

# Receptors for Purines and Pyrimidines

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## I. Introduction

### A. Overview

Extracellular purines (adenosine, ADP, and ATP) and pyrimidines (UDP and UTP) are important signaling molecules that mediate diverse biological effects via cell-surface receptors termed purine receptors. In this review particular emphasis is placed on the discrepancy

<sup>b</sup> Abbreviations: ACh, acetylcholine; ADP, adenosine 5'-diphosphate; AMP, adenosine 5'-monophosphate; ANAPP<sub>3</sub>, arylazidoaminopropionyl ATP; Ap<sub>3</sub>A, P<sup>1</sup>,P<sup>3</sup>-diadenosine triphosphate; Ap<sub>4</sub>A, P<sup>1</sup>,P<sup>4</sup>-diadenosine tetraphosphate; Ap<sub>5</sub>A, P<sup>1</sup>,P<sup>5</sup>-diadenosine pentaphosphate; Ap<sub>6</sub>A, P<sup>1</sup>,P<sup>6</sup>-diadenosine hexaphosphate; APEC, 2-[(2-aminoethylamino)carbonyl ethylphenylethylamino]-5'-N-ethylcarboxamido adenosine; APNEA, N-[2-(4-aminophenyl) ethyl] adenosine; ATP, adenosine 5'-triphosphate; A3P5P, adenosine-3'-phosphate-5'-phosphosulfate; ATP<sub>γ</sub>S, adenosine 5'-O-(3-thiotriphosphate); BzATP, 3'-O-(4-benzoyl)benzoyl ATP; cAMP, adenosine 3',5'-cyclic monophosphate; CGRP, calcitonin gene-related peptide; CGS 21680, 2-[p-(2-carbonyl-ethyl)-phenylethylamino]-5'-N-ethylcarboxamidoadenosine; CHO, chinese hamster ovary; CNS, central nervous system; CPA, N<sup>6</sup>-cyclopentyladenosine; DIDS, 4,4'-diisothiocyanatostilbene-2,2'-disulfonate; DPCPX, 1,3-dipropyl-8-cyclopentylxanthine; EDRF, endothelium-derived relaxing factor; EDHF, endothelium-derived hyperpolarizing factor; GRK, G protein-coupled receptor specific kinase; IB-MECA, N<sup>6</sup>-(3-iodobenzyl)-5'-(N-methylcarbamoyl)adenosine; IP<sub>3</sub>, inositol 1,4,5-trisphosphate; KFM 19, (±)-8-(3-oxocyclopentyl)-1,3-dipropylxanthine; MAPK, mitogen-activated protein kinase; α,β-

between the pharmacological properties of native and recombinant receptors for these agents.

There are two main families of purine receptors, adenosine or P1 receptors, and P2 receptors, recognizing primarily ATP, ADP, UTP, and UDP. Adenosine/P1 receptors have been further subdivided, according to convergent molecular, biochemical, and pharmacological evidence into four subtypes, A<sub>1</sub>, A<sub>2A</sub>, A<sub>2B</sub>, and A<sub>3</sub>, all of which couple to G proteins. Based on differences in molecular structure and signal transduction mechanisms, P2 receptors divide naturally into two families of ligand-gated ion channels and G protein-coupled receptors termed P2X and P2Y receptors, respectively; to date

meATP, α,β-methylene ATP; β,γ-meATP, β,γ-methylene ATP; 2MeSATP, 2-methylthio ATP; mRNA, messenger RNA; NECA, N-ethylcarboxamidoadenosine; NF023, symmetrical 3'-urea of 8-(benzamido)naphthalene-1,3,5-trisulfonic acid; PKC, protein kinase C; PLA<sub>2</sub>, phospholipase A<sub>2</sub>; PLC, phospholipase C; PLD, phospholipase D; PNS, peripheral nervous system; PPADS, pyridoxal phosphate-6-azophenyl-2',4'-disulfonic acid; R-PIA, (R)-N<sup>6</sup>-phenylisopropyl adenosine; RNA, ribonucleic acid; SCG, superior cervical ganglion; suramin, 8-(3-benzamido-4-methylbenzamido)-naphthalene-1,3,5-trisulfonic acid; 8-SPT, 8-(p-sulphophenyl)theophylline; TM, transmembrane; UDP, uridine 5'-diphosphate; UTP, uridine 5'-triphosphate; XAC, xanthine amine congener.

seven mammalian P2X receptors (P2X<sub>1-7</sub>) and five mammalian P2Y receptors (P2Y<sub>1</sub>, P2Y<sub>2</sub>, P2Y<sub>4</sub>, P2Y<sub>6</sub>, P2Y<sub>11</sub>) have been cloned, characterized, and accepted as valid members of the P2 receptor family. As correlates between cloned and endogenous receptors are established, the structural subdivision will replace an earlier system of subclassification identifying endogenous P<sub>2X</sub>, P<sub>2Y</sub>, P<sub>2U</sub>, P<sub>2T</sub>, and P<sub>2Z</sub> receptors principally according to their pharmacological profiles. A prominent issue addressed in this review is the apparent mismatch of pharmacological data in biological tissue relating to the P2 receptor subtypes classified on the basis of molecular structure. While it is logically satisfying to base receptor subclassification on amino acid sequencing where differences of 30 to 40% are generally regarded as justification for subtyping, it would seem that differences in sequence of less than 5% (even single point mutations) can result in substantial differences in pharmacological profile. Thus, receptor heterogeneity among species, together with receptor coexpression and the possible expression of new receptor subtypes that have not yet been cloned, complicates interpretation of pharmacological responses in some tissues. Thus, it will become apparent in the present review that, at least with the use of currently available, largely unselective agonists and antagonists, some response profiles do not fit those expected for the known P2 receptor subtypes.

### B. Historical Perspective

Extracellular purines and pyrimidines have important and diverse effects on many biological processes including smooth muscle contraction, neurotransmission, exocrine and endocrine secretion, the immune response, inflammation, platelet aggregation, pain, and modulation of cardiac function. The concept of purines as extracellular signaling molecules was instigated by Drury and Szent-Györgyi in 1929, in a comprehensive report showing that adenosine and adenosine 5'-monophosphate (AMP), extracted from heart muscle, have pronounced biological effects, including heart block, arterial dilatation, lowering of blood pressure, and inhibition of intestinal contraction. Gillespie, in 1934, drew attention to the structure-activity relationships of adenine compounds, showing that deamination greatly reduces pharmacological activity, and that removal of the phosphates from the molecule influences not only potency, but also the type of response. Removal of phosphates was shown to increase the ability of adenine compounds to cause vasodilatation and hypotension, and ATP caused an increase in rabbit and cat blood pressure that was rarely or never observed with AMP or adenosine. Furthermore, ATP was shown to be more potent than AMP and adenosine in causing contraction of guinea-pig ileum and uterus (Gillespie, 1934). This was the first indication of different actions of adenosine and ATP and, by implication, the first indication of the existence of different purine receptors.

Early investigations into the effects of adenosine and ATP were made on a variety of tissues, but particularly the heart and vasculature (Gaddum and Holtz, 1933; Emmelin and Feldberg, 1948; Folkow, 1949; Green and Stoner, 1950). Initial studies on the effects of extracellular UTP also focused on its cardiovascular effects (Hashimoto *et al.*, 1964; Boyd and Forrester, 1968; Urquilla, 1978; Sakai *et al.*, 1979). Other early lines of purine research concerned the effects of purines on platelet aggregation (Born, 1962) and on mast cells (Cockcroft and Gomperts, 1980). Diverse responses to extracellular purines and pyrimidines have now been documented in a wide range of biological systems, from single cells to whole organisms, and include smooth muscle contraction, neurotransmission in the peripheral and central nervous system, exocrine and endocrine secretion, the immune response, inflammation, platelet aggregation, pain, and modulation of cardiac function (Burnstock and Kennedy, 1986; Gordon, 1986; Seifert and Schultz, 1989; Burnstock, 1990; Olsson and Pearson, 1990; Ralevic and Burnstock, 1991a; Jacobson *et al.*, 1992b; Dubyak and el-Moatassim, 1993; Dalziel and Westfall, 1994; Fredholm, 1995; Burnstock and Wood, 1996; Ongini and Fredholm, 1996; Sebastião and Ribeiro, 1996).

Insight into the physiological roles of extracellular purines and pyrimidines comes from studies of their biological sources and the stimuli for their release. In this respect, an important line of research stemmed from studies showing that adenosine is released from the heart during hypoxia to play an important role in reactive hyperemia (Berne, 1963; Gerlach *et al.*, 1963). The general hypothesis of coupling of purine release to metabolic demands via local regulation of blood flow has been applied to other tissues and includes the release of adenine nucleotides, particularly ATP, from skeletal muscle during contraction (Boyd and Forrester, 1968; Forrester and Lind, 1969).

Reports of ATP release from sensory nerves in the rabbit ear (Holton and Holton, 1953; Holton, 1959) were the first in a major line of research concerned with purines as neurotransmitters. ATP was detected in the venous perfusate following antidromic stimulation of the rabbit auricular nerve to elicit vasodilatation of the ear capillary bed, and both antidromic vasodilatation and vasodilatation to arterial infusion of ATP (but not that to other agents) were blocked by cholinesterase inhibitors (Holton and Holton, 1953; Holton, 1959). It is now known that ATP is an important neurotransmitter or cotransmitter and adenosine an important neuromodulator in both the peripheral and central nervous systems (see Stone, 1991; Burnstock, 1990; Edwards and Gibb, 1993; Fredholm, 1995). There are also hints that adenine dinucleotides may play neurotransmitter or neuromodulator roles in the central nervous system (Pintor and Miras-Portugal, 1995b).



Adrenal chromaffin granules (Cena and Rojas, 1990), platelets (Born and Kratzer, 1984; Gordon, 1986), mast cells (Osipchuk and Cahalan, 1992), erythrocytes (Forrester, 1990; Ellsworth *et al.*, 1995), basophilic leukocytes (Osipchuk and Cahalan, 1992), cardiac myocytes (Forrester, 1990), fibroblasts (Grierson and Meldolesi, 1995b), and endothelial (Ralevic *et al.*, 1991a, 1991c, 1995b; Bodin *et al.*, 1992) and epithelial cells (Enomoto *et al.*, 1994; Ferguson *et al.*, 1997) are important sources of purines that can be released under physiological and pathophysiological conditions, which may act on the purine receptors associated with these or neighboring cells. Adenine dinucleotides are released from secretory granules of thrombocytes, chromaffin cells and neurons, and may represent a novel class of signaling molecules (Hoyle, 1990; Ogilvie, 1992; Ogilvie *et al.*, 1996). Not enough is known about the sources and release of pyrimidines, which limits our understanding of the role played by the widely distributed receptors that are activated by pyrimidines. However, steps toward resolving this are being made with the demonstration that UTP is released by physiologically relevant stimuli from cultured endothelial, epithelial, and astrocytoma cells (Enomoto *et al.*, 1994; Saiag *et al.*, 1995; Lazarowski *et al.*, 1997a).

Purines and pyrimidines mediate their effects by interactions with distinct cell-surface receptors. Early pharmacological evidence for the existence of adenosine receptors has been provided by specific antagonism by methylxanthines of adenosine-mediated accumulation of adenosine 3',5'-cyclic monophosphate (cAMP) in rat brain slices (Sattin and Rall, 1970). "Purinergetic" receptors were first formally recognized by Burnstock in 1978, when he proposed that these can be divided into two classes termed "P<sub>1</sub>-purinoceptors", at which adenosine is the principal natural ligand, and "P<sub>2</sub>-purinoceptors", recognizing ATP and ADP (Burnstock, 1978). This division was based on several criteria, namely the relative potencies of ATP, ADP, AMP, and adenosine, selective antagonism of the effects of adenosine by methylxanthines, activation of adenylate cyclase by adenosine, and stimulation of prostaglandin synthesis by ATP and ADP.

This major division remains a fundamental part of purine receptor classification, although adenosine/P<sub>1</sub> and P<sub>2</sub> receptors are now characterized primarily according to their distinct molecular structures, supported by evidence of distinct effector systems, pharmacological profiles, and tissue distributions. In addition, receptors for pyrimidines are now included within the P<sub>2</sub> receptor family (table 1) (Fredholm *et al.*, 1994, 1996). Note that it has been recommended that "P<sub>1</sub> receptor" and "P<sub>2</sub> receptor" replace the "P<sub>1</sub>/P<sub>2</sub>-purinoceptor" terminology (Fredholm *et al.*, 1996). The terms "adenosine receptor" and "P<sub>1</sub> receptor" are synonymous.

Adenosine/P<sub>1</sub> receptors are further divided into four subtypes, A<sub>1</sub>, A<sub>2A</sub>, A<sub>2B</sub>, and A<sub>3</sub>, on the basis of their distinct molecular structures and show distinct tissue distributions and pharmacological profiles. All couple to G proteins.

P<sub>2</sub> receptors were shown to be ligand-gated cation channels (Benham and Tsien, 1987) or involved G protein activation (Dubyak, 1991), which formed the basis of their subdivision into two main groups termed P<sub>2X</sub> receptors (ligand-gated cation channels) and P<sub>2Y</sub> receptors (G protein-coupled receptors) (Abbracchio and Burnstock, 1994; Fredholm *et al.*, 1994). Subtypes are defined according to the molecular structure of cloned mammalian P<sub>2</sub> receptors, discriminated by different numerical subscripts (P<sub>2X<sub>n</sub></sub> or P<sub>2Y<sub>n</sub></sub>) (Burnstock and King, 1996; Fredholm *et al.*, 1996). This forms the basis of a system of nomenclature that will replace the earlier subtype nomenclature (including P<sub>2X</sub>, P<sub>2Y</sub>, P<sub>2U</sub>, P<sub>2T</sub>, and P<sub>2Z</sub> receptors) as correlations between cloned and endogenous receptors are established. P<sub>3</sub>, P<sub>4</sub>, and P<sub>2Y<sub>Ap4A</sub></sub> (or P<sub>2D</sub>) receptors have been proposed, but evidence for their existence is based solely on the distinct pharmacological profiles exhibited by some biological tissues. As this is no longer tenable for the identification and subclassification of receptors, it remains to be determined, preferably by molecular studies, how these correlate with cloned P<sub>2</sub> receptors, and therefore exactly how they will fit within a unifying system of purine and pyrimidine receptor nomenclature.

TABLE 1  
Families of receptors for purines and pyrimidines

	Adenosine/P <sub>1</sub> receptors	P <sub>2</sub> receptors	
Natural ligands	Adenosine	ATP ADP UTP UDP Adenine dinucleotides	
Subgroup	—	P <sub>2X</sub>	P <sub>2Y</sub>
Type	G protein-coupled	Ion channel Nonselective pore <sup>a</sup>	G protein-coupled
Subtypes	A <sub>1</sub> , A <sub>2A</sub> , A <sub>2B</sub> , A <sub>3</sub>	P <sub>2X<sub>1-7</sub></sub> , P <sub>2X<sub>n</sub></sub>	P <sub>2Y<sub>1</sub></sub> , P <sub>2Y<sub>2</sub></sub> , P <sub>2Y<sub>4</sub></sub> , P <sub>2Y<sub>6</sub></sub> , P <sub>2Y<sub>11</sub></sub> , P <sub>2Y<sub>ADP</sub></sub> (or P <sub>2T</sub> ) Uridine nucleotide-specific <sup>b</sup>

AMP does not activate P<sub>2</sub> receptors, but may be an agonist at adenosine/P<sub>1</sub> receptors.

P<sub>2X<sub>n</sub></sub>, heteropolymeric receptors such as P<sub>2X<sub>2</sub></sub>P<sub>2X<sub>3</sub></sub> and possibly others with subunit combinations currently unknown.

<sup>a</sup> P<sub>2X<sub>7</sub></sub> (or P<sub>2Z</sub>) receptor only.

<sup>b</sup> Endogenous uridine nucleotide-specific receptors, which may have counterparts in P<sub>2Y<sub>4</sub></sub> and P<sub>2Y<sub>6</sub></sub> receptors.

The main aim of this review is to present the characteristics of receptors for purines and pyrimidines within a framework whereby comparisons can be made between cloned and endogenous receptors. For the P2 receptor family this is in order to promote the conversion from a system of nomenclature that is rapidly losing its value, to a unifying system of classification based on structurally distinct cloned receptors. However, pharmacological characterization of endogenous P2 receptors is often equivocal, largely because of the current lack of selective agonists and antagonists and because of complications introduced by the common and widespread coexpression of different types of P2 receptors. Thus, it will become apparent in the present review that in assigning names to endogenous P2 receptors we have needed to strike a balance between caution (against overinterpretation) and anticipation of the direction in which this field is heading. Signal transduction mechanisms, pharmacological response profiles, receptor desensitization, tissue distribution, and biological effects of receptors for purines and pyrimidines are considered. Because ATP and ADP are rapidly degraded to adenosine, and because most cells and tissues coexpress P1 and P2 receptors, we also consider the interactions that may occur between receptors belonging to these two families. Although modulation of ecto-nucleotidase expression and activity is an important means by which to regulate purine receptor function, this aspect of purinergic signaling is not dealt with in detail in this article; the reader is referred to other reviews on the subject (Ziganshin *et al.*, 1994a; Zimmerman, 1996).

## II. Adenosine/P1 Receptors

### A. Introduction

The adenosine/P1 receptor family comprises A<sub>1</sub>, A<sub>2A</sub>, A<sub>2B</sub>, and A<sub>3</sub> adenosine receptors, identified by conver-

gent data from molecular, biochemical, and pharmacological studies (table 2). Receptors from each of these four distinct subtypes have been cloned from a variety of species and characterized following functional expression in mammalian cells or *Xenopus* oocytes (table 3). A<sub>1</sub> and A<sub>2</sub> receptors were described by Van Calcar *et al.* in 1979, in studies showing that activation of these receptors by adenosine and its derivatives inhibited, via A<sub>1</sub>, or stimulated, via A<sub>2</sub>, adenylate cyclase activity in cultured mouse brain cells (Van Calcar *et al.*, 1979). The effects of adenosine could be antagonized by methylxanthines and the order of potency of adenosine analogs was different for the two receptors (Van Calcar *et al.*, 1979). Londos *et al.* (1980) independently drew similar conclusions using membrane preparations from rat adipocytes, hepatocytes, and Leydig tumor cells; the adenosine receptors coupled to inhibition of adenylate cyclase (those in adipocytes) they named R<sub>i</sub> (corresponding to the A<sub>1</sub> subtype) and the adenosine receptors coupled to stimulation of adenylate cyclase (those in hepatocytes and Leydig cells) they termed R<sub>a</sub> (synonymous with the A<sub>2</sub> subtype). This alternative system of nomenclature was based on "R" to designate the "ribose" moiety of the nucleoside and "i" and "a" to indicate inhibition and activation of adenylate cyclase respectively (Londos *et al.*, 1980). The A<sub>1</sub>/A<sub>2</sub> nomenclature is now used, which is fortunate because A<sub>1</sub> receptors act through a variety of transduction mechanisms in addition to adenylate cyclase. A<sub>1a</sub> and A<sub>1b</sub> receptors have been proposed (Gustafsson *et al.*, 1990), but this subdivision of the A<sub>1</sub> receptor remains equivocal.

A<sub>2</sub> receptors are further subdivided into types A<sub>2A</sub> and A<sub>2B</sub>. The suggestion that A<sub>2</sub> receptors could be divided into two classes was originally based on the recognition that adenosine-mediated stimulation of adenylate cyclase in rat brain was effected via distinct high affinity

TABLE 2  
Classification of adenosine/P1 receptors

	A <sub>1</sub>	A <sub>2A</sub>	A <sub>2B</sub>	A <sub>3</sub>
G protein-coupling	G <sub>i/o</sub>	G <sub>s</sub>	G <sub>s</sub> G <sub>q</sub>	G <sub>i</sub> G <sub>q</sub>
Effects	↓ cAMP ↑ IP <sub>3</sub> ↑ K <sup>+</sup> ↓ Ca <sup>2+</sup>	↑ cAMP	↑ cAMP ↑ IP <sub>3</sub>	↓ cAMP ↑ IP <sub>3</sub>
Selective agonists	CPA, CCPA, CHA, R-PIA	CGS21680, HE-NECA, APEC, CV 1808, DPMA, WRC-0470	—	IB-MECA, 2Cl-IB-MECA
Selective antagonists	DPCPX, XAC, KW-3902, ENX, KFM 19, N 0861, FK 453, WRC 0571	KF17837, ZM241385, CSC, SCH 58261	—	I-ABOPX <sup>a</sup> , L-268605, L-249313, MRS 1067, MRS 1097

**Abbreviations:** APEC, 2-[(2-aminoethylamino)carbonylethylphenylethylamino]-5'-N-ethylcarboxamidoadenosine; CGS21680, 2-[p-(2-carbonyl-ethyl)-phenylethylamino]-5'-N-ethylcarboxamidoadenosine; CCPA, 2-chloro-CPA; CHA, N<sup>6</sup>-cyclopentyladenosine; 2Cl-IB-MECA, 2-chloro-N<sup>6</sup>-(3-iodobenzyl)-5'-(N-methylcarbamoyl)adenosine; CPA, N<sup>6</sup>-cyclopentyladenosine; CSC, 8-(3-chlorostyryl)caffeine; CV 1808, 2-phenylaminoadenosine; DPCPX, 1,3-dipropyl-8-cyclopentylxanthine; DPMA, N<sup>6</sup>-[2(3,5-dimethoxyphenyl)-2-(2-methylphenyl)ethyl]-adenosine; ENX, 1,3-dipropyl-8-[2-(5,6-epoxy)norbornyl]xanthine; FK 453, (+)-R-(E)-3-(2-phenylpyrazolo[1,5-α]pyridin-3-yl)acryloyl]-2-piperidine ethanol; HE-NECA, 2-hexyl-5'-N-ethylcarboxamidoadenosine; I-ABOPX, 3-(3-iodo-4-aminobenzyl)-8-(4-oxyacetate)phenyl-1-propylxanthine; IB-MECA, N<sup>6</sup>-(3-iodobenzyl)-5'-(N-methylcarbamoyl)adenosine; KF17837, 1,3-dipropyl-8-(3,4-dimethoxystyryl)-7-methylxanthine; KFM 19, [(±)-8-(3-oxocyclopentyl)-1,3-dipropylxanthine]; KW-3902, 8-noradamant-3-yl-1,3-dipropylxanthine; L-249313, 6-carboxymethyl-5,9-dihydro-9-methyl-2-phenyl-[1,2,4]-triazolo[5,1-α][2,7]naphthyridine; L-268605, 3-(4-methoxyphenyl)-5-amino-7-oxo-thiazolo[3,2]pyrimidine; MRS 1067, 3,6-dichloro-2'-isopropoxy-4'-methylflavone; MRS 1097, 3,5-diethyl 2-methyl-6-phenyl-4-(trans-2-phenylvinyl)-1,4(R,S)-dihydropyridine-3,5-dicarboxylate; N 0861, 1,3-dipropyl-8-[2,(5,6-epoxy)norbornyl]xanthine; R-PIA, (R)N<sup>6</sup>-phenylisopropyladenosine; SCH 58261, 5-amino-7-(2-phenylethyl)-2-(2-furyl)-pyrazolo[4,3-e]-1,2,4-triazolo[1,5-c]pyrimidine; WRC 0470, 2-cyclohexylmethylidenehydrazinoadenosine; WRC 0571, 8-(N-methylisopropyl)amino-N<sup>6</sup>-(5'-endohydroxy-endonorbornyl)-9-methyladenine; XAC, xanthine amine congener; ZM 241385, 4-(2-[7-amino-2-(2-furyl)]1,2,4-triazolo[2,3-α][1,3,5]triazin-5-ylamino)ethylphenol.

