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REVIEW

Muscarinic receptors: their distribution and function in body systems, and the implications for treating overactive bladder

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1 The effectiveness of antimuscarinic agents in the treatment of the overactive bladder (OAB) syndrome is thought to arise through blockade of bladder muscarinic receptors located on detrusor smooth muscle cells, as well as on nondetrusor structures.

2 Muscarinic M_3 receptors are primarily responsible for detrusor contraction. Limited evidence exists to suggest that M_2 receptors may have a role in mediating indirect contractions and/or inhibition of detrusor relaxation. In addition, there is evidence that muscarinic receptors located in the urothelium/suburothelium and on afferent nerves may contribute to the pathophysiology of OAB. Blockade of these receptors may also contribute to the clinical efficacy of antimuscarinic agents.

3 Although the role of muscarinic receptors in the bladder, other than M_3 receptors, remains unclear, their role in other body systems is becoming increasingly well established, with emerging evidence supporting a wide range of diverse functions. Blockade of these functions by muscarinic receptor antagonists can lead to similarly diverse adverse effects associated with antimuscarinic treatment, with the range of effects observed varying according to the different receptor subtypes affected.

4 This review explores the evolving understanding of muscarinic receptor functions throughout the body, with particular focus on the bladder, gastrointestinal tract, eye, heart, brain and salivary glands, and the implications for drugs used to treat OAB. The key factors that might determine the ideal antimuscarinic drug for treatment of OAB are also discussed. Further research is needed to show whether the M_3 selective receptor antagonists have any advantage over less selective drugs, in leading to fewer adverse events.
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Abbreviations: ACh, acetylcholine; ATP, adenosine triphosphate; BBB, blood–brain barrier; CIBIC, clinician's interview based impression of change; CNS, central nervous system; CR, controlled release; DO, detrusor overactivity; ER, extended release; IR, immediate release; OAB, overactive bladder; M_1–M_5, muscarinic receptor subtypes 1–5; NK, neurokinin; 4-DAMP, 4-diphenylacetoxy-*N*-methylpiperidine; 5-HT, 5-hydroxytryptamine (serotonin)

Introduction

Antimuscarinic agents are commonly used to treat patients suffering from the overactive bladder (OAB) syndrome (see Andersson *et al*., 2002; 2005). OAB is defined as urgency, with or without urgency incontinence, usually with increased daytime frequency and nocturia (Abrams *et al*., 2002). Antimuscarinic drugs have, for a long time, been considered to produce their beneficial effects by acting solely *via* muscarinic receptors located on detrusor smooth muscle. However, new evidence has led to the suggestion that antimuscarinics could work by affecting muscarinic receptors within the urothelium and on bladder afferent (sensory) nerves (see Andersson & Yoshida, 2003; Andersson, 2004).

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Distribution and functional role of muscarinic receptors

Muscarinic receptors are widely distributed throughout the human body and mediate distinct physiological functions according to location and receptor subtype (see Caulfield & Birdsall, 1998). Five distinct muscarinic receptor subtypes (M_1–M_5) are known to exist, although the exact location and functional role of all these subtypes has to date not been fully

elucidated. In particular, these receptors may have differing but vital roles within the same body system, with potential interplay between subtypes. Thus, a thorough understanding of these differing muscarinic receptor subtypes is important.

The bladder

Under normal conditions, human detrusor contractility is predominantly under the control of the parasympathetic nervous system, where the primary input is *via* acetylcholine (ACh) acting on muscarinic receptors.

Studies show that the detrusor muscle of various species (including humans) contains all muscarinic receptor subtypes but that M_2 and M_3 receptors are predominant, with the M_2 subtype outnumbering the M_3 receptor subtype (3 : 1 ratio) (see Wang *et al*., 1995; Hegde & Eglen, 1999). However, it is the minority population of M_3 receptors that mediate human detrusor contraction *in vitro* (Chess-Williams *et al*., 2001; Fetscher *et al*., 2002) (Figure 1), given that the correlation between functional affinity in human isolated detrusor and recombinant receptor affinity across a range of muscarinic antagonists is greatest for the M_3 subtype. Further evidence to support the functional role of the M_3 subtype comes from studies in M_3 knockout mice. In bladder strips from such mice, 95% of the contraction induced by carbachol is mediated by M_3 receptors, as shown by a reduction in the maximal contractile response to only 5% of that seen in wild-type mice (Matsui *et al*., 2000). However, these mice have an almost normal cystometric pattern owing to the remaining purinergic activation mechanism (Igawa *et al*., 2004).

The functional role of the large M_2 receptor population in detrusor muscle remains unclear. An investigation using M_2, M_3 and M_2/M_3 double knockout mice revealed that that the M_2 receptor may have a role in indirectly mediating bladder contractions by enhancing the contractile response to M_3 receptor activation, and that minor M_2 receptor-mediated contractions may also occur (Ehlert *et al*., 2005). The authors of another rodent study suggest that the stimulation of M_2 receptors may serve to inhibit sympathetically (i.e. beta-adrenoceptor) mediated relaxation, which in turn leads to more efficient emptying of the bladder (Hegde *et al*., 1997). A functional role for M_2 receptors in bladder function may emerge in certain disease states, as observed in studies of outflow obstruction in rats (Braverman *et al*., 1998; Braverman & Ruggieri, 2003) and neurogenic human bladder (Pontari *et al*., 2004). In denervated rat bladder, for example, there is an increase in M_2 receptor density (with a corresponding increase in the $M_2 : M_3$ ratio), with functional affinity of muscarinic antagonists more closely resembling their affinity for M_2 than for M_3 receptors (Braverman *et al*., 1998). However, the functional affinity of the M_3 selective antagonist 4-DAMP did not differ in normal and obstructed rat bladder (Krichevsky *et al*., 1999). Sympathetic modulation of the human bladder *via* M_2 receptors may also be inferred as noradrenergic innervation, albeit scarce, has been demonstrated in human bladder body and increases in the outflow region (see Gosling *et al*., 1999).

Two studies presented at the American Urological Association meeting in 2004 reported that the M_3 receptor was responsible for mediating the direct contractile response in human detrusor muscle tissue taken from patients with neurogenic and idiopathic detrusor overactivity (DO) and those with normal bladder function (Stevens *et al*., 2004a, b). Furthermore, no changes in receptor subtype contribution to detrusor contractions in the disease state were observed. The concentration–response curves to carbachol indicated that muscarinic receptor-mediated function was enhanced in the neurogenic and idiopathic DO tissue compared with normal bladder tissue *in vitro*. The presence of the M_3 receptor selective antagonist 4-DAMP reduced the contractile response to carbachol in the normal bladder and in the neurogenic and idiopathic DO, whereas the M_2 receptor selective antagonist, methoctramine, was less effective in all tissues. However, the study did not show any significant differences from unity in the Schild slopes for either antagonist (Stevens *et al*., 2004b). As such, an indirect role of M_2 receptors in mediating contractile responses cannot be discounted.

