranded nucleotide sequences of two transcriptional regulatory elements, the CT and CA boxes, are also shown. Transcription factors Sox10 and Purα are depicted as yellow and pink colored ovals with Sp1, Sp3, and c-Jun depicted as colored squares above the CA box. Factors shown previously to physically interact are depicted touching each other.
Limitations and Future Perspectives

These studies provide insight into the functional role that the two transcription factors, hnRNP K and Purα, play at the CHRNB4 promoter. As hnRNP K was found to interact with the CHRNB4 promoter in OBL21 cells siRNA experiments should be extended to OBL21 cells as well as other cell lines with low levels of CHRNB4 gene expression. These experiments may yield evidence that will contribute to a better understanding of the role that hnRNP K plays at the CHRNB4 promoter. siRNA experiments were not performed in OBL21 and PC12 cells due to technical difficulties in the optimization of the transfection procedure. However, the Neuro 2A cell line was easily transfected and cells remained healthy during the siRNA treatment. In Neuro 2A cells, knockdown of Purα was found to negatively impact transcription of the CHRNA5, CHRNA3 and CHRNB4 genes, while in the ChIP experiments no interaction of Purα with the CHRNB4 promoter was observed. In addition to the positive control PCRs discussed above, as well as the use of different anti-Purα antibodies, future Purα ChIP experiments could be performed in a set of cell lines or tissue types with varying levels of CHRNB4 gene expression.

As discussed above, Purα ChIP derived DNA should also be used as template in PCR with primers designed to amplify a promoter fragment of a gene that has been shown previously to be regulated by Purα. One possible candidate for a Purα ChIP positive control is the neuron-specific FE65 gene. Much like the CHRNB4 gene, FE65 is transcribed from a TATA-less promoter, is positively regulated by Sp1 and is expressed primarily in neurons (Zambrano et al., 1997; Yu et al., 2010). ChIP-
derived DNA could be used as template in PCR with primers designed to amplify the region of Purα interaction with the FE65 gene promoter. In these experiments, I would expect enrichment of the FE65 promoter fragment in Purα ChIPs to be several fold higher than IgG and Mock IP negative controls.

In addition to ChIP assays, the Purα siRNA knockdown experiments should also be extended to cells that have low levels of CHRNA4 gene expression. This course of experimentation is particularly important when considering that Purα has been shown to function as either a repressor or activator of transcription based on its interaction with other co-factors (Gallia et al., 2000). Thus, the expression of cell-type specific cofactors may influence whether Purα plays a positive or negative transcriptional regulatory role at the CHRNA4 promoter. An examination of Purα knockdown under conditions where CHRNA4 is expressed at low levels may provide insight into the possible regulatory role that Purα plays in cells that express low levels of the CHRNA4 gene.

In order to test the hypothesis that fewer functional α4-containing receptors are expressed in Neuro 2A cells following Purα siRNA treatment, additional functional assays should be performed. For example, I would expect that when performing whole-cell patch clamp recordings from Purα siRNA treated cells you would observe a less potent reduction of nicotine-induced currents by the α3β4 subtype selective nicotinic antagonist AuIB (Azam and McIntosh, 2009) when compared to negative siRNA treated cells. These data would indicate that fewer functional α3β4 receptors
are expressed in Purα siRNA treated cells as a result of reduced nAChR mRNA production.

These studies have investigated the roles that hnRNP K and Purα play with respect to the transcriptional regulation of the CHRNA5, CHRNA3 and CHRNB4 genes. Using the ChIP assay, I was able to focus my investigation on the interaction of these proteins with the CHRNB4 promoter in the chromatin environment. These results demonstrated that hnRNP K interacts with the CHRNB4 promoter in OBL21 cells but not in PC12 cells +/- NGF or in Neuro 2A cells. Despite negative results in Purα ChIP assays, additional experimentation is required to determine if Purα does not interact with the CHRNB4 promoter in the cell lines tested. In addition, siRNA experiments demonstrated that, in Neuro 2A cells, Purα positively regulates expression of the CHRNA5, CHRNA3 and CHRNB4 genes, while hnRNP K neither positively nor negatively regulates expression of these genes. These results have provided the first evidence suggesting that Purα positively regulates expression of the CHRNA5, CHRNA3 and CHRNB4 genes and have lead to the modification of our current model of transcriptional control of the CHRNB4 gene (Fig. A1.13).
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