<sup>a</sup> High affinity (nM) at sheep and human, but not rat A<sub>3</sub> adenosine receptors.

TABLE 3  
Cloned adenosine/P1 receptors

	Number of amino acids	cDNA library source	References
A <sub>1</sub>	326	Human brain	Libert <i>et al.</i> , 1992; Townsend-Nicholson and Shine, 1992
	326	Canine thyroid	Libert <i>et al.</i> , 1989, 1991
	326	Bovine brain	Tucker <i>et al.</i> , 1992; Olah <i>et al.</i> , 1992
	328	Rabbit kidney	Bhattacharya <i>et al.</i> , 1993
	326/327	Rat brain	Reppert <i>et al.</i> , 1991; Mahan <i>et al.</i> , 1991
	326	Mouse brain	Marquardt <i>et al.</i> , 1994
A <sub>2A</sub>	326	Guinea-pig brain	Meng <i>et al.</i> , 1994a
	409	Human hippocampus	Furlong <i>et al.</i> , 1992
	411	Canine thyroid	Libert <i>et al.</i> , 1989; Maenhaut <i>et al.</i> , 1990
	410	Rat brain	Chern <i>et al.</i> , 1992; Fink <i>et al.</i> , 1992
	409	Guinea-pig brain	Meng <i>et al.</i> , 1994b
A <sub>2B</sub>	410	Mouse bone marrow-derived mast cells	Marquardt <i>et al.</i> , 1994
	328	Human hippocampus	Pierce <i>et al.</i> , 1992
	332	Rat brain	Stehle <i>et al.</i> , 1992; Rivkees and Reppert, 1992
A <sub>3</sub>	332	Mouse bone marrow-derived mast cells	Marquardt <i>et al.</i> , 1994
	318	Human striatum	Salvatore <i>et al.</i> , 1993
	318	Human heart	Sajjadi <i>et al.</i> , 1993
	317	Sheep pars tuberalis	Linden <i>et al.</i> , 1993
	320	Rabbit lung	Hill <i>et al.</i> , 1997
	320	Rat brain	Zhou <i>et al.</i> , 1992
	320	Rat testis	Meyerhof <i>et al.</i> , 1991; Zhou <i>et al.</i> , 1992

binding sites (localized in striatal membranes) and low affinity binding sites (present throughout the brain) (Daly *et al.*, 1983). This subdivision was supported in a study which compared the high affinity striatal A<sub>2</sub> binding site with a low-affinity A<sub>2</sub> binding site characterized in a human fibroblast cell line; the two sites were termed A<sub>2A</sub> and A<sub>2B</sub>, respectively (Bruns *et al.*, 1986). Definitive evidence for the existence of these two subtypes comes from the cloning and sequencing of distinct A<sub>2A</sub> and A<sub>2B</sub> receptors which show distinct pharmacological profiles in transfected cells similar to those of the endogenous receptors.

Consistent with the fact that these are distinct receptors, there is a considerable lack of amino acid sequence homology between cloned A<sub>1</sub>, A<sub>2A</sub>, A<sub>2B</sub>, and A<sub>3</sub> receptors. For example, the homology between rat A<sub>1</sub> and A<sub>2B</sub> receptors is only 45% (Stehle *et al.*, 1992), and the human A<sub>3</sub> receptor only shows approximately 50%, 43%, and 40% homology with human A<sub>1</sub>, A<sub>2A</sub>, and A<sub>2B</sub> receptors, respectively (Linden, 1994). The homology between A<sub>2A</sub> and A<sub>2B</sub> receptors is also slight, being approximately 46% when these subtypes are cloned from rat and 61% when cloned from human (Stehle *et al.*, 1992; Pierce *et al.*, 1992).

An adenosine binding site with high affinity for 2-phenylaminoadenosine (CV 1808) (A<sub>2A</sub>-selective agonist) in rat striatal membranes has been suggested to be a novel "A<sub>4</sub>" adenosine receptor (Cornfield *et al.*, 1992). The very low affinity of 2-[p-(2-carbonyl-ethyl)-phenylethylamino]-5'-N-ethylcarboxamidoadenosine (CGS 21680) and N-ethylcarboxamidoadenosine (NECA) at this site were taken to indicate that this is not an A<sub>2</sub> receptor. However, the binding studies were carried out at 4°C (Cornfield *et al.*, 1992), and the existence of a distinct A<sub>4</sub> receptor has been challenged by the demonstration that when similar binding studies are carried out at 21°C, the potency order

of compounds at the striatal membrane site is characteristic of the A<sub>2A</sub> adenosine receptor (Luthin and Linden, 1995). Furthermore, in COS cells transfected with adenosine A<sub>2A</sub> receptors, binding studies carried out at 4°C produce an "A<sub>4</sub>" binding profile (Luthin and Linden, 1995). This justifies the more rigorous criteria now demanded for classification of receptors, whose identity must be proved by molecular as well as by biochemical or pharmacological means.

There is a vast and rapidly growing literature on adenosine/P1 receptors; it has not been possible to do justice to this in the present review. Out of necessity, therefore, we focus on the more recent literature.

### B. Structure

All adenosine receptors couple to G proteins. In common with other G protein-coupled receptors, they have seven putative transmembrane (TM) domains of hydrophobic amino acids, each believed to constitute an  $\alpha$ -helix of approximately 21 to 28 amino acids. The N-terminal of the protein lies on the extracellular side and the C-terminal on the cytoplasmic side of the membrane. A pocket for the ligand binding site is formed by the three-dimensional arrangement of the  $\alpha$ -helical TM domains, and the agonist is believed to bind within the upper half of this pore. The transmembrane domains are connected by three extracellular and three cytoplasmic hydrophilic loops of unequal size; typically the extracellular loop between TM4 and TM5 and the cytoplasmic loop between TM5 and TM6 is extended. These features are illustrated in a schematic of the A<sub>1</sub> receptor in figure 1.

N-linked glycosylation often occurs on the second extracellular loop; the roles of the carbohydrate moieties of the glycosylated receptor are not clear, although suggested functions include stabilization of protein conformation, protection of proteins from proteases, and mod-



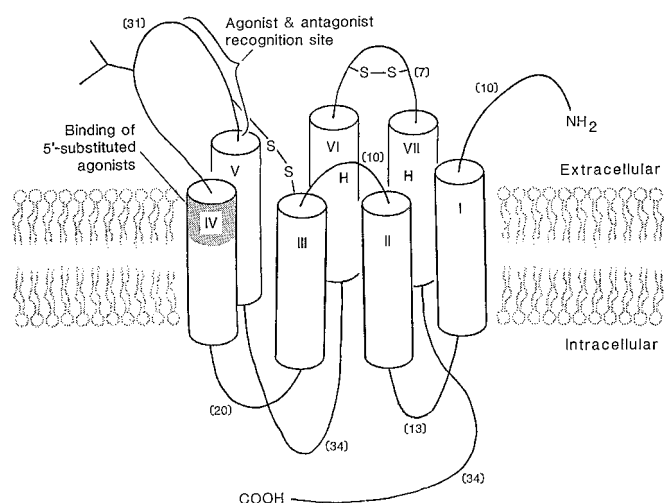


FIG. 1. Schematic of the  $A_1$  adenosine receptor. In common with other G protein-coupled receptors, the  $A_1$  receptor has seven putative transmembrane domains (I-VII) of hydrophobic amino acids, each believed to constitute an  $\alpha$ -helix, which are connected by three extracellular and three intracellular hydrophilic loops. The number of amino acids comprising the extra- and intracellular loops and the extracellular N-terminal and intracellular C-terminal regions of the bovine  $A_1$  receptor are indicated in parentheses (Olah *et al.*, 1992). The transmembrane regions comprise 23 to 25 amino acids in the bovine  $A_1$  receptor (Olah *et al.*, 1992). The arrangement of the transmembrane regions forms a pocket for the ligand binding site. The location of histidine residues (H) in transmembrane regions VI (position 254) and VII (position 278) in the bovine  $A_1$  receptor, which are believed to be important in ligand binding (Olah *et al.*, 1992), are indicated. Extracellular and transmembrane regions of the protein believed to be important in agonist and antagonist binding are indicated (Olah *et al.*, 1994b,c). S-S denotes the presence of hypothetical disulfide bridges (Jacobson *et al.*, 1993c). Glycosylation occurs on the second extracellular loop.

ulation of protein function. Current evidence suggests that glycosylation has no obvious influence on ligand binding (Piersen *et al.*, 1994). The intracellular segment of the receptor interacts with the appropriate G protein with subsequent activation of the intracellular signal transduction mechanism. The third intracellular loop of the adenosine  $A_{2A}$  receptor seems to be the main determinant of its G protein selectivity (Olah, 1997). Phosphorylation by protein kinases of amino acid residues on the cytoplasmic domains seems to be involved in desensitization of  $A_{2A}$  and  $A_3$  receptors (Palmer and Stiles, 1997a, 1997b).

The transmembrane regions are generally highly conserved, with particularly long stretches of amino acid homology being found in TM2, TM3, and TM5. Most sequence differences have been observed in a hypervariable region located at the N-terminal half of the second extracellular loop (Tucker and Linden, 1993). It is the residues within the transmembrane regions that are crucial for ligand binding and specificity and, with the exception of the distal (carboxyl) region of the second extracellular loop, the extracellular loops, the C-terminal and the N-terminal do not seem to be involved in ligand recognition (Olah *et al.*, 1994b, 1995). A number of amino acid residues contribute, in different ways, to ligand specificity within the binding pocket. Site-

directed mutagenesis of the bovine  $A_1$  adenosine receptor suggests that conserved histidine residues in TM6 and TM7 are important in ligand binding. Histidine 278 in TM7 seems to be particularly important because mutation of this amino acid abolishes ligand binding (Olah *et al.*, 1992). Mutagenesis of the human  $A_1$  adenosine receptor has shown that threonine 277 in TM7 is important in binding of the non-selective adenosine receptor agonist NECA, but has little effect on the affinity of binding of the  $A_1$  selective agonist (R)- $N^6$ -(2-phenyl-1-methyl-ethyl)-adenosine (R-PIA), or of antagonists (Townsend-Nicholson and Schofield, 1994). Modification of Glu 16 in TM1 and Asp 55 in TM2 of the human  $A_1$  receptor alters the affinity of binding for [ $^3$ H]CCPA (2-chloro- $N^6$ -cyclopentyladenosine) and other agonists, but does not affect antagonist binding (Barbhaiya *et al.*, 1996). Site-directed mutagenesis of the human  $A_{2A}$  adenosine receptor has identified several residues in TM5-7 that are involved in ligand binding (Kim *et al.*, 1995). Glu 13 in TM1 of the human  $A_{2A}$  receptor seems to be critically involved in agonist, but not antagonist recognition (Ijzerman *et al.*, 1996).

A potential problem inherent in the methodology of site-directed mutagenesis is that changes in primary structure may cause changes in tertiary structure of the molecule. This has been addressed by studies with chimeras constructed from structurally similar, but pharmacologically different receptors. The ligand binding properties of  $A_1/A_3$  chimeric receptors support the concept of a crucial role for histidine residues in TM6 and TM7 in ligand binding (Olah *et al.*, 1995). In addition, a critical role in ligand binding of the distal region of the second extracellular loop has been identified, although its specific interactions are not yet clear (Olah *et al.*, 1994b). Possible roles include direct interaction of an amino acid residue(s) within this region with the ligand, an influence on the conformation of the receptor and/or steric hindrance. Construction of chimeric human  $A_1$  and rat  $A_{2A}$  adenosine receptors was used to show that TM1-4 are important in  $A_1$  receptor agonist and antagonist binding and ligand specificity (Rivkees *et al.*, 1995a).

### C. Agonists

Analogs with greater stability than adenosine are produced by modification of the  $N^6$  and C2 positions of the adenine ring and the 5'-position of the ribose moiety of adenosine, and have been used extensively in the characterization of adenosine/P1 receptors. NECA (Williams, 1989), N-[2-(4-aminophenyl)ethyl] adenosine (APNEA) (Fozard and Carruthers, 1993), and  $N^6$ -(3-[ $^{125}$ I]iodo-4-aminobenzyl)-5'-N-methylcarboxamidoadenosine ( $^{125}$ I-AB-MECA) (Olah *et al.*, 1994a) do not discriminate between adenosine receptor subtypes. Agonists with subtype selectivity are detailed in the sections on individual adenosine receptor subtypes and the chemical structure of some of these are illustrated in figure 2.



## Non-selective

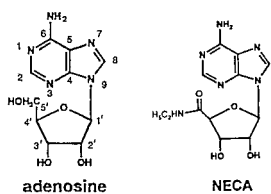
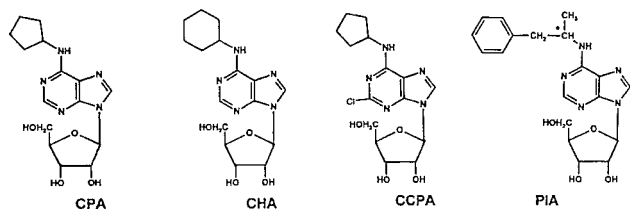
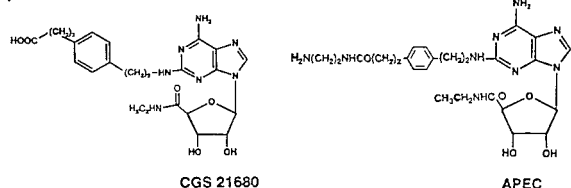
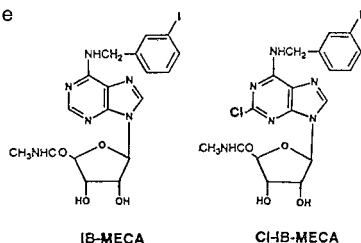
A<sub>1</sub> selectiveA<sub>2A</sub> selectiveA<sub>3</sub> selective

FIG. 2. The chemical structure of some agonists at adenosine/P1 receptors.

ATP and metabolically stable ATP derivatives, i.e., adenosine 5'-O-(3-thiotriphosphate)(ATP $\gamma$ S) and  $\beta$ , $\gamma$ -methylene ATP ( $\beta$ , $\gamma$ -meATP), can act directly as agonists at adenosine/P1 receptors in some tissues where responses are blocked by methylxanthines, but are not affected by adenosine deaminase or by blockade of 5'-nucleotidase.  $\beta$ , $\gamma$ -MeATP is approximately equipotent with adenosine at mediating contraction of smooth muscle adenosine/P1 receptors of rat colon (Bailey and Hourani, 1990), and relaxation via adenosine/P1 receptors of rat duodenum (Hourani *et al.*, 1991), and guinea-pig trachealis muscle (Piper and Hollingsworth, 1996). ATP, ATP $\gamma$ S, and  $\beta$ , $\gamma$ -meATP inhibit [ $^3$ H]-NA release in a variety of tissues via receptors that are blocked by the A<sub>1</sub> selective antagonist 1,3-dipropyl-8-cyclopentylxanthine (DPCPX) as well as by the P2 receptor antagonist ciba-cron blue (Von K $\ddot{u}$ gelgen *et al.*, 1992, 1995b, 1996). ATP (Collis and Pettinger, 1982) and diadenosine polyphosphates (Hoyle *et al.*, 1996; Vahlensieck *et al.*, 1996) have been reported to stimulate directly adenosine/P1 receptors in guinea-pig atria, eliciting negative inotropic and

chronotropic effects without prior conversion to adenosine. These effects are not consistent with the pharmacological profile of any of the established subtypes of adenosine/P1 receptor, and in some respects are similar to the profile described for the P3 receptor.

## D. Antagonists

Xanthines and xanthine derivatives, including the natural derivatives theophylline and caffeine, are non-selective adenosine/P1 receptor antagonists. They are not universal adenosine/P1 receptor antagonists; xanthine-resistant relaxations to adenosine and its analogs were observed in guinea-pig aorta (Collis and Brown, 1983; Martin, 1992), rat aorta (Prentice and Hourani, 1996), guinea-pig trachea (Brackett and Daly, 1991), porcine coronary artery (Abebe *et al.*, 1994), and guinea-pig taenia cecum (Prentice *et al.*, 1995). Some A<sub>3</sub> receptors, namely those of rat, rabbit, and gerbil, are characteristically insensitive to methylxanthines, thus it is possible that the xanthine-resistant responses to adenosine described in some tissues occur following actions of adenosine at mast cell A<sub>3</sub> receptors and the subsequent release of vasoactive mediators. This hypothesis would predict that guinea-pig and pig A<sub>3</sub> receptors are also xanthine-insensitive, because xanthine-resistant responses to adenosine have been reported in these species. It would be interesting to see if these responses can be blocked by inhibitors of mast cell degranulation.

8-Phenyltheophylline and the more water soluble 8-(p-sulfophenyl)theophylline (8-SPT) (Daly *et al.*, 1985) are more potent than theophylline at adenosine/P1 receptors, but are not subtype-selective. 8-SPT and its derivative 1,3-dipropyl-8-sulfophenylxanthine (DPSPX) do not cross the blood-brain barrier, being purely peripherally acting adenosine/P1 receptor antagonists (Daly *et al.*, 1985) and thus can be used to discriminate between central and peripheral adenosine receptors. A number of xanthines and non-xanthines identified as adenosine receptor antagonists with reasonable subtype selectivity are described below (see Sections III.F., IV.F., and VI.F.) and their chemical structures illustrated in figure 3.

III. A<sub>1</sub> Receptor

Subdivision of A<sub>1</sub> receptors into high affinity A<sub>1a</sub> receptors and low affinity A<sub>1b</sub> receptors has been proposed (Gustafsson *et al.*, 1990). This was based on the description of high-affinity binding sites for adenosine agonists and antagonists in rat and guinea-pig brain (A<sub>1a</sub>) and low-affinity binding sites in rat vas deferens and guinea-pig ileum (A<sub>1b</sub>) (Gustafsson *et al.*, 1990). However, there are no cloned equivalents for these putative subtypes and their existence remains equivocal. It is possible that these reflect high and low affinity states of the same A<sub>1</sub> receptor.

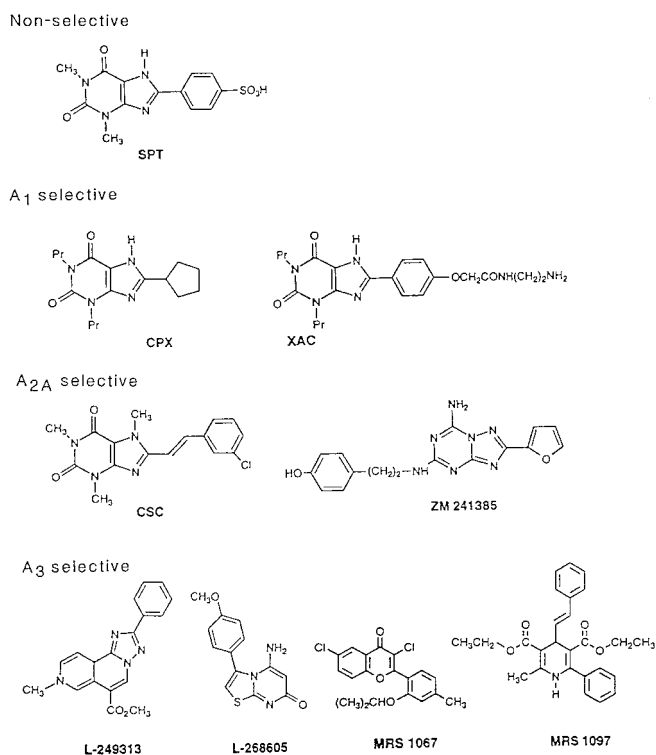


FIG. 3. The chemical structure of some antagonists at adenosine/P<sub>1</sub> receptors.

### A. Cloned A<sub>1</sub> Receptors

A<sub>1</sub> receptors have been cloned from several species (table 3). The human adenosine A<sub>1</sub> receptor subtype gene (ADORA1) has been localized to chromosome 1q32.1 (Townsend-Nicholson *et al.*, 1995a). The variability in the primary sequence of the A<sub>1</sub> receptor between species is less than 10% for A<sub>1</sub> receptors from dog, rat, and cow, and less than 5% between bovine and human A<sub>1</sub> receptors, but this seems to be sufficient to cause considerable interspecies differences in ligand binding (Tucker and Linden, 1993) and subtle differences in the mechanisms underlying receptor desensitization (Ramkumar *et al.*, 1991; Nie *et al.*, 1997; Palmer and Stiles, 1997b). Species homologs of A<sub>1</sub> receptors have been suggested to differ in their ability to discriminate among the related G<sub>o</sub>/G<sub>i</sub> protein alpha subunits (Jockers *et al.*, 1994).