Findings from *in vitro* research using human and guinea-pig bladder tissue have led to the proposal that a network of interstitial cells – similar to the interstitial cells of Cajal in the gut (myofibroblasts) – within the suburothelial layer may augment and coordinate autonomous detrusor activity (see Fry *et al*., 2004; Gillespie, 2004a, b). Immunocytochemical evidence from rodents has also demonstrated the presence of M_3 receptors located on interstitial cells in the suburothelial layer (Gillespie *et al*., 2003), and it has been postulated that such cells expressing M_3 receptors may contribute to the generation of phasic contractions (Gillespie, 2004a, b), and may be activated by ACh generated and released from the urothelium/suburothelium (see Yoshida *et al*., 2004). One hypothesis is that such cells can activate phasic activity, whereas ATP-releasing and peptidergic neurons present within

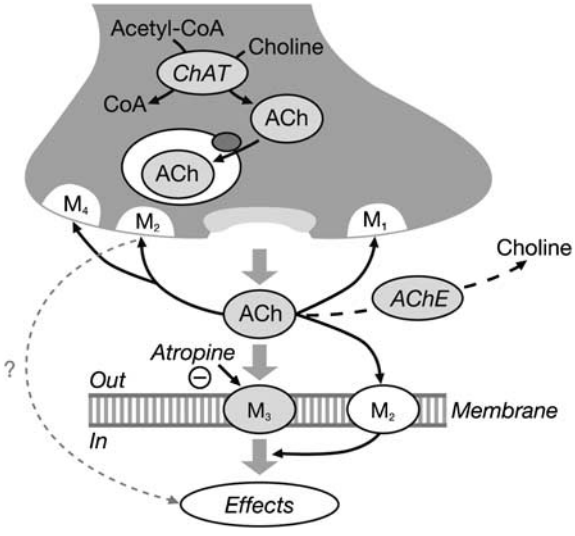

Figure 1 The role of the M3 receptor in detrusor contraction. Acetylcholine (ACh), produced in the presynaptic terminal by the action of choline acetyl transferase (ChAT) on choline and acetyl coenzyme A (acetyl-CoA), is released by exocytosis. ACh is metabolized by acetyl cholinesterase (AChE) to release choline. Detrusor contraction is mediated by the binding of ACh on postjunctional membrane muscarinic M_3 receptors (M_3), resulting in activation of the contractile proteins within the detrusor muscle (Effects). Prejunctional M_2 and M_4 receptors inhibit, whereas prejunctional M_1 receptors facilitate the release of ACh. The M_2 receptor also appears to have an indirect functional role in detrusor contractility, and possibly a minor direct effect, but the mechanism remains unclear. Atropine inhibits contraction by blockade of muscarinic receptors.

the network of interstitial cells modulate bladder sensations. Indeed, activation of cholinergic receptors in feline epithelial cells has been shown to facilitate ATP release (Birder *et al*., 2003), which in turn may activate adjacent afferent nerves or myofibroblasts. Thus, inappropriate phasic activity could contribute to DO and be responsible for generating 'sensory urgency'. Although intriguing, further investigations are needed to understand the subtypes and functional role of muscarinic receptors within the urothelium.

Muscarinic receptors are also located prejunctionally on cholinergic nerve terminals within the bladder, where M_1 receptors facilitate transmitter release and M_2/M_4 receptors inhibit transmitter release (see Chess-Williams, 2002; Zhou *et al*., 2002). However, the functional role of these prejunctional receptors remains unclear (see Somogyi *et al*., 1996; Chess-Williams, 2002). Current *in vitro* research suggests that the M_1 receptor is a prominent modulator of ACh release, the stimulation of which, during increased nerve traffic, may act to promote more efficient voiding. Evidence also suggests that the prejunctional facilitatory receptors exhibit plasticity following spinal cord injury (see Somogyi & De Groat, 1999). Prejunctional high-affinity M_3 receptors at cholinergic nerve endings are upregulated in bladders of chronic spinal cord transected rats and replace low-affinity M_1 muscarinic receptors (Somogyi *et al*., 2003). Conversely, it has been suggested that inhibitory M_2 and M_4 prejunctional receptors may function to promote urine storage, with enhanced activity at times of low-frequency nerve traffic, for example in pathologic states such as bladder denervation or spinal cord injury (see Chapple, 2000).

It is clear that the control of normal and pathological bladder function and the functional role of muscarinic receptors is highly complex. It remains unknown as to whether the efficacy of antimuscarinic agents in the treatment of OAB is specific to an effect on M_3 receptors within the detrusor muscle, or whether actions at other receptor sites such as sensory nerves or urothelium/suburothelium contribute to the therapeutic effect.

The salivary glands

The parasympathetic nervous system plays a pivotal role in the production of saliva by serous and mucous cells of the acinar structures in salivary glands (see Baum, 1993) and by serous cells in the parotid glands. Human and rodent studies show that both M_1 and M_3 receptors are present in the salivary glands, whereas the parotid glands express predominantly M_3 receptors (Culp *et al*., 1996; Watson *et al*., 1996; Beroukas *et al*., 2002). Similarly, functional studies in mice and rats have demonstrated that submandibular gland secretion is mediated through M_1 and M_3 receptors, whereas parotid gland secretion is mediated *via* M_3 (and possibly M_4) receptors (Tobin *et al*., 2002; Bymaster *et al*., 2003; Gautam *et al*., 2004); the robustness of these findings may be inferred from the finding that these effects were observed across different modes of induction of salivation (*via* electrical stimulation of the parasympathetic nervous system or stimulated by oxotremorine or pilocarpine). Thus, salivation is predominantly mediated by the M_3 receptors that are involved in the control of both high- and low-viscosity secretions and saliva volume, whereas the M_1 subtype is involved in the control of high-viscosity lubrication. This has been illustrated by preclinical studies in rats and cats which demonstrated that selective antagonism of M_3 receptors inhibits, but does not eliminate, salivary responses to carbachol or electrical stimulation (Gillberg *et al*., 1998; Ikeda *et al*., 2002).

