AN ABSTRACT OF THE THESIS OF

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Title: Interaction of the Muscarinic Acetylcholine Receptor with Effector Proteins

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The purified porcine atrial muscarinic acetylcholine receptor was reconstituted into a lipid environment with proteins with which it was believed to interact in vivo. One such protein was the inhibitory guanine nucleotide binding protein (Gi). This signal transducing protein was purified from porcine atria and reconstituted with the mAcChR into a defined lipid system consisting of phosphatidylcholine, phosphatidylserine and cholesterol (1:1:0.1 w/w). The proteins were shown to be interactive when mAcChR, reconstituted with Gi, displayed a high-affinity guanine-nucleotide sensitive carbachol binding site. 5'-Guanylyl imidodiphosphate (0.1 mM) converted this high affinity site (K_d equal to 1 μM) to low affinity (K_d equal to about 100 μM) but had no effect on the binding of the muscarinic antagonist L-quinuclidinylbenzilate. The agonist carbachol was able to increase the GTPase of mAcChR coupled Gi by 11 fold. Carbachol also reduced the affinity of Gi for GDP by 50 fold and increased the observed rate constant for GDP dissociation by 38 fold. Thus, the increase in
steady-state GTPase activity observed for carbachol is largely, if not exclusively, due to the increase in GDP dissociation from Gi—probably the rate-limiting step in the steady-state mechanism. The carbachol-stimulated GTPase and high-affinity agonist binding were sensitive to ADP-ribosylation of reconstituted Gi by pertussis toxin.

A protein complex consisting of the bovine brain stimulatory guanine nucleotide binding protein (Gs) and calmodulin-sensitive adenylyl cyclase was added to the reconstituted mAChR and Gi. Conditions were chosen so that each of the G proteins could be selectively activated by guanosine 5'-O-(3-thiotriphosphate) (GTPγS) in the presence of GDP. The inhibitory effects of Gi were examined with non-activated, Gs activated, forskolin activated, and calcium-calmodulin activated adenylyl cyclase. Addition of carbachol to the mAChR-Gi complex further activated Gi by increasing the rate of GDP release and allowed more GTPγS to bind. GTPγS bound Gi then mediated inhibition of adenylyl cyclase. Adenylyl cyclase activated by calcium plus calmodulin was the most sensitive to inhibition by carbachol.

Studies using the resolved subunits of Gi showed that while the βγ subunits could inhibit all forms of adenylyl cyclase, only the calmodulin stimulated enzyme was inhibited by the α subunit.
Interaction of the Muscarinic Acetylcholine
Receptor with Effector Proteins

by

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Chapter II

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The muscarinic acetylcholine receptor (mAcChR) was one of the first neurohormone receptors to be studied. Initial investigation of the naturally occurring alkaloid muscarine played an important role in developing modern neurohormonal theory. The mushroom Amanita muscaria, the source of muscarine, has been known since ancient times as a deadly poison. The action of muscarine was correlated with a response to vagal stimulation of the heart, and it was proposed that the vagus nerve released a muscarine like substance (Dixon, 1907). Vagal stimulation results in a decrease in the rate of contraction in the heart. Several other muscarinic ligands have been known for centuries. Pilocarpine, isolated in 1875 from the leaflets of the South American shrub of the genus Pilocarpus, acts as an agonist for the mAcChR. An agonist is a chemical which binds to and activates a receptor. Chewing of the leaf was known to cause salivation, which is a muscarinic response of the salivary glands. Atropa belladonna, which contains the anti-muscarinic drugs atropine and scopolamine, have been used as medicine (or poison) since the Middle Ages. As early as 1867, atropine was demonstrated to block the effects of vagal stimulation in cardiac tissue (Koelle, 1975). Dale (1914) used these naturally occurring compounds to investigate the pharmacology of
acetylcholine. Acetylcholine had recently been identified as the physiological agent that acted like muscarine (Ewins, 1914). The acetylcholine effects were separated into two categories. The first was muscarinic and was antagonized by atropine, and the second was nicotinic and was blocked by curare and by large doses of nicotine. Acetylcholine was confirmed as a neurotransmitter by Loewi (1921) and was the first molecule demonstrated to be a neurotransmitter compound.

The activation of the mAcChR results in a decrease in the rate and force of contraction in the heart, constricts airways, increases motility and secretion in the gastrointestinal tract, and increases secretion from salivary and sweat glands. Muscarinic receptors are also present in the central nervous system and are involved in memory, learning, and control of movement (Nathanson, 1987).

While the nicotinic acetylcholine receptor is in itself an ion channel and will thus directly effect the movement of ions across the cell membrane of target cells, the mAcChR does not contain an ion channel. Activation by muscarinic agonists leads to interaction of the receptor with other proteins, such as guanine nucleotide binding proteins, which in turn regulate effector proteins, either ion channels or enzymes which regulate second messenger levels. The biochemical responses regulated by muscarinic receptors include decreased levels of cAMP, increased levels of cGMP, and an increased turnover of some inositol phospholipids. Muscarinic activation is also known to regulate the conductance of ion channels, such as potassium, chloride, and calcium (Giles and Noble, 1976; Oron et al., 1985; Biegon and Pappano, 1980; Nathanson, 1987).
Biochemical Responses Mediated by the mAChR

Inhibition of Adenylyl Cyclase

Activation of the mAChR in many cell lines leads to a decrease in cAMP levels. This muscarinic effect has frequently been shown to require GTP (Watanabe et al., 1978; Jakobs et al., 1979) and is sensitive to Pertussis toxin (Kurose et al., 1983; Hazeki and Ui, 1981; Schlegal et al., 1985). The mAChR does not directly interact with adenylyl cyclase, but is coupled via Pertussis toxin sensitive guanine nucleotide binding (G) proteins. While adenylyl cyclase is coupled to stimulatory receptors (e.g. β-adrenergic receptors) via the stimulatory guanine nucleotide binding protein (Gs), it is also coupled to inhibitory receptors via the inhibitory guanine nucleotide protein (Gi), which is ADP-ribosylated by the toxin from **Bordetella pertussis** (Gilman and Casey, 1987; Gilman, 1988, for recent reviews). Go (the "other" guanine nucleotide binding protein) can also interact with adenylyl cyclase (Katada et al., 1986a, 1987) and is sensitive to Pertussis toxin. Muscarinic acetylcholine receptors from the brain interact with both brain Gi and G0 (Florio and Sternwies, 1985; Kazuko et al., 1986).

In 1321N1 astrocytoma cells (Hughes et al., 1984) a muscarinic induced decrease in cAMP was observed. This was not sensitive to Pertussis-toxin and was believed to be the result of activation of a calmodulin stimulated phosphodiesterase (Tanner et al., 1986). Thus there must be another mechanism whereby muscarinic activation regulates cAMP levels, presumably by altering the amount of free
calcium in the cell available for calmodulin.

The force of cardiac contraction is related to cAMP levels. Activation of the β-adrenergic receptor leads to an accumulation of cAMP which activates cAMP dependent protein kinases. Subsequent phosphorylation of calcium channels (Hosey et al., 1986) will open the channels and allow extracellular calcium to enter and bind to troponin C, thus allowing a muscle contraction cycle to begin (Katz, 1977).

In addition to the hormone-regulated adenylyl cyclase, there also exists a calmodulin-regulated adenylyl cyclase which is stimulated by calcium and calmodulin. This calmodulin-sensitive adenylyl cyclase has been documented in only a few cell types including kidney (Sulimovici et al., 1983), adrenal medulla (Valverde et al., 1979), pancreatic islet cells (Le Donne and Coffee, 1979), and brain (Brostorm et al., 1975). Calmodulin-sensitive adenylyl cyclase has been purified from bovine brain. Purification may or may not include a 5'guanylylimidodiphosphate (GppNHp) pretreatment of membranes. Pretreatment of membranes results in a higher yield and higher specific activity of adenylyl cyclase but renders the enzyme insensitive to activation by GppNHp and thus is undesirable for studies involving regulation by Gs. The non GppNHp treated adenylyl cyclase was stimulated by guanosine triphosphates (which activate Gs), but was more sensitive to stimulation by calmodulin (Yeager et al., 1985a; Rosenberg et al., 1987). The purified, untreated calmodulin-sensitive adenylyl cyclase has been reconstituted with pure β-adrenergic receptor. Cyclase activity was enhanced by β-adrenergic agonists, but to a lesser degree than by calmodulin (Rosenberg et al., 1987).
Phosphatidylinositol Turnover

Many hormones also regulate cellular events by stimulating the hydrolysis of phosphoinositides. The hormone receptor activates a phospholipase C which then cleaves phosphatidylinositol 4,5-bis-phosphate (PIP$_2$) to produce two second messengers, inositol 1,4,5-trisphosphate (IP$_3$) and diacylglycerol. Phospholipase A$_2$ may then act on diacylglycerol and ultimately produce arachidonate, a precursor of prostaglandins (Berridge, 1984).

Receptors, such as the mAChR, are believed to couple to phospholipase C through a guanine nucleotide binding protein. This proposed $G_p$ has so far eluded detection. Coupling of the mAChR to phospholipase C has been demonstrated to be insensitive to pertussis toxin in chick heart cells (Helper and Harden, 1984) and in 1321N1 astrocytoma cells (Masters et al., 1985). Thus, $G_i$ and $G_o$ are ruled out as possible candidates for $G_p$ in these systems. However, other systems have shown sensitivity to pertussis toxin (Ohta et al., 1985). Phospholipase A$_2$ also shows sensitivity to pertussis toxin and may be another enzyme regulated by G protein coupled receptors (Nakahima et al., 1987).

Inositol 1,4,5-trisphosphate acts as a second messenger and releases calcium from internal reserves. The mechanism of how IP$_3$ releases calcium has not yet been established (Berridge, 1984). A mAChR induced mobilization of calcium has been observed in neuroblastoma cells (Oshako and Deguchi, 1984), pancreatic acinar cells (Candler and Williams, 1978), chicken fibroblasts (Oettling et al., 1985), and astrocytoma cells (Masters et al., 1984). The
increase in calcium may be the means by which secretory cells are stimulated by muscarinic activation. A rise in intracellular calcium may also activate calmodulin regulated phosphodiesterases, thus providing an alternative mechanism for lowering the levels of cAMP (Nathanson, 1987; Schimerlik, 1988).

Diacylglycerol serves as a second messenger by activating protein kinase C. The mechanism of activation is to increase the affinity of calcium for protein kinase C, which is calcium dependent. Thus, diacylglycerol acts synergistically with IP₃, which raises the level of available calcium. Although the targets of protein kinase C are largely unknown, it is known that tumor promoting phorbol esters can activate the kinase and transform the target cell (Berridge, 1984). Protein kinase C may be involved in a feedback regulation of mAChR coupling to phospholipase C (Orellana, 1987) and potassium channels (Dascal et al., 1985), possibly by phosphorylating and inactivating the G protein involved.

### Stimulation of cGMP synthesis

By an as yet unidentified mechanism, muscarinic stimulation causes an increase in the levels of the second messenger cGMP. The muscarinic cGMP response in NE1-115 neuroblastoma cells can be lowered by disrupting metabolism of arachidonate or by inhibiting the phospholipase A₂ catalyzed release of arachidonate. These results suggest that a metabolite of arachidonate may regulate guanylyl cyclase (McKinney and Richelson, 1986; Nathanson, 1987). It has been proposed that guanylyl cyclase is activated by a metabolite of
arachidonate, and that arachidonate is liberated by a calcium dependent phospholipase A2. Thus receptors that mobilize intracellular calcium may activate guanylyl cyclase through some metabolite of arachidonate and by releasing calcium (Berridge, 1984). The role of cGMP as a second messenger is still somewhat unclear. In heart tissue cGMP activates a cGMP dependent phosphodiesterase, thus reducing cAMP dependent calcium entry into the cell (Hartzell and Fischeister, 1986). Therefore, cGMP can function as an antagonist to cAMP. A cGMP-dependent protein kinase in smooth muscle cells has also been linked with a muscarinic induced relaxation of vascular smooth muscles (Nathanson, 1987).

Ion Channels

The mAcChR regulated decrease in the rate of cardiac contraction is due to an increased permeability of the cardiac sarcolemma to K+, resulting in a hyperpolarizing effect (Katz, 1977). The ion channel responsible for the increased permeability is the inward rectifying potassium channel. The lengthy time lag following muscarinic activation and the temperature dependence of the phenomena suggested that the mAcChR does not contain, or is not directly coupled to the ion channel. Regulation by cyclic nucleotides was also ruled out (Nathanson, 1987). The muscarinic response is sensitive to Pertussis toxin, implying that either G1 and/or Go are involved in this signal transduction (Martin et al., 1985). Recent work has suggested that the transducing protein is G1, the mechanism by which G1 regulates the channel is currently under debate (see below, under G proteins).
Muscarinic activation may also result in depolarization in some tissues. In these tissues the muscarinic activation decreases an M-current. M-currents are K⁺ channels which are activated by depolarization. Attenuation of M-currents results in an excitatory postsynaptic potential. Spinal chord neurons (Nowak and MacDonald, 1983) and hippocampal neurons (Cole and Nicoll, 1984) are examples of tissue which shows this type of regulation.

Muscarinic Receptor Subtypes and Structure

The large diversity of physiological and biochemical responses that occur as a consequence of muscarinic activation can be explained, in part, by the existence of multiple muscarinic receptor subtypes. The existence of receptor subtypes was suggested by the heterogeneous response of mAChRs to the antagonist pirenzepine (Hammer et al., 1980). Following isolation of homogeneous mAChR proteins (Peterson et al., 1984; Haga and Haga, 1985) it has been possible to obtain molecular clones of the mAChR from porcine atria (PM2 receptors, Kubo et al., 1986b; Peralta et al., 1987) and porcine cerebellum (PM1, Kubo et al., 1986). Those clones revealed that the two muscarinic subtypes were polypeptide products from two different genes, but share the same overall structure of seven hydrophobic transmembrane regions. The structural motif is similar to that observed for other G protein coupled receptors, such as the ß-adrenergic receptor and visual rhodopsins (Dohlman et al., 1987).

While screening a human genomic library to isolate HM1 (human mAChR type 1) and HM2 (human mAChR type 2), two additional human
subtypes were isolated and characterized. These were designated HM3 and HM4. The seven transmembrane regions of the four receptors appeared to be homologous, the region of largest amino acid sequence diversity was a large hydrophilic stretch between transmembrane segment 5 and 6. This region was used as a probe for Northern analysis to localize the receptor subtypes to specific tissues (Peralta et al., 1988).

The HM1 subtype showed a 98.9% sequence homology to porcine M1, and showed a closer homology to HM4 than to HM2 or HM3. The finding that HM1 has high affinity for the M1 selective antagonist pirenzepine, and low affinity for the cardioselective antagonist AFDX-116, were consistent with HM1 being located in the cerebral cortex, but not the heart (Peralta et al., 1988).

Conversely, HM2 has a low affinity for pirenzepine and a high affinity for AFDX-116. HM2 shared a high identity with HM3, and a 97.4% identity with PM2 from the myocardium. The only subtype detected in the heart was HM2, although HM2 was also detected in the brain (Peralta et al., 1988). The PM2 receptor appears to be more tightly coupled to regulation of adenylyl cyclase than to regulation of phospholipase C (Ashkenazi et al., 1987; Peralta et al., 1988).

The HM3 receptor shares the highest homology with HM2, but has a high affinity for pirenzepine and a low affinity for AFDX-116. Despite the difference in ligand selectivity, the HM3 receptor appears to be similar to HM2 in that it is more tightly coupled to adenylyl cyclase than to phosphoinosatide turnover. HM3 is abundant in the brain.

The HM4 receptor also has a high affinity for pirenzepine and a
low affinity for AFDX-116. While HM4 has been located in the brain, it is the only receptor subtype expressed in pancreas cells. This observation, together with the distinctively large molecular weight of this subtype (590 amino acids vs 460 in HM1) has led to the suggestion that HM4 is a glandular type receptor. A high molecular weight mAcChR has been observed in pancreas. Muscarinic mediated phosphatidylinositol turnover and calcium mobilization seem to be linked to excretion in glandular type cells, so HM4 may be coupled to phosphatidylinositol turnover. Despite the difference in molecular weight, HM4 has the highest overall sequence identity with HM1 (Peralta et al., 1988).

Since HM4 shares a high sequence identity with HM1, it is interesting to note that HM1 has also been observed to couple to phosphatidylinositol turnover (Lai et al., 1988). So, there appear to be two receptor subtypes that couple to phosphatidylinositol turnover, and two subtypes that couple to adenylyl cyclase. It has been noted that individual subtypes do not exclusively, but preferentially couple to a particular biochemical response (Peralta et al., 1988).

**Ligand Binding**

Most muscarinic antagonists bind to the mAcChR with a single class of binding sites (Hulme et al., 1978). Labelled antagonists such as \[^3\text{H}\] L-quinuclidinyl benzilate ([\(^3\text{H}\) L-QNB]) and \[^3\text{H}\] N-methyl scopolamine have been used to identify and characterize the mAcChR. Kinetic analysis of \[^3\text{H}\] L-QNB binding to the porcine atrial mAcChR has shown that the binding of QNB is a two step process involving a
rapid binding step followed by a slow isomerization of the receptor-ligand complex to a more stable form (Schimerlik and Searles, 1980).

Displacement of labelled antagonist by unlabelled agonists has demonstrated that agonists bind to the receptor with at least two classes of binding sites. The binding sites were designated as high and low affinity with the possible existence of a super high affinity site. Selective alkylation of the receptor revealed that the heterogeneity of agonist binding was not due to negative cooperativity, but to two separate classes of binding sites (Birdsall et al., 1978).

High affinity sites are converted to low affinity sites by the addition of guanine nucleotides in the heart (Berrie et al., 1979) and in the cerebellum and brainstem (Korn et al., 1983). It has been postulated that the high affinity binding sites represent mAChR coupled to a G protein. The high affinity hormone-receptor-G protein complex binds GTP and 1) dissociates the G protein from the receptor, returning the receptor to the low affinity state and 2) activates the G protein (Gilman, 1988). It is apparently the high affinity form of the mAChR that is coupled to adenylyl cyclase (Brown and Brown, 1984; Martin et al., 1985) indicating that the G protein is involved in signal transduction.

Muscarinic agonists display some heterogeneity with regard to receptor response. Certain agonists show a preference in coupling to adenylyl cyclase rather than inositol lipid metabolism. Despite a higher affinity for the receptor, the partial agonist oxotremorine was much more effective in inhibiting cAMP formation than stimulating phosphoinositide breakdown (Brown and Brown, 1984).
G Proteins

Most of our knowledge of muscarinic signal transduction pertains to the coupling of the mAChR to G proteins. These regulatory proteins are probably the major intermediate by which the receptor communicates with biochemical effector systems in target cells.

The G proteins are a family of membrane associated proteins which transduce information from a variety of hormone receptors to effector enzymes or ion channels (recent reviews can be found in Gilman, 1987; and Casey and Gilman, 1988).

The G proteins characterized to date are heterotrimeric of α, β, and γ subunits. The α subunits bind guanine nucleotides with high affinity, are the substrates for ADP-ribosylation by bacterial toxins, and are unique for the different classes of G proteins. Since the α subunits provide the major structural diversity for the G proteins, it is not unexpected that they play an important role in the function of most G proteins. The activation of a G protein occurs when the α subunit binds one guanosine triphosphate and the protein then dissociates into α and βγ subunits. The subunits then perform the regulatory activity associated with the particular G protein. An alpha subunit containing a bound GTP is considered the active form of this subunit.

The stimulatory guanine nucleotide binding protein (Gs) has an alpha subunit of about 45K which is ADP-ribosylated by cholera toxin. Guanosine triphosphate bound Gsα stimulates adenylyl cyclase. Treatment with Cholera toxin results in persistent activation of the protein, presumably by preventing the hydrolysis of GTP. Hydrolysis
of GTP to GDP by the $\alpha$ subunit results in deactivation. There are at least 4 types of $G_{\alpha}$ subunits, but their significance is not yet known (Casey and Gilman, 1988).

The inhibitory guanine nucleotide binding protein ($G_{i}$) has an $\alpha$ subunit of about 40-41K and is ADP-ribosylated by Pertussis toxin. Treatment with Pertussis toxin uncouples $G_{i}$ from interacting with hormone receptors. Since the normal role of the protein is to mediate inhibition of adenylyl cyclase, treatment with Pertussis toxin also results in a persistent activation of adenylyl cyclase. The physiological mechanism of $G_{i\alpha}$ function is somewhat uncertain. It may bind to and weakly inhibit adenylyl cyclase, or compete with $G_{\alpha\alpha}$ for a binding site on the enzyme (Cerione et al., 1986; Katada et al., 1984b, 1986a, 1987). As discussed below, the $\beta\gamma$ subunits may also play an important role for $G_{i}$. There are also at least three subtypes of $G_{i\alpha}$, and their functional differences have not yet been determined (Casey and Gilman, 1988). The G protein ($G_{k}$) which is believed to interact with the atrial potassium channel may be the same as $G_{i}$ (Codina et al., 1987).