### B. Signal Transduction Mechanisms

The A<sub>1</sub> receptor mediates a broad range of signaling responses, which may be caused by its coupling to different G proteins within the G<sub>i/o</sub> family (Freissmuth *et al.*, 1991; Munshi *et al.*, 1991). The G proteins G<sub>i</sub> and G<sub>o</sub> are substrates for pertussis toxin that ADP-ribosylates the  $\alpha$ -subunit of G<sub>i/o/t</sub> family members, uncoupling them from receptors. Accordingly, effects mediated by A<sub>1</sub> receptors are generally blocked by pertussis toxin. However, presynaptic A<sub>1</sub> receptors seem to be at least partly resistant to pertussis toxin (Fredholm *et al.*, 1989; Ha-

suo *et al.*, 1992); the reason for this could be the very tight coupling of the presynaptic A<sub>1</sub> receptors to potentially pertussis toxin-sensitive G proteins, rather than coupling to pertussis toxin-insensitive G proteins (Van der Ploeg *et al.*, 1992). A partially-purified protein with selectivity for G protein  $\alpha$  subunits has been shown to stabilize the rat brain A<sub>1</sub> receptor-G protein complex, thereby promoting tight coupling of the A<sub>1</sub> receptor with its G protein (Nanoff *et al.*, 1997). Interestingly, this is a feature of the rat brain but not the human brain A<sub>1</sub> receptor; the latter is not under the control of a coupling cofactor, but operates according to the classic ternary complex model of receptor-G protein coupling (Nanoff *et al.*, 1997).

The most widely recognized signaling pathway of A<sub>1</sub> receptors is inhibition of adenylate cyclase causing a decrease in the second-messenger cAMP (Van Calker *et al.*, 1978; Londos *et al.*, 1980). This in turn modulates the activity of cAMP-dependent protein kinase, which phosphorylates diverse protein targets. A<sub>1</sub> coupling to adenylate cyclase has been described in a number of tissues including brain, adipose tissue, and testes. In addition to direct modulation of signaling pathways downstream to cAMP, inhibition of adenylate cyclase via A<sub>1</sub> receptors blocks the effects of other agents which act by stimulating adenylate cyclase activity in cells.

Another signaling mechanism of A<sub>1</sub> receptors is activation of phospholipase C (PLC) leading to membrane phosphoinositide metabolism and increased production of inositol 1,4,5-triphosphate (IP<sub>3</sub>) [and diacylglycerol (DAG)] and Ca<sup>2+</sup> mobilization. This has been described in chinese hamster ovary (CHO)-K1 cells expressing the cloned human A<sub>1</sub> receptor (Iredale *et al.*, 1994; Megson *et al.*, 1995) as well as at endogenous A<sub>1</sub> receptors in a number of tissues including DDT<sub>1</sub> MF-2 smooth muscle cells (Gerwins and Fredholm, 1992a,b; White *et al.*, 1992), heart (Scholz *et al.*, 1993), myometrium (Schiemann *et al.*, 1991a,b), rabbit cortical collecting tubule cells (Arend *et al.*, 1989), renal cells (Weinberg *et al.*, 1989), tracheal epithelial cells (Galiotta *et al.*, 1992), cultured mesangial cells (Olivera *et al.*, 1992), and primary astrocytes (Peakman and Hill, 1995). IP<sub>3</sub> stimulates the release of Ca<sup>2+</sup> from intracellular stores via interactions with specific receptors located on the sarcoplasmic reticulum. Elevation of cytosolic Ca<sup>2+</sup> by IP<sub>3</sub> can stimulate a variety of signaling pathways, including a family of phosphatidyl serine-dependent serine/threonine-directed kinases collectively called protein kinase C (PKC) (of which there are at least 11 different isoforms), phospholipase A<sub>2</sub> (PLA<sub>2</sub>), Ca<sup>2+</sup>-dependent K<sup>+</sup> channels, and nitric oxide synthase (NOS). Depletion of Ca<sup>2+</sup> from IP<sub>3</sub>-sensitive pools may promote Ca<sup>2+</sup> influx from extracellular sources.

Activation of phospholipase D (PLD) via A<sub>1</sub> adenosine receptors in DDT<sub>1</sub> MF-2 smooth muscle cells has been described (Gerwins and Fredholm, 1995a, 1995b), although as in the majority of cell systems this may be

downstream of phosphoinositide hydrolysis and may require the intermediate activation of PKC or  $\text{Ca}^{2+}$ .

Stimulation of  $\text{A}_1$  receptors can activate several types of  $\text{K}^+$  channel, described principally in cardiac muscle and neurons. In supraventricular tissues (sino-atrial and atrioventricular node, and atrium), the  $\text{A}_1$  receptor couples directly via pertussis toxin-sensitive G proteins to  $\text{K}^+$  channels (the same  $\text{K}^+$  channels are activated by both adenosine and acetylcholine), and activation causes bradycardia (Belardinelli *et al.*, 1995a; Bünemann and Pott, 1995; Ito *et al.*, 1995).  $\text{A}_1$  adenosine receptors also couple to ATP-sensitive  $\text{K}^+$  channels ( $\text{K}_{\text{ATP}}$  channel); the activity is additionally regulated by metabolic demand (they close when intracellular ATP levels are high). Coupling seems to occur through the G protein in a membrane-delimited manner (Kirsch *et al.*, 1990; Dart and Standen, 1993), although coupling via cytosolic factors is possible given the strong evidence that  $\text{A}_1$  receptors,  $\text{K}_{\text{ATP}}$  channels, and PKC all have a role in ischemic preconditioning.  $\text{A}_1$  receptor coupling to  $\text{K}_{\text{ATP}}$  channels has been described in rat and guinea-pig ventricular myocytes (Kirsch *et al.*, 1990; Ito *et al.*, 1994), porcine coronary arteries (Merkel *et al.*, 1992; Dart and Standen, 1993), rabbit heart (Nakhostine and Lamontagne, 1993), and rat cerebral cells (Heurteaux *et al.*, 1995). Activation of  $\text{K}_{\text{ATP}}$  channels mediates a reduction in action potential duration, vasodilatation and an increase in blood flow, which is consistent with their having a pivotal role in the coupling of vascular tone to metabolic demand determined both by intracellular purines (ATP/ADP levels) and by the extracellular actions of adenosine (released, for instance, during hypoxia or ischemia).

Neurons express multiple  $\text{K}^+$  channels that  $\text{A}_1$  receptors may couple to regulate membrane potential and determine action potential frequency and duration.  $\text{A}_1$  receptors reduce neuronal excitability and decrease firing rate by a hyperpolarizing effect mediated mainly by an increase in  $\text{K}^+$  conductance (Trussell and Jackson, 1985; Greene and Haas, 1991; Pan *et al.*, 1995).

$\text{A}_1$  receptors also couple to inhibition of  $\text{Ca}^{2+}$  currents, which may account for inhibition of neurotransmitter release, although other or multiple mechanisms may be involved in this process (see Fredholm, 1995). Inhibition of  $\text{Ca}^{2+}$  currents by  $\text{A}_1$  receptors has been described in dorsal root ganglion neurons (Dolphin *et al.*, 1986), rat hippocampal pyramidal neurons (Scholz and Miller, 1991), rat sympathetic neurons (N-type  $\text{Ca}^{2+}$  channels, plus an unidentified  $\text{Ca}^{2+}$  channel) (Zhu and Ikeda, 1993), rat brainstem (predominantly N-type, but also P-type  $\text{Ca}^{2+}$  channels) (Umemiya and Berger, 1994), hippocampal CA1 neurons (N-type, plus some unidentified  $\text{Ca}^{2+}$  channels) (Wu and Saggau, 1994), hippocampal CA3 neurons (N-type  $\text{Ca}^{2+}$  channel) (Mogul *et al.*, 1993), and mouse motoneurons (N-type  $\text{Ca}^{2+}$  channel) (Mynlieff and Beam, 1994). In atrial myocytes adenosine has an inhibitory effect on basal L-type  $\text{Ca}^{2+}$  current,

although this is small and may be secondary to a reduction in basal cAMP (Belardinelli *et al.*, 1995a).

### C. Desensitization

Several mechanisms, operational at different levels of the signal transduction cascade, contribute to differential desensitization of G protein-coupled receptors. Rapid desensitization (occurring within a few minutes of agonist exposure) seems to involve phosphorylation of specific residues on the receptor C-terminal or the cytoplasmic loops by G protein-coupled receptor-specific kinases (GRKs) and/or kinases regulated by levels of intracellular second-messengers such as cAMP-dependent protein kinase. The phosphorylated receptor may bind to members of a family of proteins called arrestins, which cause uncoupling of the receptor from its G proteins. Desensitization occurring over a longer time course also involves uncoupling of the receptor-G proteins complex, but phosphorylation does not seem to be a prerequisite. Sequestration of receptors into an intracellular compartment may occur, as described for the increase in  $\text{A}_1$  receptors in light vesicle membrane fractions prepared from the hamster vas deferens smooth muscle cell line, DDT<sub>1</sub> MF-2 cells, after chronic exposure to R-PIA (Ramkumar *et al.*, 1991). Prolonged exposure to agonist may additionally lead to down-regulation of receptors and/or of the associated G proteins.

Desensitization of  $\text{A}_1$  receptors by exposure to adenosine analogs has consistently been described both in vitro and in vivo, but this usually requires prolonged exposure to agonist (from 15 minutes to several hours or even days) (Parsons and Stiles, 1987; Ramkumar *et al.*, 1991; Abbracchio *et al.*, 1992; Green *et al.*, 1992; Lee *et al.*, 1993; Longabaugh *et al.*, 1989; Casati *et al.*, 1994). This is considerably longer than the time to desensitization of  $\text{A}_3$  receptors which typically undergo significant desensitization within several minutes. Interestingly, while an agonist-stimulated increase in phosphorylation has been described for  $\text{A}_1$  receptors in hamster DDT<sub>1</sub> MF-2 cells in association with receptor uncoupling from G proteins and desensitization, presumably by GRKs (Ramkumar *et al.*, 1991; Nie *et al.*, 1997), phosphorylation does not occur for the human  $\text{A}_1$  receptor expressed in CHO cells at a time when receptor down-regulation is observed (Palmer and Stiles, 1997b). Down-regulation of  $\text{A}_1$  receptors and/or of the associated G proteins after prolonged exposure to agonist has been reported in most of the cells and tissues in which this has been studied (Parsons and Stiles, 1987; Longabaugh *et al.*, 1989; Green *et al.*, 1992; Ramkumar *et al.*, 1991, 1993a; Abbracchio *et al.*, 1992).

Down-regulation of G proteins following  $\text{A}_1$  receptor activation may lead to heterologous receptor desensitization. Chronic stimulation of  $\text{A}_1$  receptors in adipocytes in vivo (Longabaugh *et al.*, 1989) and in isolated adipocytes (Green *et al.*, 1992) with (-)-N<sup>6</sup>-phenylisopropyl adenosine (PIA) for up to 6 and 7 days, respectively,



causes down-regulation of  $A_1$  receptors, non-uniform down-regulation of  $G_i$  proteins, and heterologous desensitization of other lipolytic hormone responses. In contrast, chronic (7 days) infusion of (R) $N^6$ -phenylisopropyl adenosine (R-PIA) in guinea-pigs homologically desensitizes the atrioventricular nodal response to adenosine: there is down-regulation of  $A_1$  adenosine receptors, a decrease in high affinity  $A_1$  receptors, and a decrease in  $G_i$  and  $G_o$  proteins, but no change in responses mediated by muscarinic receptors (Dennis *et al.*, 1995).

#### D. Sensitization/Up-Regulation

Long-term treatment with adenosine/ $P_1$  receptor antagonists generally leads to an increase in the effects of adenosine via a selective increase in the number of  $A_1$  receptors, receptor sensitization and/or altered interaction between the receptor and the associated G proteins (Fredholm, 1982; Murray, 1982; Fredholm *et al.*, 1984; Green and Stiles, 1986; Ramkumar *et al.*, 1991; Fastbom and Fredholm, 1990; Zhang and Wells, 1990; Lupica *et al.*, 1991a, 1991b; Shi *et al.*, 1994). Long-term (12 day) caffeine treatment of rats increases the number of hippocampal  $A_1$  (but not  $A_{2A}$ ) receptors, without any changes in  $A_1$  messenger ribonucleic acid (mRNA), suggesting that the adaptive changes are at the posttranslational level (Johansson *et al.*, 1993a). An increase in the density of cortical  $A_1$  receptors has been described after chronic caffeine injection in mice, but surprisingly, given that striatal adrenergic, cholinergic, GABA, and serotonin receptors and  $Ca^{2+}$  channels are also affected by this treatment, there is no change in the density of striatal  $A_{2A}$  receptors (Shi *et al.*, 1993).

#### E. Agonists

Certain  $N^6$ -substituted adenosine derivatives, such as  $N^6$ -cyclopentyladenosine (CPA),  $N^6$ -cyclohexyladenosine (CHA), and R-PIA, are selective agonists at  $A_1$  receptors with  $K_i$  values in the range of 0.6 to 1.3 nM (see Jacobson *et al.*, 1992b) (table 2).

Substitutions at both the  $N^6$ - and C2-positions have produced 2-chloro-CPA (CCPA) which is  $A_1$  selective, 1500-fold versus  $A_2$  receptors in binding studies in rat brain, with a  $K_i$  of 0.6 nM (Lohse *et al.*, 1988; Thompson *et al.*, 1991; Jacobson *et al.*, 1992b). N-[1S, *trans*,2-hydroxycyclopentyl] adenosine (GR79236) has been reported to be an  $A_1$  selective agonist, which is approximately equipotent with CPA in a variety of isolated tissues and cell types (Reeves *et al.*, 1993; Gurden *et al.*, 1993).

#### F. Antagonists

Most of the selective  $A_1$  receptor antagonists described to date are xanthine-based derivatives. The introduction of hydrophobic (particularly phenyl or cycloalkyl) substituents into position 8 of the xanthine ring has yielded potent and  $A_1$ -selective antagonists, including 1,3-dipropyl-8-phenyl(2-amino-4-chloro)xanthine

(PACPX), DPCPX, and xanthine amine congener (XAC) (Bruns *et al.*, 1987; Martinson *et al.*, 1987; Shimada *et al.*, 1991) (fig. 3). Of these, DPCPX has the greatest affinity ( $K_i$  1.5 nM) for  $A_1$  receptors and the greatest  $A_1$ -subtype selectivity ( $A_2/A_1$  affinity ratio 740), as shown in rat brain membranes (Bruns *et al.*, 1987; Lohse *et al.*, 1987). The human  $A_1$  receptor has an approximately lower affinity for DPCPX (Libert *et al.*, 1992; Klotz *et al.*, 1998). A number of other 8-substituted xanthines, including ( $\pm$ )-8-(3-oxocyclopentyl)-1,3-dipropylxanthine (KFM 19) and KW-3902 (8-noradamant-3-yl-1,3-dipropylxanthine), have been shown to be selective antagonists at  $A_1$  receptors (see Williams, 1989; Jacobson *et al.*, 1992b). The alkylxanthine 1,3-dipropyl-8-[2-(5,6-epoxy)norbornyl]xanthine (ENX) is a potent ( $K_B$  3.6 nM) and selective antagonist at  $A_1$  receptors in the guinea-pig heart and brain and in DDT<sub>1</sub> MF-2 cells, with 400-fold greater affinity of binding versus  $A_{2A}$  receptors in guinea-pig brain (Belardinelli *et al.*, 1995b).

Several classes of non-xanthine antagonists have been described, some showing reasonable affinity and selectivity for the  $A_1$  receptor (see Jacobson *et al.*, 1992b; Daly *et al.*, 1993). Some of the more active of these are the tricyclic non-xanthine antagonists, including the triazoloquinazolines (Francis *et al.*, 1988), the triazoloquinoxalines (Trivedi and Bruns, 1988; Sarges *et al.*, 1990), and the imidazoquinolines (Van Galen *et al.*, 1991).

The adenine derivative 1,3-dipropyl-8-[2,(5,6-epoxy)norbornyl]xanthine (N 0861) is reasonably selective (10- to 47-fold versus  $A_{2A}$  receptors) and potent at  $A_1$  receptors in a number of tissues (May *et al.*, 1991; Martin *et al.*, 1993a; Belardinelli *et al.*, 1995b). This compound has been superceded by the S-enantiomer 12 (CVT-124) with nanomolar selectivity and 1800- and 2400-fold selectivity at rat and cloned human  $A_1$  receptors, respectively (Pfister *et al.*, 1997), and by 8-(N-methylisopropyl)amino- $N^6$ -(5'-endohydroxy-endonorbornyl)-9-methyl adenine (WRC 0571) with 62-fold selectivity versus the  $A_{2A}$  receptor and 4670-selectivity versus the  $A_3$  receptor (Martin *et al.*, 1996).

(+)-(R)-[(E)-3-(2-phenylpyrazolo[1,5- $\alpha$ ]pyridin-3-yl)acryloyl]-2-piperidine ethanol, FK 453, has been reported to be a potent and selective  $A_1$  receptor antagonist with  $IC_{50}$  values of approximately 17 nM at rat cortical  $A_1$  receptors and 11  $\mu$ M at striatal  $A_2$  receptors (Terai *et al.*, 1995). Chiral pyrrolo[2,3-d]pyrimidine and pyrimido[4,5-b]indole derivatives have been shown to be potent and highly stereoselective  $A_1$  adenosine receptor antagonists (Müller *et al.*, 1996a).

#### G. Distribution and Biological Effects

$A_1$  receptors are widely distributed in most species and mediate diverse biological effects. There is considerable literature in this area. Thus, this section is intended to give an indication of the ubiquity and diversity of actions mediated by adenosine at  $A_1$  receptors, rather



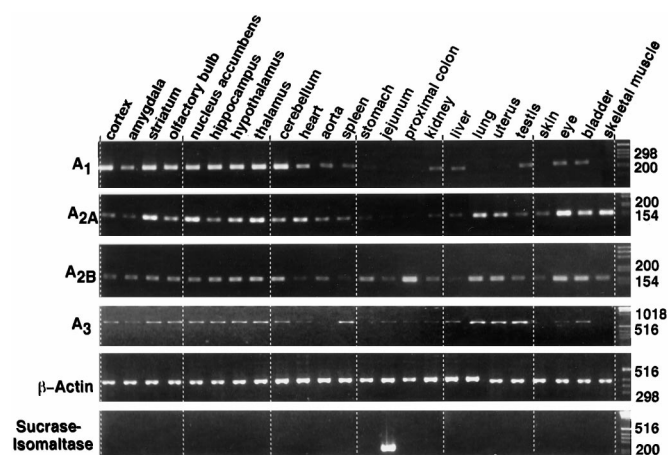


FIG. 4. Tissue distribution of adenosine receptor mRNA expression as examined by RT-PCR. Sizes of PCR products are given in base pairs. (From Dixon *et al.*, 1996, *Br J Pharmacol* 118:1461–1468; with permission from McMillan Press Limited.)

than to provide a comprehensive account of  $A_1$  receptor distribution and effects.

$A_1$  receptors are particularly ubiquitous within the central nervous system (CNS), with high levels being expressed in the cerebral cortex, hippocampus, cerebellum, thalamus, brain stem, and spinal cord (Reppert *et al.*, 1991; Dixon *et al.*, 1996) (fig. 4). Immunohistochemical analysis using polyclonal antisera generated against rat and human  $A_1$  adenosine receptors has identified different labeling densities of individual cells and their processes in selected regions of the brain (Rivkees *et al.*, 1995b).  $A_1$  receptor mRNA is widely distributed in peripheral tissues having been localized in vas deferens, testis, white adipose tissue, stomach, spleen, pituitary, adrenal, heart, aorta, liver, eye, and bladder (Reppert *et al.*, 1991; Dixon *et al.*, 1996). Only very low levels of  $A_1$  mRNA are present in lung, kidney, and small intestine (Reppert *et al.*, 1991; Stehle *et al.*, 1992; Dixon *et al.*, 1996) (fig. 4).

It is now well established that adenosine is released from biological tissues during hypoxia and ischemic conditions. One of its effects is to reduce neuronal activity and thereby oxygen consumption; thus it acts as a neuroprotective agent. A significant part of these effects seem to be mediated by the  $A_1$  receptor.  $A_1$  receptors are located pre and postsynaptically on cell bodies, and on axons, where they mediate inhibition of neurotransmission by decreasing transmitter release, hyperpolarizing neuronal membranes, reducing excitability and firing rate, and altering axonal transmission. Adenosine can also exert behavioral effects: adenosine actions at  $A_1$  receptors have been implicated in sedative, anticonvulsant, anxiolytic, and locomotor depressant effects (Nikodijevic *et al.*, 1991; Stone, 1991; Jain *et al.*, 1995; Malhotra and Gupta, 1997). Conversely, xanthine antagonists such as caffeine and theophylline have central stimulatory properties ascribed, at least in part, to inhibition of endogenous adenosine, although inhibition of

cyclic nucleotide phosphodiesterases may contribute to this effect.

$A_1$  receptors mediate cardiac depression through negative chronotropic, dromotropic, and inotropic effects (see Olsson and Pearson, 1990). Slowing of the heart rate occurs via  $A_1$  receptors on sinoatrial and atrioventricular nodes causing bradycardia and heart block, respectively, while the inotropic effects include a decrease in atrial contractility and action potential duration (Olsson and Pearson, 1990). This aspect of  $A_1$  receptor-mediated effects has found application in the clinical use of adenosine to treat supraventricular tachycardia, and in the use of adenosine receptor antagonists in the treatment of bradyarrhythmias.

In the kidney, activation of  $A_1$  receptors mediates diverse effects including vasoconstriction (principally of the afferent arteriole), a decrease in glomerular filtration rate, mesangial cell contraction, inhibition of renin secretion, and inhibition of neurotransmitter release (Olivera *et al.*, 1989; Agmon *et al.*, 1993; Barrett and Droppleman, 1993; Munger and Jackson, 1994). Intravenous and intra-aortic administration of adenosine in rats decrease water and sodium excretion via  $A_1$  receptors, while selective antagonism of  $A_1$  receptors causes diuresis and natriuresis (see Mizumoto *et al.*, 1993; Van Beuren *et al.*, 1993). Intrarenal administration of adenosine, but not of the  $A_{2A}$  selective agonist CGS 21680, in dogs also decreases water and sodium excretion (Levens *et al.*, 1991a,b). Furthermore,  $A_1$  receptors increase transepithelial resistance and reduce  $Na^+$  uptake in inner medullary collecting duct cells in culture (Yagil *et al.*, 1994). On the other hand, intrarenal administration of adenosine and the  $A_1$ -selective agonist CHA in rats has been shown to induce marked diuresis and natriuresis which can be inhibited by the  $A_1$ -selective antagonist DPCPX (Yagil, 1994).