Although salivation is primarily mediated by M_3 receptors, the functional importance of multiple muscarinic receptor subtypes in the quantity and quality of salivary secretion is highlighted by the fact that agonist-induced salivation (using oxotremorine, pilocarpine or isoproterenol) is depressed in the M_3 knockout mouse, yet the buccal cavity remains lubricated (Matsui *et al*., 2000; Bymaster *et al*., 2003). In contrast, mice devoid of M_1 and M_4 receptors show an intermediate response, whereas while M_2 and M_5 knockout mice have normal salivation (Bymaster *et al*., 2003). As pilocarpine-induced salivation is abrogated in M_1/M_3 receptor double-knockout mice (Gautam *et al*., 2004), and maximal salivary secretion induced by carbachol requires both M_1 and M_3 receptors (Luo *et al*., 2001), it is evident that salivation is mediated by two different postjunctional muscarinic receptors. In addition to the postjunctional receptors, there are neuronal M_2 and M_1 receptors on the nerves supplying the salivary glands. These neuronal receptors have a contributory role in salivation by inhibiting (M_2) or enhancing (M_1) ACh release from the nerves (Tobin, 2002).

In the clinical context, some studies have shown that M_3-selective and nonselective muscarinic receptor antagonists (with activity at both M_1 and M_3 receptors) appear to reduce salivation in similar proportions of patients (Diokno *et al*., 2003; Haab *et al*., 2004; Armstrong *et al*., 2005). In contrast, in a crossover study of 65 patients with OAB comparing darifenacin with oxybutynin, treatment with oxybutynin immediate release (IR) 5 mg three times daily was associated with significantly greater reductions ($P<0.05$) in salivary flow than darifenacin controlled release (CR) (15 mg once daily or 30 mg once daily) (Chapple & Abrams, 2005). It is possible that, compared with antagonism of both receptor subtypes, sparing the M_1 receptors in the salivary glands may help to maintain enough lubrication to alleviate the sensation and severity of dry mouth. This is supported by low discontinuation rates owing to dry mouth ($<3\%$) during darifenacin treatment, based on a pooled analysis of three darifenacin studies (Chapple *et al*., 2005).

The gastrointestinal tract

Although gut smooth muscle has been shown to contain all five muscarinic receptor subtypes in differing proportions in guinea-pigs (So *et al*., 2003), M_2 and M_3 receptors are thought to be the most functionally important in humans. As with the bladder, M_2 receptors outnumber the M_3 receptor population by up to 4 : 1 in humans (Gomez *et al*., 1992; Kerr *et al*., 1995) but data from studies in rodents and dogs suggest that the M_3 receptor appears to play the prominent role in cholinergic stimulation of gastrointestinal motility (Eglen & Harris, 1993; Chiba *et al*., 2002; Li *et al*., 2002; Matsui *et al*., 2002). As such, antagonism of these receptors may contribute to a reduction in colonic transit. A functional role for other muscarinic receptor subtypes, particularly the M_2 receptor, is beginning to emerge (see Matsui *et al*., 2000; Eglen, 2001). Indeed, *in vitro* research using murine smooth muscle has indicated that M_2 receptors may have a greater contribution to contractility in the gastrointestinal tract than in the bladder (Matsui *et al*., 2000).

Numerous other signaling mechanisms, mediated by a variety of neurotransmitters within the enteric nervous system, also appear to play a major role in physiological control of gastrointestinal function. Serotonergic (5-HT) receptors have been shown to be important in the control of gastrointestinal motility and sensitivity. For example, the 5-HT_4 receptor subtype mediates excitatory effects (Gershon, 2003) and directly influences gastrointestinal secretion. Other signalling mechanisms implicated in the control of gastrointestinal function include substance P and neurokinin (NK) A acting at NK_1 and NK_2 receptors, and the inhibition of nitric oxide release. The complex interplay between these mechanisms helps explain why M_3 knockout mice have no overt gastrointestinal problems (Matsui *et al*., 2000).

As with the bladder, many gaps in knowledge still exist regarding the functional role of muscarinic receptors and the contribution of specific subtypes within the gastrointestinal tract. These include the role of muscarinic receptors expressed by interstitial cells of Cajal and enteric neurons, the role of M_4 and M_5 receptors on smooth muscle and the mechanisms of long-term compensation for muscarinic deprivation. In the clinical setting, constipation following muscarinic antagonist therapy is often reported as one of the classic muscarinic adverse events. This is to be expected given the need to target the M_3 receptor to achieve clinical efficacy in OAB, and the role of this receptor in the complex mechanisms involved in gastrointestinal transit. In a pooled analysis of fixed dose clinical studies with the M_3 selective receptor antagonist darifenacin, an increase was observed in the reported incidence of constipation compared with placebo (14.8 and 21.3% all-causality incidence for darifenacin CR 7.5 and 15 mg once daily, respectively, compared with 6.2% for placebo) (Chapple *et al*., 2005). Although the incidence of constipation appears to be higher with darifenacin than for other antimuscarinics, a clinical comparison of darifenacin and the nonselective muscarinic receptor antagonist tolterodine IR showed that that the two agents were associated with similar incidences of new-onset laxative use for constipation and discontinuations owing to constipation (Thomas *et al*., 2005). However, further detailed studies are needed to investigate the comparative clinical effects of M_3 selective and nonselective muscarinic receptor antagonists on the gastrointestinal tract.

The brain

Muscarinic receptors in the brain activate a multitude of signaling pathways important for the modulation of neuronal excitability, synaptic plasticity and feedback regulation of ACh release. All five muscarinic receptor subtypes are expressed in the brain (see Volpicelli & Levey, 2004). M_1 receptors, for example, are most abundant in the neocortex, hippocampus and neostriatum, whereas M_2 receptors are located throughout the brain. In contrast, levels of M_3 receptors are low whereas M_4 receptors are abundant in the neostriatum, and M_5 receptors have been localized to the projection neurons of substantia nigra, pars compacta, ventral tegmental area and the hippocampus (Table 1).

Central muscarinic receptors are involved in higher cognitive processes such as learning and memory. It is generally accepted that M_1 receptors play an important functional role in this regard. Indeed, antagonism of central M_1 receptors with intrahippocampal pirenzepine impaired spatial memory in rat models (Messer *et al*., 1990). Also, mice lacking the M_1 receptor exhibit defects in a number of cognitive processes (Anagnostaras *et al*., 2003), and M_1 receptor agonists reverse learning and spatial memory impairment in animal models of Alzheimer's disease (see Fisher *et al*., 2003). In clinical studies, an M_1/M_4 receptor agonist has been reported to improve cognition in patients with Alzheimer's disease, as measured on the Clinician's Interview Based Impression of Change, although treatment was associated with a high incidence of systemic side effects (Bodick *et al*., 1997). Central M_1 antagonism may therefore give rise to cognitive dysfunction and other central nervous system (CNS)-related adverse events. These effects are becoming increasingly associated with antimuscarinic agents with a relatively high affinity for this receptor (Donnellan *et al*., 1997; Katz *et al*., 1998; Womack & Heilman, 2003). Moreover, activity at central M_2 receptors may also contribute to impaired cognitive function, given that mice devoid of such receptors display cognitive deficits (Tzavara *et al*., 2003). These findings were expanded in a further study, which showed a deficit in behavioral flexibility, working memory and hippocampal plasticity in M_2 knockout mice (Seeger *et al*., 2004). Although such studies cannot be replicated in man, Perry *et al*. (2003) showed that patients with Parkinson's disease, treated for over 2 years with less selective antimuscarinic agents (orphenadrine, oxybutynin, trihexyphenidyl), had more pathological stigmata of Alzheimer's disease than patients who had not been treated with these agents. These findings suggest that both M_1 and M_2 receptors in the CNS play an important functional role in cognitive function. In contrast, M_3 knockout mice show normal cognition and behavior (Yamada *et al*., 2001a).