The $\alpha$ subunit of $G_{o}$ is a 40K peptide which is also a substrate for ADP-ribosylation by Pertussis toxin. An explicit role for $G_{o\alpha}$ has not yet been determined, thus its designation as the "other" G protein. However, $G_{o\alpha}$ has been recently shown to mediate the neuropeptide Y induced inhibition of dorsal root ganglion calcium channels (Ewald et al., 1988).

The $\alpha$ subunit of transducin is 40K and can be ADP-ribosylated by either pertussis toxin or cholera toxin. There are two forms of this peptide, one for the rod outer segment and one for cones (Lerea et
al., 1986). Transducin communicates signals from visual opsins to cGMP phosphodiesterases. Both of the transducin \( \alpha \) subunits activate the phosphodiesterase.

The \( \beta \) and \( \gamma \) subunits remain closely associated and, in general, are considered interchangeable among the G protein classes. There are two similar forms of the \( \beta \) subunit, one 35K and one 36K. The two forms of the \( \beta \) subunit are usually seen together except for transducin which only has a 36K \( \beta \) subunit associated with it. The \( \gamma \) subunits are about 8-10K and there may be multiple forms. It is clear that the \( \gamma \) subunit of transducin is distinct from those of the other G proteins (Hildebrandt et al., 1985).

The \( \beta \gamma \) subunits serve several roles. As a consequence of being more hydrophobic, they help to anchor the \( \alpha \) subunit to the membrane (Sternweis, 1986). They also seem to be required for G protein coupling to receptors (Florio and Sternweis, 1985). The most established functional role for the \( \beta \gamma \) subunits is to deactivate \( G_\alpha \). In this sense both \( G_\iota \) and \( G_\o \) could serve as inhibitory proteins for adenylyl cyclase by providing an excess of \( \beta \gamma \) subunits, thus removing free \( G_\alpha \) by mass action equilibrium (Gilman, 1987).

There is some evidence that the \( \beta \gamma \) subunits may directly inhibit adenylyl cyclase (Katada et al., 1986a). There have also been observations that \( G_\iota \) and \( G_\o \) interact with calmodulin. The \( \beta \gamma \) subunits and \( G_{1\alpha} \) inhibited calmodulin activated phosphodiesterase activity, and it appeared that \( G_\iota \) and \( G_\o \) functioned as inhibitors by binding to calmodulin (Asano et al., 1986), thus reducing the amount available for the phosphodiesterase activation. It was later observed (Katada et al., 1987) that \( \beta \gamma \) subunits could bind to calmodulin and inhibit
the calmodulin-sensitive adenylyl cyclase, presumably by reducing the calmodulin available for adenylyl cyclase.

A highly debated role for G proteins is the regulation of the muscarinic regulated atrial inward rectifying potassium channel. Some investigators have observed that the α subunit of a Gi-like protein from erythrocytes activated the channel (Codina et al., 1987). Others claim the channel is regulated by βγ subunits (Logothetis et al., 1987), or perhaps both α and βγ (Clapham and Neer, 1988).

There has been some confusion with regard to the term Gp. It may pertain to the as yet unidentified G protein that regulates phospholipase C (Schimerlik, 1988). Alternatively, Gp pertains to a GTPγS-binding protein with an apparent molecular weight of 21,000. This protein has been isolated from placenta; it is not a substrate for ADP-ribosylation by cholera toxin or pertussis toxin, and does not associate with βγ subunits (Evans et al., 1986). No function has been assigned to this protein. It is possible that the two Gp's define the same protein.

As stated above, G proteins are activated by binding GTP which results in a separation of subunits. Activation is terminated when GTP is hydrolyzed to GDP and the subunits reassociate. The GDP bound form of Gi is believed to associate with a hormone receptor, the receptor then being transformed to a high affinity agonist form. The formation of a hormone-receptor-G protein complex renders the G protein in an "open" conformation by increasing the rate of GDP release and perhaps increasing the rate of GTP binding. Association of GTP to this complex uncouples the receptor from the G protein.
Reconstitution

The successful solubilization of mAChR using the detergent mixture of digitonin and cholate (Cremo et al., 1981) and subsequent purification of the receptor to homogeneity from atria (Peterson et al., 1984) and brain (Haga and Haga, 1985) have opened the possibility for reconstitution of the pure receptor with regulatory and effector proteins.

Reconstitution procedures are required to remove the receptor from a detergent environment before interaction of the receptor with effector proteins can be studied. An example of the disruption of the interaction between the mAChR and Gi caused by digitonin can be seen when the receptor is solubilized. The crude extract showed an apparently homogeneous class of agonist binding sites (Herron et al., 1982) indicating uncoupling from Gi, even though GTPγS binding studies indicated that Gi was present in the extract and could be purified from the extract (Chapter II, this thesis).

Reconstitution of partial purified brain mAChR with pure brain Gi and Go demonstrated that both proteins could interact with the receptor and induce a guanine nucleotide sensitive high affinity site (Florio and Steinweiss, 1985). The βγ subunits alone did not have an effect on the receptor but enhanced the effects of the α subunit.

The ability of pure brain mAChR to interact with pure Gi and Go was confirmed by Haga et al. (1986). The receptor was also able to increase the $V_{max}$ of the intrinsic GTPase of Gi by 20-50%, and increase the apparent association constant of GTPγS (Kurose et al., 1986).
Objectives

The intent of this thesis was to explore the mechanism of signal transduction from the muscarinic receptor to effector proteins. It was necessary to place the mAChR into a lipid environment where its interactions with other protein components could be examined. Emphasis was placed on examining the interaction of the atrial mAChR with atrial G_i.

Chapter II describes the purification of atrial G_i. Atrial G_i was isolated as a by-product from the purification of atrial mAChR. The availability of this protein for study will be important because it is certain to be compatible with atrial mAChR. It could also provide some clues about the regulation of the atrial potassium channel. The putative G_K that has been tested with the atrial potassium channel is from erythrocytes. Data obtained with this protein indicated that the α subunit was the active component, not the βγ subunits (Codina et al., 1987). Other groups using brain G_i claim that the α subunit was ineffective, while the βγ subunits were active (Logothetis et al., 1987). This quandary provides additional motivation for isolating the atrial form of G_i.

A fortuitous advantage of the atrial G_i purification was the limited number of G proteins isolated. The only major contaminant was a GTP_γS binding protein of 23K which was not a substrate for ADP-ribosylation and did not associate with βγ subunits. Speculations are made as to whether this protein is similar to the placental G protein (Evans et al., 1986), or a proteolytic degradation of other G proteins.
Chapter III describes the reconstitution of atrial mAChR and $G_i$ into a lipid environment in order to examine the mechanism of activation of $G_i$ by the agonist-bound receptor. One consequence of activation was an increased GTPase activity of $G_i$. The rate limiting step of the GTPase reaction under non-stimulated conditions was shown to be the rate of GDP release. It will be shown that the agonist bound muscarinic receptor functions as an efficient catalyst and increases the rate of GDP release, thus the receptor-$G_i$ had a lower affinity of GDP for $G_i$. However, the affinity for $GTP_\gamma S$ remained unaltered, implying only the affinity for the diphosphate was effected. Most of these measurements would not have been possible in a heterogeneous system. The effects of the mAChR on GDP release have not been previously directly demonstrated.

In Chapter IV the reconstituted system was extended to include $G_s$, calmodulin, and the calmodulin-sensitive adenylyl cyclase, thus reconstituting a hormone mediated inhibition of adenylyl cyclase. In addition to establishing the minimum components required for reconstitution, these experiments also demonstrate a new role for $G_{1\alpha}$, inhibiting only the calmodulin stimulated adenylyl cyclase. Thus cells which contain calmodulin-sensitive adenylyl cyclase and muscarinic receptors may have an as yet unexplored mechanism of regulation.

The hormone mediated stimulation of adenylyl cyclase has also been performed in a reconstituted system using purified components (Cerione et al., 1985; May et al., 1985; Rosenberg et al., 1987). Thus it is now possible to perform experiments studying the regulation of reconstituted adenylyl cyclase with multiple receptors and $G$ proteins.
The existence of multiple muscarinic biochemical responses and the identification of multiple muscarinic subtypes and multiple G proteins that could potentially interact with them have posed the questions of which receptors interact with which G proteins. An important advantage in these reconstitution experiments is that specific mAChR subtypes and G protein subtypes may be examined.
Chapter II

Purification of the Inhibitory Guanine Nucleotide-binding Protein (G\textsubscript{i}) from Porcine Atria

Contributions of Co-authors

This chapter describes the purification and characterization of atrial G\textsubscript{i}. I originally made the observation that the procedure used for solubilizing mAcChR also solubilized a large amount of G proteins. The bulk of these G proteins could be separated from the mAcChR during the first subsequent purification step, the wheat germ agglutinin column. Professor Schimerlik then began to develop purification procedures based on the purification of G\textsubscript{i} from brain. One of the major problems of this purification was the presence of a 23K Da contaminating G protein. Professor Schimerlik, Gary Peterson and I contributed to solving this problem.

Gary Peterson also contributed to the majority of the electrophoresis work and offered interpretation and suggestions regarding various stages of purification. He also pursued isolating and identifying the 23K Da peptide, G protein βγ subunits, and other G proteins that might have been lost during the purification.

My contribution was to adapt for use in this lab the \[^{35}\text{S}]\text{GTP}_{\gamma}\text{S}\) binding assay, the assay for GTPase activity, and the methodology for the ADP-ribosylation of G\textsubscript{i}. These methodologies were essential for the isolation and identification of G\textsubscript{i}. I also contributed to the adaptation of published G\textsubscript{i} purification procedures to our system. One
problem was how and when to switch detergents from digitonin-cholate to cholate.

I was also responsible for characterizing the interaction of the purified G\textsubscript{i} with guanine nucleotides. After the initial purification, I was responsible for the handling and storage of the protein.
Abstract

The inhibitory guanine nucleotide-binding protein (Gi) was purified from porcine atria as a by-product of muscarinic acetylcholine receptor purification. By using guanosine 5'-0-(3-thio-triphosphate) (GTP\(_\gamma\)S) to monitor G protein purification, a G protein was isolated which consisted of an \(\alpha\) subunit of 41 kDa, a \(\beta\) subunit of 35/36 kDa and a low molecular weight \(\gamma\) subunit. The \(\alpha\) subunit was a substrate for pertussis toxin. On the basis of its molecular weight, its ability to act as a substrate for pertussis toxin, and its interaction with guanine nucleotides, this protein was assumed to be Gi. Little or no Go was isolated, but a low molecular weight GTP\(_\gamma\)S binding protein (approximately 23 kDa) co-purified with Gi through most of the purification and was finally separated by sucrose gradient centrifugation. It is not certain whether this low molecular weight protein was a proteolytic fragment of Gi or another G protein. Reconstituted Gi had a high affinity for GTP\(_\gamma\)S (\(K_d = 456 \text{ pM}\)) and demonstrated GTPase activity (\(K_m = 8 \text{ nM}, k_{\text{cat}} = 0.19 \text{ min}^{-1}\)).
mAcChR, muscarinic acetylcholine receptor; PC, soybean
L-α-phosphatidylcholine; PS, bovine brain L-α-phosphatidyl-L-serine;
CHAPS, (3-[3-cholamidopropyl]-dimethylammonio]-1-propanesulfonate; Gs,
the stimulatory guanine nucleotide binding protein; Gi, the inhibitory
guanine nucleotide binding protein; GppNHp,
5′guanylylimidodiphosphate; GTPγS, guanosine
5′-0-(3-Thio-triphosphate); DTT, dithiotreitol; HEPES,
4-(2-hydroxyethyl)-1-piperazineethanesulfonate; EGTA,
ethyleneglycol-bis-(β-aminoethyl ether)-N,N,N′,N′-tetraacetic acid;
EDTA, ethylene diamine tetraacetic acid; PMSF, phenylmethylsulfonyl
fluoride; TED, 20 mM Tris HCl, 1 mM EDTA, 1 mM DTT, and 0.1 mM PMSF,
pH 8.0; HEMD, 10 mM Na HEPES, 0.1 M NaCl, 1 mM EGTA, 5 mM MgCl₂, 1 mM
DTT and 0.1 mM PMSF, pH 7.4.
Introduction

The guanine nucleotide-binding proteins are a family of membrane associated proteins consisting of trimers of heterologous subunits (αβγ). Two members of this family were originally characterized with regard to the regulation of adenylyl cyclase. The stimulatory (Gs) and inhibitory (Gi) guanine nucleotide-binding proteins appear to be involved in signal transduction from either stimulatory or inhibitory receptors respectively, to adenylyl cyclase (see Rodbell, 1980; Stryer and Bourne, 1986; for reviews).

The Gi has been purified from several tissue sources including brain (Neer et al., 1984; Sternweis and Robshaw, 1984; Katada et al., 1986b; Milligan and Klee, 1985), erythrocytes (Codina et al., 1984) and liver (Bokoch et al., 1984). The distinguishing α subunit of Gi, molecular weight of 40 or 41 kDa was shown to be a substrate for ADP-ribosylation by pertussis toxin. Several preparations of Gi have also included a pertussis toxin substrate of 39 kDa (Katada et al., 1984; Sternweis and Robishaw, 1984; Neer et al., 1984), classified as the α subunit of another G protein, Go. All purifications report the existence of a 35 kDa and/or 36 kDa β subunit. The β doublet seen in many preparations has been determined to be two distinct proteins (Evans et al., 1987; Fong et al., 1987). Although sometimes difficult to distinguish by SDS electrophoresis because of low molecular weight and poor silver staining qualities, a γ subunit was also believed to be associated with G proteins (Hilderbrandt et al., 1984).

The mAcChR is one of the inhibitory types of receptors coupled through Gi to adenylyl cyclase. There has been direct evidence that
the brain mAChR can interact with both bovine brain $G_i$ and $G_o$ (Haga et al., 1986). A guanine nucleotide binding protein other than $G_i$ or $G_o$ is thought to couple the mAChR to phosphatidylinositol turnover (Nathanson et al., 1987). In addition, the atrial mAChR is coupled through a G protein to an inward rectifying potassium channel (Breitweiser and Szabo, 1985; Pfaffinger et al., 1985). This G protein is thought to be $G_i$; however, there is considerable disagreement as to whether the $\alpha$ or $\beta\gamma$ subunit interacts directly with the potassium channel (Codina et al., 1987; Logothetis et al., 1987; Yatina et al., 1987). Thus it is uncertain how many different G proteins the atrial mAChR recognizes and if there are any G proteins unique to the atria.

To date, no G proteins have been isolated from atrial tissue, perhaps because this tissue has a lower abundance of GTP binding proteins and is more difficult to work with than other sources, such as brain. In the present study, atrial $G_i$ was purified as a by-product in the purification of atrial mAChR. The availability of a purified atrial $G_i$ should help to clarify the role of this protein in atria.
Materials and Methods

$[^{35}S]GTP_{\gamma}S$ (1000 Ci/mmol), [$\gamma-^{32}P$]GTP (20-30 Ci/mmol), and
[adenylate-32P] NAD (31 Ci/mmol) were purchased from New England Nuclear. Cholesterol, P.C. (type III-s), P.S. (bovine brain), CHAPS, digitonin, GTP, NAD and activated charcoal were purchased from Sigma. Cholic acid was purchased from Sigma and purified by the method of Ross and Shatz (1978). GDP and GTP$\gamma$S were purchased from Boehringer Mannheim. The purity of GTP and GTP$\gamma$S was determined by thin layer chromatography using a solvent of 1-propanol:NH$_4$OH:H$_2$O (6:3:1). When necessary, these nucleotides were purified by applying them to DEAE Biogel A and eluting with a 0-0.5 M LiCl gradient. Amido Black 10B was from BioRad. Pertussis toxin was from List Biological Laboratories and was stored in 50 mM sodium phosphate, 0.25 M NaCl, pH 7.0, at 100 $\mu$g/ml. A mixture of brain G$_i$G$_o$ was a generous gift from Dr. Lutz Birnbaumer.

Membrane Preparation and Detergent Extraction. Porcine atrial plasma membranes were enriched for mAChR and extracted with 0.4% digitonin and 0.08% sodium cholate as described (Peterson and Schimerlik, 1984) except for the addition of 1 $\mu$g/ml soybean trypsin inhibitor and 1 mM benzamidine (protease inhibitor) to all buffers. The solubilized protein (extract) was applied to a wheat germ agglutinin (WGA) column as described for the purification of the mAChR (Peterson et al., 1984) except that the extract was supplemented with 5 mM MgCl$_2$ to increase the yield of mAChR from the WGA column by improving glycoprotein binding to the immobilized lectin. The material that did not bind to the WGA column was
collected and referred to as WGA void (600-700 ml/preparation). The WGA void was supplemented with 0.9% Na cholate and 1 mM DTT, and the pH was adjusted to 8.0 with 1 M tris base. This material was either used immediately for G\textsubscript{i} purification or supplemented with 75 mM sucrose and stored at -80 C.

The WGA voids (1.8 to 2.1 liters) from three mAChR preparations were applied to a 4.9 x 42 cm DEAE Sephacel column which was equilibrated in TED/0.9% cholate/2 \( \mu \)g/ml STI. The column was washed at 2 ml/min with 350 ml of equilibration buffer containing 20 mM NaCl and eluted with a 20-400 mM NaCl gradient in 2.2 l of equilibration buffer. Twenty ml fractions were collected at 2 ml/min. Figure II-1A shows the profile of \( [35S] \)GTP\textsubscript{\gamma}S binding and absorbance at 280 nM for the DEAE Sephacel column. Fractions 46-65 containing GTP\textsubscript{\gamma}S binding activity were pooled and concentrated to 16.5 ml by pressure filtration through an Amicon YM-10 membrane.

The concentrated DEAE pool was then loaded on a 4.9 x 51 cm Ultragel AcA 34 (LKB) exclusion column which was equilibrated with TED/0.9% cholate/0.1 M NaCl/2 \( \mu \)g/ml STI. Equilibration buffer was used to elute the column at 1 ml/min collecting 10 ml/tube (Fig. II-1B).

Fractions 75 to 98 containing the peak GTP\textsubscript{\gamma}S binding activity from the Ultragel column were pooled and diluted three fold into TED/0.1 M NaCl/2 \( \mu \)g/ml STI to yield 540 ml of solution in TED buffer containing 0.1 M NaCl and 0.3% sodium cholate. This was loaded at 0.4 ml/min onto a 3 x 25 cm octyl-sepharose column equilibrated in the same buffer and then washed with 100 ml of equilibration buffer followed by 400 ml of TED/0.3% cholate/0.5 M NaCl/2 \( \mu \)g/ml STI. The column was
eluted with a 500 ml NaCl/sodium cholate gradient starting with 0.25 M NaCl, 0.3% sodium cholate and ending with 50 mM NaCl, 1.2% sodium cholate in TED/2 μg/ml STI at a flow rate of 0.5 ml/min. 6.8 ml fractions were collected.

Fractions 50 to 60 of the octyl-sepharose column, which contained the peak of the GTPγS binding activity Fig. II-2, were concentrated on a 1.4 x 2.5 cm hydroxylapatite column prepared and equilibrated in TED/0.9% cholate/0.1 M NaCl and eluted with equilibration buffer plus 0.2 M potassium phosphate, pH 8.0. The column was loaded and eluted at 0.3 ml/min and 0.75 ml fractions were collected.

The final purification procedure was a 5-20% linear sucrose gradient. Multiple 35 ml gradients in TED/0.9% cholate were used and 2-3 ml of material concentrated by hydroxylapatite (approximately 3 μM in [35S]GTPγS sites) were applied to each gradient and were centrifuged in a SW28 rotor at 27,000 rpm for 72 hours. Gradients were fractionated from the bottom into 1 ml fractions. Protein which bound [35S]GTPγS and contained the 41 kDa subunit as determined by SDS polyacrylamide gel electrophoresis (Fractions 15-21, Fig. II-3), was pooled and concentrated by applying to 1/10 volume of DEAE Bio-Gel A which had been equilibrated in TED/0.9% cholate. The G_i was eluted with TED/0.9% cholate/0.3 M NaCl/75 mM sucrose and dialyzed against TED/0.9% cholate/75 mM sucrose. The purified G_i was either used directly or supplemented with 5 mM MgCl2 and stored at -80 C. G_i was also concentrated by using a Centricon 10 microconcentrator (Amicon).

[35S]GTPγS binding. The binding of [35S]GTPγS was performed essentially as described by Northup et al. (1982). The samples in cholate were diluted at least 10-fold into (HEMD) buffer supplemented
with 25 mM MgCl₂, 0.1% lubrol PX, and 1 μM [³⁵S]GTP₇S (3-8 ci/mmol), incubated for one hour at 32°C and filtered over nitrocellulose paper. Assays of reconstituted Gᵢ were performed in HEMD buffer without lubrol for one hour at 32°C.

GTPase activity was determined by measuring ³²P released as described (Appendix II).

**Protein Determination.** Protein was estimated either by the Folin phenol method (Peterson, 1983) or by staining with Amido Black as described by Schaffner and Weissman (1973).