Direct effects on blood vessel tone via adenosine actions on  $A_1$  receptors are rare. A more significant role of  $A_1$  receptors with regard to regulation of blood vessel tone appears to be prejunctional modulation of neurotransmitter release. Prejunctional inhibition of neurotransmission via  $A_1$  receptors on perivascular sympathetic (Gonçalves and Queiroz, 1996) and capsaicin-sensitive sensory afferents (Rubino *et al.*, 1993) has been shown. However,  $A_1$  receptors have been observed to mediate relaxation of porcine coronary artery (Merkel *et al.*, 1992), and contraction of guinea-pig aorta (Stogdall and Shaw, 1990) and pulmonary artery (Szentmiklósi *et al.*, 1995).  $A_1$  receptors have also been reported to mediate contraction of rat isolated spleen (Fozard and Milavec-Krizman, 1993) and rat vas deferens (Hourani and Jones, 1994), as well as bronchoconstriction and bronchial hyperresponsiveness (Ali *et al.*, 1994a, 1994b; Pauwels and Joos, 1995; el-Hashim *et al.*, 1996). Diverse  $A_1$ -mediated effects in the gut have been described, including inhibition of peristalsis of rat jejunum (Hancock and Coupar, 1995b), relaxation of longitudinal muscle of

rat duodenum (Nicholls *et al.*, 1992, 1996), and contraction of rat colonic muscularis mucosa (Bailey *et al.*, 1992; Reeves *et al.*, 1993). Interestingly, adenosine mediates contraction of guinea-pig myometrial smooth muscle via  $A_1$  receptors that in non-pregnant animals are coupled to the formation of  $IP_3$ , but in pregnant animals are coupled both to  $IP_3$  and negatively to adenylate cyclase (Schiemann and Buxton, 1991; Schiemann *et al.*, 1991a,b).

Selective inhibition of the synthesis of  $A_1$  receptors with antisense oligonucleotides confirmed that these receptors are involved in an animal model of asthma (Nyce and Metzger, 1997). There was a marked reduction in the number of  $A_1$  receptors in the lung and attenuation of airway constriction to adenosine, histamine, and dust-mite allergen (Nyce and Metzger, 1997). Although the site of action remains to be determined, selective antagonism of  $A_1$  receptors offers a possible new approach in asthma therapy.

$A_1$  receptors on bovine pulmonary artery endothelial cells have been shown to mediate  $Cl^-$  efflux (Arima *et al.*, 1994). In human airway epithelial cells,  $A_1$  receptors have been reported to mobilize intracellular  $Ca^{2+}$  and activate  $K^+$  and  $Cl^-$  conductance (Rugolo *et al.*, 1993), while selective inhibition of  $A_1$  receptors with DPCPX increases cAMP-activated  $Cl^-$  conductance (McCoy *et al.*, 1995).

$A_1$  adenosine receptors on rat cochlear membranes (Ramkumar *et al.*, 1994), astrocytes (Peakman and Hill, 1994), and epididymal spermatozoa (Minelli *et al.*, 1995) have been described. Release of  $Ca^{2+}$  from internal stores in perisynaptic glial cells of the frog neuromuscular junction via  $A_1$  receptors has been described (Robitaille, 1995).

Adenosine acts via  $A_1$  receptors and inhibition of cAMP to inhibit lipolysis and increase insulin sensitivity in adipose tissue (Londos *et al.*, 1985; Green, 1987). Abnormal  $A_1$  receptor function in genetic obesity has been proposed, showing that lipolysis is less active and  $A_1$  receptor signaling more active, which may be caused by changes in receptor phosphorylation, but also possibly by adenylate cyclase activity (LaNoue and Martin, 1994; Berkich *et al.*, 1995). In contrast, insulin sensitivity is decreased by activation of  $A_1$  receptors in skeletal muscle (Challis *et al.*, 1992).  $A_1$  receptors on pancreatic  $\beta$  cells mediate inhibition of insulin secretion (Hillaire-Buys *et al.*, 1989).

$A_1$  receptors have been widely reported to mediate the protective effects of adenosine in preconditioning and during ischemia or during reperfusion injury in the heart (Tsuchida *et al.*, 1993, 1994; Yao and Gross, 1993; Lee *et al.*, 1995; Lasley and Mentzer, 1995; Strickler *et al.*, 1996; Grover *et al.*, 1992; van Winkle *et al.*, 1994; Sakamoto *et al.*, 1995; Mizumura *et al.*, 1996; Stambaugh *et al.*, 1997), lung (Neely and Keith, 1995), and brain (Heurteaux *et al.*, 1995). Strong evidence for a protective role of  $A_1$  adenosine receptors comes from

studies with transgenic mice over expressing the  $A_1$  receptor. Mice over expressing the  $A_1$  receptor have been shown to have an increased myocardial resistance to ischemia (Matherne *et al.*, 1997). The mechanism involved is not yet clear; it may involve  $A_1$  receptor activation of  $K_{ATP}$  channels as infarct size reduction after activation of  $A_1$  receptors has been reported to be completely abolished by the blockade of  $K_{ATP}$  channels (Grover *et al.*, 1992; van Winkle *et al.*, 1994; Mizumura *et al.*, 1996). On the other hand, there seems to be a general consensus that PKC is involved in ischemic preconditioning, and activation of PKC was shown to be the critical factor involved in limitation of myocardial infarct size by  $A_1$  receptors in anaesthetized rabbits (Sakamoto *et al.*, 1995). However, not all researchers are in agreement that adenosine is cardioprotective, or that  $A_1$  receptors mediate ischemic preconditioning (Asimakis *et al.*, 1993; Ganote *et al.*, 1993; Hendrikx *et al.*, 1993; Lasley *et al.*, 1993; Liu *et al.*, 1994). In addition, a protective role for adenosine  $A_3$  receptors has been suggested (see Section VI.G.).

Reperfusion of ischemic tissue results in locally increased permeability and pulmonary edema that is associated with neutrophil accumulation in the microvasculature; neutrophil-endothelial cell interactions are known to be a prerequisite for the associated microvascular injury. Paradoxically, given the protective role of  $A_1$  receptors in ischemia-reperfusion injury, adenosine contributes to inflammatory reactions via effects on neutrophil and/or endothelial  $A_1$  receptors. This is done by augmenting responses to microbial stimuli, promoting chemotaxis, adhesion to endothelium, phagocytosis, and release of reactive oxygen intermediates (Cronstein *et al.*, 1990; Cronstein, 1994; Zahler *et al.*, 1994; Bullough *et al.*, 1995; Felsch *et al.*, 1995). It is possible that the local concentration of adenosine is crucial in determining which type of response predominates. A concentration-dependent dual protective-destructive role has also been described for the  $A_3$  adenosine receptor, but what is even more intriguing is that it involves high and low levels of activation of  $A_3$  receptors on the same cell (in both HL-60 and U 937 cells) (Yao *et al.*, 1997).

$A_1$  adenosine receptors have been implicated in modulation of nociception in the spinal cord (Reeve and Dickenson, 1995) and in the periphery (Karlsten *et al.*, 1992; Ocana and Baeyens, 1994). This may involve inhibition of sensory neurotransmitter release, because  $A_1$  receptors have been shown to mediate inhibition of calcitonin gene-related peptide (CGRP) release from capsaicin-sensitive sensory neurons in the spinal cord (Santicoli *et al.*, 1993) and in the periphery (Rubino *et al.*, 1993), as well as inhibit GABA currents in dorsal root ganglion neurons (Hu and Li, 1997). Analgesic effects of caffeine have also been described. These effects have been attributed to caffeine's effects on supraspinal  $A_1$  receptors because caffeine's effect is mimicked by the  $A_1$ -selective agonist 8-cyclopentyltheophylline (CPT);

spinally or peripherally administered caffeine lacks antinociceptive effects (Sawynok and Reid, 1996).

Synergistic interactions between  $A_1$  adenosine receptors and receptors coupled to a different class of G protein, typically pertussis toxin insensitive  $G_{q/11}$  proteins, have been described, whereby coactivation of the receptors results in an augmented increase in effectors/second-messengers derived from the  $G_{q/11}$  protein coupled pathway. The intracellular mechanisms underlying this potentiation are not well understood and have been suggested variously to involve intra- and extracellular calcium, second-messengers, and  $G_i$  protein  $\beta\gamma$  subunits. Early evidence for this kind of interaction came with the observation that adenosine enhances  $\alpha_1$ -adrenoceptor-induced accumulation of cAMP in rat vas deferens (Häggblad and Fredholm, 1987). Synergistic interactions have since been shown in DDT<sub>1</sub> MF-2 cells for  $A_1$  receptors and ATP receptors (Gerwins and Fredholm, 1992a), histamine  $H_1$  receptors (Dickenson and Hill, 1994), and bradykinin receptors (Gerwins and Fredholm, 1992b).  $A_1$  receptors transfected into CHO cells act synergistically with receptors for thrombin (Dickenson and Hill, 1997), cholecystokinin A (Dickenson and Hill, 1996), and ATP (Megson *et al.*, 1995).  $A_1$  receptors in astrocytes interact synergistically with histamine  $H_1$  receptors (Peakman and Hill, 1995) and glutamate receptors (Ogata *et al.*, 1994) to raise levels of  $[Ca^{2+}]_i$ . Synergistic interactions between  $A_1$  and  $\alpha_1$ -adrenoceptor mediated increases in inositol phosphate accumulation has been shown in mouse striatal astrocytes (el-Etr *et al.*, 1992a,b; Marin *et al.*, 1993). In hippocampal neurons, positive interactions have been described between adenosine  $A_1$  and  $GABA_A$  receptors (Akhondzadeh and Stone, 1994), as well as negative interactions between  $A_1$  and metabotropic glutamate receptors (de Mendonça and Ribeiro, 1997). Cross-talk between  $A_1$  and other receptors is clearly widespread; its physiological significance is an important area for future research.

#### IV. $A_{2A}$ Receptor

##### A. Cloned $A_{2A}$ Receptors

The  $A_{2A}$  receptor has been cloned from several species (table 3) and has a characteristic pharmacological profile in transfected cells consistent with that of the endogenous receptor. The first cloned adenosine receptor, RDC8, cloned from a canine thyroid cDNA library (Libert *et al.*, 1989), was subsequently identified as an  $A_{2A}$  receptor based on the binding of [<sup>3</sup>H]NECA and [<sup>3</sup>H]CGS 21680, and by activation of adenylate cyclase in cells transfected with the receptor (Maenhaut *et al.*, 1990). The exogenous  $A_{2A}$  receptor was shown to have a tissue distribution similar to endogenous  $A_{2A}$  binding sites in brain, that is, limited to the striatum, nucleus accumbens and olfactory tubercle (Schiffmann *et al.*, 1990). Subsequently,  $A_{2A}$  receptors were cloned from rat brain (Chern *et al.*, 1992; Fink *et al.*, 1992), human hippocampus (Furlong *et al.*, 1992), and guinea-pig

brain (Meng *et al.*, 1994b). Both  $A_{2A}$  and  $A_{2B}$  receptors have been cloned from mouse bone marrow-derived mast cells (Marquardt *et al.*, 1994). The gene for the  $A_{2A}$  receptor has been mapped to human chromosome 22 (MacCollin *et al.*, 1994; Peterfreund *et al.*, 1996) with reported chromosomal localizations of 22q11.2 (Le *et al.*, 1996) and 22q11.2-q13.1 (Libert *et al.*, 1994).

In common with the other adenosine receptor subtypes, there is significant interspecies differences in the amino acid sequences of cloned  $A_{2A}$  receptors; for example, between rat and human  $A_{2A}$  receptors there is approximately 84% amino acid homology (Chern *et al.*, 1992; Fink *et al.*, 1992; Furlong *et al.*, 1992; Linden, 1994), and between rat and dog  $A_{2A}$  receptors 82% homology (Chern *et al.*, 1992; Fink *et al.*, 1992).

The significantly greater molecular weight of the  $A_{2A}$  receptor (45 kDa) compared with the other adenosine receptor subtypes (36 to 37 kDa) can largely be attributed to its substantially longer carboxy terminal domain. This region is not involved in tight coupling to  $G_s$  proteins because this is a function predominantly of the N-terminal segment of the third intracellular loop (Olah, 1997). A truncated mutant of the canine  $A_{2A}$  adenosine receptor was used to show that neither the long carboxy-terminus nor the glycosidic moieties are required for ligand binding (Piersen *et al.*, 1994). Site-directed mutagenesis of the human  $A_{2A}$  adenosine receptor has been used to identify the various residues involved in agonist and antagonist binding (Kim *et al.*, 1995; Ijzerman *et al.*, 1996).

##### B. Signal Transduction Mechanisms

The most commonly recognized signal transduction mechanism for  $A_{2A}$  receptors is activation of adenylate cyclase. This implies coupling with the G protein  $G_s$ , although other G proteins may also be involved. *Vibrio cholerae* (cholera toxin) ADP-ribosylates the  $\alpha$ -subunit of  $G_s$  family members, inhibiting the intrinsic GTPase activity of  $G_{\alpha s}$  and thus has been useful in characterizing members of this family. Coupling of the  $A_{2A}$  receptor to its G protein is tight (see Palmer and Stiles, 1995). Hence, there is only slow dissociation of agonist from the receptor and stabilization of the receptor-G protein complex.

cAMP-independent signaling has been suggested for  $A_{2A}$  receptors on striatal GABA nerve terminals (Kirk and Richardson, 1995) and striatal cholinergic nerve terminals (Gubitz *et al.*, 1996). In striatal nerve terminals,  $A_{2A}$  receptors are suggested to mediate dual signaling via P- and N-type  $Ca^{2+}$  channels linked to  $G_s$ /adenylate cyclase/PKA and cholera toxin-insensitive G protein/PKC, respectively (Gubitz *et al.*, 1996). It has been suggested that  $A_{2A}$  receptor-mediated inhibition of superoxide anion generation in neutrophils may be mediated via cAMP-independent activation of a serine/threonine protein phosphatase (Revan *et al.*, 1996).



$A_{2A}$  receptor-mediated facilitation of synaptic transmission and transmitter release seems to occur through potentiation of presynaptic P-type  $Ca^{2+}$  channels, and probably involves adenylate cyclase and activation of a cAMP-dependent protein kinase (Mogul *et al.*, 1993; Correia-de-Sá and Ribeiro, 1994a; Umemiya and Berger, 1994; Gubitz *et al.*, 1996).

$K_{ATP}$  channels are suggested to be involved in coronary vasodilatation mediated by  $A_2$  receptors in the dog (Akatsuka *et al.*, 1994). Activation of  $K_{ATP}$  channels by  $A_2$  receptors in arterial myocytes is suggested to involve a cAMP-dependent protein kinase (Kleppisch and Nelson, 1995).

### C. Desensitization

Desensitization of  $A_{2A}$  receptors has been reported, which may be more rapid, similar to, or less rapid than that of  $A_1$  receptors. In DDT<sub>1</sub> MF-2 cells, the  $t_{1/2}$  for desensitization of  $A_{2A}$  receptors (45 min) is more rapid than that for  $A_1$  receptors, and in contrast to  $A_1$  receptors, there is no change in  $A_{2A}$  receptor number or affinity (Ramkumar *et al.*, 1991).  $A_{2A}$  receptor desensitization after exposure to  $A_2$ - or  $A_{2A}$ -selective agonists for up to several minutes to 4h has been observed in a number of tissues including porcine coronary artery (Makujina and Mustafa, 1993), rat aortic vascular smooth muscle cells (Anand-Srivastava *et al.*, 1989), DDT<sub>1</sub> MF-2 smooth muscle cells (Ramkumar *et al.*, 1991), rat pheochromocytoma PC12 cells (Chern *et al.*, 1993), and in canine  $A_{2A}$  receptors expressed in CHO cells (Palmer *et al.*, 1994). On the other hand, guinea-pig coronary artery  $A_{2A}$  receptors do not desensitize after more than 2h exposure to 2-[(2-aminoethylamino) carbonyl-ethylphenylethylamino]-5'-N-ethylcarboxamido adenosine (APEC) or 1,4-phenylene-diisothiocyanate, 4-isothiocyanatophenyl aminothiocarbonyl-APEC (DITC-APEC) (Niiya *et al.*, 1993). Furthermore,  $A_{2A}$  receptors seem to be relatively resistant compared with  $A_1$  receptors to desensitization in rat brain slices (Abbracchio *et al.*, 1992) and in spontaneously hypertensive rats after chronic treatment with  $A_1$  and  $A_2$  selective agonists in vivo (Casati *et al.*, 1994). In rat striatum slices,  $A_2$  receptors do not desensitize following exposure to NECA for up to 1h, whereas  $A_1$  receptors desensitize rapidly (Abbracchio *et al.*, 1992).

The mechanism underlying desensitization of  $A_{2A}$  receptors has been studied in some detail in transfected CHO cells, where it has been shown that exposure to agonist causes rapid desensitization and phosphorylation (Palmer *et al.*, 1994; Palmer and Stiles, 1997b). The threonine 298 residue of the carboxy terminal of the  $A_{2A}$  receptor seems to be essential for agonist-stimulated rapid receptor phosphorylation and short-term, but not long-term, desensitization (Palmer and Stiles, 1997a). The majority of the C terminal seems not to be involved in desensitization, because desensitization of a truncated mutant lacking the majority of the  $A_{2A}$  carboxyl-terminal (the last 95 residues) is unchanged (Palmer

and Stiles, 1997a). Evidence that desensitization may involve GRKs, implying uncoupling of the receptor-G protein complexes, has been provided by a study in NG108-15 mouse neuroblastoma × rat glioma cells mutants overexpressing GRK2, where the rate of desensitization of endogenous  $A_{2A}$  and  $A_{2B}$  receptors was markedly slowed (Mundell *et al.*, 1997). This effect was selective in that agonist-induced desensitization of secretin and IP-prostanoid receptor stimulated adenylate cyclase were not affected by dominant negative mutant GRK2 overexpression (Mundell *et al.*, 1997). Receptor sequestration, whereby a receptor translocates to a "light membrane" fraction, has been described for  $A_{2A}$  receptors expressed in CHO cells, but this seems to be involved in the recovery of the response of the receptor rather than in desensitization (Palmer *et al.*, 1994).

Studies of long-term desensitization of endogenous  $A_{2A}$  receptors in rat pheochromocytoma PC12 cells showed that whereas a 30 min exposure of  $A_{2A}$  receptors to CGS 21680 is associated with inhibition of adenylate cyclase activity, long-term agonist exposure (12–20h) is associated additionally with down regulation of  $G_s$   $\alpha$  proteins and activation of phosphodiesterase (Chern *et al.*, 1993). Long-term (24h) exposure to agonist may additionally lead to down-regulation of receptor number and up-regulation of inhibitory G proteins (Palmer *et al.*, 1994; Palmer and Stiles, 1997a). Approximately 2 weeks of continuous infusion of either NECA or CGS 21680 causes a decrease in the number of  $A_{2A}$  receptor binding sites in rat striatum (Porter *et al.*, 1988; Webb *et al.*, 1993a). A calcium-independent PKC isoenzyme seems to be involved in phosphorylation and inhibition of adenylate cyclase type VI activity after prolonged stimulation and desensitization of the  $A_{2A}$  receptor, at least in rat pheochromocytoma PC12 cells (Lai *et al.*, 1997), providing an additional mechanism by which to regulate  $A_{2A}$  receptor signal transduction.

### D. Sensitization / Up-Regulation

Striatal  $A_{2A}$  adenosine receptors in rats and mice are up-regulated after chronic caffeine ingestion (Hawkins *et al.*, 1988; Traversa *et al.*, 1994).  $A_{2A}$  receptors seem to be less prone to up-regulation after chronic blockade with non-selective antagonists than are  $A_1$  receptors (Lupica *et al.*, 1991a; Johansson *et al.*, 1993a).

### E. Agonists

$A_{2A}$  receptors do not generally bind  $N^6$ -substituted adenosine derivatives and show a preference for derivatives with modifications of the 2nd position of the adenine ring; bulky substituents in this position can selectively enhance  $A_{2A}$  receptor affinity (Jacobson *et al.*, 1992b; Cristalli *et al.*, 1994; Siddiqi *et al.*, 1995). Several synthetic  $A_{2A}$ -selective agonists are modeled according to this structural modification. It should be noted that the agonist studies detailed below have been carried out in species other than humans, and that the human  $A_{2A}$



receptor has a comparatively lower affinity of binding for CGS 21680 and other adenosine receptor agonists (Dionisotti *et al.*, 1997; Klotz *et al.*, 1998).

The C2-substituted NECA derivative, CGS 21680, is 140-fold selective for the  $A_{2A}$  versus the  $A_1$  receptor (Hutchison *et al.*, 1990) (fig. 2). CGS 21680 has only very low affinity at the  $A_{2B}$  receptor, and thus has been used extensively to discriminate between  $A_{2A}$  and  $A_{2B}$  subtypes (Jarvis *et al.*, 1989; Lupica *et al.*, 1990). [ $^3H$ ]CGS 21680 has been reported to bind in rat cortex and hippocampus to adenosine binding sites different to the classic striatal  $A_{2A}$  receptors, which does not seem to be caused by high and low affinity states of the same  $A_{2A}$  receptor, or to binding at  $A_3$  or  $A_4$  receptors (Johansson *et al.*, 1993b; Cunha *et al.*, 1996; Lindström *et al.*, 1996). Amine derivatives of CGS 21680, namely APEC (fig. 2), DITC-APEC and 2-[4-(2-([4-aminophenyl]methylcarbonyl)ethyl)-phenyl]ethylamino-5'-N-ethylcarboxamido-adenosine (PAPA-APEC), are  $A_{2A}$ -selective agonists (Barrington *et al.*, 1989; Ramkumar *et al.*, 1991; Jacobson *et al.*, 1992a; Niiya *et al.*, 1993). DITC-APEC binds covalently, causing irreversible activation of the  $A_{2A}$  receptor (Niiya *et al.*, 1993).