It is also important to note that antagonism of muscarinic M_1 and M_2 receptors in the brain is dependent not only on a drug's affinity for these receptors, but also on the drug concentration within the CNS. This is determined by the

Table 1 Location of muscarinic receptors in the brain

M_1: Abundant in neocortex, hippocampus and neostriatum
Pyramidal cells
Small fraction appear to be on axons and terminals

M_2: Throughout brain
Autoreceptor (inhibitory) in hippocampus and cortex
Noncholinergic terminals in hippocampus, cortex and olfactory bulb
Basal forebrain (e.g. GABAergic neurons in visual cortex)
Thalamus

M_3: Low levels throughout brain
Hippocampus
Thalamus
Striatal GABAergic neurons

M_4: Abundant in neostriatum; also in the cortex and hippocampus
Autoreceptor (inhibitory) in striatum
Striatal medium spiny neurons
Hippocampus

M_5: Projection neurons of the substantia nigra, pars compacta and ventral tegmental area; also in this hippocampus
Dopaminergic terminals stimulatory in the nucleus accumbens and striatum

GABA, gamma-aminobutyric acid.

balance between drug penetration through the blood–brain barrier (BBB) and efflux. Thus, the molecular size, polarity and lipophilicity, and specificity for the P-glycoprotein efflux pump may influence the risk of adverse CNS effects with antimuscarinic drugs. However, the drug levels in the CNS may change in situations where the BBB becomes 'leaky' following damage (e.g. under conditions of stress, advanced age or presence of comorbid conditions such as diabetes or multiple sclerosis) (see Liebsch *et al*., 1996; Habgood *et al*., 2000; Pakulski *et al*., 2000; Esposito *et al*., 2001; Starr *et al*., 2003; Ballabh *et al*., 2004). Indeed, older individuals, who are often prescribed multiple medications that have antimuscarinic activity (see Tune, 2001), are particularly susceptible to their CNS adverse effects, with likely contributory factors including age-related changes in drug elimination, increased BBB permeability and reductions in muscarinic receptor density. It is notable that in clinical trials, a low incidence of CNS changes and CNS adverse events has been reported with oxybutynin extended release (ER) and tolterodine ER, and these events were rarely a cause for discontinuation (see Clemett & Jarvis, 2001; Chu *et al*., 2005). However, significant effects on quantitative electroencephalogram, sleep physiology and cognitive test performance have been demonstrated with nonselective antimuscarinic therapy (Pietzko *et al*., 1994; Katz *et al*., 1998; Diefenbach *et al*., 2003). In contrast, emerging evidence suggests that M_1/M_2 receptor sparing antimuscarinic therapy may be free of CNS sedation and cognitive impairment, although it should be noted that these studies did not employ a nonselective OAB antimuscarinic as a comparator (Kay & Wesnes, 2005; Lipton *et al*., 2005).

Mechanisms implicated in increased BBB permeability include epithelial shrinkage accompanied by opening of tight junctions and dilation of the blood vessels resulting in increased blood flow and enhanced transport, as shown in a rat model (Abdel-Rahman *et al*., 2002). Other mechanisms could include enhanced pinocytotic activity, which is seen with increasing age (Pakulski *et al*., 2000). Consequently, all antimuscarinic receptor antagonists, irrespective of their physicochemical properties, have the potential to cross the BBB, although the level of affinity/serum concentration needed to affect muscarinic receptors mediating cognitive function requires investigation. However, available evidence suggests that a key issue regarding the potential for minimizing any cognitive adverse events with antimuscarinic agents would be to spare the M_1 receptor.

The eye

The findings of immunoprecipitation studies show that all five muscarinic receptor subtypes exist within the human eye, of which the M_3 receptor predominates (M_3, 60–75%; M_2, 5–10%; M_4, 5–10%; M_1, 7%, in ciliary processes and iris sphincter; M_5, 5%, located only in the iris sphincter) (Gil *et al*., 1997; Ishizaka *et al*., 1998). Functional M_3 receptors mediating contractility responses have been identified on trabecular meshwork, ciliary muscle and iris sphincter of cows (Wiederholt *et al*., 1996), Rhesus monkeys (Poyer *et al*., 1994) and humans, respectively (Woldemussie *et al*., 1993; Shade *et al*., 1996). Functional studies in M_3 knockout mice have lent support to the involvement of M_3 receptors in controlling iris sphincter contraction (Matsui *et al*., 2000; Bymaster *et al*., 2003) with other studies in the canine or rabbit eye suggesting that M_5 receptors also contribute to cholinergically mediated contraction of isolated ciliary muscle (Bognar *et al*., 1992; Choppin & Eglen, 2001). Studies using knockout mice have suggested that M_2 receptors may be involved in additional mechanisms controlling pupillary constriction and dilation. Mice lacking both M_2 and M_3 receptors had pupil constriction compared with mice lacking the M_3 receptor only (Matsui *et al*., 2002). Whether this observation reflects an effect mediated through autoreceptors was speculated, but is currently unknown. Other studies have suggested that M_2 receptors on parasympathetic and sympathetic nerve terminals in the iris can modulate ACh release in rabbits and and norepinephrine release in humans, respectively (Bognar *et al*., 1990; Jumblatt & Hackmiller, 1994). A role for M_2 receptors in the regulation of trabecular meshwork contractility has also been suggested from studies examining human and bovine tissue (Thieme *et al*., 2001).

Although M_1 and M_4 receptors are expressed in the human eye (Gil *et al*., 1997; Ishizaka *et al*., 1998), their functional roles have yet to be fully elucidated. M_1 receptors are present in human iris, sclera and native lens epithelial cells, where they are the predominant subtype and mediate changes in cytosolic calcium (Collison *et al*., 2000). A functional role for M_4 receptors in the eye remains to be determined. Of note, animal studies have shown that M_1, M_2 and M_3 receptors can mediate activation of conjunctival goblet cells – the primary source of mucins in the tear film (Kanno *et al*., 2003).