**SDS-Polyacrylamide gel electrophoresis.** Fractions obtained during purification of the G proteins were analyzed on 8-18% linear acrylamide gradient gels (0.7 cm x 8 cm x 8 cm) in SDS according to Laemmli (1970). For high resolution of 41 kDa and 39 kDa α subunit bands, the samples were alkylated with N-ethylmaleimide (Sternweis and Robishaw) and run on long (0.7 cm x 8 cm x 15 cm) 12% acrylamide gels. The gels were either stained with Coomassie blue G-250 or silver (Wray et al., 1981) as indicated in the figure legends.

**ADP ribosylation.** Reconstituted Gᵢ was diluted 10 fold into HEMD buffer supplemented with 5 mM thymidine and 3 μM [adenylate-³²P]NAD. Pertussis toxin was activated for 15 minutes at 32°C with 10 mM DTT and 50 μM ATP. The activated toxin was diluted 20 fold into the ADP-ribosylation mixture to give a final concentration of 4.5 μg/ml. The mixture was incubated for one hour at 32°C and the reaction stopped by adding 1/4 volume of 5x Laemmli sample buffer (Laemmli, 1970).

**Determination of bound GDP.** The amount of GDP bound to Gᵢ was determined by the method of Ferguson et al. (1986). The inhibitory
guanine nucleotide binding protein (1.5 μM in GTPγS sites) was
denatured by boiling for 2-3 minutes in TED/0.8% cholate buffer.
After cooling, the denatured protein was diluted 10 fold into
HEMD/0.1% lubrol buffer which contained a final concentration of 10 nM
active Gi (based on GTPγS binding). [35S]GTPγS was then added to a
concentration of 10 nM (1100 Ci/mmol). This mixture was incubated at
32°C for 1 hour and then filtered as described above. The degree of
inhibition from the denatured protein was compared to the inhibition
obtained from adding known amounts of GDP to active Gi.

Reconstitution. Atrial Gi was reconstituted into a lipid mixture
of 1:1:0.1 PC, PS, and cholesterol as described (Appendix I). In
brief, the procedure involved adding Gi to the lipid mixture which was
sonicated in the presence of 7 mM CHAPS. The mixture was diluted 25-
fold, polyethylene glycol was added to a final concentration of 10%
w/v, and the precipitate collected by centrifugation at 250,000 x g.
Results and Discussion

Table II-1 summarizes the purification of atrial \( G_\iota \) from membranes enriched in mAChR. Identification and purification of \( G_\iota \) was facilitated by using \([35S]GTP_\gamma S\) binding activity and, at latter steps of the purification, SDS gel electrophoresis. The use of membranes enriched in mAChR for purification of \( G \) proteins not only conserves resources and effort, but is also a logical strategy, used previously by Sternweis and Robishaw (1984), as an enrichment in mAChR should result in an enrichment of associated \( G \) proteins. The double extraction procedure that was optimized for mAChR (Peterson and Schimerlik, 1984) was also successful in solubilizing GTP\( \gamma S\) binding proteins. The first digitonin-cholate extract (E1) solubilized 20% of the GTP\( \gamma S\) binding sites resulting in a slight decrease in specific activity (0.079 nmol/mg), while the second digitonin-cholate extract (E2) contained 56.3% of the GTP\( \gamma S\) binding sites and a 2.6-fold increase in specific activity to 0.23 nmol GTP\( \gamma S\) bound/mg protein. The first extract was discarded and the second extract was used for purification of mAChR and \( G_\iota \).

The GTP\( \gamma S\) binding proteins were separated from the mAChR on the WGA column. The WGA column bound the receptor while the majority of the GTP\( \gamma S\) binding proteins do not bind and were collected in the fraction termed "WGA void". The mAChR was displaced from the column by eluting with 0.2 M N-acetyl-glucosamine (Peterson et al., 1984). There was some GTP\( \gamma S\) binding activity eluting with the receptor (about 5%), which probably represented GTP binding proteins coupled to the mAChR as well as other GTP binding proteins which associated with
glycoproteins. There has been no indication that the G proteins themselves are glycosylated. The α and β subunits of Gs and Gi behave as standard proteins on SDS-PAGE (Codina et al., 1984), and the apparent subunit molecular weights on SDS-PAGE agree closely with their predicted molecular weights (Fong et al., 1987; Sullivan et al., 1986).

The elution profile of the WGA void chromatographed over a DEAE-Sephacel column (See Fig. II-1A) consistently showed two peaks of GTPγS binding. The reasons for this heterogeneity are not known. The two peaks may represent the separation of two different G proteins, the separation of G proteins from proteolytic products, or the separation of monomeric subunit from heterotrimer. The two peaks did interact differently with octyl-sepharose. Most of the GTPγS binding activity of the higher salt DEAE column peak did not bind to octyl sepharose when treated separately (data not shown). In any case, these two peaks were combined and concentrated as described in methods. The DEAE-Sephacel column was not very effective for purification but it was effective in concentrating the material and exchanging digitonin/cholate for cholate. Digitonin was necessary for the stability of the mAChR but not for the GTPγS binding protein. Most G protein purifications have been performed in cholate, and switching to cholate facilitated a simpler and less expensive purification more analogous to published procedures.

After concentration, the DEAE pool was applied to an Ultragel ACA 34 column. The GTPγS binding proteins eluted after the majority of the protein (Fig. II-1B) and resulted in a three fold enrichment in GTPγS protein (Table II-1). Fractions that contained the peak of
GTPγS activity were pooled, diluted to a cholate concentration of 0.3% and applied to an octyl-sepharose column, and eluted with a reverse gradient of NaCl and cholate as described in methods. The resulting GTPγS binding profile (Fig. II-2) showed a single peak which eluted after a large protein peak giving a 4.5-fold enrichment in GTPγS binding protein. The SDS-PAGE profile of the octyl-sepharose column (Fig. II-2) showed the peak of GTPγS binding to represent nearly purified G protein (α, β and γ subunits) while the low detergent-high salt end of the elution profile contained mostly excess βγ subunits. Fractions containing GTPγS binding were concentrated on an HT column as described in methods. It was almost always necessary to further purify the G protein by sucrose gradient centrifugation. The sucrose gradient showed two peaks of GTPγS binding activity (Fig. II-3), where the faster sedimenting peak contained the typical αβγ heterotrimer expected for G proteins. Fractions from the faster sedimenting peak were pooled and concentrated as described in methods. An SDS gel of the final purified and concentrated atrial G protein is shown in Fig. II-4 lane A.

To determine the identity of the isolated atrial α subunit, a sample was alkylated with N-ethylmaleimide (NEM) (Sternweis and Robishaw, 1984) and run on a 12% acrylamide gel alongside a mixture of NEM alkylated brain G1/G0 (Fig. II-4 lanes B and C). The atrial α subunit comigrated with brain G1 (41 kDa) with little or no detectable G0 subunit. As shown in Fig. II-4 lane E, the 41 kDa atrial α subunit was ADP-ribosylated by Pertussis toxin and ³²P-NAD. On the basis of its ability to tightly bind GTPγS, its αβγ heterotrimer structure, its comigration with brain G1, and its ability to act as a substrate for
ADP-ribosylation catalyzed by pertussis toxin, the atrial G protein was provisionally termed $G_\text{i}$. The $\beta$ subunit in Fig. II-4 was a doublet of 35 kDa and 38 kDa. Other G proteins have been observed to contain a $\beta$ subunit doublet (Sternweis and Robishaw, 1984; Evans et al., 1987) and these have been demonstrated to be two distinct proteins (Fong et al., 1987).

The slower sedimenting GTP$_\gamma$S peak from the sucrose gradient contained a conspicuous band of about 23 kDa. The recovery of this protein relative to $G_\text{i}$ was variable. It was not present in all preparations, but in some preparations it was the only band which could account for the observed GTP$_\gamma$S binding activity. At present it is not clear whether this polypeptide is a stable proteolytic fragment of $G_{\text{i}a}$ similar to that generated by Winslow et al. (1986) or a low $M_r$ G protein similar to the placental 23 kDa G protein reported by Evans et al. (1986). The 23 kDa protein isolated from atria was similar to the placental G protein in that it did not associate with the $\beta\gamma$ subunits on the sucrose gradient (Figure II-3) and was not significantly ADP-ribosylated by Pertussis toxin (data not shown). However, these properties could be a result of proteolysis. The amino acid residue which is ADP ribosylated is located near the C terminal of $G_\text{i}$.

The lack of $G_\text{s}$ in our preparation was notable since a comparison of bovine brain and bovine heart cholate extracts revealed that heart extracts contained almost five times more $G_\text{s}$ per mole of GTP$_\gamma$S binding sites then brain extracts (Sternweis and Robishaw, 1984). However, octyl-sepharose chromatography has been demonstrated to completely separate $G_\text{s}$ from $G_\text{i}$ (Katada et al., 1986b). In the present study only
one GTP\(_\gamma\)S binding peak was eluted from this column, but represented less than 50% of the applied GTP\(_\gamma\)S binding sites. A small (<5%) amount of the GTP\(_\gamma\)S binding sites were recovered in the load and subsequent washes. Some additional GTP\(_\gamma\)S binding was eluted after the gradient with 2% cholate (data not shown). Since brain G\(_s\) was eluted from heptylamine-sepharose at higher cholate concentrations than brain G\(_i\)/G\(_o\) (Sternweis and Robishaw, 1984), it was conceivable that any G\(_s\) present was not eluted from octyl-sepharose with a 0.3-1.2% cholate gradient. These observations are consistent with an estimation of G\(_s\) and G\(_i\) hydrophobicity based on their ability to bind detergent, G\(_s\) binding three times as much detergent as G\(_i\) (Codina et al., 1984).

The lack (or nearly so) of G\(_o\) in atrial preparations was particularly interesting since octyl-sepharose was not successful in separating G\(_i\) from G\(_o\) in previous purification approaches using brain (Milligan and Klee, 1985) and thus could not explain its absence. It is not known if G\(_o\) composes a smaller fraction of GTP\(_\gamma\)S binding proteins in atrial tissue, or if G\(_o\) (as well as G\(_s\)) were separated from G\(_i\) at some earlier purification step, such as the first detergent extract.

Purified G proteins from liver and brain have been determined to contain tightly bound GDP (Ferguson et al., 1986). Atrial G\(_i\) has also been determined to contain a tightly bound guanine nucleotide. A direct spectrophotometric analysis of atrial G\(_i\) for the determination of bound GDP was not practical because of the large protein requirements. Bound GDP was assayed by denaturing a small amount of sample and measuring its inhibition of \([^{35}S]\)GTP\(_\gamma\)S binding to active G\(_i\). As determined from a standard curve of added GDP, atrial G\(_i\) was found to contain 2/3 to 1 GDP/GTP\(_\gamma\)S binding site (data not shown).
When the denatured Gi was first treated with charcoal and the charcoal removed by centrifugation, there was no inhibition of GTPyS binding by the supernatant. It was assumed that this compound absorbed to the charcoal was GDP.

Using reconstituted Gi, [35S]GTPyS was found to bind to a single class of high affinity (Kd = 456 pm) binding sites within the range of nucleotide tested (Fig. II-5). Reconstituted Gi also possessed a high affinity GTPase. Figure II-6 shows a Lineweaver Burke plot of the GTPase activity between 10 and 110 nM GTP. The Km (8 nM) was somewhat lower than the Km of 40 nM reported for detergent free erythrocyte Gi (Sunyer et al., 1984) but closer to the Km of 17 nM reported for reconstituted Gi brain (Kurose et al., 1986). Although atrial Gi bound GTP rather tightly, it has a low turnover (0.19 min⁻¹), similar to the value obtained for reconstituted brain Gi (0.37 min⁻¹) (Kurose et al., 1986) but an order of magnitude higher than the turnover of 0.013 for erythrocyte Gi (Sunyer et al., 1984). It has been noted that lipid also increases the GTPase activity of the 40 kDa α subunit G protein (Neer et al., 1984).

In conclusion, Gi was purified from porcine atrial membranes as a by product of mAChR purification. The overall yield of Gi was low (1% from cholate extract) when compared to brain purifications which ranged from 5-20% (Sternweis and Robishaw, 1984; Milligan and Klee, 1984; Katada et al., 1986b). This may indicate that atrial tissue is not as good a source for Gi as brain tissue. Bovine heart extracts show 1/3 the total GTPyS binding sites compared to bovine brain extracts and a high proportion of GTPyS sites in heart extracts is due to Gs (Sternweis and Robishaw, 1984). Thus heart membranes have less
total G proteins and a smaller proportion of these proteins are \( G_i \). Another source for low yields might have been proteolysis, as suggested by the presence of the lower molecular weight GTP\(_\gamma\)S binding protein. Due to longer processing time, preparation of \( G_i \) from atria has more potential for proteolytic problems than preparations from brain. For example, to produce 3.2 g of detergent extracted protein, 1.3 kg of brain tissue from six bovine brains were processed (Milligan and Klee, 1985). In our preparations, 20 Kg of atria from several hundred animals must be processed to produce 2.4 g of detergent extracted protein. The time required for the collection and preparation of this amount of heart tissue could exacerbate problems due to proteolysis. Despite these limitations, \( G_i \) was purified in quantities sufficient for further investigation.

The purified GTP\(_\gamma\)S binding protein was determined to be \( G_i \) on the basis of its electrophoretic mobility compared with brain \( G_i \) and on its ability to act as a substrate for ADP-ribosylation catalyzed by pertussis toxin. Reconstituted atrial \( G_i \) also hydrolyzes GTP in a manner similar to brain \( G_i \) (Kurose et al., 1986). In addition to \( G_i \) a 23 kDa GTP binding protein was isolated. Experiments are currently in progress to determine if this is a breakdown product of \( G_i \) or another G protein. The recovery of \( G_0 \) was low, but it was not determined whether \( G_0 \) is lost during purification or is less abundant in atria.

Isolation of atrial \( G_i \) should now allow direct investigations into the mechanism of cholinergic modulation of cardiac activity. Future work should help to clarify the role of \( G_i \) and its individual subunits in the coupling of the atrial mAChR to effector proteins such as phospholipase C, adenylyl cyclase, and the inward rectifying potassium
channel. It will also be possible to examine particular aspects of the interaction between atrial mAcChR and G_i, such as hormone induced changes in interaction of G_i with guanine nucleotides and guanine nucleotide induced changes in hormone binding to the mAcChR. Finally, using mAcChR and G_i which were both isolated from atria will remove any possible artifacts or interpretive reservations that may arise as a result of using proteins derived from different tissue sources. Studies of the interaction of atrial G_i and atrial mAcChR have already been described (Chapter III) and are ongoing in this laboratory.
**Table II-1**

Purification of $G_i$ from Porcine Atria

<table>
<thead>
<tr>
<th>Purification Step</th>
<th>Protein (mg)</th>
<th>$[^{35}S]$GTP$_\gamma$S binding sites (nmol)</th>
<th>Site recovery (%)</th>
<th>Specific activity (nmol/mg)</th>
<th>Relative purification (fold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>10,958$^a$</td>
<td>950</td>
<td>100.0</td>
<td>0.087</td>
<td>1.0</td>
</tr>
<tr>
<td>Extract 1</td>
<td>2,352$^a$</td>
<td>186</td>
<td>19.6</td>
<td>0.079</td>
<td>0.9</td>
</tr>
<tr>
<td>Extract 2</td>
<td>2,327$^a$</td>
<td>535</td>
<td>56.3</td>
<td>0.230</td>
<td>2.6</td>
</tr>
<tr>
<td>WGA void</td>
<td>996$^b$</td>
<td>404</td>
<td>42.5</td>
<td>0.406</td>
<td>4.7</td>
</tr>
<tr>
<td>DEAE-Sephacel</td>
<td>335$^b$</td>
<td>177</td>
<td>18.6</td>
<td>0.528</td>
<td>6.1</td>
</tr>
<tr>
<td>Ultragel AcA34</td>
<td>70.2$^b$</td>
<td>113</td>
<td>14.0</td>
<td>1.61</td>
<td>18.5</td>
</tr>
<tr>
<td>Octyl-sepharose</td>
<td>5.39$^b$</td>
<td>41.4</td>
<td>4.36</td>
<td>7.68</td>
<td>88.3</td>
</tr>
<tr>
<td>Sucrose gradient</td>
<td>0.70$^b$</td>
<td>5.26</td>
<td>0.55</td>
<td>7.51</td>
<td>86.3</td>
</tr>
</tbody>
</table>

$^a$Determined by Folin method (Peterson (1983))

$^b$Determined by staining with Amido Black (Schaffner and Weisman, 1973)
Figure II-1A Chromatography of GTP\textsubscript{γS}-binding proteins through DEAE-Sephacel. See methods for explanation.

II-1B Chromatography of GTP\textsubscript{γS}-binding proteins through Ultragel ACA 34. See methods for explanation.
Figure II-1
Figure II-2  Chromatography of GTP\textsubscript{\gamma}S-binding proteins through Octyl-Sepharose. See methods for explanation. Aliquots (20 \mu l) of indicated fractions were analyzed by SDS-polyacrylamide (8-18\%) electrophoresis and visualized by Coomassie staining (upper panel).
Figure II-2
Figure II-3 Chromatography of GTP$_{\gamma}$S-binding proteins through sucrose gradient. See methods for explanations. Aliquots (20 µl) of indicated fractions were analyzed by SDS-polyacrylamide (8-18%) electrophoresis and visualized by Coomassie staining (upper panel).
Figure II-3
Figure II-4  Sodium dodecyl sulfate polyacrylamide gel electrophoresis of atrial G\textsubscript{i}. Lane A, Sucrose gradient purified atrial G\textsubscript{i} analyzed using a 8-18% linear acrylamide gel. G\textsubscript{i} (400 ng) was electrophoresed along with molecular weight markers (phosphorylase a, \(M_r\) 97,114; bovine serum albumen, \(M_r\) 66,296; aldolase, \(M_r\) 39,210; Chymotropsinogen A, \(M_r\) 25,666; soybean trypsin inhibitor, \(M_r\) 20,095; and lysozyme, \(M_r\) 14,314) and visualized with silver staining. Lane B and C, atrial G\textsubscript{i} and brain G\textsubscript{i}/G\textsubscript{o} respectively were run on 12% acrylamide gel as described in methods to resolve \(\alpha_i\) from \(\alpha_o\). The gels were visualized by silver staining. Lane D, Reconstituted G\textsubscript{i} was ribosylated as described in methods and electrophoresed on a 12% acrylamide gel. The gel was visualized by silver staining and exposed to x-ray film for 3 days (Lane E). The additional lower molecular weight bands represent pertussis toxin while the higher molecular weight bands are from contaminating \(\alpha\) keratins seen as a consequence of overstaining the gel to visualize G\textsubscript{i}.
Figure II-5  Binding of $[^{35}\text{S}]\text{GTP}_{\gamma}\text{S}$ to reconstituted $G_{i}$.