The C2-substituted adenosine derivative CV 1808 displays poor selectivity (approximately 5-fold) for the  $A_{2A}$  versus the  $A_1$  receptor (Kawazoe *et al.*, 1980; Bruns *et al.*, 1986), but is a valuable precursor for the synthesis of more selective  $A_{2A}$  receptor agonists.  $N^6$ -(2(3,5-dimethoxyphenyl)-2-(2-methylphenyl)ethyl)-adenosine (DPMA) is a selective  $A_{2A}$  receptor agonist (Merkel *et al.*, 1992; Alexander *et al.*, 1994).

A series of 2-aralkynyl and 2-heteroalkynyl derivatives of NECA have been studied for their selectivity at the  $A_{2A}$  receptor (Cristalli *et al.*, 1995). Of these, the 4-formylphenylethynyl derivative shows affinity in the low nanomolar range and approximately 160-fold selectivity. 2-Hexyl-5'-N-ethylcarboxamidoadenosine (2HE-NECA) has been suggested to be selective at  $A_{2A}$  receptors with 60- and 160-fold selectivity in binding studies for  $A_{2A}$  versus  $A_1$  receptors in rat and bovine brain, respectively (Monopoli *et al.*, 1994). Although NECA itself is approximately equipotent at  $A_1$  and  $A_{2A}$  receptors, it can be useful in  $A_{2A}$  receptor characterization provided that  $A_1$ -selective ligands are shown not to have equivalent effects.

The 2-hydrazinoadenosine, WRC-0470 (2-cyclohexylmethylidenehydrazinoadenosine) has been shown to be a potent and selective  $A_{2A}$  agonist, with low nanomolar affinity at recombinant  $A_{2A}$  receptors transfected in mammalian cells and in functional assays in a variety of tissues (Martin *et al.*, 1997b).

#### F. Antagonists

Several antagonists selective for the  $A_{2A}$  receptor have been synthesized. 8-(3-chlorostyryl)caffeine (CSC) is a potent ( $K_i$  54 nM) and selective  $A_{2A}$  antagonist in radioligand binding assays in rat brain (520-fold selec-

tive versus  $A_1$  receptors), in reversing agonist effects on adenylate cyclase in PC12 cells (22-fold selective), and in blocking locomotor depression elicited by the  $A_{2A}$ -selective agonist APEC in vivo (Jacobson *et al.*, 1993a) (fig. 3). 1,3-dialkyl-7-methyl-8-(3,4,5-trimethoxystyryl)xanthine (KF-17837) has been described as a potent and selective  $A_{2A}$  antagonist with 62-fold selectivity for  $A_{2A}$  over  $A_1$  receptors in binding studies in rat brain, and 30-fold selectivity for the  $A_{2A}$  over the  $A_{2B}$  receptor in inhibition of cAMP accumulation ( $A_{2A}$   $IC_{50}$  = 53 nM;  $A_{2B}$   $IC_{50}$  = 1500 nM) (Shimada *et al.*, 1992; Kanda *et al.*, 1994; Nonaka *et al.*, 1994). DMPX (3,7-dimethyl-1-propargylxanthine) derivatives have been shown to be potent and selective  $A_{2A}$  antagonists; 8-(m-bromostyryl)-DMPX has a  $K_i$  value of 8.2 nM and is 146-fold selective versus  $A_1$  receptors (Müller *et al.*, 1996b).

ZM 241385, (4-(2-[7-amino-2-(2-furyl)[1,2,4]-triazolo[2,3- $\alpha$ ] [1,3,5]triazin-5-yl amino]ethyl)phenol) is a potent and selective non-xanthine  $A_{2A}$  adenosine receptor antagonist (Poucher *et al.*, 1995) (fig. 3). It has high affinity for the  $A_{2A}$  receptor ( $pA_2$  value approximately 9), is 1000- and 91-fold selective versus  $A_1$  and  $A_{2B}$  receptors, respectively, and has virtually no effects at  $A_3$  receptors (Poucher *et al.*, 1995).

[ $^3H$ ]SCH 58261 ([ $^3H$ -5-amino-7-(2-phenylethyl)-2-(2-furyl)-pyrazolo[4,3-e]-1,2,4-triazolo[1,5-c] pyrimidine) is a novel potent and selective  $A_{2A}$  antagonist radioligand which binds with low nanomolar affinity to  $A_{2A}$  receptors in human platelet and rat striatal membranes, and at  $A_{2A}$  receptors transfected into CHO cells (Zocchi *et al.*, 1996; Dionisotti *et al.*, 1997). The analog SCH 63390 (5-amino-7-(3-phenylpropyl)-2-(2-furyl)pyrazolo[4,3-e]-1,2,4-triazolo[1,5-c]pyrimidine) has similar potency at  $A_{2A}$  receptors, but greater selectivity (210-fold) (Baraldi *et al.*, 1996).

#### G. Distribution and Biological Effects

$A_{2A}$  receptors have a wide-ranging but restricted distribution that includes immune tissues, platelets, the CNS, and vascular smooth muscle and endothelium. Functional studies concerned with  $A_{2A}$  receptors in isolated cells and tissues, in the central and peripheral nervous systems, and in isolated blood vessels and vascular beds, are listed in tables 4, 5 and 6, and illustrate the wide distribution and diverse biological effects mediated by this receptor.

Within the brain, the highest levels of  $A_{2A}$  receptors are in the striatum, nucleus accumbens, and olfactory tubercle (regions which are rich in dopamine) (Ongini and Fredholm, 1996). Low levels of  $A_{2A}$  receptor also seem to be expressed in most other brain regions, although for striatal cholinergic neurons this is controversial (Dixon *et al.*, 1996; Peterfreund *et al.*, 1996; Jin and Fredholm, 1997; Svenningsson *et al.*, 1997). Striatal neurons express  $A_{2A}$  receptors in close association with dopamine  $D_2$  receptors and specific negative interactions have been described (Ferre *et al.*, 1991, 1992, 1997;

TABLE 4  
Distribution and effects mediated by endogenously expressed  $A_2$  adenosine receptors

Tissue	Subtype	Effects	Reference
Astrocytes	$A_2$	Reactive astroglyosis	Hindley <i>et al.</i> , 1994
Astrocytes, type 1	$A_{2B}$	—	Peakman and Hill, 1994, 1996
Astrocytes, type 2	$A_{2A}$ , $A_{2B}$	—	Peakman and Hill, 1996
Astrogloma cell line D384	$A_{2B}$	—	Altiok <i>et al.</i> , 1992; Fredholm and Altiok, 1994
Astrocytoma cell line U373	$A_{2B}$	↑ Interleukin 6	Fiebich <i>et al.</i> , 1996
Neutrophils	$A_{2A}$	↓ Apoptosis	Zhang <i>et al.</i> , 1996; Walker <i>et al.</i> , 1996
	$A_{2A}$	↓ Oxygen radical generation, phagocytosis and adhesion	Cronstein <i>et al.</i> , 1990, 1992; Salmon and Cronstein, 1990; Gurden <i>et al.</i> , 1993; Cronstein, 1994; Bullough <i>et al.</i> , 1995; Felsch <i>et al.</i> , 1995
Jurkat cells (human T-cell line)	$A_{2A}$ , $A_{2B}$	—	Nonaka <i>et al.</i> , 1994; van der Ploeg <i>et al.</i> , 1996
Mast cells (mouse)	$A_{2A}$ , $A_{2B}$	—	Marquardt <i>et al.</i> , 1994
Mastocytoma cells (canine)	$A_{2B}$	Degranulation	Auchampach <i>et al.</i> , 1997a
HMC-1 (human mast cell line)	$A_{2A}$ , $A_{2B}$	Interleukin-8 secretion by $A_{2B}$	Feoktistov and Biaggioni, 1995
Fibroblasts	$A_{2B}$	—	Bruns <i>et al.</i> , 1986; Brackett and Daly, 1994
Platelets	$A_{2A}$	↓ Aggregation	Huttemann <i>et al.</i> , 1984; Gurden <i>et al.</i> , 1993; Monopoli <i>et al.</i> , 1994; Cristalli <i>et al.</i> , 1995
Chromaffin cells	$A_{2B}$	↓ DMPP-evoked catecholamine release	Casado <i>et al.</i> , 1992; Mateo <i>et al.</i> , 1995
Pheochromocytoma PC12 cells	$A_2$	↑ ATP-evoked dopamine release	Koizumi <i>et al.</i> , 1994
Pheochromocytoma PC12 cells	$A_{2A}$ , $A_{2B}$	—	Hide <i>et al.</i> , 1992; Chern <i>et al.</i> , 1993; Nonaka <i>et al.</i> , 1994; van der Ploeg <i>et al.</i> , 1996
Pineal gland	$A_{2B}$	—	Gharib <i>et al.</i> , 1992
Retinal membranes	$A_{2A}$ , $A_{2B}$	—	Blazynski and McIntosh, 1993
Retinal pigment epithelial cells	$A_{2B}$	—	Blazynski, 1993
Outer rod segments	$A_{2A}$	—	McIntosh and Blazynski, 1994
Airways	$A_{2B}$	Bronchoconstriction	Pauwels and Joos, 1995
Trachea	$A_{2(B)}$	Relaxation	Losinski and Alexander, 1995
Taenia coli	$A_2$	Relaxation	Burnstock <i>et al.</i> , 1984
Duodenum; longitudinal muscle	$A_{2B}$	Relaxation	Nicholls <i>et al.</i> , 1992
Duodenum; muscularis mucosae	$A_{2B}$	Contraction	Nicholls <i>et al.</i> , 1996
Colon	$A_{2B}$	—	Stehle <i>et al.</i> , 1992
Caecum	$A_{2B}$	—	Stehle <i>et al.</i> , 1992
Intestine	$A_{2B}$	↓ Secretion	Hancock and Coupar, 1995a
Intestinal epithelia	$A_{2B}$	↑ $Cl^-$ secretion	Strohmeier <i>et al.</i> , 1995
Parietal cells	$A_2$	↑ Gastric acid secretion	Ain <i>et al.</i> , 1993
Liver	$A_2$	↑ Glycogenolysis	Buxton <i>et al.</i> , 1987
Hepatocytes	$A_2$	↑ Glycogenolysis	Stanley <i>et al.</i> , 1987
Kidney	$A_2$	Erythropoietin production	Nakashima <i>et al.</i> , 1993
Kidney	$A_2$	↑ Renin release	Churchill and Churchill, 1985; Churchill and Bidani, 1987
Glomeruli	$A_2$	—	Freissmuth <i>et al.</i> , 1987
Pancreatic A cells	$A_2$	↑ Glucagon secretion	Chapal <i>et al.</i> , 1985
Bladder	$A_{2B}$	—	Nicholls <i>et al.</i> , 1992; Stehle <i>et al.</i> , 1992
Sperm	$A_2$	↑ Motility	Shen <i>et al.</i> , 1993

Fink *et al.*, 1992; Schiffmann and Vanderhaeghen, 1993). Outside the brain, the most abundant expression of human  $A_{2A}$  mRNA is in immune tissues, eye and skeletal muscle; heart, lung, bladder, and uterus also show strong expression, with less abundant expression in small intestine, kidney, spleen, stomach, testis, skin, kidney, and liver (Dixon *et al.*, 1996; Peterfreund *et al.*, 1996).

$A_{2A}$  receptors in the CNS and particularly in the peripheral nervous system (PNS) generally facilitate neurotransmitter release (table 5).

The negative interactions that have been observed between  $A_{2A}$  and dopamine  $D_2$  receptors involve a reduced affinity of agonist binding to dopamine  $D_2$  receptors upon stimulation of  $A_{2A}$  receptors in rat striatal membranes (Ferré *et al.*, 1991, 1992, 1997). This raises the possibility of using  $A_{2A}$  receptor antagonists as a novel therapeutic approach in the treatment of Parkinsons disease, to reduce the profound disabling effects arising from degeneration of dopaminergic nigrostriatal neurons of the basal ganglia in this disease (Richardson

*et al.*, 1997). Interactions are not observed between  $A_{2A}$  and  $D_2$  receptors transfected into COS-7 cells; it was suggested that the receptors do not interact directly to influence agonist binding (Snarprud *et al.*, 1994). Interestingly, activation of  $A_{2A}$  receptors on rat striatal nerve terminals causes desensitization of coexpressed  $A_1$  receptors by a mechanism which seems to involve PKC (Dixon *et al.*, 1997a). It is noteworthy that both  $D_2$  dopamine and  $A_1$  adenosine receptors couple to  $G_i$  proteins to cause inhibition of adenylate cyclase. Thus, with respect to the actions of adenosine at  $A_{2A}$  receptors, negative  $A_{2A}$ - $A_1$  and  $A_{2A}$ - $D_2$  interactions will shift the balance of intracellular signaling further toward stimulation of cAMP. Interactions between  $A_{2A}$  receptors and dopamine  $D_1$  receptors, and receptors for CGRP, glutamate, and acetylcholine have also been reported (see Sebastião and Ribeiro, 1996). Negative interactions whereby activation of the  $A_{2A}$  receptor blocks the protective effects of preconditioning hypoxia, believed to be via  $A_1$  and  $A_3$  receptors, have been described (Strickler *et al.*, 1996).

TABLE 5  
 Functional distribution of endogenously expressed  $A_2$  adenosine receptors in central and peripheral nervous systems

Location	Subtype	Effects	Reference
<b>CNS</b>			
Caudate-putamen synaptosomes	$A_{2A}$	↓ $K^+$ -evoked GABA release	Kurokawa <i>et al.</i> , 1994
Cerebral cortex	$A_{2(A)}$	↓ Neuronal firing	Phillis, 1990; Lin and Phillis, 1991
Cerebral cortex	$A_{2(B)}$	↑ ACh- and $K^+$ -evoked aspartate release	Phillis <i>et al.</i> , 1993a,b
Cerebral cortex	$A_{2A}$	↓ Ischemia-evoked GABA release	O'Regan <i>et al.</i> , 1992a
Cerebral cortex	$A_{2A}$	↓ Ischemia-evoked glutamate and aspartate release	O'Regan <i>et al.</i> , 1992b
Globus pallidus	$A_{2A}$	↑ Electrically evoked GABA release	Mayfield <i>et al.</i> , 1993
Globus pallidus synaptosomes	$A_{2A}$	↓ $K^+$ -evoked GABA release	Kurokawa <i>et al.</i> , 1994
Hippocampus	$A_{2A}$	↑ Electrically evoked [ $^{14}C$ ]ACh release	Jin and Fredholm, 1997
Hippocampus (CA3 region)	$A_{2A}$	↑ Electrically evoked [ $^3H$ ]ACh release	Cunha <i>et al.</i> , 1994
Hippocampus (CA3 region)	$A_2$	↑ P-type calcium currents	Mogul <i>et al.</i> , 1993
Hippocampal synaptosomes	$A_{2A}$	↑ Veratridine-evoked [ $^3H$ ]ACh release	Cunha <i>et al.</i> , 1995
Nucleus accumbens	$A_{2A}$	↓ Locomotor activity (baroreceptor ↓, chemoreceptor ↑)	Barraco <i>et al.</i> , 1993, 1994
Nucleus tractus solitarius	$A_{2A}$	Baroreflex control (hypotension, bradycardia)	Barraco <i>et al.</i> , 1993; Ergene <i>et al.</i> , 1994
	$A_{2A}$	↑ Electrically evoked [ $^3H$ ]NA release	Barraco <i>et al.</i> , 1995
	$A_{2A}$	↓ $K^+$ -evoked glutamate release	Castillo-Meléndez <i>et al.</i> , 1994
Striatum	$A_{2A}$	Catalepsy	Hauber and Munkle, 1995
Striatum	$A_2$	↑ Dopamine release	Zetterström and Fillenz, 1990
Striatum	$A_{2A}$	↑ ACh release	Brown <i>et al.</i> , 1990; Kurokawa <i>et al.</i> , 1994
Striatum	$A_{2A}$	↑ Veratridine-evoked [ $^3H$ ]ACh release	Kirkpatrick and Richardson, 1993
Striatum	$A_{2A}$	↓ NMDA receptor conductance	Nörenberg <i>et al.</i> , 1997b
Striatal synaptosomes	$A_{2A}$	↓ $K^+$ -evoked GABA release	Kirk and Richardson, 1995
Superior colliculus	$A_{2A}$	↑ Evoked potentials	Ishikawa <i>et al.</i> , 1997
Spinal cord	$A_2$	Antinociception	DeLander and Hopkins, 1987
<b>PNS</b>			
Motor nerves; phrenic nerve-hemidiaphragm	$A_{2A}$	↑ Electrically and CGRP-evoked [ $^3H$ ]ACh release	Correia-de-Sá and Ribeiro, 1994a,b; Correia-de-Sá <i>et al.</i> , 1996
Myenteric neurones	$A_{2A}$	↑ Excitability	Christofi <i>et al.</i> , 1994
Airway sensory neurones	$A_{2(A)}$	↓ Capsaicin-evoked substance P release	Morimoto <i>et al.</i> , 1993
Vagal afferent neurones	$A_{2A}$	Depolarization	Castillo-Meléndez <i>et al.</i> , 1994
Vas deferens neurones	$A_{2A}$	↑ Electrically evoked NA release	Gonçalves and Queiroz, 1993
Rat tail artery neurones	$A_{2A}$	↑ Electrically evoked NA release	Gonçalves and Queiroz, 1996

Behavioral effects of  $A_{2A}$  receptors are evidenced by  $A_{2A}$ -mediated cataleptic activity and antagonism of apomorphine-induced climbing (an animal model of schizophrenia) (Kanda *et al.*, 1994; Kafka and Corbett, 1996).

In the vasculature,  $A_{2A}$  receptors have been described on both the smooth muscle and endothelium, where they are associated with vasodilatation (table 6). There seems to be considerable variation in  $A_{2A}$  receptor expression between blood vessels, although it is possible that vessels unresponsive to  $A_{2A}$ -selective agonists do express the receptor but at very low levels, or that the receptor is not coupled to a functional response. This functional diversity is exemplified by the fact that  $A_{2A}$  receptors mediate relaxation of rat aorta and bovine coronary artery (Conti *et al.*, 1993), whereas in guinea-pig pulmonary artery (Szentmiklósi *et al.*, 1995) and rat mesenteric arterial bed (Rubino *et al.*, 1995), adenosine-mediated relaxation is mediated via the  $A_{2B}$  receptor, and relaxation via  $A_{2A}$  receptors is weak or non-existent (fig. 5). Adenosine has a mitogenic effect on endothelial cells, which in human endothelial cells is mediated via the  $A_{2A}$  receptor and subsequent activation of mitogen-activated protein kinase (MAPK) (Sextl *et al.*, 1997). The mitogenic activation seems to be independent of  $G_s$ ,  $G_i$  and typical PKC isoforms, but is associated with activation of  $p21^{ras}$  (Sextl *et al.*, 1997).

An interesting development in this field is provided by a study of  $A_{2A}$  receptor knockout mice (Ledent *et al.*,

1997). These mice showed reduced exploratory activity. Caffeine, which normally stimulates locomotor activity, substantially depressed activity. The  $A_{2A}$  knockout mice also showed increased aggressiveness, hypoalgesia, an increase in blood pressure and heart rate, and an increase in platelet aggregation (Ledent *et al.*, 1997). It is satisfying that these findings are broadly consistent with those predicted from studies of the endogenous  $A_{2A}$  receptor in isolated cells and tissues, and in whole animals.

## V. $A_{2B}$ Receptor

### A. Cloned $A_{2B}$ Receptors

$A_{2B}$  receptors have been cloned from human hippocampus (Pierce *et al.*, 1992), rat brain (Rivkees and Rappert, 1992; Stehle *et al.*, 1992), and mouse bone marrow-derived mast cells (Marquardt *et al.*, 1994) (table 3). The human  $A_{2B}$  adenosine receptor gene (ADORA2B) has been localized to chromosome 17p11.2-p12 (Townsend-Nicholson *et al.*, 1995b) and 17p12 (Jacobson *et al.*, 1995a). A human  $A_{2B}$  receptor pseudogene has been cloned and localized to chromosome 1q32 (Jacobson *et al.*, 1995a). Although the pseudogene is unable to encode a functional receptor, it is 79% identical with the functional  $A_{2B}$  receptor. Thus, it was noted that the existence of the transcript in tissues could lead to misinterpretation of in situ hybridization and northern blot analysis when probes are used to recognize sequences common to these receptors (Jacobson



TABLE 6  
Functional distribution of endogenously expressed vascular  $A_2$  adenosine receptors

Vessel and species	Receptor	Location	Reference
Aorta; guinea-pig	$A_{2B}$	EC, SM	Hargreaves <i>et al.</i> , 1991; Martin, 1992; Martin <i>et al.</i> , 1993b; Gurden <i>et al.</i> , 1993; Alexander <i>et al.</i> , 1994
Aorta; rabbit	$A_{2A}$	N.D.	Balwierzczak <i>et al.</i> , 1991
Aorta; rat	$A_{2A}$ , $A_{2B}$	EC, SM <sup>a</sup>	Conti <i>et al.</i> , 1993; Lewis <i>et al.</i> , 1994; Monopoli <i>et al.</i> , 1994; Prentice and Hourani, 1996
Aortic EC; human	$A_{2A}$ , $A_{2B}$	EC	Iwamoto <i>et al.</i> , 1994
Aortic SM cells; rat	$A_{2B}$	SM	Dubey <i>et al.</i> , 1996
Coeliac artery; rabbit	$A_{2A}$	N.D.	Balwierzczak <i>et al.</i> , 1991
Coronary artery; bovine	$A_{2A}$	N.D.	Conti <i>et al.</i> , 1993; Monopoli <i>et al.</i> , 1994
Coronary artery; canine	$A_{2A}$	N.D.	Balwierzczak <i>et al.</i> , 1991; Gurden <i>et al.</i> , 1993
Coronary artery; human	$A_{2A}$	N.D.	Makujina <i>et al.</i> , 1992
Coronary artery; porcine	$A_{2A}$ , $A_{2(B)}$	EC, SM	Balwierzczak <i>et al.</i> , 1991; Abebe <i>et al.</i> , 1994; Monopoli <i>et al.</i> , 1994
Coronary artery EC; guinea-pig	$A_{2A}$	EC	Schiele and Schwabe, 1994
Coronary bed/vessels; guinea-pig	$A_{2A}$	EC, SM	Martin <i>et al.</i> , 1993b; Vials and Burnstock, 1993
Corpus cavernosum; rabbit	$A_{2B}$	EC, SM	Chiang <i>et al.</i> , 1994
DDT1 MF-2 cells (SM cells)	$A_{2A}$	SM	Ramkumar <i>et al.</i> , 1991
Hepatic arterial bed; rabbit	$A_{2A}$	N.D.	Mathie <i>et al.</i> , 1991a,b
Mammary artery; human	$A_{2A}$	N.D.	Makujina <i>et al.</i> , 1992
Mesenteric arterial bed; rat	$A_{2A}$	EC, SM	Hiley <i>et al.</i> , 1995
Mesenteric arterial bed; rat	$A_{2B}$	SM	Rubino <i>et al.</i> , 1995
Mesenteric artery; rabbit	$A_{2A}$	N.D.	Balwierzczak <i>et al.</i> , 1991
Placental arterial bed; human	$A_{2A}$	N.D.	Read <i>et al.</i> , 1993
Pulmonary artery; guinea pig	$A_{2B}$	SM	Szentmiklósi <i>et al.</i> , 1995
Pulmonary arterial bed; rat	$A_{2B}$	SM	Haynes <i>et al.</i> , 1995
Pulmonary artery and vein; rabbit	$A_2$	EC, SM	Steinhorn <i>et al.</i> , 1994
Pulmonary arterial bed; rabbit	$A_2$	N.D.	Pearl, 1994
Renal artery; rat	$A_{2B}$	EC	Martin and Potts, 1994
Renal bed; rat	$A_{2A}$	SM	Levens <i>et al.</i> , 1991a,b; Agmon <i>et al.</i> , 1993
Saphenous vein; canine	$A_{2B}$	N.D.	Hargreaves <i>et al.</i> , 1991
Saphenous vein; human	$A_{2A}$	N.D.	Makujina <i>et al.</i> , 1992
Umbilical vein EC; human	$A_{2A}$	EC	Sobrevia <i>et al.</i> , 1997

EC, endothelium; SM, smooth muscle; N.D., not determined.