The propensity for an antimuscarinic agent to cause ocular events will depend upon a number of factors. Consideration should be given to the serum levels necessary to affect structures within the eye, and the specific affinities of the muscarinic receptors present with a given serum level of drug. As such, although ocular events may be seen with both M_3 and M_5 receptor antagonism, blurred vision is uncommon with the selective M_3 receptor antagonist darifenacin, with one comparative study reporting no episodes of blurred vision in contrast to a 3% rate with the less selective agent oxybutynin (Zinner *et al*., 2005).

Similar to the brain, the potential for adverse effects in the eye with a particular antimuscarinic may not only depend on the selectivity of the drug but also its physical characteristics, potential to cross the blood–retina barrier, which regulates permeation of substances from the blood to the retina (see Duvvuri *et al*., 2003), and affinity for potential mechanisms regulating efflux.

The heart

Stimulation of muscarinic receptors within the mammalian heart, specifically the M_2 subtype (see Hulme *et al*., 1990; Caulfield, 1993), modulates pacemaker activity and atrioventricular conduction, and directly (in atrium) or indirectly (in ventricles) the force of contraction (see Dhein *et al*., 2001). Indeed, bradycardia in response to carbachol is abolished in M_2 knockout mice (Stengel *et al*., 2000), emphasizing the functional importance of this subtype. Although other muscarinic receptor subtypes have also been localized in the human heart (M_1, M_3 and M_5) (Hellgren *et al*., 2000; Wang *et al*., 2001; Willmy-Matthes *et al*., 2003), details of their functional roles are still emerging.

Functional M_1 receptors, which increase heart rate, have been reported in rodent cardiac tissue (Islam *et al*., 1998;

Colecraft *et al*., 1998) and human atrial myocytes (Dobrev *et al*., 2003; Wang *et al*., 2004). However, the basal heart function of mice lacking M_1 receptors is unchanged compared with wild type, and cardiac stimulation by M_1 receptors occurs through stimulation of catecholamine release from sympathetic neurons (Hardouin *et al*., 2002). Other studies have also implicated non-M_2 receptors, in addition to M_2 receptors, in the modulation of sympathetic neurotransmitter release in mouse atria (Trendelenburg *et al*., 2003).

Functional M_3 receptors have been identified in rodent and mammalian cardiac tissue (see Nishimaru *et al*., 2000; Pönicke *et al*., 2003; Wang *et al*., 2004) and in human atrial tissue (Dobrev *et al*., 2003; Willmy-Matthes *et al*., 2003), although data obtained using knockout mice suggest limited involvement of M_3 receptors in physiological cardiac function. Studies using mice lacking either M_2 or M_3 receptors have indicated an obligatory role for M_2 receptors in heart-rate regulation, and no change in the basal heart rate of M_3 knockout mice (Gomeza *et al*., 1999; Stengel *et al*., 2002).

It is important to consider whether the role of muscarinic receptor subtypes in modulating cardiac function may alter in pathological conditions. Additional data have indicated increased M_3 receptor density, but a decrease in M_2 receptors, in chronic atrial fibrillation and experimental congestive heart failure (see Wang *et al*., 2004). The genes for M_2 and M_3 receptors are expressed in human coronary arteries (Niihashi *et al*., 2000), although the functional importance of these receptors is currently unclear. Studies using knockout mice lacking M_2, M_3 or M_5 receptors (Yamada *et al*., 2001b; Lamping *et al*., 2004) have suggested that M_3 receptors predominantly mediate ACh-induced (endothelium-dependent) dilatation of mouse coronary arteries (Lamping *et al*., 2004). Whether this finding extends to human tissue remains to be determined, and data from functional studies using the human coronary artery are awaited.

In summary, available data indicate a prominent role of M_2 receptors in cardiac function. Further work is required to elucidate the role of other muscarinic receptor subtypes in the heart and how this may be altered in disease states.

Determining the ideal antimuscarinic drug for treatment of OAB

The third International Consultation on Incontinence Committee on Drug Therapy reviewed the considerable data supporting the clinical efficacy and safety of antimuscarinic drugs for the treatment of OAB. Following full development programs, darifenacin and solifenacin are the latest agents to enter the market, which includes oxybutynin, propiverine, tolterodine and trospium. There are other historically important but infrequently used drugs with antimuscarinic actions including imipramine (a tricyclic antidepressant with central and peripheral effects), flavoxate (a tertiary amine with calcium antagonistic activity in the bladder), dicyclomine (an antimuscarinic with calcium antagonistic properties) and propantheline (a quaternary amine with anticholinergic activity in the bladder and gastrointestinal tract) (see Andersson *et al*., 2005). However, the latter drugs will not be further discussed in this review.

When identifying the features of the ideal antimuscarinic drug for treatment of OAB, it is important to consider a number of factors. These agents differ with respect to structural characteristics (e.g. trospium is a quaternary ammonium compound, others are tertiary amines), pharmacokinetic profile and mechanism(s) of action (in addition to antimuscarinic action, drugs may also have a calcium channel blocking property). Furthermore, sparing or affecting a particular muscarinic receptor has the potential to be beneficial in terms of tolerability/safety.

Formerly, an ideal antimuscarinic was one that could block the efferent impulses that caused detrusor contraction, without having dose-limiting side effects. Now the ideal drug may also need to have effects on the urothelium and afferent nerves in order to maximize its clinical effectiveness (see Andersson, 2004). The existing drugs have different receptor blocking profiles, but what is not known is whether the more M_3 selective blockers have clinical advantages over the less selective drugs. 'Head-to-head' comparative studies between drugs will be needed to resolve the question: 'Which is the best available drug?' However, this question may be difficult to answer until we have more reliable instruments to assess both the symptoms of OAB, such as urgency, and the adverse effects, such as bowel disturbance.

Secondary mechanisms of antimuscarinic drug action

In theory, drugs that have actions in addition to antagonism of muscarinic receptors – such as nonspecified 'direct muscle relaxant effects' (e.g. as attributed to oxybutynin), calcium channel blocking or potassium channel opening properties – could increase effectiveness. Table 2 describes the evidence for the proposed secondary actions for the antimuscarinics in both animal (*in vitro* and *in vivo*) and human studies in OAB (see Andersson, 1984; 1988; Andersson *et al*., 1999; Yono *et al*., 2000; Andersson & Chapple, 2001).