Reconstituted $G_{i}$ was incubated with 0.1 to 11 nM $[^{35}\text{S}]\text{GTP}_{\gamma}\text{S}$ (SA = 120 cl/mmol). Duplicate 100 µl aliquots were filtered as described under Methods. Data were analyzed in the form of a Scatchard plot (insert). Least squares analysis gave a dissociation constant of 456 ± 41 pM and a total site concentration of 487 ± 52 pM.
Figure II-5

Free $[^{38}\text{S}]\text{GTP}^\gamma\text{S}$ (nM)

Specific bound $[^{38}\text{S}]\text{GTP}^\gamma\text{S}$ (nM)
Dependence of GTPase on GTP concentration. Gi was
diluted to a concentration of 1.76 nM and incubated for
15 minutes at 32°C in HEMD buffer with the indicated
concentration of $[^{32}P]$GTP. Least squares analysis of
the Lineweaver-Burke plot gave a turnover of $0.19 \pm 0.01$
min$^{-1}$ and a $K_m$ of $7.98 \pm 0.74$ nM.
Acknowledgments

The authors are very grateful to Kimberly Kahler for excellent technical assistance, Chi-Juinn Pan and David Broderick for preparation of atrial membranes, and Barbara Hanson for the typing of the manuscript.
Chapter III

Reconstitution of the Purified Porcine Atrial Muscarinic Acetylcholine Receptor with Purified Atrial Inhibitory Guanine Nucleotide Binding Protein

Contribution of Co-Authors

Kimberly Kehler assisted with some of the $[^{35}\text{S}]\text{GTP}\gamma\text{S}$ binding experiments and was involved with some of the data analysis for these experiments. The remaining experiments were performed and analyzed by myself under the guidance of Professor Michael Schimerlik. G. Scott Herron assisted in the development of the reconstitution procedure.
Abstract

Purified porcine atrial muscarinic receptor (mAChR) was reconstituted with purified porcine atrial inhibitory guanine nucleotide binding protein (G_i) in a lipid mixture consisting of phosphatidylcholine: phosphatidylserine and cholesterol (1:1:0.1 w/w). 5'-Guanylylimidodiphosphate (0.1 mM) had no effect on the binding of the muscarinic antagonist L-quinuclidinyl benzilate but converted high affinity carbachol binding sites (K_d equal to 1 µM) in the reconstituted preparation to the low affinity state (K_d equal to about 100 µM). Steady-state kinetic measurements of GTPase activity showed that the turnover number was increased from 0.19 min^{-1} in the presence of the muscarinic antagonist L-hyoscyamine to 2.11 min^{-1} for the agonist carbachol. The affinity of G_i for GDP was reduced by about fifty-fold upon interaction with the carbachol-mAChR complex, and the observed rate constant for GDP dissociation was increased by thirty-eight fold from 0.12 min^{-1} to 4.5 min^{-1}. Thus the increase in steady-state GTPase activity observed for muscarinic agonists is largely, if not exclusively, due to the increase in GDP dissociation from G_i—probably the rate limiting step in the steady-state mechanism. Carbachol stimulated GTPase was sensitive to ADP-ribosylation of the reconstituted G_i by pertussis toxin, but the high affinity agonist binding was uncoupled only when the reconstituted preparation was treated with pertussis toxin in the presence of GTP and the agonist acetylcholine. These results suggest that association with the mAChR protects G_i from ADP-ribosylation by pertussis toxin.
Abbreviations

mAcChR, muscarinic acetylcholine receptor; Buffer A, 10 mM HEPES, 0.1 M NaCl, 1 mM EGTA, 5 mM MgCl₂, 1 mM DTT, and 0.1 mM PMSF, pH 7.4; Buffer B, 10 mM HEPES, 50 mM NaCl, 1 mM EGTA, 5 mM MgCl₂, 1 mM DTT, and 0.1 mM PMSF, pH 7.4; Buffer C, 25 mM Imidazole, 0.1 M NaCl, 1 mM EDTA, 5 mM MgCl₂, 1 mM DTT, and 0.1 mM PMSF, pH 7.4; PC, soybean L-α-phosphatidylcholine; PS, bovine brain L-α-phosphatidyl-L-serine; CHAPS, (3-[3-cholamidopropyl]-dimethylammonio]-1-propanesulfonate; L-QNB, the L isomer of quinuclidinyl benzilate; Gₛ, the stimulatory guanine nucleotide binding protein; Gᵢ, the inhibitory guanine nucleotide binding protein; Gₜ, transducin; GppNHp, 5'guanylylimidodiphosphate; GTPγS, guanosine 5'-0-(3-Thio-triphosphate); DTT, dithiotreitol; IAP, islet-activating protein (pertussis toxin); HEPES, 4-(2-hydroxyethyl)-1-piperazineethanesulfonate; BHT, butylated hydroxytoluene; EGTA, ethyleneglycol-bis-(β-aminoethyl ether)-N,N',N'-tetraacetic acid; EDTA, ethylene diamine tetraacetic acid; PMSF, phenylmethylsulfonyl fluoride.
Introduction

The mAChR belongs to the class of neurotransmitter receptors in which signal transduction is mediated by guanine nucleotide binding regulatory proteins. Receptors that stimulate adenylyl cyclase have been shown to interact through G\textsubscript{s}, while receptors that inhibit the enzyme, such as the mAChR, appear to be coupled through G\textsubscript{i} (Stryer and Bourne, 1986). In atrial tissue, G\textsubscript{i} activated by mAChRs has also been shown to function as a G\textsubscript{K} (Pfaffinger et al., 1985; Breitweisser and Szabo, 1985; Yatani et al., 1987; Logothetis et al., 1987; Codina et al., 1987) to activate inward rectifying potassium channels. An analogous system can be found in vertebrate photoreceptors where light-activated rhodopsin stimulates cGMP phosphodiesterase via G\textsubscript{T} (Fung, 1983; Stryer and Bourne, 1986).

The guanine nucleotide binding regulatory proteins are heterotrimers with differing \( \alpha \) subunits (\( \alpha_1 = 41 \) kDa, \( \alpha_8 = 45 \) kDa, \( \alpha_0 = 39 \) kDa) and similar \( \beta \) (35 kDa) and \( \gamma \) (5-10 kDa) subunits (Northup et al., 1983; Bokoch et al., 1984; Codina et al., 1984; Stryer and Bourne, 1986). It is thought that light-activated rhodopsin or agonist-bound receptors activate the G protein by catalyzing the exchange of bound GDP for GTP (Cassel and Selinger, 1978; Brandt and Ross, 1986). The binding of GTP will then uncouple the G protein from the receptor (Rodbell, 1980) or rhodopsin (Fung and Stryer, 1980) as well as cause the dissociation of the heterotrimers into \( \alpha \) plus \( \beta \gamma \) subunits (Hildebrandt et al., 1984; Katada et al., 1984a; Katada et al., 1984b). The activation of the G protein results in an enhancement of G protein-mediated GTPase activity. The \( \beta \)-adrenergic
receptor-agonist complex binding to $G_\text{s}$ is thought to induce a conformational change in $G_\text{s}$ that increases the rate of GDP release and GTP association (Cassel and Selinger, 1978; Brandt and Ross, 1986).

The interactions of purified brain $G_\text{i}$ and mAcChRs resolved from guanine nucleotide binding proteins (Florio and Sternweiss, 1985) as well as the interactions of purified brain mAcChR and purified $G_\text{i}$ (Haga et al., 1985; Kurose et al., 1986; Haga et al., 1986) have been demonstrated in reconstituted systems. These studies have shown that the mAcChR agonist complex was capable of stimulating the GTPase activity of $G_\text{i}$ and that association with $G_\text{i}$ results in high affinity agonist binding to the mAcChR. ADP ribosylation of $G_\text{i}$ prior to reconstitution (Haga et al., 1986) prevented the purified brain components from interacting in the reconstituted system. ADP ribosylation of $G_\text{i}$ also uncouples the mAcChR from inhibition of adenylyl cyclase in heart tissue (Martin et al., 1985).

The purpose of this study is to characterize the interaction of purified porcine atrial mAcChR and $G_\text{i}$ in a reconstituted system. Since the heart and brain mAcChRs are known to be different gene products (Kubo et al., 1986a; Kubo et al., 1986b; Peralta et al., 1987b) and the sequence homology of brain and heart $G_\text{i}$ are as yet unknown, these studies should provide additional information regarding the similarity and possible differences in mAcChR-effector interactions in different tissues.
Materials and Methods

$[^{35}\text{S}]\text{GTP}\gamma\text{S}$ (1000 Ci/mmol), $[^{\gamma-32}\text{P}]\text{GTP}$ (20-30 Ci/mmol), and $[^{\alpha-32}\text{P}]\text{GTP}$ (800 Ci/mmol) were purchased from New England Nuclear. $[^{3}\text{H}]\text{L}-\text{QNB}$ (46 Ci/mmol) was purchased from Amersham. Cholesterol, P.C. (type III-s), P.S. (bovine brain), CHAPS, digitonin, carbachol, acetylcholine, L-hyoscyamine, GTP, GppNHp, acetylcholine esterase (type V-S), succinic thiokinase, pyruvate kinase (type VII), and activated charcoal were purchased from Sigma. GDP and GTP$\gamma$S were purchased from Boehringer Mannheim. The purity of GTP and GTP$\gamma$S was determined by thin layer chromatography using a solvent of 1-propanol:NH$_4$OH:H$_2$O (6:3:1). When necessary, these nucleotides were purified by applying them to DEAE Biogel A and eluting with a 0-0.5 M LiCl gradient. Pertussis toxin was from List Biological Laboratories and was stored in 50 mM sodium phosphate, 0.25 M NaCl, pH 7.0, at 100 µg/ml. mAcChR (10-15 nmol $[^{3}\text{H}]\text{L}-\text{QNB/mg}$) was purified from porcine atria (Peterson et al., 1984). G$_i$ (1.4-8 nmol $[^{35}\text{S}]\text{GTP}\gamma\text{S/mg}$ protein) was purified as a byproduct of the mAcChR purification procedure by sequential chromatography on DEAE Sephacel, ultragel ACA-34, and octyl sepharose, followed by sucrose gradient centrification in cholate buffers (details will be published elsewhere).

Reconstitution of mAcChR and mAcChR/G$_i$

PC:PS (1:1), plus 5% w/w cholesterol, stored in toluene:ethanol (1:1), plus 0.02% BHT, were rotovapped to dryness and resuspended in 25 mM imidazole, 0.1 M NaCl, 1 mM EDTA, 8.4 mM CHAPS, pH 7.4, to a
final concentration of 1.2 mg total lipid per ml. The suspension was sonicated to clarity at 0°C under argon. DTT (1 mM) and MgCl₂ (5 mM) were then added. The lipid-detergent solution (330 μl) was transferred to a 10 ml polycarbonate centrifuge tube. mAcChR alone (10 pmol in 10 to 20 μl of 25 mM imidazole, 1 mM EDTA, 0.08% digitonin, and 0.016% sodium cholate, pH 7.4) or mAcChR plus Gᵢ (50 pmol in 30-40 μl of 20 mM Tris, 1 mM EDTA, 5 mM MgCl₂, 75 mM sucrose, and 0.8% sodium cholate, pH 8.0) were added to the lipid detergent mixture along with acetylcholine to 50 μM. The final lipid concentration was 1 mg/ml and the final CHAPS concentration was 7 mM in a volume of 0.4 ml. This mixture was incubated on ice for five minutes and then diluted slowly with ice cold buffer C to a volume of 8 ml. Lipid was then precipitated by adding 2 ml of 50% PEG 8000 containing 5 mM MgCl₂ and 0.1 M NaCl to yield a final PEG concentration of 10%. This solution was incubated on ice for one hour followed by centrifugation at 4°C in a Beckman Ti 75 rotor at 250,000 x g for 75 minutes. The resulting pellet was resuspended in 0.25 ml of buffer A or buffer C. Typical recoveries after reconstitution were 30-40% for both mAcChR and Gᵢ.

Preparation of [α-³²P]GDP

[α-³²P]GDP was prepared from the treatment of [α-³²P]GTP with succinic thiokinase. One volume of [α-³²P]GTP (usually 160 pmole in 12.5 μl of 10 mM Tricine, pH 7.6) was added to one volume of solution containing 0.2 M Tris acetate, pH 8.0, 100 μM Coenzyme A, 20 mM sodium succinate, 10 mM MgCl₂, and 0.4 units/ml of succinic thiokinase. This
reaction was allowed to proceed for 30 minutes at room temperature after which EDTA was added to 7.5 mM and the sample was diluted into 0.5 ml of H\textsubscript{2}O and heated at 100°C for two minutes. The sample was then applied to a 4x1 cm DEAE Bio-Gel A column which had been equilibrated with 5 mM ammonium bicarbonate, pH 7.5. A 5 to 500 mM linear gradient of ammonium bicarbonate was used to elute the column at 0.1 ml/min. Fractions which contained radioactivity and eluted at the same position as unlabelled GDP were pooled, concentrated under vacuum, applied to 15x0.75 cm column of Bio-Gel P-2 pre-equilibrated in H\textsubscript{2}O, and eluted with H\textsubscript{2}O at 0.1 ml/min. The fractions which contained radioactivity were lyophilized at least twice to remove any residual ammonium bicarbonate. Purity of the [\textalpha-\textsuperscript{32}P]GDP was monitored by thin layer chromatography on Merk Silica Gel 60 F254 plates using a solvent of 6:3:1 1-propanol:NH\textsubscript{4}OH:H\textsubscript{2}O, and exposing the TLC plate to X-ray film. At least 90% of the radioactivity migrated with GDP. This material was stored at -20°C in H\textsubscript{2}O until used.

Ligand Binding

The mAcChR was quantitated in terms of [\textsuperscript{3}H]L-QNB binding sites using the DEAE filter disk assay (Peterson and Schimerlik, 1984). All binding assays for reconstituted material were performed in buffer B using 125 \mu l of sample. Non-specific binding was determined in the presence of 10 \mu M L-hyoscyamine or 0.1 M carbachol. Total mAcChR concentration was determined using 20 nM [\textsuperscript{3}H]L-QNB plus or minus 10 \mu M L-hyoscyamine or lipids without mAcChR for nonspecific binding.

[\textsuperscript{35}S]GTP\textgamma S binding was performed as described by Northup et al.
Detergent soluble G_i was incubated for 60 minutes at 32°C in buffer A, supplemented with 25 mM MgCl_2, 0.1% Lubrol PX, and 1 μM [\(^{35}\)S]GTP\(_{\gamma}\)S (3-8 Ci/mmol). Non specific binding was determined in the absence of protein and was less than 0.5% of the total radioactivity. Reconstituted G_i was assayed in buffer A. In some instances the reaction mix was diluted into wash buffer (10 mM Hepes, 0.1 M NaCl, and 25 mM MgCl_2) plus 100 μM GTP to further reduce nonspecific binding.

The determination of bound [\(\alpha-^{32}\)P]GDP was done in a similar manner except that the reaction mixture (50 μl) was diluted into ice cold wash buffer containing 0.5 mM GDP and immediately filtered and washed with 2 ml of buffer. The time from dilution to the end of the final wash was about 7 seconds.

For Scatchard plots and titration curves, duplicate aliquots of the reaction mixture were removed to determine the total radioligand present.

In experiments to determine the binding of nonlabelled GTP, a GTP regenerating system was included so that GDP, produced by the GTPase activity of G_i, would not accumulate. The regenerating system consisted of buffer B plus 5 mM KCl, 1 mM phosphoenolpyruvate, and 70 ng/ml of pyruvate kinase.

GTPase activity was determined as described in Sunyer et al. (1984) with the following alterations. Vesicles were diluted with buffer A to a final concentration between 1 and 4 nM \(^{35}\)S]GTP\(_{\gamma}\)S sites.
Muscarinic ligands were added as described in the text and allowed to equilibrate for five minutes at 32°C. The GTPase reaction was initiated by adding [α-32P]GTP and incubated at 32°C for the desired amount of time. The reaction (50 μl) was quenched by the addition of 0.25 ml of an ice cold suspension of activated charcoal (5% w/v) in 20 mM sodium phosphate (pH 2.3). This mixture was placed on ice for five minutes, then centrifuged at 15,000 x g for 15 minutes at 4°C. The 32P in 0.1 ml of the clear supernatant was measured by Cerenkov counting. Nonenzymatic hydrolysis was subtracted from all determinations. The time course of the GTPase activity was linear under the conditions in which the GTP concentration dependence was performed.

ADP-Ribosylations

Pertussis toxin was activated by incubating with 10 mM DTT and 50 μM ATP at 32°C for 15 minutes. Reconstituted G1 in buffer A was ADP-ribosylated by diluting into an assay mixture to give final concentrations of 5 μM thymidine, 2 mM NAD, and about 0.4 μg/ml activated pertussis toxin. This resulted in a two-fold dilution of vesicles. The reaction was allowed to proceed for 30 minutes at 32°C and was then diluted at least 20 fold into buffer A or B before subsequent experiments were executed.
Data Analysis

Titration curves were fit to equation 1, using Marquardt's algorithm as described by Duggleby (1984).

\[
\bar{Y} = \frac{[L]}{K} \left( \frac{F_1}{1 + [I]/K_1 + [L]/K} + \frac{F_2}{1 + [I]/K_2 + [L]/K} \right)
\]  \hspace{1cm} (1)

In equation (1) \( \bar{Y} \) equaled the fractional saturation of the protein by radioligand and \([L]\) and \([I]\) are the free radioligand and inhibitor concentrations, respectively. \( F_1 \) and \( F_2 \) are the fractions of binding sites having high affinity and low affinity for inhibitor with dissociation constants \( K_1 \) and \( K_2 \), respectively, and \( K \) is the overall dissociation constant for the radioligand. Data were normalized according to equation (2) where \( \bar{Y}_0 \) was the fractional saturation in the absence of inhibitor.

\[
\% \text{ specific bound} = \left( \frac{\bar{Y}}{\bar{Y}_0} \right) \times 100
\]  \hspace{1cm} (2)

Since \( K \) appeared to vary slightly depending on the preparation, its value was calculated for each experiment using the law of mass action and the concentration of bound protein, free protein, and \([L]\) determined in the absence of inhibitor.

Steady state GTPase kinetics were analyzed using Marquardt's algorithm (Duggleby, 1984) by a two component fit to the observed steady-state velocity.
In equation 3, \( v \) is the observed steady-state velocity at GTP concentration \( S \); \( F_1 \) and \( F_2 \) equal the fractions of enzyme having a maximum velocity of \( V_{m1} \) and \( V_{m2} \) and a Michaelis constant of \( K_{m1} \) and \( K_{m2} \), respectively. Turnover numbers for \( V_{m1} \) and \( V_{m2} \) were obtained by dividing each maximal velocity by the concentration of [\(^{35}\)S]GTP\(\gamma S\) binding sites.

Kinetic analysis of [\(\alpha\)-\(^{32}\)P]GDP dissociation was done using nonweighted least squares fitting to either equation (4) or (5)

\[
y(t) = A_1 e^{-t/\tau_1} \\
y(t) = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2}
\]

where \( y(t) \) equaled the specifically bound ligand at time \( t \), \( A_1 \)'s are the amplitudes and \( \tau_1^{-1} \)'s the reciprocal relaxation times for the exponential decay processes. For equation 5, the slow phase was analyzed after the decay of the fast kinetic phase. The fast phase was then evaluated after by subtraction of the slower component.
Results

Purified porcine atrial muscarinic mAChR reconstituted with purified porcine atrial G\textsubscript{i} (SDS gel shown in Fig. III-1) was able to bind \[^{3}H\]L-QNB in a concentration dependent manner showing a single class of binding sites within the concentration range examined (Fig. III-2). The binding of L-QNB to the mAChR was not effected by the presence of 0.1 mM GppNHp in agreement with findings on reconstituted porcine brain muscarinic receptor and G\textsubscript{i} (Haga et al., 1986). Figure III-3A shows the carbachol displacement of \[^{3}H\]L-QNB bound to mAChR reconstituted without G\textsubscript{i}. The titration curve was analysed assuming one class of carbachol binding sites and the resulting dissociation constant was not significantly different from the low affinity carbachol binding site for membrane-bound and detergent-solubilized atrial mAChR (Schimerlik et al., 1986). However, when mAChR was reconstituted with G\textsubscript{i} (Fig. III-3B) there appeared a class of high affinity carbachol binding sites which were sensitive to 0.1 mM GppNHp. Treatment of the reconstituted mAChR and G\textsubscript{i} with 0.1 mM GppNHp caused an apparent uncoupling of the two proteins since the mAChR bound carbachol as if it were reconstituted without G\textsubscript{i}. The average \(K_d\) value (n=4) for the high affinity binding site was 1.1 ± 0.5 \(\mu\text{M}\) and 44 ± 11% of the \[^{3}H\]L-QNB binding sites were sensitive to guanine nucleotides.

Coupling of the mAChR to G\textsubscript{i} was also demonstrated by the ability of carbachol to increase the GTPase activity associated with G\textsubscript{i} (Fig. III-4). The apparent dissociation constant for carbachol-stimulated GTPase activity (2.1 \(\mu\text{M}\)) was in good agreement with the GppNHp
sensitive high affinity carbachol binding site seen in the titration curves (Fig. III-3B). The carbachol induced increase in GTPase was blocked by 10 μM hyoscyamine. The GTPase activity in the presence of L-hyoscyamine was slightly lower than in the absence of ligands (76 ± 11%, n=4). The presence of acetylcholine esterase during the GTPase reaction did not alter the inhibition due to the antagonist, thus contamination by acetylcholine from the reconstitution was unlikely.

The dependence of the conversion of low affinity muscarinic agonist binding to the high affinity state on Gᵢ concentration is shown in Fig. III-5. The amount of 0.1 mM GppNHp sensitive high affinity carbachol binding was near maximal when Gᵢ and mAChR were reconstituted in a 5:1 molar ratio.

In order to more completely examine the coupling of the mAChR to Gᵢ in terms of the muscarinic agonist-stimulated GTPase, GTP concentration dependence of the GTPase activity of Gᵢ was determined in the presence of saturating concentrations of either carbachol or L-hyoscyamine. As seen in Figure III-6, treatment of the reconstituted system with carbachol resulted in an apparent four fold increase of Vₘₐₓ and a 2.6 fold increase in the Kₘ for GTP. The apparent turnover numbers in this experiment were 0.19 min⁻¹ and 0.76 min⁻¹ for the L-hyoscyamine and carbachol treated preparations, respectively.

In order to more fully elucidate the properties of the Gᵢ coupled to the mAChR, a series of ligand binding and kinetic studies were initiated. The first probe used was the nonhydrolyzable GTP analogue GTPγS. Because of the possibility of interference from bound GDP (Ferguson et al., 1986; Chapter II, this thesis) unpublished results) we did not directly examine the association rate constant of GTPγS.
The equilibrium dissociation constant for \(^{35}\text{S} \text{GTP}\gamma\text{S}\) was determined in the presence of carbachol or L-hyoscyamine (Fig. III-7). The binding studies showed that the ligand bound to homogeneous class of sites (\(K_d\) equal to about 400 nM) and the dissociation constant was not strongly affected by muscarinic ligands within the range of concentrations examined.

The effects of carbachol on GTP binding was investigated by measuring the inhibition of the initial rate of GTP\(\gamma\text{S}\) binding. The binding of \(^{35}\text{S} \text{GTP}\gamma\text{S}\) for the first 60-90 seconds of the time course was linear. The inverse of this initial rate was plotted as a function of GTP. A straight line was drawn through both the agonist and antagonist data sets and had a common intersection point on the X axis. Therefore, both the agonist and antagonist treated samples showed an inhibition constant of about 10 nM for GTP binding to \(G_i\) (Fig. III-8). As with GTP\(\gamma\text{S}\), the affinity of this triphosphate was unchanged by carbachol.