<sup>a</sup>  $A_{2A}$  adenosine receptor only.

*et al.*, 1995a). As with the other adenosine receptor subtypes, there is considerable species differences in the sequence of the  $A_{2B}$  receptor; for example, 86% amino acid sequence homology between rat and human  $A_{2B}$  receptors (Stehle *et al.*, 1992; Pierce *et al.*, 1992; Linden, 1994).

### B. Signal Transduction Mechanisms

$A_{2B}$  receptor coupling to different signaling pathways has been reported, including activation of adenylate cyclase,  $G_q/G_{11}$ -mediated coupling to PLC and  $IP_3$ -dependent increase in  $[Ca^{2+}]_i$  (in human mast cells) (Feoktistov and Biaggioni, 1995), and coupling to PLC when expressed in *Xenopus* oocytes (Yakel *et al.*, 1993).

### C. Desensitization

The lack of  $A_{2B}$  receptor-selective agonists has undoubtedly contributed to the general lack of information on  $A_{2B}$  receptor desensitization. In rat PC12 cells, the  $A_{2B}$  response has been shown to be reduced in  $A_{2A}$ -desensitized cells, possibly through common inhibition of adenylate cyclase (Chern *et al.*, 1993). In mutant NG108-15 cells overexpressing GRK2, desensitization of endogenous  $A_{2B}$  receptors was markedly less than that in normal cells ( $t_{1/2}$  15–20 min), indicating that receptor phosphorylation and uncoupling from G proteins may be involved in desensitization of  $A_{2B}$  receptors (Mundell *et al.*, 1997). Although it is not yet clear whether there are inherent differences in the rates of desensitization of  $A_{2A}$  and  $A_{2B}$  receptors, the lower af-

finity of  $A_{2B}$  receptors for adenosine raises the possibility that they may still be fully operational, and thus may act as a backup for adenosine responses, when the higher affinity coexpressed  $A_{2A}$  receptors have been activated and desensitized.

### D. Agonists and Antagonists

Despite intensive efforts in this area, there are no  $A_{2B}$ -selective agonists. Thus, at present, activation of adenylate cyclase in membranes and accumulation of cAMP in cells is used to characterize  $A_{2B}$  receptors, provided a lack of activity/binding of  $A_{1-}$ ,  $A_{2A-}$ , and  $A_{3-}$  selective agonists is confirmed. As with  $A_{2A}$  receptors,  $A_{2B}$  receptors show a preference for adenosine derivatives with modifications of the C2 position of the adenine ring. NECA is currently the most potent agonist at  $A_{2B}$  receptors, having low micromolar affinity (Brackett and Daly, 1994; Alexander *et al.*, 1996; Klotz *et al.*, 1998), but is less useful in characterization of  $A_{2B}$  receptors in cells or tissues in which  $A_{2A}$  receptors are coexpressed because it is non-selective. 2-ClADO,  $N^6$ -(3-iodobenzyl)-5'-(N-methylcarbamoyl)adenosine (IB-MECA), and R-PIA are among the more potent of other conventional adenosine-receptor agonists that act also at  $A_{2B}$  receptors, but their affinity for the  $A_{2B}$  receptor is relatively low ( $EC_{50}$  values 9 to 11  $\mu M$ ) (Brackett and Daly, 1994; Klotz *et al.*, 1998).

Enprofylline blocks  $A_{2B}$  receptors in human mast cells HMC-1 ( $K_i$  7  $\mu M$ ) and canine BR mastocytoma cells and



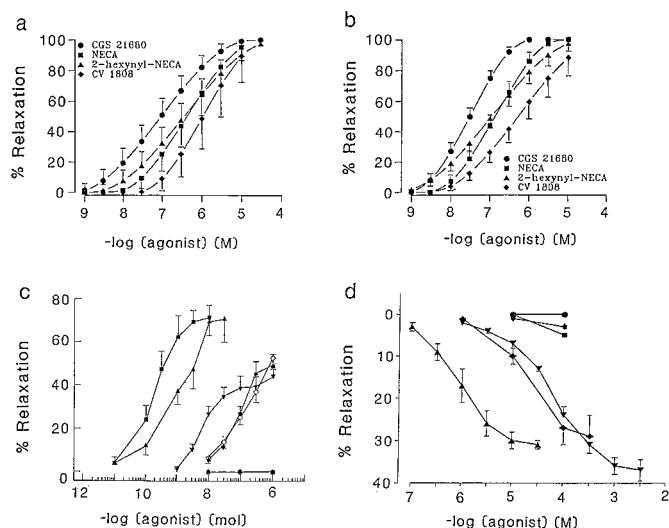


FIG. 5. Species variation in functional expression of vasodilator  $A_{2A}$  and  $A_{2B}$  receptors. Note that the agonist potencies suggest the presence of  $A_{2A}$  receptors in rat aorta (a) and bovine coronary artery (b), and  $A_{2B}$  receptors in rat mesenteric arterial bed, (c) and guinea-pig pulmonary arteries (d).

a, b. Mean dose-response curves for the vasorelaxant activity induced by some adenosine agonists in isolated rat aorta (a) and bovine coronary artery (b). Each response is expressed as the percentage of the maximum contraction induced by PGF $2\alpha$  (3  $\mu$ M). Vertical bars represent 95% confidence limits. (From Conti *et al.*, 1993).

c. Dose-response curves showing vasodilator responses of the rat mesenteric vascular bed to ATP ( $\blacktriangle$ ), 2-mSATP ( $\blacksquare$ ), adenosine ( $\diamond$ ), 2-CADO ( $\star$ ), NECA ( $\blacktriangledown$ ), CPA ( $\circ$ ) and CGS 21680 ( $\bullet$ ). Vasodilator response are shown as percent vasodilatation of the methoxamine sustained tone taken as 100% and are the mean of 4 to 7 preparations. Response are to bolus injections of drugs. Symbols show means  $\pm$  SEM (From Rubino *et al.*, 1995, *Br J Pharmacol* 115: 648–652; with permission from McMillan Press Limited).

d. Concentration-dependent relaxation of guinea pig pulmonary arteries by NECA ( $\blacktriangle$ ;  $n = 5$ ), CADO ( $\blacklozenge$ ;  $n = 5$ ), adenosine ( $\blacktriangledown$ ;  $n = 16$ ), CGS 21680 ( $\blacksquare$ ;  $n = 5$ ), R-PIA ( $\blacklozenge$ ;  $n = 5$ ) or CPA ( $\bullet$ ;  $n = 15$ ). Relaxant responses are expressed as a percentage of the noradrenaline-contraction (mean  $\pm$  SEM). (From Szentmiklósi *et al.*, 1995).

is inactive at  $A_1$ ,  $A_{2A}$ , and  $A_3$  receptors. It may, therefore, be a valuable starting compound from which to develop more potent selective  $A_{2B}$  receptor antagonists (Feoktistov and Biagioni, 1996). The non-xanthine alloxazine has been reported as having approximately 9-fold selectivity for the  $A_{2B}$  compared with the  $A_{2A}$  receptor (Brackett and Daly, 1994). XAC and CGS 15943 are antagonists with low nanomolar affinity at  $A_{2B}$  receptors, but are non-selective versus other subtypes of adenosine receptor (Alexander *et al.*, 1996; Klotz *et al.*, 1998).

### E. Distribution and Biological Effects

$A_{2B}$  receptors are found on practically every cell in most species; however, the number of receptors is small and relatively high concentrations of adenosine are generally needed to evoke a response. The sensitive technique of reverse transcription-polymerase chain reaction (RT-PCR) showed low levels of  $A_{2B}$  receptors in all rat brain regions tested (Dixon *et al.*, 1996). Northern blot analysis showed relatively high expression of  $A_{2B}$  receptors in the caecum, large intestine, and urinary

bladder, with lower levels in the brain, spinal cord, lung, vas deferens, and pituitary (Stehle *et al.*, 1992). RT-PCR revealed the highest expression of  $A_{2B}$  receptors in the proximal colon, with lower levels in the eye, lung, uterus, and bladder; still lower levels in the aorta, stomach, testis, and skeletal muscle; and the lowest levels in the jejunum, kidney, heart, skin, spleen, and liver (Dixon *et al.*, 1996).

Selected distributions and biological effects mediated by  $A_{2B}$  receptors in isolated cells and tissues are listed in tables 4 and 6. Functional studies have identified  $A_{2B}$  receptors in airway smooth muscle, fibroblasts, glial cells, the gastrointestinal tract, and the vasculature.  $A_{2B}$  receptors have been cloned from, and immunolocalized on, mouse bone marrow-derived mast cells (Marquardt *et al.*, 1994), and shown to mediate degranulation of canine BR mastocytoma cells (Auchampach *et al.*, 1997a). They have also immunolocalized and been shown to activate human mast cells (Feoktistov and Biagioni, 1996). This implies a possible role in allergic and inflammatory disorders. The antiasthmatic effects of enprofylline, a potential  $A_{2B}$  receptor antagonist, are consistent with this hypothesis (Feoktistov and Biagioni, 1996).

Vascular  $A_{2B}$  receptors identified by pharmacological and biochemical studies are listed in table 6, which shows that these receptors may couple to a functional response (vasodilatation) in both smooth muscle and endothelium. Interestingly,  $A_{2B}$  receptors seem to be important in mediating vasodilatation in some vessels, including the rat mesenteric arterial bed (Rubino *et al.*, 1995) and guinea-pig pulmonary arteries (Szentmiklósi *et al.*, 1995), but not in others where the  $A_{2A}$  subtype predominates (table 6, fig. 5). Rat aortic smooth muscle  $A_{2B}$  receptors have been implicated in inhibition of growth (Dubey *et al.*, 1996), identifying a possible long-term trophic role for these receptors.

## VI. $A_3$ Receptor

### A. Cloned $A_3$ Receptors

$A_3$ , the fourth distinct adenosine receptor, was identified relatively late in the history of adenosine/P1 receptors with the cloning, expression, and functional characterization of a novel adenosine receptor from rat striatum (Zhou *et al.*, 1992). This was identical with a clone previously isolated from a rat testis cDNA library encoding a G protein-coupled receptor with greater than 40% sequence homology with canine  $A_1$  and  $A_{2A}$  adenosine receptors, although its ligand had not then been identified (Meyerhof *et al.*, 1991). The recombinant striatal  $A_3$  receptor does not resemble any other adenosine/P1 subtypes in agonist or antagonist binding; it binds ligands with a potency order of R-PIA = NECA > S-PIA and is coupled to inhibition of adenylate cyclase activity in a pertussis toxin-sensitive manner; it binds with high affinity to the radioligand N<sup>6</sup>-2-(3-iodo-4-

aminophenyl)ethyladenosine but not to the  $A_{2A}$ -selective adenosine ligand [ $^3H$ ]CGS 21680 or the alkylxanthine antagonists XAC, IBMX, or the  $A_1$ -selective antagonist DPCPX.

Homologs of the rat striatal  $A_3$  receptor have been cloned from sheep pars tuberalis (pituitary tissue) (Linden *et al.*, 1993), human heart (Sajjadi and Firestein, 1993, and striatum (Salvatore *et al.*, 1993) (see also Linden, 1994) (table 3). Interspecies differences in  $A_3$  receptor structure are large; the rat  $A_3$  receptor shows only approximately 74% sequence homology with sheep and human  $A_3$  receptors each, although there is 85% homology of sheep and human  $A_3$  receptors. This is reflected in the very different pharmacological profiles of the species homologs, particularly with respect to antagonist binding, and this has caused considerable complications in the characterization of this receptor. The human  $A_3$  receptor has been localized to chromosome 1 p13.3 (Monitto *et al.*, 1995).

The rat, but not the human,  $A_3$  receptor transcript may be subject to extensive alternative splicing, further evidence of the profound interspecies differences involving the  $A_3$  receptor. A splice variant of the rat  $A_3$  receptor ( $A_{3i}$ ), having a 17 amino acid insertion within the second intracellular loop, has been cloned and characterized (Sajjadi *et al.*, 1996). There was no evidence for alternative splicing of the human  $A_3$  receptor transcript (Sajjadi *et al.*, 1996).

This  $A_3$  receptor has taken precedence over the controversial  $A_3$  receptor defined principally according to its pharmacological profile by Ribeiro and Sebastião (1986), which probably represents an  $A_1$  receptor (Carruthers and Fozard, 1993; Ribeiro and Sebastião, 1994).

### B. Signal Transduction Mechanisms

The  $A_3$  receptor is G protein-linked, coupling to  $G_{i\alpha_2}$ ,  $G_{i\alpha_3}$ - and, to a lesser extent, to  $G_{q/11}$  proteins (Palmer *et al.*, 1995b). In rat basophilic leukemia cells (RBL-2H3; a cultured mast cell line) (Ali *et al.*, 1990; Ramkumar *et al.*, 1993b) and in rat brain (Abbracchio *et al.*, 1995a), the  $A_3$  receptor stimulates PLC and elevates  $IP_3$  levels and intracellular  $Ca^{2+}$ . PKC has been suggested to be involved in  $A_3$  receptor-mediated preconditioning in rabbit cardiomyocytes (Armstrong and Ganote, 1994). The  $A_3$  receptor has also been shown to inhibit adenylate cyclase activity (Zhou *et al.*, 1992; Abbracchio *et al.*, 1995b).

### C. Desensitization

Recombinant rat and human  $A_3$  receptors have been shown to desensitize within minutes in response to agonist exposure; this is associated with uncoupling of the receptor-G protein complex, as indicated by a reduction in the number of high affinity binding sites (Palmer *et al.*, 1995a; Palmer *et al.*, 1997). Desensitization of the rat  $A_3$  receptor is rapid (within a few minutes), homologous, and is associated with rapid phosphorylation by a

G protein-coupled receptor kinase similar to, or identical with, GRK2 (Palmer *et al.*, 1995a; Palmer and Stiles, 1997b). Rapid, homologous functional desensitization of  $A_3$  receptors has also been described in RBL-2H3 cells (Ali *et al.*, 1990; Ramkumar *et al.*, 1993b). A chimeric  $A_1$ - $A_3$  receptor constructed from an  $A_1$  receptor (non-desensitizing under the conditions of the study) and the C-terminal domain of an  $A_3$  receptor was expressed in CHO cells and shown to undergo rapid desensitization. This indicates that the C-terminal domain of the  $A_3$  receptor is the site for phosphorylation by the G protein-coupled receptor kinases involved in desensitization (Palmer *et al.*, 1996).

The effects of long-term agonist exposure on interaction of the rat  $A_3$  receptor with G proteins was assessed using a transfected CHO cell system (Palmer *et al.*, 1995b). Chronic exposure of  $A_3$  receptors to the non-selective agonist NECA (for up to 24h) causes selective down-regulation of  $G_{i\alpha_3}$ - and  $\beta$ -subunits, without changing levels of  $G_{i\alpha_2}$  or  $G_q$ -like proteins (Palmer *et al.*, 1995b).

### D. Up-Regulation

In situ hybridization identified the  $A_3$  receptor in mesenchymal cells and eosinophils within the lamina propria of the airways and the adventitia of blood vessels in the lung, as well as in peripheral eosinophils, but interestingly, not in mast cells (Walker *et al.*, 1997). It was found that the  $A_3$  receptor transcript was greater in lung tissue from subjects with airway inflammation than in normal lung. This is consistent with the hypothesis that there is a distinct distribution of the  $A_3$  receptor in inflammatory cells and that this is up-regulated in airway inflammation (Walker *et al.*, 1997).

### E. Agonists

The main class of selective  $A_3$  receptor agonists is the  $N^6$ -substituted adenosine-5'-uronamides.  $N^6$ -benzylNECA is potent ( $K_i$  6.8 nM) and moderately selective (13- and 14-fold versus  $A_1$  and  $A_{2A}$ ) at rat  $A_3$  receptors transfected into CHO cells (van Galen *et al.*, 1994).  $N^6$ -(3-iodobenzyl)-5'-(N-methylcarbamoyl)adenosine (IB-MECA) ( $K_i$  1.1 nM) is 50-fold selective for rat brain  $A_3$  receptors versus  $A_{2A}$  or  $A_1$  receptors (Gallo-Rodriguez *et al.*, 1994) (fig. 2). The iodinated radioligand [ $^{125}I$ ]AB-MECA binds with approximately nanomolar affinity to rat brain  $A_3$  adenosine receptors expressed in CHO cells, but also binds to native  $A_1$  receptors. Selectivity is increased by 2-substitution of  $N^6$ -benzyladenosine-5'-uronamides; 2-chloro-IB-MECA (2Cl-IB-MECA,  $K_i = 0.33$  nM) is highly selective for  $A_3$  versus  $A_1$  and  $A_{2A}$  receptors, by 2500- and 1400-fold, respectively (Kim *et al.*, 1994) (fig. 2). There is pronounced interspecies differences in the relative affinities of agonist binding at  $A_3$  receptors (Ji *et al.*, 1994; Linden, 1994).

### F. Antagonists

Several classes of compounds have been developed as  $A_3$  antagonists. One class comprises xanthines and their derivatives. Rat, rabbit, and gerbil brain  $A_3$  receptors bind only weakly to xanthine derivatives compared with human and sheep  $A_3$  receptors, which exhibit high affinity (Zhou *et al.*, 1992; Linden *et al.*, 1993; Salvatore *et al.*, 1993; Ji *et al.*, 1994). The most potent of the 8-phenyl-substituted xanthines, I-ABOPX (3-(3-iodo-4-aminobenzyl)-8-(4-oxyacetate)phenyl-1-propylxanthine, or BW-A522) binds with nanomolar affinity to human and sheep  $A_3$  receptors (Linden *et al.*, 1993; Salvatore *et al.*, 1993), but by contrast with micromolar affinity at rabbit, gerbil, and rat  $A_3$  receptors (Ji *et al.*, 1994).

Five chemical classes of non-xanthine antagonists have been reported. L-268605 (3-(4-methoxyphenyl)-5-amino-7-oxo-thiazolo [3, 2]pyrimidine) is a potent and selective  $A_3$  antagonist with a  $K_i$  value of 18 nM and no appreciable affinity for human  $A_1$  and  $A_{2A}$  receptors (Jacobson *et al.*, 1996) (fig. 3). Another class is represented by L-249313 (6-carboxymethyl-5,9-dihydro-9-methyl-2-phenyl-[1, 2, 4]-triazolo[5,1-a][2, 7]naphthyridine) with high affinity at cloned human  $A_3$  receptors,  $K_i$  value of 13 nM, but low affinity at native rat brain  $A_3$  receptors,  $K_i$  58  $\mu$ M, and selectivity of approximately 300- and 1460-fold over  $A_1$  and  $A_{2A}$  receptors, respectively (Jacobson *et al.*, 1996) (fig. 3).

The three other categories of molecules with promise as  $A_3$  receptor antagonists are the flavonoid MRS 1067 (3,6-dichloro-2'-isopropoxy-4'-methyl-flavone), the 6-phenyl-1,4-dihydropyridines MRS 1097 (3,5-diethyl[2-methyl-6-phenyl-4-(2-phenyl-(*E*)-vinyl]-1,4-( $\pm$ )-dihydropyridine-3,5-dicarboxylate) and MRS 1191 (3-ethyl 5-benzyl 2-methyl-6-phenyl-4-phenylethynyl-1,4-( $\pm$ )-dihydropyridine-3,5-dicarboxylate) and the triazoloquinazoline MRS 1220 (9-chloro-2-(2-furyl)-5-phenylacetyl amino[1, 2, 4]triazolo[1,5-c]quinazoline). Of these, MRS 1220 and MRS 1197 show promise as potent and selective competitive antagonists, with  $K_i$  values of 0.6 and 31 nM, respectively, for inhibition of [ $^{125}$ I]AB-MECA binding and  $K_B$  values of 1.7 and 92 nM at human recombinant  $A_3$  receptors (Jacobson *et al.*, 1997). A much lower affinity was observed at the rat  $A_3$  receptor: >2000-fold for MRS1220 and 112-fold for MRS 1197 (Jacobson *et al.*, 1997) as has been noted with xanthine-based antagonists.