Clearly, such secondary actions can also result in undesirable effects. For example, terodiline – a drug widely perceived by patients and clinicians alike as an effective antimuscarinic – was withdrawn by the regulatory authorities in 1991 owing to its cardiac adverse event profile. This drug possessed calcium channel blocking activity, and induced a specific cardiac arrhythmia known as 'Torsades de Pointes' (see Roden, 2004). By contrast, a clinical study demonstrated that the M_3 receptor selective muscarinic antagonist, darifenacin, does not prolong the QT interval and is therefore not expected to cause any harmful effects on cardiac repolarisation (Serra *et al*., 2005).

Dosing and pharmacokinetic considerations

Patient compliance with medication is influenced by a number of factors including dosing schedules (Richter *et al*., 2003). Compliance decreases with increasing number of daily doses, with a pronounced effect noted when more than two doses per day are prescribed (Claxton *et al*., 2001). If the assumption is made that once-daily dosing is optimal, then a single dose needs to provide clinically significant efficacy over a period as close as possible to 24 h. For some patients, treatment given when needed might be preferable, perhaps for 'special occasions' such as socializing. Here, a faster-onset shorter-acting preparation may be useful, although it is important that rapid efficacy is not achieved at the penalty of an unacceptable increase in side effects.

Table 2 Muscarinic receptor antagonists with secondary mechanisms of action

Agent	*Mechanisms of action*	*Evidence*	*Reference*
Oxybutynin	Muscarinic M_1/M_3 receptor antagonist, calcium antagonist and local anesthetic actions	*In vitro* smooth muscle relaxant effect (500 times weaker than antimuscarinic activity) Efficacy in OAB shown in clinical studies Effective on intravesical administration	Reviewed by Andersson & Chapple (2001)
Dicyclomine	Nonselective muscarinic receptor antagonist, calcium antagonist action	Efficacy in OAB shown in clinical studies	Reviewed by Andersson *et al.* (1999)
Propiverine	Nonselective muscarinic receptor antagonist, calcium antagonist action	Efficacy in OAB shown in clinical studies	Reviewed by Andersson *et al.* (1999)
Temiverine	Selective muscarinic M_3 receptor antagonist, calcium antagonist action	*In-vitro* inhibition of carbachol- and Ca-induced contractions in human detrusor muscle No published clinical data	Yono *et al.* (2000)
Terodiline	Nonselective muscarinic receptor antagonist, calcium antagonistic action	Efficacy in OAB shown in clinical studies Induced ventricular arrhythmias (Torsades de Pointes)	Reviewed by Andersson (1984; 1988)

Figure 2 shows the serum concentrations of the commonly available antimuscarinics with curves calculated for oxybutynin and tolterodine ER preparations, trospium 20 mg twice daily, darifenacin 7.5 and 15 mg CR once daily and solifenacin 10 mg once daily (Olsson & Szamosi, 2001; Appell *et al.*, 2003; Prescribing Information, 2004; Smulders *et al.*, 2004; Product Information, Enablex (US), 2005). Of note, owing to the long half-life (40.2 and 49.4 h for the 5 and 10 mg doses, respectively) (Smulders *et al.*, 2004), solifenacin is an outlier in relation to the other drugs. In theory, a longer duration of action following a single dose may be beneficial in smoothing out serum peaks that are believed to increase the prevalence of side effects. However, if the duration of action exceeds 24 h following a single daily dose, then drug accumulation could be an issue. Also, should side effects occur, the patient may have to wait longer before these effects subside. A further downside of a long half-life may be that time to reach steady state is likely to be longer.

Figure 3 shows the difference between the IR and ER versions of oxybutynin and tolterodine in terms of serum concentrations of drug over a 24-h period (Gupta & Sathyan, 1999; Olsson & Szamosi, 2001; Appell *et al.*, 2003). There is some evidence, for each drug, that once-daily dosing of the ER preparation leads to a modest increase in efficacy and a decrease in side effects (Table 3) (Anderson *et al.*, 1999; Gupta & Sathyan, 1999; Appell *et al.*, 2001; Olsson & Szamosi, 2001; Van Kerrebroeck *et al.*, 2001; Appell *et al.*, 2003; Barkin *et al.*, 2004; Product Information (Ditropan/Ditropan XL), 2004; Product Information, Detrol (US), 2005; Product Information, Ditropan (US), 2005). No information is available on the proportion of patients who would prefer to receive treatment when needed rather than as continuous therapy. However, it seems important to preserve the option of an IR version for such individuals.

Thus, there are marked differences in pharmacokinetics between antimuscarinic agents, and some additional parameters are listed for ease of comparison in Table 4 (Douchamps *et al.*, 1988; Prescribing Information (Sanctura), 2004; Prescribing Information, VESIcare (US), 2004; Product Information, Detrol LA (US), 2005; Product Information, Ditropan XL (US), 2005; Product information (Enablex), 2005). Of particular note are the high levels of protein binding

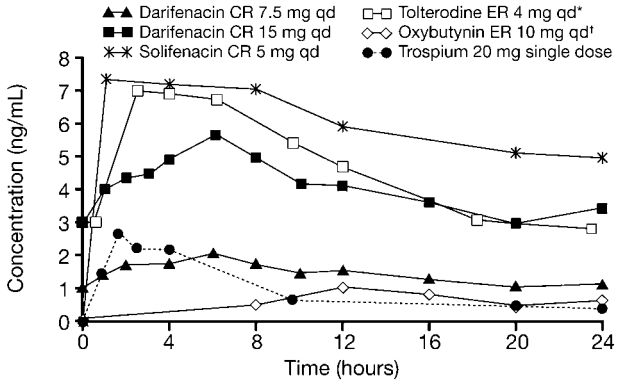

Figure 2 Mean plasma concentration *versus* time profiles of available antimuscarinic agents (Olsson & Szamosi, 2001; Prescribing Information (Sanctura), 2004; Product Information, Ditropan/Ditropan XL, 2004; Smulders *et al.*, 2004; Product Information, Enablex (US), 2005). *Median serum concentration of active metabolite (5-hydroxymethyl) in healthy volunteers identified as extensive metabolizers. †Mean plasma concentration of R-oxybutynin.

reported for most antimuscarinic agents, which would suggest that levels of circulating free drug would be too low to exert pharmacodynamic effect. Despite this, the efficacy of these antimuscarinics is well established. Clearly, therefore, other properties must also be important, and these may include factors such as steady-state levels of receptor occupancy, data on which are not readily available, and the role of active metabolites. The plasma concentration profiles of the active metabolites of tolterodine (4-hydroxymethyltolterodine) and oxybutynin (*N*-desethyloxybutynin) are shown in Figures 2 and 3(a), respectively. Although these clearly exert a pharmacodynamic effect, it is not clear what proportion of total effect may be attributed to the active metabolite *versus* parent molecule.