The dissociation constant of GDP was, however, strongly affected by muscarinic ligands (Fig. III-9). When incubated with L-hyoscyamine, the displacement of \(^{35}\text{S} \text{GTP}\gamma\text{S}\) by GDP could be fit by assuming one class of binding sites for GDP (\(K_d = 7 \text{ nM}\)). Incubation with carbachol produced a shallower titration curve which was fit by assuming two classes of binding sites for GDP. Thus the presence of carbachol had produced a population of \(G_i\) with a low affinity for GDP (32%, \(K_d = 499 \text{ nM}\)) with no significant change in the remaining population (\(K_d = 12.7 \text{ nM}\)).

In order to determine to what extent the change in GDP affinity caused by carbachol was due to a change in the dissociation rate of
GDP, the release of \([\alpha-^{32}P]GDP\) was measured in the presence of a muscarinic agonist and antagonist (Fig. III-10). The results indicated a single phase of GDP release from antagonist treated material with \(\tau^{-1}\) of 0.1 min\(^{-1}\). In the presence of carbachol there was a rapid phase of GDP release \((\delta A_1/\delta At = 27\%, \tau_1^{-1} = 4.5\) min\(^{-1}\)) followed by a slower phase \((\delta A_2/\delta At = 63\%, \tau_2^{-1} = 0.13\) min\(^{-1}\)) which was similar to the rate of GDP release in the presence of L-hyoscyamine. Although the fast phase was poorly defined, a value could be estimated that was 33 to 44 times faster than the slow phase of GDP release. The change in \(K_d\) for GDP could therefore be explained by a change in the dissociation rate for GDP.

Since 30% of the \([^{35}S]GTP_y\) sites were affected by muscarinic agonists, it was necessary to re-evaluate the carbachol stimulated GTPase data assuming that 30% of the \(G_i\) was responsive to carbachol and the remaining protein hydrolysed GTP with a rate similar to that found in the presence of L-hyoscyamine. The concentration dependence of the steady-state velocity of GTP hydrolysis in the presence of carbachol was then analyzed as the sum of two simultaneous reactions (see Fig. III-6, Equation 3) where 30% of the total enzyme appeared to interact with the mAcChR. This gave a \(K_m\) for GTP equal to \((31 \pm 4)\) nM and a turnover number of \(2.1 \pm 0.1\) min\(^{-1}\) for the carbachol stimulated GTPase. In three experiments where the ratio of \(G_i/mAcChR\) was between 5:1 and 4:1 the average value of the carbachol stimulated turnover was \(2.17 \pm .07\) min\(^{-1}\). This value was independent of slight variations in the ratio of \(G_i\) and mAcChR recovered after reconstitution, and the value of 30% obtained from the two GDP binding experiments was used without corrections in other experiments where the ratio of the two
proteins were not exactly the same. Therefore carbachol promoted an actual 11-fold increase in turnover number rather than the observed 4 fold stimulation.

The effectiveness of guanine nucleotides in altering the binding of \(^{3}H\)L-QNB in the presence of 100 \(\mu M\) carbachol could be related to their affinity for \(G_i\) in the presence of agonist (Fig. III-11). The apparent \(K_d\) for GDP was similar to the thermodynamic dissociation constant obtained from competition binding with \(^{35}S\)GTP\(_\gamma\)S and the apparent dissociation constant for GTP was similar to the \(K_m\) value obtained from the GTP concentration dependence of the carbachol-stimulated GTPase activity. The order of potency was GTP\(_\gamma\)S > GTP > GDP where GTP was about 17 fold more potent than GDP in eliciting a change in carbachol binding.

The effect of ADP-ribosylation on muscarinic agonist-stimulated GTPase was then determined for the reconstituted preparation. A solution containing 0.13 pmol of \(^{3}H\)L-QNB sites and 0.61 pmol of \(^{35}S\)GTP\(_\gamma\)S sites in 8 \(\mu l\) was ADP-ribosylated as described in methods in a total reaction volume of 20 \(\mu l\). The IAP-treated mixture was diluted 20-fold into buffer A and assayed for GTPase activity with 500 nM \([\gamma^{32}p]\)GTP and either 2 mM carbachol or 10 \(\mu M\) L-hyoscyamine (assays were performed in triplicate). When NAD was omitted, 67.2 ± 0.2 nM \([^{32}p]\) was released in one hour in the presence of carbachol while 25.6 ± 3.4 nM was released in the presence of L-hyoscyamine. When 2 mM NAD was included the amount of \([^{32}p]\) released was 26.0 ± 3.2 and 21.6 ± 4.4 nM for carbachol and L-hyoscyamine treated samples, respectively. Thus pertussis toxin plus NAD attenuated most, if not all, of the agonist stimulated GTPase. Neither the non-stimulated GTPase nor the
amount of $[^{35}S]GTP_yS$ sites were affected by ADP-ribo
sylation (data not shown). A similar treatment of reconstituted material had no effect
on the ability of carbachol to displace $[^3H]L-\alpha$NB or on the ability of
0.1 mM GppNHp to alter carbachol binding (Fig. III-12A and III-12B).
The ADP-ribo
sylation experiment was then repeated in the presence of
acetylcholine and GTP. Prior to titration curve experiments
acetylcholine was removed from the system by treatment with
acetylcholine esterase and the majority of the GTP should have been
hydrolysed to GDP by the activated G_i. Any residual GTP and GDP were
diluted below a concentration (less than 2 nM) in which they were
effective in uncoupling the proteins. Under these conditions the
binding of carbachol to the mAcChR was decreased and there was no
further effect of 0.1 mM GppNHp (compare Fig. III-12C and III-12D).
Discussion

The data presented above demonstrated that porcine atrial mAChR effectively coupled to porcine atrial G_i in the reconstituted system. The criteria for coupling were (1) the ability of muscarinic ligands to alter the interaction of guanine nucleotides with G_i, (2) the tenfold stimulation of steady-state GTP hydrolysis by the muscarinic agonist carbachol and (3) the appearance of a guanine nucleotide-sensitive high affinity carbachol binding by the mAChR.

Treatment of the coupled system with 0.1 mM GppNHP resulted in an apparent uncoupling of the two proteins. After treatment with the nucleotide the receptor interacted with carbachol in a manner similar to mAChR reconstituted without G_i. mAChR reconstituted alone had a homogenous low affinity binding as seen in Fig. III-3. It should be noted that there was some variability between receptor preparations and that mAChR reconstituted alone or mAChR and G_i treated with 0.1 mM GppNHP did not always show a homogenous low affinity carbachol binding site. This heterogeneity with respect to carbachol binding has been previously observed both in detergent soluble preparations (Peterson and Schimerlik, 1984) and for the reconstituted brain mAChR (Haga et al., 1986), and has not yet been adequately explained.

Although, a fraction of the mAChR high affinity sites occasionally remained in the high affinity state in the presence of saturating GppNHP, guanine nucleotide sensitive high affinity agonist binding was observed for all reconstituted preparations. The average dissociation constant for carbachol binding to the GppNHP sensitive high affinity site was $1.1 \pm 0.5 \mu M$ and $44 \pm 11\%$ of the $[^3H]L-QNB$ sites were
sensitive to guanine nucleotides. This maximum value of mAChR that can be coupled to $G_i$ agrees with that found for the brain mAChR reconstituted with brain $G_i$ (48 ± 11%, Haga et al., 1986); however, in the atrial system only a five-fold excess of $G_i$ over receptor was necessary to see the maximum effect as opposed to a 20-fold excess for the brain system. The reasons for this difference are not known, but may be due to the different structures of the brain and heart mAChRs (Kubo et al., 1986a; Kubo et al., 1986b; Peralta et al., 1987) or to the differences in reconstitution procedures. The $K_d$ of carbachol for the coupled receptor (1.1 μM) agreed quite well with the $K_{app}$ for the carbachol stimulated GTPase activity ($K_{app} = 2.1 ± 0.3$ μM). This was further evidence that the high affinity carbachol binding site was interacting with $G_i$.

The mAChR could also be uncoupled from $G_i$ by treatment with other guanine nucleotides. The order of potency for this effect was GTP$_\gamma$S > GTP > GDP (Fig. III-11). The ability of GDP to uncouple the mAChR from $G_i$ has also been noted by others (Haga et al., 1986). A $K_{app}$ was determined for each of these nucleotides and the $K_{app}$ for GDP (557 nM) agreed with the dissociation constant of GDP from receptor activated $G_i$ (500 nM). A $K_{app}$ for GTP was determined to be 33 nM. It was somewhat difficult to rigorously interpret this value, since even though there was a GTP regenerating system included, GTP would be converted to GDP on $G_i$. However the value obtained was similar to the $K_m$ of GTP for the carbachol-activated $G_i$ (31 nM). Determination of the $K_{app}$ for GTP$_\gamma$S was also not straightforward. Because of the low $K_d$ (about 0.4 nM from Scatchard analysis) certain assumptions had to be made in terms of free ligand. Since both carbachol and
L-hyoscyamine treated mAcChR-G_\textsubscript{i} had about the same high affinity binding for GTP\textsubscript{γ}S, all of the G_\textsubscript{i} present was assumed to participate equally in binding GTP\textsubscript{γ}S for the calculation of free nucleotide. This gave a value of 2.7 ± 3.4 nM for an estimation of K\textsubscript{app} which was almost an order of magnitude greater than the estimated K\textsubscript{d}. However the value for K\textsubscript{app} is not well defined and may reflect the inaccuracies arising from the use of an inappropriate G_\textsubscript{i} concentration. In any case, it was clear that GTP\textsubscript{γ}S was more effective than GTP in uncoupling the receptor. Also both GTP and GDP uncouple the receptor by binding to the activated agonist mAcChR-G_\textsubscript{i} complex.

Coupling between mAcChR and G_\textsubscript{i} was also sensitive to ADP-ribosylation by pertussis toxin. As seen for brain system (Haga et al., 1985), ADP-ribosylation interferes with the carbachol stimulated GTPase. However, ADP-ribosylation using similar conditions did not show any effect on carbachol binding. The mAcChR still demonstrated high affinity guanine nucleotide-sensitive carbachol binding (Fig. III-12A,B). Addition of GTP and acetylcholine during ADP-ribosylation resulted in a loss of this guanine nucleotide-sensitive carbachol binding site. Kurose et al. (1986) also report a similar uncoupling when G_\textsubscript{i} was ADP-ribosylated before reconstitution. In the reconstituted system the ADP-ribosylation must be performed in the presence of acetylcholine and GTP in order to see an effect on carbachol binding, but these conditions were not necessary for seeing an attenuation of carbachol-stimulated GTPase. A possible explanation was that the addition of GTP during the GTPase assay is sufficient to increase ADP-ribosylation efficiency either by
further activating the toxin or stabilizing $G_i$. Such a phenomena has been previously noted (Mattera et al., 1986).

Based on IC50 values, ATP binds to pertussis toxin about 140 times tighter than GTP (Mattera et al., 1986). Therefore, it seems unlikely that 500 nM GTP would have an effect in the presence of 25 μM ATP. It is also unlikely that the effect was due to additional stabilization of $G_i$. Without any added guanine nucleotides during ADP-ribosylation there was still some $G_i$ coupled to the mAcChR. If $G_i$ was denatured during the half hour preincubation with IAP, it would not explain the ability of GppNHp to convert high affinity agonist sites to lower affinity (Fig. III-12B). An alternative explanation is that the mAcChR was precoupled to $G_i$ and this protected the associated $G_i$ from ADP ribosylation. Free $G_i$ was still ADP-ribosylated. The GTPase assay of the ADP-ribosylated sample showed no increase of activity when carbachol was added because all the free $G_i$ was ADP-ribosylated and each precoupled $G_i$ was only able to complete one GTPase cycle before it was also ADP-ribosylated.

The regulation of $G_i$ by agonist occupied mAcChR was shown by a stimulation of GTPase activity. As seen in Figure III-6 there was an apparent four fold stimulation of the GTPase activity of carbachol treated $G_i$-mAcChR compared to L-hyoscyamine treated, and a 2.6 fold increase in $K_m$. The $K_m$ (9.8 nM) and $V_{max}$ (0.19 min$^{-1}$) obtained for L-hyoscyamine treated reconstituted mAcChR and $G_i$ were similar to the values determined with brain mAcChR and brain $G_i$ (Kurose et al., 1986), determined in the absence of ligand. However, the apparent stimulation observed in the presence of carbachol was greater in the present study. Using the assumption that 30% of the $G_i$ was stimulated
by the mAcChR the GTPase kinetics were re-evaluated to give a turnover of 2.1 min\(^{-1}\) for G\(_i\) coupled to receptor. This value was similar to the turnover obtained for the activated catecholamine stimulated GTPase associated with G\(_s\) after similar corrections were performed (Brandt and Ross, 1986). L-hyoscyamine-treated mAcChR and G\(_i\) showed a 24% lower GTPase activity compared to the absence of ligands (n=4). Addition of acetylcholine esterase (PMSF was omitted for this experiment) did not alter these results. Thus contamination by acetylcholine seems unlikely. The reason for these observations are not yet known.

It has been suggested that activation of G\(_s\) by its associated receptors results in an "open" G protein in which there is an accelerated turnover of guanine nucleotides (Stryer and Bourne, 1986) and a recent study suggested that the agonist stimulation of G\(_s\) involves both an increase in the rate of GTP binding and dissociation of GDP (Brandt and Ross, 1986). In other hormone-G protein systems, agonists were seen to regulate the binding of GTP\(_\gamma S\) (Brandt and Ross, 1986) and an agonist-induced effect on the apparent association rate of GTP\(_\gamma S\) has been noted for the reconstituted brain mAcChR and brain G\(_i\) (Kurose et al., 1986). In the present study differences in GTP\(_\gamma S\) binding between carbachol and L-hyoscyamine treatments were observed (data not shown); however, the effects of bound GDP can not be ruled out. At 100 nM GTP\(_\gamma S\) in the presence of L-hyoscyamine, the rate of GTP\(_\gamma S\) binding was similar to the rate of GDP release and was preceded by a burst phase. In the presence of carbachol the predominant difference was a change in the amplitude of the burst phase which was assumed to represent the fraction of G\(_i\) which had no GDP bound or
bound GDP with low affinity. When the equilibrium binding of GTP\textsubscript{yS} was examined there was no significant difference between incubation with carbachol or L-hyoscyamine (Fig. III-7). Although there was no change in GTP\textsubscript{yS} binding, there was a 3.2 fold increase in the $K_m$ of GTP when the GTPase reaction was performed in the presence of carbachol. It is not yet clear if this is due to a difference in the affinity of $G_i$ for GTP, or a change in some other intermediate step of the mechanism.

The GTPase activity of $G_i$ precluded or at least complicated measuring the $K_d$ of GTP by displacement of GTP\textsubscript{yS} in an equilibrium titration curve as was done for GDP. An alternative was to measure the initial rate of $[^{35}\text{S}]$GTP\textsubscript{yS} binding in the presence of simultaneously added GTP. It was hoped this would minimize the effects of GTP hydrolysis. The faster GTP\textsubscript{yS} binding observed in the presence of carbachol was due to the apparent burst phase GTP\textsubscript{yS} binding caused by the agonist induced increase in GDP dissociation. The initial linear portion of the binding curve was used. A replot of the inverse of initial rate as a function of GTP concentration gave a straight line for such data set (Fig. III-8). The extrapolated dissociation constant for GTP (~10 nM) was unchanged by the addition of muscarinic agonist and was similar to $K_m$ values (9.8 nM for L-hyoscyamine treated, 31.0 nM for carbachol treated) estimated for GTPase and was similar to the $K_{app}$ of GTP for uncoupling mAChR from $G_i$ (33 nM). This is further evidence that the affinity of GTP for the mAChR-$G_i$ complex was unchanged by muscarinic agonists.

The data presented in Figure III-9 demonstrated that agonist stimulation of mAChR coupled to $G_i$ resulted in a decrease in affinity
of GDP for $G_i$. The change in affinity for GDP (50-fold) could be explained by the change in GDP dissociation rate (38-fold) if the binding of GDP was a simple bimolecular reaction. Such an assumption would predict an association rate between $1.5 \times 10^5$ and $2.0 \times 10^5$ M$^{-1}$ sec$^{-1}$. This value is within the range of values determined for the association rate of GDP binding to $G_o$ (Higashijima et al., 1987c).

The average value for the slow phase of GDP release was about 0.12 min$^{-1}$ and the turnover of the GTPase reaction in the presence of L-hyoscyamine was 0.19 min$^{-1}$. The rate limiting step for the non-stimulated GTPase was therefore the release of GDP. Any stimulation of $V_{\text{max}}$ must alter this step, and stimulation caused by agonist bound mAcChR increases $V_{\text{max}}$ to about 2.1 min$^{-1}$. Therefore stimulation by the mAcChR causes an increase in GDP release; however, GDP release may be only partially rate-limiting in the steady-state mechanism. (The GDP dissociation rate in the presence of carbachol was 4.5 min$^{-1}$.)

In summary, the atrial mAcChR is able to functionally interact with atrial $G_i$. The evidence indicates that the proteins are precoupled after reconstitution. Treatment with agonist caused an activation of the GTPase associated with $G_i$ by, at least in part, increasing the dissociation rate of GDP. Guanine nucleotides were able to uncouple the mAcChR from $G_i$. After uncoupling, the low affinity form of the receptor for agonists may then combine with another (GDP bound) $G_i$. Both rhodopsin (Fung and Styrer, 1980) and the adrenergic receptor (Brandt and Ross, 1986) seem to act catalytically with respect to G protein activation. The findings in this study indicated that if the $G_i$/mAcChR ratio is about 5:1 and 30\%
of the $G_i$ is activated then about 1.5 $G_i$ are activated per mAChR.

Since only 40% of the mAChR can couple, then 3-4 $G_i$ are activated per receptor.
Figure III-1 SDS polyacrylamide gel of purified porcine atrial mAcChR and purified porcine atrial Gi used for reconstitution studies. Samples and molecular weight markers (phosphorylase a, $M_T$ 97,114; bovine serum albumen, $M_T$ 66,296; aldolase, $M_T$ 39,210; chymotrypsinogen A, $M_T$ 25,666; soybean trypsin inhibitor, $M_T$ 20,095; and lysozyme, $M_T$ 14,314) were electrophoresed on an 8-18% linear acrylamide gradient gel using the discontinuous buffer system of Laemmli (1970) and visualized by silver staining (Wray et al., 1981).
Figure III-1

mAChR  G_i

97.1K  66.3K
39.2K  25.7K
20.1K  14.3K

-α  -β  -γ
Figure III-2  Binding of $[^3H]L$-QNB to reconstituted $G_i$ and mAChR.

The reconstituted preparation containing approximately 150 pM $[^3H]L$-QNB sites and 975 pM $[^35S]GTP_\gamma S$ sites was equilibrated in buffer B with 0.05 to 5.00 nM $[^3H]L$-QNB for two hours at 32°C in the presence (○) or absence (●) of 100 μM GppNHp. The data points represent the mean ± SD of triplicate determinations. After correction for nonspecifically bound label in the presence of 10 μM L-hyoscyamine, data were analysed in the form of a Scatchard plot (insert). Least squares analysis gave a dissociation constant of (297 ± 26) pM and a total site concentration of (154 ± 16) pM for the control and a dissociation constant of 292 ± 12 pM and a site concentration of (146 ± 8) pM for GppNHp treated vesicles.
Figure III-2
Figure III-3 Carbachol titration of specifically bound $[^3H]L$-QNB.

A. Reconstituted mAChR alone was diluted in buffer B to a concentration of 141 pM in $[^3H]L$-QNB sites. Samples were added to tubes containing the indicated final concentration of carbachol and after 30 minutes at 32°C, 550 pM $[^3H]L$-QNB was added. After 2 hours specific binding was determined as described in methods. Data points represent the average ± SD of triplicate determinations. The data were fit to equation (1) holding $F_1$ at 1.0 to give a $K_d$ for carbachol of (122 ± 11) μM using a $K_d$ of 305 pM for L-QNB. B. Reconstituted mAChR and Gi were diluted into buffer B in the presence (●) or absence (○) of 0.1 mM GppNHp and titrated with carbachol as described above. The titration in the absence of GppNHp contained 73 pM $[^3H]L$-QNB sites and 350 pM $[^35S]GTP\gamma S$ sites. The data were fit to equation (1) using a $K_d$ for L-QNB of 460 pM. Analysis gave $F_1$ equal to 0.53 ± 0.04, $K_1$ equal to (1.0 ± 0.3) μM, $F_2$ equal to 0.47 ± 0.04 and $K_2$ equal to (66.5 ± 11.7) μM. In the presence of GppNHp the curve was fit to equation (1) holding $F_1$ at 1.0 using 93 pM $[^3H]L$-QNB total binding sites and a $K_d$ for L-QNB equal to 431 pM. The $K_d$ for carbachol was calculated to equal (121.6 ± 10.3) μM.
Figure III-3
Figure III-4  Carbachol dependence of mAChR stimulated GTPase.