### G. Distribution and Biological Effects

The  $A_3$  receptor is widely distributed, but its physiological role is still largely unknown.  $A_3$  mRNA is expressed in testis, lung, kidneys, placenta, heart, brain, spleen, liver, uterus, bladder, jejunum, proximal colon, and eye of rat, sheep, and humans (Zhou *et al.*, 1992; Linden *et al.*, 1993; Salvatore *et al.*, 1993; Linden, 1994; Rivkees, 1994; Dixon *et al.*, 1996) (fig. 4).  $A_3$  mRNA was not detected in rat skin or skeletal muscle (Dixon *et al.*, 1996) (fig. 4). Rat testis seems to have particularly high

concentrations of  $A_3$  mRNA (in spermatocytes and spermatids), compared with rather lower levels in most other rat tissues (Linden *et al.*, 1993; Salvatore *et al.*, 1993). The highest levels of human  $A_3$  mRNA are found in lung and liver, with lower levels in aorta and brain (Salvatore *et al.*, 1993). In sheep, the highest levels of  $A_3$  mRNA are found in lung, spleen, pars tuberalis, and pineal gland (Linden *et al.*, 1993). PCR was used to establish the presence of  $A_3$  receptors in rabbit cardiac myocytes (Wang *et al.*, 1997).

The  $A_3$  receptor on mast cells facilitates the release of allergic mediators including histamine, suggesting a role in inflammation (Ramkumar *et al.*, 1993b). Systemic administration of 3-IB-MECA causes scratching in mice that is prevented by coadministration of a histamine antagonist (Jacobson *et al.*, 1993b). APNEA has been shown to be a bronchoconstrictor in rats in vivo, an effect that may be mediated by mast cells (Pauwels and Joos, 1995), but it does not elicit bronchoconstriction in rabbits (el-Hashim *et al.*, 1996). Constriction mediated by adenosine in isolated arterioles of golden hamster cheek pouches is blocked by an inhibitor of mast cell degranulation, which suggests a role for  $A_3$  receptors on mast cells in this response (Doyle *et al.*, 1994).

The  $A_3$  receptor has been implicated in the 8-SPT-resistant hypotensive response to APNEA in the pithed rat (Fozard and Carruthers, 1993). The response is pertussis toxin-sensitive and is blocked by the  $A_3$  receptor antagonist BW-A522 (Fozard and Hannon, 1994). However, it seems that the hypotensive response may be caused by the secondary action of histamine released after activation of mast cell  $A_3$  receptors (Hannon *et al.*, 1995).

Systemic administration of 3-IB-MECA depresses locomotor activity in mice, which may suggest a role for brain  $A_3$  adenosine receptors in modulation of behavior (Jacobson *et al.*, 1993b). Interestingly, activation of rat hippocampal  $A_3$  receptors has been shown to desensitize  $A_1$  receptor-mediated inhibition of excitatory neurotransmission in this brain region, indicating cross-talk between these two receptors (Dunwiddie *et al.*, 1997).

$A_3$  receptors on human eosinophils (Kohno *et al.*, 1996a) and human promyelocytic HL-60 cells (Kohno *et al.*, 1996b; Yao *et al.*, 1997) seem to be involved in apoptosis, an active self-destructive process caused by a genetically programmed cascade of molecular events involving DNA degradation and death of the cell by nuclear and cytoplasmic breakup. This seems to require high concentrations of agonist or chronic activation of the  $A_3$  receptor in a manner that mimicks the requirement of high levels of ATP to activate the non-specific pore-formation of the P2X<sub>7</sub> receptor and apoptosis, and suggests that this potentially autocatalytic process may occur during pathological conditions resulting in cell damage and release of high levels of purines. Apoptotic effects are caused by high concentrations (micromolar) of  $A_3$  receptor agonist in HL-60 leukemia and U-937



lymphoma cells, but paradoxically,  $A_3$  receptor antagonists also induce apoptotic cell death, and this is opposed by low (nanomolar) concentrations of Cl-IB-MECA (Yao *et al.*, 1997). This indicates that low-level activation of  $A_3$  receptors may result in cell protection, and furthermore that this may occur as a consequence of endogenously released adenosine (Yao *et al.*, 1997). Acute stimulation of  $A_3$  receptors with micromolar concentrations of Cl-IB-MECA has also been shown to cause lysis of granular hippocampal neurons in culture (Von Lubitz *et al.*, 1996).

$A_3$  receptors may be involved in the cardioprotective effect of adenosine in ischemia and preconditioning during ischemia reperfusion injury (Liu *et al.*, 1994; Armstrong and Ganote, 1994, 1995; Auchampach *et al.*, 1997b; Stambaugh *et al.*, 1997). Preconditioning is blocked by  $A_3$  receptor antagonists, whereas APNEA ( $A_1/A_3$  selective), but not R-PIA ( $A_1$  selective), protect against ischemia in rabbit cardiomyocytes (Armstrong and Ganote, 1995).  $A_3$  receptors have been shown to mediate preconditioning and to reduce myocardial injury (Strickler *et al.*, 1996; Tracey *et al.*, 1997). In isolated cardiac myocytes, maximal preconditioning-induced cardioprotection was shown to require activation of both  $A_1$  and  $A_3$  receptors (Wang *et al.*, 1997). Acute IB-MECA has a detrimental effect on ischemic brain injury, whereas chronic IB-MECA has a protective effect (Von Lubitz *et al.*, 1994). This dual effect mimicks the effects of Cl-IB-MECA on leukemia and lymphoma cell lines (Yao *et al.*, 1997). Activation of an  $A_3$  receptor in basophilic leukemia cells (RBL-2H3), endothelial cells, cardiac myocytes, and smooth muscle cells activates the cellular antioxidant defense system by increasing the activity of superoxide dismutase, catalase, and glutathione reductase, thereby providing a means by which adenosine may have a cytoprotective action in ischemia (Maggirwar *et al.*, 1994).

## VII. Integrated Effects of Adenosine/P1 Receptors

$A_1$ ,  $A_{2A}$ ,  $A_{2B}$ , and  $A_3$  adenosine receptors have distinct but frequently overlapping tissue distributions. The fact that more than one adenosine/P1 receptor subtype may be expressed by the same cell raises questions about the functional significance of this colocalization. Because the different adenosine/P1 receptor subtypes have quite different affinities for the endogenous agonist, the local concentration of adenosine in physiological and pathophysiological conditions is likely to be extremely important.  $EC_{50}$  values for adenosine at rat  $A_1$ ,  $A_{2A}$ ,  $A_{2B}$ , and  $A_3$  receptors of 73 (Daly and Padgett, 1992), 150 (Daly and Padgett, 1992), 5100 (Peakman and Hill, 1994), and 6500 (Zhou *et al.*, 1992), respectively, have been reported. At rat phrenic motor nerve terminals (Correia-de-Sá *et al.*, 1996) and prejunctional receptors in rat vas deferens (Gonçalves and Queiroz, 1993), the concentration of adenosine needed to increase transmitter release

via activation of  $A_{2A}$  receptors seems to be higher than that required to inhibit transmitter release via  $A_1$  receptors. Because adenosine is formed as a breakdown product of ATP released from nerves, this implies that the adenosine concentration is crucially linked to the ongoing neuronal activity, which therefore may be an important determinant of the subtype of autoregulatory adenosine receptor that is activated. In rat hemidiaphragm, the frequency and intensity of stimulation of motor nerves and subsequent formation of endogenous adenosine was shown to be critical, with high-intensity, high-frequency nerve stimulation favoring  $A_{2A}$  receptor-mediated facilitation of [ $^3$ H]acetylcholine (ACh) release (Correia-de-Sá *et al.*, 1996). Thus, adenosine concentration and receptor affinity may determine the pattern of differential activation of coexpressed  $A_1$  and  $A_{2A}$  receptors (and other adenosine receptors).

Expression of more than one type of adenosine/P1 receptor on the same cell may allow the common agonist adenosine to activate multiple signaling pathways. Adenylate cyclase is a common effector, which is negatively coupled to  $A_1$  and  $A_3$  receptors and positively coupled to  $A_2$  receptors, affording the opportunity for reciprocal control and, therefore, fine tuning of this signaling pathway. Coexisting  $A_1$  and  $A_2$  adenosine receptors with opposite actions on adenylate cyclase activity have been described in a number of cells, including the smooth muscle cell line DDT<sub>1</sub> MF-2 (Ramkumar *et al.*, 1991), cultured porcine coronary artery smooth muscle cells (Mills and Gewirtz, 1990), and glomeruli and mesangial cells (Olivera and Lopez-Novoa, 1992).  $A_1$  and  $A_{2B}$  receptors on primary rat astrocytes each regulate adenylate cyclase activity, but independently (Peakman and Hill, 1994).

The extracellular adenosine concentration may be a crucial determinant of the differential activation of coexisting adenosine/P1 receptors under pathophysiological as well as physiological conditions. Induction and inhibition of the inflammatory response by neutrophil  $A_1$  and  $A_2$  receptors, respectively, has been reported (Cronstein, 1994; Bullough *et al.*, 1995). Low concentrations of adenosine caused activation of the  $A_1$  receptor and induced superoxide anion generation, phagocytosis via Fc receptors, and adhesion to endothelial cells, whereas higher concentrations of adenosine (>500 nM) required to saturate  $A_2$  receptors lead to inhibition of these effects.  $A_{2A}$  and  $A_{2B}$  receptors coexist on fetal chick heart cells; the high affinity  $A_{2A}$  receptor has been suggested to be an important modulator of myocyte contractility under physiological conditions, whereas under pathophysiological conditions, such as cardiac ischemia resulting in release of large amounts of adenosine, the low affinity  $A_{2B}$  receptor may assume functional significance (Liang and Haltiwanger, 1995). Such studies are helping to expand on the established link between adenosine release and the metabolic demands of tissues by

building in specific actions on identified cell-surface adenosine/P1 receptors.

Stimulation of the  $A_{2A}$  receptor on rat striatal synaptosomes causes desensitization of coexpressed  $A_1$  receptors, favoring  $A_{2A}$  receptor-mediated signaling (Dixon *et al.*, 1997a). This has important implications for other coexpressed adenosine receptors, and it would be interesting to see if this is a general phenomenon for these subtypes.

There is an interesting sidedness to the opposite responses evoked by  $A_1$ -like and  $A_{2A}$ -like adenosine receptors colocalized on monolayers of renal epithelial cells (Casavola *et al.*, 1997). The  $A_1$ -like receptors are located on the apical surface and mediate inhibition of transepithelial  $Na^+$  transport by (a) inhibition of the basolaterally located  $Na^+/H^+$  exchanger and (b) an increase in intracellular  $H^+$ , probably via  $Ca^{2+}/PKC$ . The  $A_{2A}$ -like receptors are located on the basolateral side and stimulate transepithelial  $Na^+$  transport, suggested to be via stimulation of  $Na^+/H^+$  exchange and thereby cellular alkalization, probably via an increase in cAMP/PKA (Casavola *et al.*, 1997). The same adenosine receptor can elicit a different functional response in different tissues. In rat duodenum,  $A_{2B}$  (and  $A_1$ ) adenosine receptors on the longitudinal muscle mediate relaxation, whereas  $A_{2B}$  receptors on the muscularis mucosae mediate contraction (Nicholls *et al.*, 1996).

Integrated effects of adenosine/P1 receptors in whole tissue responses are considered, together with P2 receptors, in Section XXII.

## VIII. P2 Receptors

### A. Introduction

P2 receptors are divided into two main classes based on whether they are ligand-gated ion channels (P2X receptors) or are coupled to G proteins (P2Y receptors) (Abbraccio and Burnstock, 1994; Fredholm *et al.*, 1994) (table 7).

The P2X/P2Y nomenclature was adopted from that originally used in a subdivision of P2 receptors proposed in 1985 by Burnstock and Kennedy, who described "P<sub>2X</sub>" and "P<sub>2Y</sub>-purinoceptors" with distinct pharmacological profiles and tissue distributions: the "P<sub>2X</sub>-purinoceptor" was shown to be most potently activated by the stable analogs of ATP,  $\alpha,\beta$ -methylene ATP ( $\alpha,\beta$ -meATP), and  $\beta,\gamma$ -meATP. At the "P<sub>2Y</sub>-purinoceptor" 2-methylthio ATP (2MeSATP) was the most potent agonist and  $\alpha,\beta$ -meATP and  $\beta,\gamma$ -meATP were weak or inactive. Furthermore, the "P<sub>2X</sub>-purinoceptor" was shown to be selectively desensitized by  $\alpha,\beta$ -meATP and to be antagonized by 3'-O-(3-[N-(4-azido-2-nitrophenyl)amino]-propionyl)ATP (ANAPP<sub>3</sub>) (Burnstock and Kennedy, 1985). Distinct tissue distributions and functions reinforced this subdivision: "P<sub>2X</sub>-purinoceptors" were shown to be present in vas deferens, urinary bladder, and vascular smooth muscle, and to mediate contraction; "P<sub>2Y</sub>-purinoceptors" were

shown to be present in guinea-pig taenia coli and on vascular endothelial cells, as well as to mediate relaxation. P2 receptors have since been cloned from smooth muscle and endothelium; the pharmacological profiles originally attributed to "P<sub>2X</sub>" and "P<sub>2Y</sub>-purinoceptors" seem to correspond most closely to activation of P2X<sub>1</sub>-like and P2Y<sub>1</sub>-like receptors, respectively. However, it is now apparent that there is heterogeneity of P2X responses among different smooth muscles, and of P2Y responses between taenia coli and endothelium, which may be caused by different receptor subtypes or small differences in structure of the same receptor.

Other P2 receptors that have been identified in biological tissue principally according to their different pharmacological profiles are the P<sub>2U</sub> receptor (activated equally by ATP and UTP; widely distributed), the P<sub>2T</sub> receptor (platelet ADP receptor; mediates aggregation), and the P<sub>2Z</sub> receptor (found on mast cells and lymphocytes; mediates cytotoxicity and degranulation) (Gordon, 1986; O'Connor *et al.*, 1991). P<sub>2S</sub> (Wiklund and Gustafsson, 1988), P<sub>2R</sub> (Von K ugelgen and Starke, 1990), P<sub>2D</sub> (Pintor *et al.*, 1993), uridine nucleotide-specific receptors ("pyrimidinoceptors") (Seifert and Schultz, 1989; Von K ugelgen and Starke, 1990), P3 (Shinozuka *et al.*, 1988; Forsythe *et al.*, 1991), and P4 (Pintor and Miras-Portugal, 1995a) receptors have also been proposed. Of these the P<sub>2U</sub>, P<sub>2Z</sub>, and uridine nucleotide-specific receptors have been cloned. Because receptor subclassification based on pharmacological criteria alone is no longer tenable, the separate identity of the other proposed subtypes remains to be proved.

The revision of P2 receptor nomenclature was prompted by evidence that extracellular ATP works through two different transduction mechanisms, namely intrinsic ion channels and G protein-coupled receptors (Benhan and Tsien, 1987; Dubyak, 1991), and by the cloning of the first two P2 receptors, P2Y<sub>1</sub> (a "P<sub>2Y</sub>-purinoceptor") (Webb *et al.*, 1993b) and P2Y<sub>2</sub> (a "P<sub>2U</sub>-purinoceptor") (Lustig *et al.*, 1993). It was also becoming increasingly apparent that there was significant heterogeneity among native P2 receptors, reflected in an increasing diversity of pharmacological response profiles that could not easily be accommodated within the existing system of receptor subclassification. Thus, in 1994 it was formally suggested that P2 receptors should be divided into two broad groups termed P2X and P2Y according to whether they are ligand-gated ion channels or are coupled to G proteins, respectively, with subtypes defined by the different structure of mammalian P2 receptors (Abbraccio and Burnstock, 1994; Barnard *et al.*, 1994; Fredholm *et al.*, 1994).

To date seven mammalian P2X receptors, P2X<sub>1-7</sub>, and five P2Y receptors, P2Y<sub>1</sub>, P2Y<sub>2</sub>, P2Y<sub>4</sub>, P2Y<sub>6</sub>, and P2Y<sub>11</sub> have been cloned, characterized pharmacologically and accepted as valid members of the P2 receptor family. The use of lower case to define the cloned p2y3 receptor reflects the possibility that this may be the avian ho-

TABLE 7  
*P2 receptor signal transduction mechanisms, agonists, and antagonists*

Family		P2X	P2Y
Receptor type		Ion channel Nonselective pore <sup>a</sup>	G protein-coupled: G <sub>q/11</sub> , G <sub>i</sub> <sup>b</sup>
Signaling pathway		N.A.	PLC, AC, <sup>c</sup> K <sup>+</sup> channels <sup>d</sup> PLC <sub>PC</sub> , <sup>e</sup> PLA <sub>2</sub> , <sup>f</sup> PLD <sup>f</sup> PKC MAPK <sup>g</sup>
Effectors		Ca <sup>2+</sup> ≫ Na <sup>+</sup> > K <sup>+</sup>	↑ IP <sub>3</sub> , ↑ Ca <sup>2+</sup> , ↑ DAG ↓ cAMP <sup>c</sup> Ca <sup>2+</sup> , Cl <sup>-</sup> , K <sup>+</sup> currents <sup>h</sup>
Agonists	<i>Nonselective</i>	ATP ATP-γS 2MeSATP	ATP <sup>i</sup> ATP-γS <sup>j</sup> 2MeSATP <sup>k</sup>
	<i>P2X/P2Y-selective</i>	Ap <sub>4</sub> A α,β-meATP <sup>l</sup> β,γ-meATP <sup>l</sup> BzATP <sup>a</sup>	Ap <sub>4</sub> A <sup>i</sup> ADP <sup>c</sup> UTP <sup>m</sup> UTP-γS <sup>j</sup> UDP <sup>n</sup> 2Cl-ADP <sup>c</sup> 2MeSADP <sup>c</sup> ADPβS, <sup>c</sup> ADPβF <sup>c</sup>
Antagonists	<i>Nonselective</i>	Suramin PPADS Reactive blue 2	Suramin PPADS Reactive blue 2
	<i>P2X/P2Y-selective</i>	NF023 NF279 KN-62 <sup>a</sup>	ARL 67085 <sup>o</sup> FPL 66096 <sup>o</sup> A3P5PS <sup>k</sup> MRS 2179 <sup>h</sup> 2-hexylthio-ATP <sup>p</sup> 2-cyclohexylthio-ATP <sup>p</sup>

N.A., not applicable.

<sup>a</sup> P2X<sub>7</sub> and endogenous P2X<sub>7</sub>-like receptor.

<sup>b</sup> P2Y<sub>1</sub> and endogenous P2Y<sub>1</sub>-like receptors acting through PLC couple to G<sub>q/11</sub> proteins; P2Y<sub>1</sub> and endogenous P2Y<sub>1</sub>-like receptors acting through adenylate cyclase couple to G<sub>i</sub> proteins; P2Y<sub>2</sub> and endogenous P2Y<sub>2</sub>-like receptors, P2Y<sub>4</sub> and P2Y<sub>ADP</sub> receptors couple to G<sub>q/11</sub> and G<sub>i</sub> proteins; p2y3 and P2Y<sub>6</sub> receptors couple to G<sub>q/11</sub> proteins.

<sup>c</sup> P2Y<sub>1</sub> and endogenous P2Y<sub>1</sub>-like receptors and P2Y<sub>ADP</sub> receptors.

<sup>d</sup> Some endogenous P2Y<sub>1</sub>-like receptors activate K<sup>+</sup> channels via interactions with their G protein subunits.

<sup>e</sup> P2Y<sub>1</sub> and endogenous P2Y<sub>1</sub>-like receptor signaling; possibly downstream of PKC.

<sup>f</sup> P2Y<sub>1</sub> and P2Y<sub>2</sub> receptors and their endogenous counterparts; signaling possibly downstream of PKC.

<sup>g</sup> P2Y<sub>1</sub> and P2Y<sub>2</sub> receptors and their endogenous counterparts; signaling downstream of PKC.

<sup>h</sup> Secondary to activation of PLC, although activation of K<sup>+</sup> currents by some endogenous P2Y<sub>1</sub>-like receptors is via direct interactions with G protein subunits.

<sup>i</sup> P2Y<sub>1</sub> and P2Y<sub>2</sub> receptors and their endogenous counterparts; ATP is an antagonist at P2Y<sub>ADP</sub> receptors.

<sup>j</sup> P2Y<sub>2</sub> and endogenous P2Y<sub>2</sub>-like receptors.

<sup>k</sup> P2Y<sub>1</sub> and endogenous P2Y<sub>1</sub>-like receptors.

<sup>l</sup> P2X<sub>1</sub>, P2X<sub>3</sub> and heteromeric P2X<sub>2</sub>P2X<sub>3</sub> receptors.

<sup>m</sup> P2Y<sub>2</sub> and endogenous P2Y<sub>2</sub>-like receptors and P2Y<sub>4</sub> receptors.

<sup>n</sup> P2Y<sub>6</sub> receptor.

<sup>o</sup> P2Y<sub>ADP</sub>.

<sup>p</sup> P2Y<sub>1</sub> and endogenous P2Y<sub>1</sub>-like receptors coupled to AC.