Receptor activity of antimuscarinic agents

The receptor activity of antimuscarinics can be expressed in different ways, including pharmacologically derived characteristics (Table 5) (Napier & Gupta, 2002) and clinical

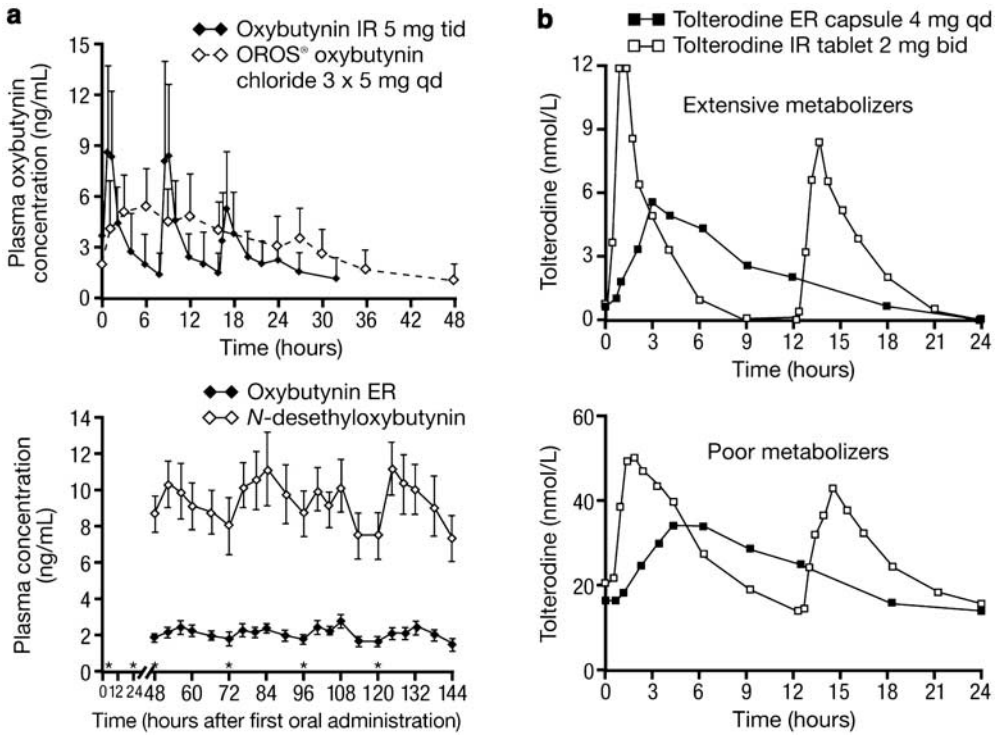

Figure 3 Mean plasma concentration *versus* time profiles of immediate release and extended release versions of (a) oxybutynin and (b) tolterodine (extensive and poor metabolizers) (Gupta & Sathyan, 1999; Olsson & Szamosi, 2001; Appell *et al*., 2003). *Oral tablet administration. (a) (Upper figure). Reproduced with permission from Gupta S.K. & Sathyan G. Pharmacokinetics of an oral once-a-day controlled-release oxybutynin formulation compared with immediate release oxybutynin. *J. Clin. Pharmacol*. 1999; **39**: 289–296. Copyright 2006, Reprinted by permission of Sage Publication Inc. (Lower figure). Reproduced with permission from Appell RA *et al*. Pharmacokinetics metabolism, and saliva output during transdermal and extended-release oral oxybutynin administration in healthy subjects. *Mayo. Clin. Proc*. 2003; **78**: 696–702. (b) Reproduced with permission from Olsson B *et al*. Multiple dose pharmacokinetics of a new once daily extended release tolterodine formulation *versus* immediate release tolterodine. *Clin. Pharmacokinet*. 2001; **40**: 227–235.

Table 3 Comparison of safety/efficacy profile of ER and IR formulations of tolterodine and oxybutynin (Anderson *et al*., 1999; Appell *et al*., 2001; Van Kerrebroeck *et al*., 2001; Barkin *et al*., 2004; Product information (Ditropan), 2004; Product Information, Detrol LA (US), 2005; Product Information, Ditropan (US), 2005)

	Tolterodine ER 4 mg q.d.	*Tolterodine IR 2 mg b.i.d.*	*Oxybutynin ER 5–30 mg q.d.*	*Oxybutynin IR 5 mg q.d.–q.i.d.*
No. of incontinence episodes, mean change from baseline (%)	–53	–46	–64 to –99	–73 to –88
Incidence of dry mouth (%)	23	35	61	71.4
Incidence of constipation (%)	6	7	13	12.6

ER, extended-release; IR, immediate release; q.d., once daily; b.i.d., twice daily; q.i.d., four times daily.

uroselectivity. In general, animal models have been used to demonstrate uroselectivity, with studies focusing on how beneficial effects on the bladder predominate over unwanted effects on saliva production (dry mouth) and cardiac effects. Such models demonstrate a wide variation in apparent uroselectivity between drugs (i.e. depending on the model chosen, a selected antimuscarinic may be more uroselective than the others). Nevertheless, such models have been used for the selection of drugs for further development. However, there have been few investigations of uroselectivity performed in humans. One study by Chapple (2001) investigated tolterodine ER (6 mg) and oxybutynin ER (5, 15 and 25 mg) in 16 healthy male volunteers. Tolterodine ER 6 mg produced an increase in bladder capacity comparable with that expected with an oxybutynin ER dose of approximately 20 mg, and a reduction in salivation comparable to that expected with an oxybutynin ER dose of approximately 10 mg.

If it were accepted that the M_3 receptor is the only receptor that is important when treating OAB, then it would be expected that a drug that spares other muscarinic receptors would give rise to an optimal tolerability and safety profile. However, the adverse event of constipation associated with the antimuscarinic class of agents might also still be expected.

Establishing and comparing risk:benefit profiles

Adverse event profiling of each drug may shed light on the relationships between beneficial effects and adverse events for

each drug. However, to date few studies have been completed that systematically compare the clinical efficacy and safety of the available antimuscarinics. Large clinical trials in patients with OAB have demonstrated clinical efficacy for antimuscarinic agents that differ widely in terms of relative selectivity for the M_3 receptor, for example, from the highly M_3 receptor selective agent darifenacin (Steers *et al*., 2005) to the relatively nonselective agents tolterodine (see Clemett & Jarvis, 2001) and trospium (Halaska *et al*., 2003). However, comparison of drug profiles using existing clinical study data is difficult due to the lack of standardization of inclusion/exclusion criteria, measurement instruments and the drug dosages used. At present, therefore, it is difficult to draw firm conclusions as to which type of antimuscarinic does, or will, offer the best benefit-to-risk ratio. The recommendations of the International Continence Society's Clinical Trials Standardisation Committee and use of the International Consultation Incontinence modular questionnaire may be helpful. These may enable trials to be conducted that will allow easier comparison between antimuscarinic drugs by making available a standard basic protocol, together with valid instruments to assess outcomes. Nevertheless, a major difficulty will always be how to compare the drugs at similar clinically relevant doses.