Samples were pre-incubated in buffer A for 5 minutes at 32°C with the indicated final carbachol concentrations. The GTPase reaction was initiated by adding \([\gamma-\text{\textsuperscript{32P}}]\text{GTP}\) to a concentration of 500 nM and incubating for an additional hour. Samples (50 \(\mu\text{l}\) containing 4.8 nM \(\text{[\textsuperscript{35S}]GTP}\) sites and 0.82 nM \(\text{[\textsuperscript{3H}]L-QNB}\) sites) were assayed for \(\text{\textsuperscript{32P}}\) released as described in methods. The data points represent the average ± SD of triplicate determinations and were fit to the law of mass action to give an apparent dissociation constant of (2.1 ± 0.3) \(\mu\text{M}\) for carbachol.
Figure III-4

GTPase activity (nM h⁻¹)

-Log[Carbachol], (M)
Dependence of high agonist affinity nucleotide sensitive binding sites on $G_i$ concentration present during reconstitution. mAChR (10 pmol) was reconstituted with the indicated amounts of $G_i$ as described in methods. The recovered mAChR was then adjusted to 500 pM $[^3H]$L-QNB binding sites in buffer B and incubated for 30 min with 10 μM carbachol either with or without 0.1 mM GppNHp. $[^3H]$L-QNB was then added to 500 pM, allowed to incubate for 2 hours, and filtered as described in methods. Assays were performed in triplicate. The fraction of conversion was defined as $1 - \frac{\text{sp. bd. cpm in the absence of GppNHp}}{\text{sp. bd. cpm with GppNHp present}}$ and plotted as percent of maximum. The line drawn through the data points has no theoretical significance.
Figure III-5
Dependence of GTPase Activity of G_i Reconstituted with mACChR on GTP concentration. Reconstituted material (0.8 nM [35S]GTPγS binding sites and 0.2 nM [3H]L-QNB binding sites) in buffer A was incubated with either 2 mM carbachol (●); or 10 μM L-hyoscyamine (○) for five minutes at 32°C and the GTPase reaction was started by adding [γ-32P]GTP and allowed to continue for 15 minutes. Values represent the mean ± standard deviation of triplicate determinations. Data were analysed by a direct fit to the Michaelis-Menten equation to give a $K_m$ of $(9.79 ± 1.42)$ nM and a $V_{max}$ of $(154 ± 8)$ pM min$^{-1}$ for L-hyoscyamine treated vesicles and a $K_m$ of $(25.5 ± 1.3)$ nM and a $V_{max}$ of $(612 ± 11)$ pM min$^{-1}$ for carbachol treated vesicles. Alternatively, data were analysed according to equation (3) as described in results assuming 30% interactive G_i. The theoretical curve from this analysis was virtually superimposable over the curve drawn in the Figure.
Figure III-6

$V$ (pM min$^{-1}$) vs. [GTP], (nM)
Figure III-7  Binding of \(^{35}\text{S}\)GTP\(_\gamma\)S to reconstituted G\(_i\) plus mAChR.

The reconstituted preparation containing approximately 122 pM \(^{35}\text{S}\)GTP\(_\gamma\)S sites and 35 pM \(^3\text{H}\)L-QNB binding sites was equilibrated in buffer A with \(^{35}\text{S}\)GTP\(_\gamma\)S for 2 hours at 32°C in the presence of either 2 mM carbachol (●) or 10 μM L-hyoscyamine (○). Duplicate 100 μl aliquots were filtered as described under Methods. Data were analysed in the form of a Scatchard plot (insert). Least squares analysis gave a dissociation constant of (332 ± 32) pM, and a total site concentration of (128 ± 15) pM for carbachol treated vesicles. L-hyoscyamine treated vesicles showed a dissociation constant of (454 ± 70) pM and a total site concentration of (117 ± 21) pM.
Figure III-7

Specific Bound $[\text{GTP}^\text{35S}]_\text{free}$, (nM)

Free $[\text{GTP}^\text{35S}]$, (nM)

Bound $[\text{GTP}^\text{35S}]$, (nM)
The inhibition of the initial rate of $[^{35}\text{S}]\text{GTP}_\gamma\text{S}$ binding to $G_i$ by GTP. A liposome preparation containing 0.40 nM $[^{35}\text{S}]\text{GTP}_\gamma\text{S}$ binding sites and 70.0 pM $[^{3}\text{H}]\text{L-QNB}$ sites was incubated with either 2 mM carbachol (●) or 10 μM L-hyoscyamine (○) for 5 minutes at 32°C. The reaction was initiated by adding $[^{35}\text{S}]\text{GTP}_\gamma\text{S}$ together with GTP to give 10 nM $[^{35}\text{S}]\text{GTP}_\gamma\text{S}$ and the indicated concentrations of GTP. Samples were removed and filtered at 15-30 second intervals for 5 minutes. Using data from the first 60-90 seconds of the reaction, the inverse of the initial rate of $[^{35}\text{S}]\text{GTP}_\gamma\text{S}$ binding was plotted as a function of GTP concentration. The data was then fit by a linear least squares method.
Inhibition of Initial Rate of GTP\(\gamma\)S Binding by GTP

\[ v^{-1} \times 10^{-3} \left( \frac{cpm}{min} \right)^{-1} \]

L-Hyoscyamine
\[ k_i = 9.1 \pm 1.7 \text{ nm} \]

Carbachol
\[ k_i = 11.1 \pm 2.1 \text{ nm} \]

Figure III-8
Figure III-9  GDP titration of specifically bound $[^{35}\text{S}]{\text{GTP}}_{\gamma}\text{S}$. The reconstituted preparation containing approximately 170 pM $[^{3}\text{H}]{\text{L-}}\text{QNB}$ binding sites and 940 pM $[^{35}\text{S}]{\text{GTP}}_{\gamma}\text{S}$ sites in buffer A was supplemented with either 2 mM carbachol ($\bullet$) or 10 $\mu$M L-hyoscyamine (○). Samples were then added to tubes containing the indicated final concentrations of GDP and incubated for 15 minutes at 32°C. $[^{35}\text{S}]{\text{GTP}}_{\gamma}\text{S}$ was then added to a final concentration of 1.6 nM and the incubation continued for an additional two hours at which time samples were filtered as described in Methods. Data for carbachol treated vesicles were analysed using equation (1) and a $K_d$ of 280 pM for $[^{35}\text{S}]{\text{GTP}}_{\gamma}\text{S}$ and 188 pM for the total number of $\text{GTP}_{\gamma}\text{S}$ sites. A fit to equation (1) gave $F_1 = 0.68 \pm 0.04$, $K_1 = (12.7 \pm 2.1)$ nM, $F_2 = 0.32 \pm 0.04$, and $K_2 = (499 \pm 86)$ nM. The analysis for L-hyoscyamine treated vesicles assumed one class of binding site with a $K_d$ of 277 pM for $[^{35}\text{S}]{\text{GTP}}_{\gamma}\text{S}$ and 164 pM in $\text{GTP}_{\gamma}\text{S}$ binding sites. The dissociation constant for GDP was calculated to equal $(7.0 \pm 0.3)$ nM from the fit to equation (1) fixing $F_1$ at 1.0.
Figure III-9
Figure III-10  Time course for [α-32P]GDP dissociation. Reconstituted mAcChR (360 pM in [3H]L-QNB binding sites) and G\textsubscript{i} (2 nM in [35S]GTP\textsubscript{γ}S sites) were incubated in buffer A at 32°C in the presence of 100 nM [α-32P]GDP for 30 minutes. The dissociation reaction was initiated by adding unlabelled GDP to a final concentration of 100 µM plus either 2 mM carbachol (●) or 10 µM L-hyoscyamine (○). Aliquots were removed at the time indicated and filtered as described in methods. L-hyoscyamine data were analysed by a least squares fit to a single exponential (equation 4) which gave an ordinate intercept of 94 ± 3% bound and a rate constant of (0.100 ± 0.004) min\(^{-1}\). The time course for dissociation in the presence of carbachol contained two kinetic phases and was analysed according to equation 5. The slow phase (δA\textsubscript{2}/δA\textsubscript{t} = 63 ± 4%; \textit{τ}_{2}^{-1} = (0.136 ± 0.001) min\(^{-1}\)) was analysed by a least squares fit using data obtained after one minute. The fast phase was then evaluated after subtraction of the slow phase. (δA\textsubscript{1}/δA\textsubscript{t} = 27 ± 8%; \textit{τ}_{1}^{-1} = 4.5 ± 0.8 min\(^{-1}\)).
Figure III-10

Bound [α-32P]GDP (percent) vs. Time (min)

Data points and trend lines illustrating the decrease in bound [α-32P]GDP over time.
Figure III-11 Guanine nucleotide titration of carbachol affinity change. Respective guanine nucleotides (O, GTP γ S; △, GTP; 0 GDP) were added to the reconstituted preparation in buffer B containing 0.25 nM [3H]L-QNB binding sites and 3 nM [35S]GTP γ S sites plus 0.1 mM carbachol to give the final concentrations of nucleotides shown. Samples which contained GTP also contained the GTP regenerating system described in methods. After one half hour incubation at 32°C [3H]L-QNB was added to 585 pM. After incubation for 2 hours, samples were filtered as described in methods. Data points are the average ± SD of triplicate determinations and represent the percentage of [3H]L-QNB binding in the presence of 0.1 mM carbachol and 0.1 mM GppNHp compared to [3H]L-QNB binding in absence of GppNHp. Data were fit to the law of mass action to give K_{app} of (2.7 ± 3.4) nM for GTP γ S, (33.2 ± 5.3) nM for GTP, and (557.4 ± 207.3) nM for GDP.
Figure III-11

Guanine nucleotide response (% of max)

-Log [Nucleotide], (M)
mAcChR and Gi were ADP-ribosylated as described in Methods with (B,D) or without (A,C) NAD. C and D were supplemented with 500 nM GTP and 5 μM acetylcholine and after a 30 minute incubation were allowed to incubate 5 additional minutes at 32°C with 0.76 U ml⁻¹ of acetylcholine esterase. Reaction mixtures were then diluted into buffer B to give an [³H]L-QNB site concentration of 72 pM and a GTPγS site concentration of 334 pM for A and B and 78 pM [³H]L-QNB sites and 400 pM GTPγS sites for C and D. Carbachol titration of specifically bound [³H]L-QNB was performed in the presence (●) or absence (○) of 100 μM GppNHP. Lines through the data were drawn by eye and have no theoretical basis.
Figure III-12

![Graph showing specific bound {[^3]H}-QNB (%)](image)

-Log [Carbachol], (M)
Acknowledgments

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Chapter IV

Reconstitution of Acetylcholine Mediated Inhibition of Adenylyl Cyclase

Contributions of Co-authors

Zhengui Xia, working under the direction of Professor Daniel R. Storm, purified and assayed the adenylyl cyclase used in this study. The remainder of the experiments and procedures were performed by myself under the direction of Professor Schimerlik. Professor Storm also offered some suggestions on how to manipulate the adenylyl cyclase and suggested detergents which would interfere the least with adenylyl cyclase-$G_\text{S}$ interactions.
Abstract

Inhibition of bovine brain calmodulin-sensitive adenylyl cyclase, initiated by the muscarinic agonist carbachol, was examined in a system consisting of the reconstituted purified porcine atrial muscarinic acetylcholine receptor and inhibitory guanine nucleotide binding protein (G\textsubscript{i}) in addition to the stimulatory guanine nucleotide binding protein (G\textsubscript{s}) adenylyl cyclase complex. Experimental conditions were chosen such that, in the absence of carbachol, G\textsubscript{i} was complexed mainly to GDP while adenylyl cyclase was selectively preactivated with guanosine 5'-O-(3-thiotriphosphate) (GTP\textsubscript{y}S). Adenylyl cyclase was also activated by forskolin and calcium plus calmodulin. Addition of carbachol to form the receptor-carbachol complex increased the dissociation rate of GDP from G\textsubscript{i} (Tota, M.R., Kahler, K.R., and Schimerlik, M.I. (1987) Biochemistry 26, 8175-8182) such that GTP\textsubscript{y}S could bind and initiate G\textsubscript{i} mediated inhibition of the enzyme. Adenylyl cyclase activated by calcium plus calmodulin was more sensitive to inhibition by carbachol than either nonstimulated enzyme or enzyme activated by GTP\textsubscript{y}S or forskolin.

Studies using the resolved subunits of G\textsubscript{i} showed that while the \(\beta\gamma\) subunits could inhibit all forms of the adenylyl cyclase, only the calmodulin stimulated enzyme was inhibited by the \(\alpha\) subunit. Possible explanations are given for these results.
Abbreviations

mAcChR, muscarinic acetylcholine receptor; PC, soybean
L-α-phosphatidylcholine; PS, bovine brain L-α-phosphatidyl-L-serine;
CHAPS, (3-[(3-cholamidopropy1)-dimethylammonio]-1-propanesulfonate;
G$_s$, the stimulatory guanine nucleotide binding protein; G$_i$, the
inhibitory guanine nucleotide binding protein; G$_o$, a similar guanine
nucleotide binding protein of unknown function; GppNHp,
5′guanylylimidophosphate; GTP$_\gamma$S, guanosine
5′-O-(3-Thio-triphosphate); DTT, dithiothreitol; HEPES,
4-(2-hydroxyethyl)1-piperazineethanesulfonate; EGTA,
ethyleneglycol-bis-(β-aminoethyl ether)N,N,N′,N′-tetraacetic acid;
EDTA, ethylenediaminetetraacetic acid; PMSF, phenylmethylsulfonyl
fluoride.
Introduction

Activation of mAcChR's in several tissues including heart (Murad et al., 1962) and brain (Olianans et al., 1983) results in a decrease in the rate of cAMP accumulation. In atrial tissue, as in several other cell types (reviewed in Nathanson, 1987), the acetylcholine induced attenuation of cAMP levels is mediated by pertussis toxin sensitive guanine nucleotide binding proteins G\textsubscript{i} and/or G\textsubscript{o}. This mechanism is not absolute, however, since it has been shown in at least one system (1321N1 astrocytoma cells; Hughes et al., 1984; Hughes and Harden, 1986) that mAcChR's regulate cAMP levels by activating a calmodulin-sensitive phosphodiesterase in a Pertussis toxin insensitive manner.

Recent work (Ashkenazi et al., 1987; Peralta et al., 1988a) has indicated that the PM2 muscarinic subtype, found in the atria, interacts preferentially with guanine nucleotide binding proteins that regulate adenylyl cyclase. Of the four mAcChR human subtypes whose coupling to physiological effector systems have been characterized, the HM2 and HM3 mAcChR appear to couple more tightly to adenylyl cyclase inhibition than to stimulation of inositol phospholipid metabolism (Peralta et al., 1988). Furthermore, Northern analysis has indicated that both of these subtypes are found in the brain, suggesting that they play a role in the regulation of adenylyl cyclase activity in that tissue.

Regulation of adenylyl cyclase by G proteins requires that the G proteins are first activated by their respective receptors. The binding of hormone to the receptor will stimulate the turnover of a
tightly bound GDP on the α subunit of the G protein and allow a GTP to bind. When GTP is bound to the G protein the heterotrimer apparently dissociates into α and βγ subunits. The individual subunits are then thought to be involved in the regulation of adenylyl cyclase activity. The GTP bound α subunit of Gs acts to stimulate adenylyl cyclase activity. Stimulation is terminated when GTP hydrolyzes to GDP and the Gs subunits reassociate (Gilman, 1987).

Recently, several laboratories have examined the effects of isolated G protein subunits on adenylyl cyclase activity using reconstituted (Smigel, 1986; Cerione et al., 1986; Cerione et al., 1987; Hekeman et al., 1987) or detergent solublized preparations (Katada et al., 1986a; Katada et al., 1987). The results from these studies were somewhat conflicting with regard to the function of the Gi subunits. One proposed mechanism is that inhibition of adenylyl cyclase by the βγ subunits of pertussis toxin-sensitive G proteins is predominantly due to mass action equilibria favoring reassociation of the Gs heterotrimer (Katada et al., 1984b; Cerione et al., 1986). However, alternative mechanisms have also been proposed (Katada et al., 1986a, 1987) in which (1) Giβγ could inhibit adenylyl cyclase by either binding to the protein directly or, in the case of calmodulin sensitive adenylyl cyclase, competing for the calcium calmodulin complex or (2) Giα=GTPγS could compete directly with Gsα for a binding site on the enzyme. Giα=GTPγS also directly inhibited adenylyl cyclase in Cyc- S49 cells, but the effect was small (Katada et al., 1984a).

Adenylyl cyclase, Gs, and stimulatory hormone receptors have been successfully coreconstituted into liposomes (Cerione et al., 1984; May
et al., 1985; Rosenberg et al., 1987). These studies define the minimum requirement for hormone induced activation of adenylyl cyclase. It has been more difficult to prepare a reconstituted system in which the adenylyl cyclase was under the control of inhibitory receptor proteins. Light activated rhodopsin had little effect when reconstituted with adenylyl cyclase, $G_s$, and either $G_i$ or transducin because, under the experimental conditions chosen, both regulatory $G$ proteins were activated (Cerione et al., 1985).

Reconstitution of the atrial mAChR and $G_i$ has been reported (Tota et al., 1987). The purpose of this study was to demonstrate that the purified atrial mAChR and atrial $G_i$ are able to interact with calmodulin sensitive adenylyl cyclase-$G_s$ complex from bovine brain in a reconstituted system. Conditions were chosen such that adenylyl cyclase could be activated through $G_s$ and/or calmodulin while remaining sensitive to inhibition by mAChR activated $G_i$. It was also possible to test the effects of the resolved subunits of $G_i$ on the activity of the unstimulated adenylyl cyclase or adenylyl cyclase activated by $G_s$ or calmodulin.
Methods

Porcine atrial mAcChR was purified as described by Peterson et al. (1984). Atrial G_i was purified as a by product of mAcChR purification (Tota et al., 1987). Bovine brain calmodulin-sensitive adenylyl cyclase was prepared as described by Yeager et al. (1985a) and had a specific activity of 10 nmol/min/mg protein when assayed in the presence of 10 mM MnCl_2. The preparation was not pretreated with guanine nucleotides and thus co-purified with G_s and maintained sensitivity to GTP analogs. mAcChR and G_i were reconstituted as described (Tota et al., 1987). Briefly, both proteins were added to a mixture of 7 mM CHAPS and 1 mg/ml lipid (1:1:0.1 PC:PS:cholesterol), diluted 25 fold, precipitated by adding 10% PEG, and collected by centrifugation. All experiments used between 30 and 50 pmol of G_i and between 20 to 30 pmol of muscarinic receptor. The concentration of recovered proteins is indicated in the figure legends.

Adenylyl Cyclase Assays. One volume of adenylyl cyclase·G_s complex (64 µg/ml in 0.1% Tween 20) was added to 9 volumes of either control lipids or lipids with reconstituted G_i and mAcChR. GDP was added to 167 µM and the mixture was incubated on ice for 10 minutes. Aliquots were then diluted 3.3 fold to a final volume of 50 µl and a final concentration of 10 mM Na HEPES pH 7.4, 100 mM NaCl, 5 mM MgCl_2, 240 mM GTP\_S, 50 µM GDP, 50 µM cAMP, 5 mM theophylline, 0.2 mg/ml BSA, 1 mM DTT, 0.1 mM PMSF, and 500 µM ATP with about 3x10^6 cpm of [α^32P] ATP (120 cpm/pmol) per assay. In experiments which examined calmodulin stimulated adenylyl cyclase, 50 nM calmodulin and 100 µM CaCl_2 were added. In experiments where calcium·calmodulin was omitted
100 μM EGTA was added. The examination of Gs stimulated adenylyl cyclase was performed by preincubating the Tween soluble adenylyl cyclase•Gs complex with 8 μM GTPγS for 30 minutes at 32°C before addition to lipids and GDP. No additional GTPγS was added in these experiments and the final GTPγS concentration was 240 nM, as in the controls. All assays contained a residual Tween 20 concentration of 0.003% v/v and 2.5% v/v ethanol (stock solutions of theophylline were prepared in ethanol).

The subunits of Gi were separated as described by Katada et al. (1986b). Gi was incubated with 10 μM GTPγS for 2 hours at 32°C (50 μg Gi in 250 μl of 10 mM Na•HEPES pH 7.4 mM MgCl2, 5 mM EGTA, 1 mM DTT, 0.1 mM PMSF, and 0.1% Lubrol PX). The activated protein was diluted into 5 ml of 20 mM Tris•HCl pH 8.0, 10 mM MgCl2, 1 mM EDTA, 0.1 M NaCl, 0.25% cholate, 0.1 mM PMSF, and 1 mM DTT and then applied to 10 ml of heptyl agarose. The column was washed with 20 ml of equilibration buffer and then eluted with a 60 ml linear gradient starting with 0.25% cholate, 0.25 M NaCl and ending with 1.2% cholate, 0.025 M NaCl. All buffers contained Tris, MgCl2, DTT, and PMSF as in the equilibration buffer. All chromatography was performed at 4°C. Giα was eluted in the wash and Gβγ was eluted at about 0.8% cholate. Heptyl agarose was prepared by reacting Affigel 10 (Biorad) with an excess of heptylamine.