Table 4 Comparison of pharmacokinetic parameters potentially influencing drug availability and activity for selected antimuscarinic agents (Douchamps *et al*., 1988; Prescribing Information (Sanctura), 2004; Prescribing Information, VESIcare (US), 2004; Product information (Enablex), 2005; Product Information, Detrol LA (US), 2005; Product Information, Ditropan XL (US), 2005)

	Bioavailability (%)	*Protein binding* (%)	*Distribution volume at steady state* (l)	*Terminal elimination half-life* (h)
Darifenacin	15–19	98	163	7–20
Tolterodine	⩾77	96	113	2–10
Oxybutynin	6	NA	193	13
Solifenacin	90	98	600	45–68
Trospium	⩽10	50–85	395	18

NA, not available.

Etiology of DO

Finally, the etiology of DO is another factor that impacts the efficacy of antimuscarinic therapy. Although it is well established that the contractions of the detrusor muscle are in response to the cholinergic stimulation of muscarinic receptors located in the bladder, the exact etiology of DO is largely unknown. The pathophysiology of DO may be neurogenic, myogenic or a combination of both. Neurogenic pathophysiology may possibly involve reduced suprapontine inhibition, damaged axonal paths through the spinal cord, increased afferent input from the lower urinary tract, loss of peripheral inhibition and/or enhanced excitatory neurotransmission in the micturition reflex pathway (see de Groat, 1997). In contrast, myogenic pathophysiology has been postulated to develop following local denervation of bladder smooth muscle leading to increased excitability and easier signal transmissibility between myocytes, thus stimulating the propagation of coordinated contractions (see Turner & Brading, 1997) or micromotions.

Data from guinea-pig studies has also linked DO with inappropriate activation or modulation of autonomous activity *via* suburothelial interstitial cells, resulting in pathological localized contractions and 'sensory urgency' (Gillespie, 2004a). There is also evidence that ACh may be released or leak from postganglionic parasympathetic neurons or from non-neuronal sources during bladder filling, with subsequent micromotions in the detrusor causing an increase in afferent stimulation (see Andersson, 2004).

Table 5 Comparison of muscarinic receptor affinities and M_3 selectivity profiles of antimuscarinic agents (mean binding affinity ratios) (Napier & Gupta, 2002)

(a) *Affinity (pK_i) of antimuscarinic compounds for the human recombinant receptor subtypes M_1–M_5*

	M_1	M_2	M_3	M_4	M_5
Darifenacin	8.2 (0.04)	7.4 (0.10)	9.1 (0.10)	7.3 (0.10)	8.0 (0.10)
Tolterodine	8.8 (0.01)	8.0 (0.10)	8.5 (0.10)	7.7 (0.10)	7.7 (0.03)
Oxybutynin	8.7 (0.04)	7.8 (0.10)	8.9 (0.10)	8.0 (0.04)	7.4 (0.03)
Propiverine	6.6 (0.10)	5.4 (0.10)	6.4 (0.10)	6.0 (0.10)	6.5 (0.10)
Trospium	9.1 (0.10)	9.2 (0.10)	9.3 (0.10)	9.0 (0.10)	8.6 (0.10)

(b) *Comparison of the M_3 selectivity of each compound*

	M_3 *versus* M_1	M_3 *versus* M_2	M_3 *versus* M_4	M_3 *versus* M_5
Darifenacin	9.3***	59.2***	59.2***	12.2***
Tolterodine	0.6*[a]	3.6***	7.3***	6.3***
Oxybutynin	1.5*[a]	12.3***	6.9***	27.0***
Propiverine	0.6*[a]	9.6***	2.8***	0.8
Trospium	1.5	1.3	2.0*	4.6***

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pK_i data presented as mean (s.e.m.) ($n = 3$–6).
K_i ratios were compared by ANOVA. The ratio of the K_i values in (b) were derived from the antilog of the difference in the mean pK_i values shown in (a).
*$P<0.05$, ***$P<0.001$.
[a]Statistically significant selectivity for M_1, although unlikely to be biologically relevant.

Conclusions

It is well established that muscarinic receptor subtypes are widely distributed throughout the human body, each type having a specific functional and physiological role in each tissue. This distribution of muscarinic receptor subtypes can represent a considerable therapeutic challenge when trying to target receptors specific to an organ system. For example, both in normal bladders and in OAB, detrusor muscle contractions are primarily mediated by stimulation of bladder muscarinic M_3 receptors; blockade of M_3 receptors can alleviate the symptoms of OAB, although the classic antimuscarinic adverse events of constipation and dry mouth remain. In addition, as evidence is emerging for an indirect role of M_2 receptors in detrusor contractility, the potential benefits and risks of M_2 receptor antagonism should be further investigated.

Thus, there are a number of important factors that need to be considered when identifying the features of the ideal antimuscarinic drug for treatment of OAB. In the case of OAB, clinical uroselectivity is important (i.e. targeting the bladder) – unwanted effects such as cognitive impairment and blurred vision can only occur if the drug crosses the BBB and blood–retina barrier, respectively; if the drug has a chemical structure which imparts a limited ability to cross these barriers then receptor selectivity in those end organs becomes less of an issue. It remains to be established whether antagonist activity at the M_3 receptor subtype, together with blockade of M_2 receptors or a secondary nonmuscarinic effect (e.g. direct muscle relaxant effect *via* calcium channel antagonism or potassium channel activation), will increase effectiveness in treating OAB. However, it will be important to establish the risk:benefit ratio for such agents with secondary mechanisms of action. Furthermore, considering the age of patients receiving OAB treatments, it would be preferable to identify those agents that are free of CNS sedation and impairment, and that do not add to the CNS anticholinergic burden.

When considering the pharmacodynamic and pharmacokinetic properties of an antimuscarinic agent, it is important that the pharmacokinetics of the drug (or the formulation of the drug) are such that dosing is once (or no more than twice) daily, as this imparts greatest patient compliance to the dosing schedule.

Antimuscarinic agents relatively selective for the M_3 receptor subtype are now available for the treatment of OAB. Current evidence suggests that efficacy observed in pivotal phase III studies with M_3 receptor selective agents is comparable to existing less selective agents. Whether M_3 relative receptor selectivity can reduce the adverse events and safety concerns theoretically attributed to the untargeted blockade of muscarinic receptors has yet to be determined. Limited data are available that directly compare the efficacy and safety profiles of drugs with differing muscarinic receptor subtype selectivity. In this regard further data are needed.

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