Liposomes were prepared with 30 pmol of α subunit or 1.0 μg of βγ subunit. The recovery of the α subunit was similar to that of the Gi heterotrimer (about 30%) and the final concentration in the adenylyl cyclase assay was 7.8 nM. The recovery of the βγ subunit was monitored by gel electrophoresis (12% acrylamide gel; Laemmli, (1970))
using silver staining (Wray et al., 1981). The recovery was about 40% which gave a final protein concentration of 0.63 μg/ml (about 13 nM) in the adenylyl cyclase assay.

The adenylyl cyclase reactions were started by adding ATP, [$\alpha^{32}\text{P}$]-ATP, cAMP, theophylline, BSA, and HEPES buffer as a 5X stock solution and the reaction was allowed to proceed for one hour at 32°C. [$\alpha^{32}\text{P}$]-cAMP was then isolated as described by Salomon (1979) using [$^3\text{H}$] cAMP to quantitate recoveries.

**Binding assays.** [$^3\text{H}$]L-QNB and [$^{35}\text{S}$] GTP$_\gamma$S assays were performed for the reconstituted proteins as described by Tota et al. (1987). In order to examine L-QNB and GTP$_\gamma$S binding under the conditions of the adenylyl cyclase assays, slight modifications were made. When [$^3\text{H}$]L-QNB binding was performed in a 50 μl volume with high ionic strength, aliquots were removed and diluted 2.5 fold with 10 mM sodium phosphate, 1 mM EDTA pH 7.4 buffer immediately before applying to DE81 paper. [$^{35}\text{S}$]GTP$_\gamma$S binding was assayed by substituting 240 nM [$^{35}\text{S}$]GTP$_\gamma$S for unlabeled nucleotide and filtering 15 μl aliquots.

**Materials.** Bovine brain calmodulin was a generous gift from Sonia R. Anderson. The source of all other materials used have been described previously (Tota et al., 1987).
**Results**

Adenylyl cyclase activity was stimulated by either forskolin, Gs, calcium-calmodulin, or a combination of Gs and calcium-calmodulin. Assays were performed on adenylyl cyclase added to either control lipids, or lipids containing reconstituted mAChR and Gi with either the muscarinic antagonist L-hyoscyamine or the agonist carbachol. Stimulation by Gs was achieved by preactivating the Tween soluble adenylyl cyclase-Gs complex with GTPyS before adding to lipids and GDP. The results (Fig. IV-1) indicate that adenylyl cyclase was activated by forskolin, Gs, or calcium-calmodulin. The largest single stimulation was by forskolin (4.2-fold), followed by calcium-calmodulin (4.1-fold). Stimulation by Gs was more modest (1.9-fold). Activating Gs by 193 &micro;m instead of 8 &micro;m GTPyS gave no additional stimulation. Increasing calmodulin from 50 to 250 nM gave only a 3% further increase in activity while a 5 fold increase in calcium reduced activity by 40% (data not shown). A combination of calcium-calmodulin and Gs stimulation gave more than an additive response.

The purpose of performing these assays in the presence of high concentrations of GDP was to inhibit binding of GTPyS to Gs and Gi. This concentration of GDP, 50 &micro;m, completely blocked GTPyS binding to Gs. Based on the known affinities of GDP and GTPyS (Chapter III), a small fraction (~16%) of Gi was expected to bind GTPyS at the concentrations of GDP and GTPyS used. Activation of Gi by agonist bound mAChR should decrease the affinity of Gi for GDP but not affect the GTPyS binding affinity (Chapter III). Thus when an agonist bound
receptor is present, there would be an increase in GTP$_\gamma$S binding to G$_i$ (Fig. IV-2). GTP$_\gamma$S-activated G$_i$ would then function to inhibit adenylyl cyclase activity, while G$_s$ would not be activated.

As seen in Figure 1, the addition of adenylyl cyclase to liposomes containing mAcChR, G$_i$, and L-hyoscyamine resulted in a decrease in adenylyl cyclase activity when compared to adenylyl cyclase added to control lipids. (Inhibition ranged from 14 to 36%, depending on the mode of stimulation, Fig. IV-1.) Replacing L-hyoscyamine with carbachol resulted in a further decrease in adenylyl cyclase activity resulting from mAcChR mediated activation of G$_i$. Stimulation of adenylyl cyclase by calcium-calmodulin was most sensitive to inhibition by G$_i$ and mAcChR. G$_s$ and forskolin-stimulated adenylyl cyclase were less sensitive to G$_i$ while nonstimulated adenylyl cyclase also showed some mAcChR mediated inhibition. The inhibition of adenylyl cyclase activity in the presence of carbachol as compared to L-hyoscyamine was 30±1% for calmodulin stimulated, 16±3% for calmodulin and GTP$_\gamma$S stimulated, 9±3% for GTP$_\gamma$S stimulated, 5±4% for forskolin stimulated, and 17±4% for nonstimulated adenylyl cyclase.

Liposomes containing calmodulin activated adenylyl cyclase, G$_i$, and mAcChR were titrated with carbachol and the inhibition of adenylyl cyclase activity was measured (Fig. IV-3). The apparent dissociation constant for carbachol measured in this manner (K$_{app}$=9.5 ± 0.6 μM) agreed with the binding constant of the high affinity site for carbachol for the receptor as measured by the displacement of [³H]L-QNB (Fig. IV-4, K$_1$=19 ± 10 μM).

In order to investigate the mechanism of receptor induced inhibition of adenylyl cyclase by G$_i$ in more detail, adenylyl cyclase
was added to liposomes containing GTPγS plus either Gia or Giβγ. The results in Fig. IV-5 suggest that while the βγ subunit could inhibit Gs stimulated, calmodulin stimulated, or basal adenylyl cyclase activity, Gia could only inhibit calmodulin stimulated adenylyl cyclase. The forskolin stimulated activity was also inhibited by βγ subunits and not GTPγS•Gia (data not shown).
Discussion

The adenylyl cyclase used for this study was stimulated by Gs, calcium-calmodulin, and forskolin. That calmodulin and forskolin were more effective than Gs, is in agreement with previous studies (Yaeger et al., 1985a).

In order to study the inhibition of the adenylyl cyclase-Gs complex by Gi it was necessary to choose conditions which would permit Gs and Gi to be activated independently of each other and still allow Gi to be sensitive to changes in nucleotide binding caused by the mAcChR. The experimental conditions were chosen (50 μM GDP and 240 nM GTPγS) such that GTPγS would not bind to Gs unless it was preincubated with it, and the activation of Gi by the mAcChR would give a maximal effect on adenylyl cyclase activity. Under these conditions a small amount of GTPγS could still bind to Gi, and thus some inhibition of adenylyl cyclase activity was found in the absence of muscarinic agonists. Therefore, when adenylyl cyclase was added to liposomes containing Gi, mAcChR, and the muscarinic antagonist L-hyoscyamine, there was an inhibition of adenylyl cyclase activity when compared to adenylyl cyclase added to control liposomes (Fig. IV-1).

GTPγS-activated Gi was expected to inhibit adenylyl cyclase activity (Katada et al., 1986a; Katada et al., 1987). When the assay was performed in the presence of the muscarinic agonist carbachol instead of an antagonist, there was a further decrease in adenylyl cyclase activity resulting from a larger fraction of Gi activated by GTPγS (Figs. IV-1 and IV-2). The increase in GTPγS-activated Gi presumably resulted from a decrease in affinity of Gi for GDP caused by agonist
bound receptor (Chapter III), permitting more GTP\(_\gamma\)S to bind.

It has been previously demonstrated that soluble adenylyl cyclase could reconstitute into preformed liposomes (Yeager et al., 1985b). Since an interaction between adenylyl cyclase and reconstituted mAcChR and G\(_i\) was observed, it is reasonable to assume that in this case the adenylyl cyclase was reconstituting into liposomes containing mAcChR and G\(_i\). This preparation of adenylyl cyclase has been functionally reconstituted with the \(\beta\)-adrenergic receptor and the \(\beta\)-adrenergic agonist isoproterenol was able to stimulate the calmodulin-sensitive adenylyl cyclase two fold (Rosenberg et al., 1987).

The calcium-calmodulin stimulated adenylyl cyclase was clearly more sensitive to inhibition by G\(_i\) than either the forskolin or GTP\(_\gamma\)S activated enzyme. As was observed by others (Katada et al., 1987), the effects of G\(_i\) on forskolin and G\(_s\) stimulated activity were much less potent. It seems that this form of adenylyl cyclase is more sensitive to regulation by calcium than by stimulatory hormones. However, since G\(_s\) and calcium-calmodulin have a more than additive effect on adenylyl cyclase activity (2.7 fold for GTP\(_\gamma\)S activated, 3.3 fold for calmodulin, and 10 fold for both stimulation together), the mechanism of regulation appears to be complex.

The mAcChR mediated inhibition of adenylyl cyclase observed in this reconstituted system (about 30%) was comparable to inhibition caused by muscarinic agonists in native membrane preparations. Developing chick atrial membranes have been reported to show a carbachol-induced inhibition of 26-30% (Halvorsen and Nathanson, 1984). Acetylcholine inhibited basal adenylyl cyclase activity by 30-40% in rat striation synaptic plasma membranes (Olianas et al.,
GTP-isoproterenol activated adenylyl cyclase was inhibited 17% by methacholine in canine myocardial membranes, or 26% in canine myocardial homogenates (Watanabe et al., 1976). The degree of hormone mediated inhibition was about the same when the calmodulin sensitive adenylyl cyclase was known to be involved. In the presence of calmodulin and GTP, the adenosine receptor agonist (1)-N\(^6\)-phenylisopropyladenosine was able to inhibit adenylyl cyclase activity by 26% in rat cerebral cortex membranes (Perez-Reyes and Cooper, 1987).

Titration of mAcChR with carbachol indicated that the mAcChR population having high affinity for agonists was involved in inhibition of adenylyl cyclase (Figs. IV-3 and IV-4). This was expected since this is the receptor form that interacts with the G\(_i\).

The actual affinity of ligands for the receptor was somewhat lower than expected for the reconstituted system (Chapter III). The reason for this effect was believed to be the residual Tween 20 in the adenylyl cyclase assay. When adenylyl cyclase (and Tween 20) were added to the liposomes, the receptor L-QNB complex was unstable. Most of the receptor L-QNB complex was not recovered after 90 minutes at 32°C, whereas without Tween 20 nearly 100% was recovered. Although these conditions were not optimal for the receptor, the mAcChR was stable enough to stimulate G\(_i\). As seen in Fig. IV-2, the presence of adenylyl cyclase (and Tween 20) has little effect on the ability of the receptor to promote GTP\(_\gamma\)S binding to G\(_i\).

Since the effect of GTP\(_\gamma\)S binding to G\(_i\) is to promote subunit dissociation (reviewed in Gilman, 1987), the effects of resolved subunits on adenylyl cyclase activity were examined and the results
are shown in Figure IV-5. The $\beta \gamma$ subunit was able to inhibit calmodulin, $G_\delta$, and forskolin stimulated adenylyl cyclase in addition to inhibiting nonstimulated adenylyl cyclase. These data argue that the $\beta \gamma$ subunits must inhibit the enzyme by means other than reducing the concentration of activated $G_{\delta \alpha}$. Katada et al. (1986a, 1987) have reported that the $\beta \gamma$ subunits inhibited adenylyl cyclase by direct binding and also inhibited the calmodulin sensitive form by competing with the enzyme for calmodulin. In the present study it was not possible to distinguish between these two possible mechanisms, but since $\beta \gamma$ seemed equally effective at inhibiting basal and calmodulin stimulated adenylyl cyclase, it would favor a mechanism where $\beta \gamma$ acted primarily by directly inhibiting the enzyme.

The $\alpha$ subunit was also able to inhibit calmodulin stimulated adenylyl cyclase but not $G_\delta$ stimulated adenylyl cyclase. $G_{\delta \alpha}$ has not been previously tested directly on the calmodulin sensitive adenylyl cyclase, but in studies using other adenylyl cyclase preparations $G_{\delta \alpha}$ was able to inhibit only the $G_\delta$ stimulated adenylyl cyclase (Katada et al., 1986a). There are several possibilities to explain these discrepancies. That $G_{\delta \alpha}$ did not compete for $G_{\delta \alpha}$ in these experiments could be explained by there not being a high enough concentration of $G_{\delta \alpha}$ to displace $G_{\delta \alpha}$, or that the dissociation rate of $G_{\delta \alpha}$ was too slow in this reconstituted system. Alternatively, $G_{\delta \alpha}$ may not directly compete with $G_{\delta \alpha}$ for binding to the calmodulin sensitive adenylyl cyclase.

$G_{\delta \alpha}$ was not expected to inhibit calmodulin activated adenylyl cyclase. Perhaps when the adenylyl cyclase was activated by calmodulin it was able to release tightly bound $G_\delta$•GDP, allowing
$G_{\alpha}^i\cdot GTP_\gamma S$ to bind. $G_{\alpha}^i\cdot GTP_\gamma S$ bound to the calmodulin sensitive adenylyl cyclase then resulted in a direct inhibition of adenylyl cyclase activity.

Another mechanism that cannot be ruled out from these data is that $G_{\alpha}^i\cdot GTP_\gamma S$ could compete with calmodulin for binding to adenylyl cyclase. This would explain why the $\alpha$ subunit could only inhibit the calmodulin activated adenylyl cyclase. This mechanism may be supported by a recent report that mastoparan can activate G proteins, possibly by mimicking a mastoparan like structure found in many receptors (Higashijima et al., 1988). Mastoparan forms a tight complex with calmodulin (Malencik and Anderson, 1983). It is possible that both $G_{\alpha}^i\cdot GTP_\gamma S$ and calmodulin recognize similar targets and $G_{\alpha}^i\cdot GTP_\gamma S$ could compete with calmodulin for binding to the calmodulin activated adenylyl cyclase.

In conclusion, this study demonstrated that the only components necessary for muscarinic receptor mediated inhibition of calmodulin-sensitive adenylyl cyclase were the adenylyl cyclase, the G protein(s) and the receptor. A methodology was also developed to allow the examination of all these components together.

The coupling of the atrial muscarinic receptor with brain calmodulin-sensitive adenylyl cyclase may be physiologically relevant since HM2 receptors are also located in the brain. The mechanism for coupling of PM2 or HM2 receptors to calmodulin sensitive adenylyl cyclase may also serve as a model for other receptor subtypes (i.e. HM3), and other inhibitory receptors that couple to calmodulin sensitive adenylyl cyclase (Perez-Reyes and Cooper, 1987). The data presented here may also suggest another mechanism for inhibition by
Giα other than competing for a Gα binding site on the adenylyl cyclase. The alternative role for Giα could be to inhibit the calmodulin activated adenylyl cyclase, possibly by competing with calmodulin for a binding site on adenylyl cyclase.
Figure IV-1. G\textsubscript{i} mediated inhibition of adenylyl cyclase activity in the presence of various adenylyl cyclase stimulating agents. Adenylyl cyclase was assayed in the presence of A, EGTA (control); B, EGTA and GTP\textsubscript{\gamma}S activated G\textsubscript{s}; C, CaCl\textsubscript{2} and 50 nM calmodulin; D, EGTA and forskolin; and E, CaCl\textsubscript{2}, calmodulin, and GTP\textsubscript{\gamma}S-activated G\textsubscript{s}. Adenylyl cyclase was added to liposomes containing mAcChR, G\textsubscript{i}, and 2 mM carbachol; to liposomes containing mAcChR, G\textsubscript{i}, and 1 \mu M L-hyoscyamine; or to liposomes containing no protein or ligands. The final concentration of adenylyl cyclase in the assay was 1.9 \mu g/ml. The final concentration of mAcChR and G\textsubscript{i} were 6.9 nM 10.8 nM, respectively. Assays were performed as described in methods. Measurements were the average of triplicate determinations and the standard deviations were less than 4% of the average values.
Figure IV-2. GTP$_\gamma$S binding to liposomes containing mAChR and Gi.

Assay conditions for (A) were identical to adenylyl cyclase assay conditions described in Figure IV-1 except that no [$\alpha^{32}$P]ATP was added and [$^{35}$S]GTP$_\gamma$S was used. Samples contained either Carbachol $\mathbb{X}$, or L-hyoscymine $\mathbb{X}$. (B) No adenylyl cyclase or Tween 20 was added. (C) No GDP was added. The error bars indicate the standard deviation of triplicate determinations. The receptor concentration was estimated to be 5.4 nM.
Specifically Bound GTPγS, nM

Figure IV-2

A  B  C
Figure IV-3. Dependence of mAChR mediated adenylyl cyclase inhibition on carbachol concentration. Calcium calmodulin activated adenylyl cyclase was measured as described in Figure IV-1 with the indicated concentration of carbachol. The receptor concentration was estimated to be 6.5 nM and the $G_i$ concentration was 11.3 nM. Data points were the average of duplicate determinations and the data was fit assuming one class of carbachol binding sites giving a $K_d$ of $9.5 \pm 0.6 \mu M$. The curve through the data points is the theoretical curve calculated using the above $K_d$ for carbachol. The activity in the absence of carbachol was $44.0 \pm 2.3 \text{ pmol/tube}$, and at the maximum carbachol concentration, the activity was $28.7 \pm 0.1 \text{ pmol/tube}$. 
Figure IV-3

% Maximum Inhibition

-log [Carbachol]
Figure IV-4. Carbachol titration of \([^{3}\text{H}]\text{L-QNB}\) binding sites.

\([^{3}\text{H}]\text{L-QNB}\) binding was performed in the presence of varying carbachol concentrations under the same conditions as Figure IV-1 except that labeled ATP was replaced by unlabeled ATP and the reaction was allowed to proceed for 20 minutes instead of one hour. Also, guanine nucleotides were omitted for this assay. The samples were diluted and immediately applied to DE81 paper and the assay completed as described in methods. The data were fit assuming 4.7 nM L-QNB sites, and a \(K_d\) for L-QNB of 12.1 nM. The \(K_d\) for L-QNB was determined by Scatchard analysis under similar conditions (data not shown). The fitted parameters were \(F_1 = 0.22 \pm 0.03, \ K_1 = 19.0 \pm 10.5 \ \mu M, \ F_2 = 0.78 \pm 0.03, \ K_2 = 4.1 \pm 0.7 \ mM\).
Figure IV-5. Effects of $G_1$ subunits on adenylyl cyclase activity.

Liposomes were reconstituted as described in methods with GTP$_y$S $G_1$ subunit, $\Box$; $\beta\gamma$ subunits, $\otimes$; or with no subunits, $\square$. The adenylyl cyclase,$G_s$ complex was added and adenylyl cyclase was stimulated by (A), $G_s$; (B), calmodulin; or (C), no stimulation. Measurements were the average of triplicate determinations and the standard deviations were less than 4%.
Figure IV-5

pmol cAMP/tube

A  B  C
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Chapter V

Discussion

The initial objective of this thesis was to study the interaction of the atrial mAcChR with atrial G\textsubscript{i}. The successful co-reconstitution of mAcChR and G\textsubscript{i}, together with the availability of the bovine brain calmodulin-sensitive adenylyl cyclase, prompted the further investigation of the interaction of mAcChR and G\textsubscript{i} with this effector enzyme.

The reconstituted mAcChR and G\textsubscript{i} were judged to be functionally interactive on the basis of the appearance of high affinity-guanine nucleotide sensitive-agonist binding sites when the mAcChR was reconstituted with G\textsubscript{i}. Functional coupling could also be observed from the perspective of the G protein when the intrinsic GTPase activity of G\textsubscript{i} was stimulated by a muscarinic agonist. An increased GTPase activity of G\textsubscript{i} could generally be associated with activation of the G protein. Studies were then undertaken to explore the mechanism by which the mAcChR activated this GTPase. From these experiments, the increase in GTPase activity could be explained almost entirely by an increase in the rate of GDP release from G\textsubscript{i}, the rate limiting step in the basal GTPase reaction of G\textsubscript{i}. Equilibrium binding studies showed that the dissociation constant for GTP\textsubscript{γ}S was not altered by muscarinic agonists. The inhibition of the initial rate of GTP\textsubscript{γ}S binding by GTP showed that muscarinic agonists had no effect on the dissociation constant of GTP.

Although it is assumed that receptors activate G proteins by
forcing them into an "open" state with respect to guanine nucleotide binding (Cassel and Selinger, 1978), there seems to be some question as to whether the open state results solely from the increased rate of GDP release, or if there is also an increase in the rate of GTP binding. The β-adrenergic receptor was shown to activate Gs by increasing the rate of GDP release and by increasing the rate of GTPγS association (Brandt and Ross, 1986). However, more recent work has seemed to emphasize that much of the observed increase in GTPγS binding can be explained by an increase in GDP release, followed by rapid binding of GTPγS to the unliganded G protein (May and Ross, 1988). The data presented in Chapter III supports a similar conclusion. Therefore, reports of the brain mAChR stimulating GTPγS to brain Gi (Kurose et al., 1986) should be viewed with some hesitation as the effects on GDP release were not taken into consideration. The mAChR acts as an efficient catalyst and increases the slowest step in the GTPase reaction of Gi, the rate of GDP release. GTP will then rapidly bind to the alpha subunit and the protein will be ready to begin the next step in the regulation of target proteins. Carbachol increased the rate of GDP release by 38 fold, but only increased kcat by 11 fold. The rate of GDP release may not be limiting in this case, but could still be a partial rate limiting step for the hormone activated Gi.

The rate of GDP release from Gi and the kcat for activated Gi are controlling factors by which the mAChR regulates effector proteins. These values should then be related to the time it takes the mAChR to initiate its response. The direct determination of guanine nucleotide binding parameters and GTPase parameters for receptor coupled G
proteins could be difficult in heterogeneous systems, such as isolated cellular membranes. Interference from a large excess of G proteins and other enzymes that hydrolyze GTP would make data interpretation difficult. It is here that a defined reconstituted system would be useful, and the values generated from this system can begin to be related to specific biochemical responses of mAcChR activation, such as the activation of ion channels.

There is widely believed to be a delay time of 100-300 msec for the hormone bound mAcChR to activate the inward rectifying potassium channel in cardiac tissue (Hills-Smith and Purves, 1978; Hartzel, 1980; Nargeot et al., 1982). A rate constant for activation of 230 min\(^{-1}\) was determined by Nargeot et al. (1982). Recent studies on the atrial inward rectifying potassium channel have indirectly measured guanine nucleotide binding properties of G\(_{k}\) in vivo by studying the rate of potassium channel activation with various nonhydrolyzable GTP analogues (Breitweiser and Szabo, 1988). The investigators concluded that the rate of channel activation in the absence of muscarinic agonist was limited by the release of GDP from G\(_{k}\), a rate of 0.3 min\(^{-1}\). This value agrees with the rate of GDP release from detergent soluble G\(_{o}\) (Higashijima et al., 1987b), with the k\(_{\text{cat}}\) of nonstimulated reconstituted brain G\(_{i}\) (Kurose et al., 1986), and with the k\(_{\text{cat}}\) and rate of GDP release determined in this study for nonstimulated G\(_{i}\). In the presence of acetylcholine, the k\(_{\text{cat}}\) for GTP turnover was estimated to be 135 min\(^{-1}\). While this k\(_{\text{cat}}\) is consistent with the time required for potassium channel activation, it is significantly faster than the k\(_{\text{cat}}\) determined for mAcChR activated G\(_{i}\) as determined in Chapter III (k\(_{\text{cat}}\) = 2 min\(^{-1}\)). The problem of tissue compatibility
between the mAcChR and \( G_i \) can be ruled out in this study since both proteins used in this study were from the atria. Breitweiser and Szabo (1988) noted that detergent solubilized \( G_o \) also had a \( k_{cat} \) of about 2 min\(^{-1}\) (Higashijima et al., 1987a) and speculated that this low \( k_{cat} \) could be due to deleterious effects of detergent. While the presence of phospholipids was shown to effect the GTPase activity of \( G_i \), this effect was only about 2 fold (Neer et al., 1984). In this study detergent was removed and the \( k_{cat} \) was still about 2 min\(^{-1}\). Reconstituted hormone activated \( G_s \) also had a \( k_{cat} \) of 1.7 min\(^{-1}\) (Brandt and Ross, 1986). It is possible that the receptor-G protein interaction could be very sensitive to the lipid environment or any residual detergents and function correctly only in native membranes. Poor or improper receptor-G protein coupling might not reveal the maximum \( k_{cat} \) possible for \( G_i \).

An alternative explanation is that there is a missing component in the transducing system. The missing component would perhaps assist the mAcChR in increasing the GTPase activity of \( G_i \). There is already one protein identified that might perform such a function. The GTPase activating protein (GAP) was required to demonstrate the full GTPase activity associated with the ras protein (Trahey and McCormik, 1987). This ras protein is a novel G protein regulator whose cellular activity is related to its GTPase activity. The target for the ras protein is unknown, but certain mutations are known to transform mammalian cells. The role of GAP is unclear, but it is speculated to be the elusive target of the ras protein (Sigal, 1988). If GAP represents the existence of another class of proteins involved in signal transduction, then it could explain the paradox observed...
between the \textit{in vivo} $k_{\text{cat}}$ and the $k_{\text{cat}}$ observed for reconstituted $G_i$.

The reconstituted system described here provides a quantitative description of the signal transduction mechanism and may provide evidence that a key component is still lacking. The reconstituted mAcChR and $G_i$ have proved useful in several other respects. These liposomes have been used to study the effects of phosphorylation by the cAMP dependent protein kinase on the mAcChR. Reconstituted mAcChR was phosphorylated at a fifteen fold higher level than the detergent solubilized protein and, unlike the detergent solubilized mAcChR, was still able to bind L-QNB after phosphorylation. In the presence of $G_i$, the reconstituted receptor was able to show a carbachol-stimulated increase in phosphorylation (Rosenbaum et al., 1987). These results may provide clues as to how chronic exposure of the receptor to agonists results in a down regulation of receptor number (Galper and Smith, 1980). Phosphorylation of the mAcChR by cAMP and calmodulin dependent protein kinases has been suggested as a means to regulate receptor number (Burgoyne et al., 1983). Recently, the involvement of these kinases was disputed, but correlation of the phosphorylation of high affinity GTP-sensitive agonist-binding sites with mAcChR desensitization was emphasized (Kwatra et al., 1987). In any case, the data presented by Rosenbaum et al. (1987) suggested that the G protein-coupled agonist-bound receptor was more susceptible to phosphorylation than was antagonist bound, unliganded, or uncoupled mAcChR.

The reconstituted mAcChR and $G_i$ were also used to examine the hormonal regulation of calmodulin-sensitive adenylyl cyclase. These experiments were the first to show a hormone-mediated inhibition of
adenylyl cyclase using purified components in a reconstituted system. This establishes a minimum requirement for the components that need to participate in cyclase regulation and provides a good foundation for future work with this system. An unexpected result was the ability of the alpha subunit of G_i to inhibit the calmodulin-sensitive adenylyl cyclase only in the presence of calmodulin. G_iα may perform this function by competing for the binding of calmodulin to adenylyl cyclase. In any case, an as yet unexplored role for G_iα has been uncovered. Although the calmodulin-sensitive adenylyl cyclase has not yet been observed in the atria, the ability of the atrial G_i/mAcChR to regulate the brain calmodulin-sensitive adenylyl cyclase has interesting implications for other tissues. Both of the mAcChR subtypes that are believed to couple to adenylyl cyclase (M2 and M3) have been identified in the brain (Peralta et al., 1988). It is not unlikely that certain mAcChR subtypes may naturally attenuate the calmodulin-activated adenylyl cyclase activity. The mAcChR may also be involved in a complicated feedback loop as certain subtypes also function to release calcium, possibly resulting in stimulation and inhibition of cyclase activity. These situations could be resolved when individual cell types are characterized with respect to mAcChR subtypes, muscarinic biochemical responses, adenylyl cyclase subtypes, and prevalent G proteins.

Much of the future work on mAcChR's will undoubtedly entail trying to match mAcChR subtypes, with G proteins, and with effector proteins. It should be possible to purify all subtypes and reconstitute them with various G proteins. Effector enzymes, such as adenylyl cyclase, could also be included and the overall interactions of the mAcChR, G
protein, and effector enzyme coupling could be monitored. Although interactions between these components could be examined individually, a multiple component system could be used to monitor the interactions of one or more mAcChR subtypes with one or more G proteins using regulation of the effector enzyme as an assay for coupling. Thus, heterogeneous \textit{in vivo} systems may be studied in a direct manner.

In conclusion, the work presented here has contributed to the understanding of the signal transduction mechanism used by the mAcChR and should provide the basis for future work involving the signal transduction mechanism, mAcChR regulation, and the role of individual mAcChR subtypes.
BIBLIOGRAPHY


APPENDICES
Appendix I

Reconstitution of the Muscarinic Acetylcholine Receptor and G_i into Liposomes

Preparation of the lipid stock solution. All lipids were purchased from Sigma Chemical Company. Soybean L-α-phosphatidylcholine (Sigma P-6263) was supplied as a chloroform solution at 100 mg/ml. Bovine brain L-α-phosphatidyl-L-serine was supplied as a chloroform:methanol (95:5) solution (Sigma P-8518) or as a solid (Sigma P-7769). Cholesterol (Sigma C-8253) was supplied as a solid, but dissolved in chloroform at 10 mg/ml immediately before use. Phosphatidylcholine (25 mg), phosphatidylserine (25 mg), and cholesterol (2.5 mg) were rotovaped to dryness in a 50 ml roundbottom flask. The solid was resuspended in 2.5 ml of toluene:ethanol (1:1) with 0.02% butylated hydroxytoluene. The solution was stored under argon at -80°C in a 3 ml reacti-vial. If solid phosphatidylserine was used, it was added to the toluene:ethanol solution of phosphatidylcholine and cholesterol at a concentration of 10 mg/ml. The final ratio of lipids was phosphatidylcholine:phosphatidylserine:cholesterol 1:1:0.1 (w/w).

Reconstitution. A typical reconstitution used 30 pmol of mAcChR and 30 pmol of G_i. The lipid was removed from the stock vial with a Hamilton syringe. For two reconstitutions, 50 μl of lipid (21 mg/ml; 1.05 mg) was removed and placed in a glass centrifuge tube. The solution was rotovaped to dryness and 787 μl of 25 mM imidazole pH 7.4, 100 mM NaCl, 1 mM EDTA, and 0.02% sodium azide was added,
followed by 47 μl of 0.15 M CHAPS in 25 mM imidazole pH 7.4, 1 mM EDTA. The solution was supplemented with 1 mM DTT, capped under argon, and sonicated to clarity. After sonication, 8.3 μl of 0.5 M MgCl₂ was added to give a final concentration of 5 mM. Next, 333 μl of the CHAPS-lipid solution was added to one μl of a 20 mM acetylcholine solution in a polycarbonate centrifuge bottle (Beckman 355651). Gₐ (30 pmol; about 20 μl of 1.5 μM GTPγS sites in 20 mM Tris HCl pH 8.0, 1 mM EDTA, 0.8% sodium cholate, and about 10% sucrose) and mAChR (30 pmol; about 20 μl of 1.5 L-QNB sites in 25 mM imidazole pH 7.4, 250 mM NaCl, 1 mM EDTA, 0.08% digitonin, 0.016% sodium cholate and 0.02% sodium azide) were added to the CHAPS-lipid solution. The volume was brought to 400 μl with dilution buffer (25 mM imidazole pH 7.4, 100 mM NaCl, 1 mM EDTA, 5 mM MgCl₂, 1 mM DTT, 0.1 mM PMSF, and 0.02% sodium azide). The final lipid concentration was about one mg/ml, and the final CHAPS concentration was 7.0 mM. This solution was kept on ice for 5 minutes and then diluted to 8 ml by adding 7.6 ml of ice cold dilution buffer, one ml at a time. Liposomes precipitation was begun by adding 2 ml of 50% polyethylene glycol (molecular weight 8000, Sigma P-2139) containing 100 mM NaCl, 5 mM MgCl₂, and 0.02% sodium azide. The biphasic solution was gently rocked until homogeneous. After a one hour incubation on ice, the liposomes were centrifuged for 75 minutes at 61000 rpm in a Ti75 rotor (250000 Xg). The pellet was resuspended in 0.25 ml of dilution buffer by repeated pipetting with a sterile transfer pipette. Typical recoveries for [³H] L-QNB sites and [³⁶S]GTPγS sites were about 25-35%. The binding sites were stable for about one week on ice. If a muscarinic ligand binding study was to be performed, the lipids were
resuspended in 10 mM HEPES pH 7.4, 100 mM NaCl, 1 mM EDTA, 5 mM MgCl₂, 1 mM DTT, and 0.1 mM PMSF instead of the imidazole buffer. Imidazole binds to the mAcChR ligand binding site and therefore interferes with ligand binding studies (Peterson and Schimerlik, 1984).
Appendix II

Enzyme Assays and Ligand Binding Assays

[^3]H L-QNB Assays. The quantitation of mAChR was achieved by assaying the specific binding of [^3]H L-QNB using a DEAE filter disk assay essentially as described by Peterson and Schimerlik (1984). Slight modifications were made to accommodate reconstituted mAChR. Saturation binding was routinely achieved by incubating 10 µl of reconstituted mAChR with 140 µl of 10 mM Na HEPES, 50 mM NaCl, 1 mM EGTA, 5 mM MgCl₂, 1 mM DDT, 0.1 mM PMSF, and 20 nM [^3]H L-QNB (20-40 ci/mmol, New England Nuclear NET-656 or Amersham TRK.604). The solution was incubated for 90-120 minutes at 32°C and then 125 µl was applied to a 2.5 cm DE81 ion exchange paper which was perforated with a pin and suspended in air. After soaking for about 30 seconds the paper was placed in a beaker containing about 500 ml of 10 mM sodium phosphate pH 7.4, 1 mM EDTA, and 0.05% (v/v) triton X-100. The paper was washed in this buffer for 10 minutes, the buffer drained and replaced with fresh, and washed for an additional 10 minutes. After this washing, the filter paper was blotted dry on a paper towel, placed in a scintillation vial, and dried for 5 minutes at 80°C. The vial was filled with 3.5 ml of scintillation fluid and counted on a Beckman LS 6800 on user 1 (channels 0-400) for tritium with an efficiency of 0.443. The scintillation cocktail was 23.8% v/v triton X-100, 0.3% w/v Permablend III (United Technologies Packard, 91% PPO {2,5 diphenyloxazole} 9% bis-MSB {1,4 Bis(2-methylstyryl)benzene} in toluene).
**[^35S]GTP<sub>γ</sub>S Assays.** This method of quantitating G<sub>i</sub> was adapted from Northup et al. (1982). Labelled GTP<sub>γ</sub>S was purchased from New England Nuclear (NEN-030H) and diluted with unlabeled GTP<sub>γ</sub>S from Boehringer Mannheim. It was sometimes necessary to purify the Boehringer Mannheim product in order to remove contaminating GDP. This procedure was described in Chapter III.

Detergent solubilized G<sub>i</sub> was assayed by incubating 5 µl of sample with 45 µl of 10 mM Na HEPES pH 7.4, 0.1 M NaCl, 1 mM EGTA, 30 mM MgCl<sub>2</sub>, 0.1% deionized lubrol PX, 1 mM DDT, 0.1 mM PMSF, and 1.1 µM[^35S]GTP<sub>γ</sub>S (3-8 ci/mmol). The final nucleotide concentration was one µM. The assay was allowed to incubate for one hour at 32°C, at which time 2 ml of ice cold 10 mM Na HEPES pH 7.4, 100 mM NaCl, and 25 mM MgCl<sub>2</sub> was added and the entire solution was filtered under vacuum through a BA85 nitrocellulose paper that was prewashed with 2 ml of the above cold buffer. The filter was rinsed 4 more times with 2 ml of the same ice cold buffer. The nitrocellulose filters were added to a scintillation vial, dried for 5 minutes at 80°C, cooled, and dissolved with one ml of ethylene glycol monomethyl ether. Scintillation fluid was then added (3.5 ml) and the mixture was vortexed until homogeneous and counted on a standard ^14C channel with a counting efficiency of 0.70.

Reconstituted G<sub>i</sub> was assayed in a similar manner except the buffer used was 10 mM Na HEPES pH 7.4, 100 mM NaCl, 1 mM EGTA, 5 mM MgCl<sub>2</sub>, 1 mM DDT, and 0.1 mM PMSF (the same buffer as the GTPase assay). The final[^35S]GTP<sub>γ</sub>S concentration was 100 nM (100 ci/mmol).

Determination of the background value was done by using either non G<sub>i</sub> containing lipids or buffer alone and was less than 0.5% of the
total radioactivity. The background could be lowered by adding 100 μM cold GTP to the first 2 ml of wash buffer used to dilute the reaction.

**GTPase Measurements.** The assay for GTPase used gamma $^{32}$P labelled GTP as a substrate. $[^{32}P]$ phosphate was released upon hydrolysis and unreacted GTP was removed from solution by the addition of activated charcoal followed by centrifugation. The supernatent was then counted for $[^{32}P]$. The procedures used here were modeled after Sunyer et al (1984). For measuring a GTP concentration dependence, the following protocol was used: Reconstituted G<sub>i</sub> (with or without mAcChR) was diluted to a concentration of 1 nM ([<sup>35</sup>S]GTPγS sites) with 10 mM sodium HEPES pH 7.4, 100 mM NaCl, 1 mM EGTA, 1 mM MgCl<sub>2</sub>, 1 mM DDT, and 0.1 mM PMSF. Any muscarinic ligands were added at this point and the solution was incubated at 32°C for 5 minutes. The final volume was about 175 μl. The GTPase reaction was initiated by adding the labelled nucleotide (about 5 Ci/mmol of [$γ^{32}$P]GTP, obtained from a dilution of New England Nuclear NEG-004 with the appropriate volume of unlabeled GTP of about the same concentration). GTP was added to give a final concentration between 10 and 75 mM for L-hyoscyamine treated liposomes, or between 25 and 200 mM for agonist treated liposomes. After 15 minutes at 32°C, 50 μl aliquotes were removed and added to 250 μl of an ice cold suspension of 5% w/v activated charcoal in 20 mM phosphate, pH 2.3, made by combining appropriate amounts of sodium phosphate and phosphoric acid. (The activated charcoal (Sigma C-5260) was previously washed 10 times in distilled H<sub>2</sub>O to remove fines before being suspended in the sodium phosphate solution.) The mixture of charcoal and enzyme reaction solution was placed on ice for 5 minutes and then centrifuged at 15,000 g for 15 minutes at 4°C in an Eppendorf
centrifuge. The \([^{32}P]\) in 0.1 ml of the clear supernatent was measured by Cerenkov counting (user channel 3, open counting window). A sample of the original reaction mix was also measured by Cerenkov counting to accurately determine the concentration of total GTP added.

Routine assays were also performed using a G\(_i\) concentration between 1 and 4 nM, and a GTP\(^{32}P\) concentration of 500 nM. The time could also be extended to either 30 minutes or 1 hour. Assays performed in this manner gave a larger signal.

**Adenylyl Cyclase Assay.** Cyclic AMP production was monitored by the method of Salomon (1979). \([^{32}P]\) ATP (New England Nuclear NEG-003X) was used as the substrate and the reaction product was isolated by chromatography over a Dowex AG 50W-X4 column followed by chromatography over a neutral alumina WN-3. Details of how to prepare these columns and several other reagents can be found in Salomon (1979). Prepackaged Dowex columns were purchased from Biorad (Biorad 731-6225). Before the assay is begun, these columns are prepared by (1) washing the alumina column (0.5 g) with 2 x 4 ml of 0.1 M imidazole pH 7.4, and (2) by washing the Dowex column with 2 x 8 ml of H\(_2\)O.

Routine adenylyl assay solutions were 50 \(\mu l\) in volume and contained 10 mM Na HEPES pH 7.4, 100 mM NaCl, 5 mM MgCl\(_2\), 5 mM theophylline, 0.2 mg/ml BSA, 1 mM DDT, 0.1 mM PMSF, 50 \(\mu\)M CAMP, 500 \(\mu\)M ATP, and 3x10\(^6\) cpm \([\alpha^{32}P]\) ATP (120 cpm/pmole). EGTA, calcium, calmodulin, and guanine nucleotides were added according to the needs of the particular experiment (see Chapter IV). Assays of reconstituted adenylyl cyclase also contained 8 mM Imidazole pH 7.4 and 300 \(\mu M\) EDTA, these components were carried over from the
reconstitution buffer. Each assay contained 1.9 μg/ml of adenylyl cyclase. The reaction was initiated by the addition of 10 μl of a cocktail containing a 5x solution of the Na HEPES, BSA, Theophylline, cAMP, and ATP to 40 μl containing the remaining components. Theophylline was originally prepared as a 100 mM solution in 50% ethanol. The enzyme assay was incubated at 32°C for one hour and then quenched by the addition of 100 μl of stopping solution (2% sodium dodecyl sulfate, 45 mM ATP, 1.3 mM cAMP adjusted to pH 7.5 with Tris base). [3H] cAMP standard was then added (New England Nuclear NET-275; 75 μl of an H2O solution containing about 2500 cpm. A stock solution was routinely prepared by diluting one μl of the New England Nuclear product into 20 ml of H2O). The quenched reaction mix was then diluted to one ml with H2O, was applied to the 2 ml Dowex column, and allowed to drain to a waste container. The column was washed with 2x 1.5 ml of H2O, then placed over the alumina column and eluted with 5 ml of H2O. After the alumina column had dripped dry, it was eluted with 4 ml of 0.1 M imidazole pH 7.4 into 14 ml of scintillation fluid. The scintillation vials were shaken until homogeneous and counted on user 6. User 6 was a duel label counting program set to count tritium between channels 0-200 and 32P between channels 400-1000. In this manner both 3H and 32P cAMP could be counted and the recovery of the [3H] cAMP standard was used to monitor the loss of [32P] cAMP during the purification procedure. [3H] cAMP recovery was usually between 50 and 80%.