**Abbreviations:** AC, adenylate cyclase; ADPβF, adenosine 5'-O-(2-fluoro)-diphosphate; ADPβS, adenosine 5'-O-(2-thio)-diphosphate; cAMP, adenosine 3',5'-cyclic monophosphate; A3P5PS, adenosine 3'-phosphate 5'-phosphosulfate; ARL 67085, 6-N,N-diethyl-D-β,γ-dibromomethylene ATP; ATP-γS, adenosine 5'-O-(3-thiotriphosphate); BzATP, 3'-O-(4-benzoyl)benzoyl ATP; DAG, diacylglycerol; FPL 66096, 2-propylthio-D-β,γ-difluoromethylene ATP; IP<sub>3</sub>, inositol 1,4,5-trisphosphate; KN-62, 1-[N-bis(5-isoquinolinesulfonyl)-N-methyl-L-tyrosyl]-4-phenylpiperazine; MAPK, mitogen-activated protein kinase; α,β-meATP, α,β-methylene ATP; β,γ-meATP, β,γ-methylene ATP; 2MeSADP, 2-methylthio ADP; 2MeSATP, 2-methylthio ATP; MRS 2179, N<sup>6</sup>-methyl modification of 2'-deoxyadenosine 3',5'-bisphosphate; NF023, symmetrical 3'-urea of 8-(benzamido)naphthalene-1,3,5-trisulfonic acid; NF279, 8,8'-(carbonylbis(imino-4,1-phenylenecarbonylimino-4,1-phenylenecarbonylimino))bis(1,3,5-naphthalenetrisulfonic acid); PLC<sub>PC</sub>, phosphatidylcholine-specific phospholipase C; PKC, protein kinase C; PLA<sub>2</sub>, phospholipase A<sub>2</sub>; PLC, phospholipase C; PLD, phospholipase D; PPADS, pyridoxal phosphate-6-azophenyl-2',4'-disulfonic acid; suramin, 8-(3-benzamido-4-methylbenzamido)-naphthalene-1,3,5-trisulfonic acid; UTP-γS, uridine 5'-O-(3-thiotriphosphate).

molog of the human P2Y<sub>6</sub> receptor, although this has not yet been confirmed. The jump in sequence in the numbering of the P2Y receptor family is caused by the recognition that certain receptors had been erroneously identified as belonging to this family, leading to the subsequent withdrawal of P2Y<sub>5</sub> (Webb *et al.*, 1996b) and P2Y<sub>7</sub> (Akbar *et al.*, 1996). The cloned receptors P2Y<sub>9</sub> and P2Y<sub>10</sub> are also not nucleotide receptors. A P2Y receptor cloned from *Xenopus* neural plate (provisionally called P2Y<sub>8</sub>) is not included in the definitive P2Y receptor family recognized by the IUPHAR committee, based largely on the rationale that this is a non-mammalian receptor. The platelet ADP receptor P2Y<sub>ADP</sub> (or P<sub>2T</sub> receptor) has not yet been cloned and, therefore, as recom-

mended by the IUPHAR committee, the name of this receptor is given in italics.

P2Y<sub>4</sub> (human but not rat receptor) and P2Y<sub>6</sub> are uridine nucleotide-specific receptors (receptors not activated or only weakly activated by purines) that have been cloned and shown to be sensitive preferentially to UTP and UDP, respectively (the rat P2Y<sub>4</sub> receptor is also activated potently by ATP; see Section XV). Their identification complements earlier suggestions of the existence of endogenous uridine nucleotide-specific receptors based on distinct pharmacology of some biological tissue. Before the cloning of these receptors, the possibility that there were subtypes of endogenous uridine nucleotide-specific receptors was not considered,



and by implication the possibility of different UTP/UDP selectivities for members of this family was not appreciated. Thus, in much of the literature to date, the agonist potency profiles documented for endogenous uridine nucleotide-specific receptors are incomplete, leaving open the possibility that these are P2Y<sub>4</sub> or P2Y<sub>6</sub> receptors, or some other subtype not yet cloned. The lack of selective agonists and antagonists, and complications introduced by receptor coexpression and agonist interconversion, means that the subtype identity of most endogenous uridine nucleotide-specific receptors is currently unclear. Because of this, a separate section in this review is devoted to endogenous uridine nucleotide-specific receptors (see Section XVIII.). Interestingly, the P2Y<sub>11</sub> receptor is so far the only P2Y receptor selective for ATP versus other purine and pyrimidine nucleotides.

For researchers in this field, important discoveries made in the last 10 years have been the source of insight, and in some cases frustration, because these demand a reevaluation of conclusions drawn from earlier studies on P2 receptors. These include the discovery that: (a) multiple P2X receptor proteins are often coexpressed in different proportions in different tissues; (b) P2X receptors are multisubunit receptors that may exist as heteromers with different pharmacology compared with the homomers; (c) cations can profoundly affect P2X channel activity; (d) 2MeSATP, previously widely regarded as a selective "P<sub>2Y</sub>-purinoceptor" agonist, is also a potent agonist at P2X receptors; (e) ecto-nucleotidases can profoundly alter agonist potencies; and (f) antagonists previously used with some confidence as P2 receptor blockers are non-selective, can modulate ecto-nucleotidase activity and may have allosteric effects on P2 receptors. The general lack of selective agonists and antagonists, together with complications introduced by coexistence of different P2 receptors and impure solutions caused by purine and pyrimidine degradation and interconversion, also has significantly hindered advances in P2 receptor characterization.

Although much valuable information can be derived from studies of populations of cells in culture, there are potential pitfalls associated with this technique. Thus, emerging evidence that the expression of P2 receptors may alter in culture conditions adds another potential complication to the study of purine receptors. For example, astrocytes studied *in situ*, or after acute isolation from rat brain, are insensitive or only a few cells respond to ATP, whereas in primary cultures, there is a profound increase in the number of cells responding to ATP (Jabs *et al.*, 1997; Kimelberg *et al.*, 1997). Similarly, up-regulation of the P2Y<sub>2</sub> receptor in rat salivary gland cells in culture compared with acutely isolated cells has been reported (Turner *et al.*, 1997). Thus, caution is needed in the interpretation of studies of P2 receptors on cells in culture.

Autocatalytic release of ATP has been shown from endothelial cells (Yang *et al.*, 1994) and it is possible that

this phenomenon will be described for other cell types as well as for other purines and pyrimidines. In addition, ATP is released from many different cells in response to stimuli such as shear stress and hypoxia, which may be relevant for the ongoing level of activation of purine receptors expressed by the same or neighboring cells. This may be particularly important with respect to the activity of P2X<sub>1</sub> and P2X<sub>3</sub> receptors, as these receptors desensitize rapidly.

Because of the diverse reasons discussed above, it is currently a considerable challenge to dissect out and characterize endogenous receptors for purines and pyrimidines in different biological systems, and even more of a challenge to identify for each of these a physiological or pathophysiological role. However, endogenous receptor counterparts have been shown for some cloned P2 receptors, matching both in terms of receptor distribution, signaling mechanisms, and pharmacology. In this review, we use the name of the clone in preference to the classical nomenclature where possible to promote the conversion from the older system to the newer terminology. However, because for the majority of cases this characterization is currently equivocal, we qualify this with the term "-like". Thus, "P2X<sub>1</sub>-like receptor" replaces the classical "P<sub>2X</sub>-purinoceptor" of smooth muscle, "P2X<sub>7</sub>-like receptor" is used for the "P<sub>2Z</sub>-purinoceptor", "P2Y<sub>1</sub>-like receptor" is used in preference to the classical "P<sub>2Y</sub>-purinoceptor," and "P2Y<sub>2</sub>-like receptor" replaces "P<sub>2U</sub>-purinoceptor". Unequivocal characterization of endogenous P2 receptors awaits the development and use of subtype-selective agonists and antagonists.

### B. Agonists

P2 receptors have broad natural ligand specificity, recognizing ATP, ADP, UTP, UDP, and the diadenosine polyphosphates (table 7). The chemical structures of some principal P2 receptor agonists are illustrated in figure 6. At present there are no agonists or antagonists that discriminate adequately between families of P2X and P2Y receptors, or between subtypes of receptors within each of these groups (table 7). Some of the most useful agonists are the stable ATP analogs  $\alpha,\beta$ -meATP and  $\beta,\gamma$ -meATP, which if effective, strongly imply actions at P2X receptors (specifically at P2X<sub>1</sub> and P2X<sub>3</sub> subtypes) and are generally inactive at P2Y receptors. Also useful are ADP, adenosine 5'-O-(2-thiodiphosphate)(ADP $\beta$ S,) and UTP, as these are agonists at some P2Y receptors, but are weak or inactive at P2X receptors.

Agonist potency orders, important in the characterization of cloned and native P2 receptors, are profoundly influenced by the different stabilities of P2 receptor ligands in the presence of ecto-nucleotidases.  $\alpha,\beta$ -MeATP is considerably more stable than ATP and 2MeSATP when ecto-nucleotidase activity is not suppressed, which contributes significantly to its greater potency (up to 100-fold more potent) at native P2X<sub>1</sub> receptors in vascular smooth muscle, bladder, and vas deferens. However,

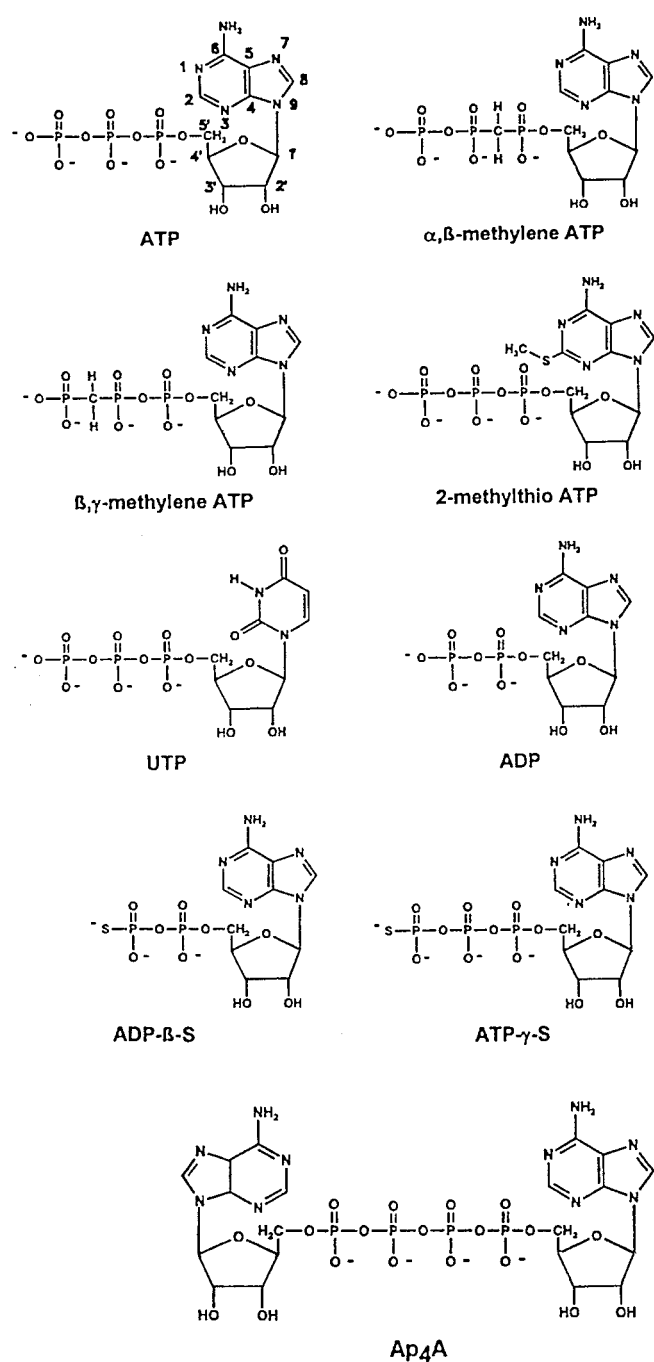


FIG. 6. The chemical structure of some key agonists at P2 receptors. (Adapted from Windscheif, 1996).

when ecto-ATPase effects are controlled by use of single cells and rapid concentration-clamp applications of agonist, or by inhibition of ecto-ATPase activity [for instance using 6-N,N-diethyl-D- $\beta,\gamma$ -dibromomethylene ATP (ARL 67156) or removal of divalent cations],  $\alpha,\beta$ -meATP is less potent than 2MeSATP and ATP at native and cloned P2X<sub>1</sub> receptors (Crack *et al.*, 1994; Evans and Kennedy, 1994; Humphrey *et al.*, 1995; Khakh *et al.*, 1995b). Thus, greater caution is now advised in the interpretation of the order of agonist potency where ecto-nucleotidase activity has not been suppressed. This

is a particularly important consideration in the pharmacology of P2X receptors because of the wide range of stabilities of commonly-used P2X agonists, but seems to have had less of an impact on P2Y receptor profiles, probably because many of the commonly used P2Y agonists are similarly unstable. An additional consideration is that many P2 receptor antagonists inhibit ecto-nucleotidase activity, which may reduce their effectiveness against biologically unstable P2 agonists.

### C. Antagonists

Antagonists selective for subtypes of P2X and P2Y receptors are considered in later sections on individual receptors (see Sections X.F., XII.E., XIV.D.). This section considers other established and putative P2 receptor antagonists, which, unfortunately, do not discriminate well, if at all, between P2X or P2Y receptors, let alone for subtypes within these families (table 7). Many of these also inhibit ecto-nucleotidases and may have allosteric effects on the receptor (Michel *et al.*, 1997). Table 8 summarizes the potencies of some of the most commonly used antagonists at recombinant and endogenous P2 receptors. The general lack of selective antagonists highlights the problems currently encountered in subtype-identification of P2 receptors using ligand binding. The chemical structures of some P2 receptor antagonists are illustrated in figure 7.

In principle, any P2 receptor antagonist should be tested for its selectivity against all known subtypes of this family. Evaluation of antagonist selectivity at heteromeric P2X receptors is also important because of its relevance for biological tissue where P2X receptor proteins are typically coexpressed; such studies might additionally provide useful information about the specific contribution of the different subunits to the pharmacology of the receptor heteromer. A commonly used biological assay is antagonism of constriction by  $\alpha,\beta$ -meATP of vas deferens and vascular smooth muscle. This is generally taken as an indication of actions at endogenous P2X<sub>1</sub>-like receptors for a number of reasons: (a) the P2X<sub>1</sub> receptor has been cloned from smooth muscle; (b) immunohistochemical studies have shown that it is the predominant P2X receptor protein expressed by smooth muscle; (c)  $\alpha,\beta$ -meATP is selective for P2X<sub>1</sub> and P2X<sub>3</sub> receptors, but the latter is not expressed by smooth muscle; and (d) the smooth muscle P2X response shows a similar pharmacology to the recombinant P2X<sub>1</sub> receptor, and as with the P2X<sub>1</sub> receptor, undergoes rapid desensitization. Relaxant effects of 2MeSATP or ADP $\beta$ S at guinea-pig taenia coli and via the vascular endothelium have been used to examine antagonist potencies at endogenous P2Y<sub>1</sub>-like receptors. The potencies of antagonists at endogenous P2 receptors in these and other biological assays are reported in table 8b.

1. *Suramin*. The trypanoside suramin (8-(3-benzamido-4-methylbenzamido)-naphthalene-1,3,5-trisulfonic acid) is generally selective as an antagonist at P2

TABLE 8a  
Antagonist selectivities at cloned P2 receptors

Receptor	Suramin	PPADS	P5P	RB2	NF023	References <sup>g</sup>
P2X <sub>1</sub>	IC <sub>50</sub> 1–5	IC <sub>50</sub> 1	IC <sub>50</sub> 10–20	N.D.	N.D.	1,2
P2X <sub>2</sub>	IC <sub>50</sub> 1–5	IC <sub>50</sub> 2	IC <sub>50</sub> 10–20	Yes	N.D.	1,2
P2X <sub>3</sub>	IC <sub>50</sub> 3	IC <sub>50</sub> 1	IC <sub>50</sub> 10	N.D.	N.D.	1
P2X <sub>4</sub> rat	Inactive (>500 μM)	Inactive (>100 μM)	Inactive (>100 μM)	Inactive <sup>a</sup> (>50 μM) IC <sub>50</sub> 46–50 <sup>b</sup> IC <sub>50</sub> 120–128 <sup>c</sup> IC <sub>50</sub> 38 <sup>b</sup> IC <sub>50</sub> 39 <sup>c</sup>	N.D.	1,3–6
P2X <sub>4</sub> human	IC <sub>50</sub> 178	IC <sub>50</sub> 27.5				
P2X <sub>5</sub>	IC <sub>50</sub> 4	IC <sub>50</sub> 3	N.D.	N.D.	N.D.	1
P2X <sub>6</sub>	Inactive	Inactive	N.D.	N.D.	N.D.	1
P2X <sub>7</sub> -human	IC <sub>50</sub> 4	IC <sub>50</sub> 4.2	N.D.	N.D.	N.D.	7,8
P2X <sub>7</sub> -rat	IC <sub>50</sub> 4.1	IC <sub>50</sub> 4.3				
P2Y <sub>1</sub>	pA <sub>2</sub> 5.4–6	pA <sub>2</sub> 6	N.D.	N.D.	N.D.	9–11
P2Y <sub>2</sub>	pA <sub>2</sub> 4.3	Inactive	N.D.	N.D.	N.D.	10
p2y3	pA <sub>2</sub> 5	N.D.	N.D.	N.D.	N.D.	12
P2Y <sub>4</sub> -human	Inactive	IC <sub>50</sub> 15/inactive	N.D.	Yes <sup>d</sup>	N.D.	14,15
P2Y <sub>4</sub> -rat	Weak	Inactive	N.D.	IC <sub>50</sub> 21	N.D.	16
P2Y <sub>6</sub>	Slight <sup>e</sup>	Slight <sup>f</sup>	N.D.	IC <sub>50</sub> 31	N.D.	15,17
P2Y <sub>11</sub>	N.D.	N.D.	N.D.	N.D.	N.D.	18

IC<sub>50</sub> and pA<sub>2</sub> values are μM; N.D., not determined.

<sup>a</sup> RB2.

<sup>b</sup> Basilen blue (isomer of RB2).

<sup>c</sup> Cibacron blue (isomer of RB2).

<sup>d</sup> 33% inhibition of the UTP response.

<sup>e</sup> Less potent than RB2 and PPADS.

<sup>f</sup> Less potent than RB2.

<sup>g</sup> References: 1 Collo *et al.*, 1996; 2 Evans *et al.*, 1995; 3 Bo *et al.*, 1995; 4 Soto *et al.*, 1996a; 5 Buell *et al.*, 1996b; 6 Garcia-Guzman *et al.*, 1997a; 7 Surprenant *et al.*, 1996; 8 Rassendren *et al.*, 1997; 9 Brown *et al.*, 1995; 10 Charlton *et al.*, 1996a; 11 Schachter *et al.*, 1996; 12 Webb *et al.*, 1996a; 13 Charlton *et al.*, 1996b; 14 Communi *et al.*, 1996a; 15 Chang *et al.*, 1995; 16 Bogdanov *et al.*, 1998; 17 Robaye *et al.*, 1997; 18 Communi *et al.*, 1997.

receptors versus other types of receptors (Dunn and Blakeley, 1988) (but see later this section), but is not a universal P2 receptor antagonist, and does not discriminate between P2X and P2Y receptors (table 8). Furthermore, suramin inhibits ecto-nucleotidase (Crack *et al.*, 1994; Beukers *et al.*, 1995; Ziganshin *et al.*, 1995; Bültmann *et al.*, 1996b; Chen *et al.*, 1996c) and neural ecto-diadenosine polyphosphate hydrolase (Mateo *et al.*, 1996) activity, which may complicate interpretation of antagonist activity when it is used against ligands which are biologically unstable.

Antagonism by suramin of recombinant and endogenous P2X and P2Y receptors occurs with relatively low potency (pA<sub>2</sub> values approximately 5) (table 8). Antagonism is frequently non-competitive. Suramin is weak or inactive at recombinant P2X<sub>6</sub> and P2X<sub>4</sub> receptors (Buell *et al.*, 1996b) and at P2Y<sub>6</sub> and human P2Y<sub>4</sub> receptors (Chang *et al.*, 1995; Communi *et al.*, 1996a; Robaye *et al.*, 1997). Suramin is an antagonist at a subpopulation of endogenous P2Y<sub>2</sub>-like receptors (Hoiting *et al.*, 1990; Murrin and Boarder, 1992; Henning *et al.*, 1992, 1993; Carew *et al.*, 1994; Chen *et al.*, 1994b; Sipma *et al.*, 1994; Ho *et al.*, 1995; Paulais *et al.*, 1995; Ziyal, 1997), and blocks native P2X<sub>7</sub> (or P<sub>2Z</sub>) receptors in human lymphocytes (Wiley *et al.*, 1993).

Inhibition by suramin of nicotinic receptors in chick cultured sympathetic neurons (Allgaier *et al.*, 1995b), GABA and glutamate receptors in rat hippocampal neurons (Nakazawa *et al.*, 1995), and vasoactive intestinal polypeptide (VIP)- and 5-hydroxytryptamine (5-HT)-mediated relaxations of the guinea-pig proximal colon

(Briejer *et al.*, 1995) have been described, at concentrations within the range used for block of P2 receptors. Suramin at 100 μM inhibits, by approximately 40%, GABA and glutamate receptor currents in rat hippocampal neurons (Nakazawa *et al.*, 1995), and 300 μM suramin produces approximately 40% block of 1,1-dimethyl-4-phenylpiperazinium (DMPP; nicotinic receptor agonist)-induced overflow of [<sup>3</sup>H]NA in cultured chick sympathetic neurons (Allgaier *et al.*, 1995b). Inhibition by suramin of NMDA-gated ion channels (IC<sub>50</sub> 68 μM) was described in mouse hippocampal neurons (Peoples and Li, 1998). In guinea-pig proximal colon, 300 μM suramin is a more potent inhibitor of relaxant responses to VIP (virtually abolishing responses) than of responses to ATP, and also produces a modest block of 5-HT-induced relaxation (Briejer *et al.*, 1995).

Other diverse effects of suramin include inhibition of the binding of growth factors, inhibition of the GTPase activity of certain G proteins, and inhibition of DNA and RNA polymerases (see Voogd *et al.*, 1993). Suramin and its analogs have been shown to block responses at A<sub>1</sub> adenosine and D<sub>2</sub> dopamine receptors in brain membranes by inhibiting the formation of the agonist/receptor/G protein complex (Beindl *et al.*, 1996). Although this should be borne in mind when interpreting the effects of suramin in biological systems, it should be noted that these studies were carried out on brain membrane preparations and that because of its highly polar nature, suramin does not readily cross cell membranes.

2. *NF023*. NF023 (symmetrical 3'-urea of 8-(benzami- do)naphthalene-1,3,5-trisulfonic acid) is a suramin-



TABLE 8b  
 Antagonist selectivities at endogenous P2 receptors

Tissue	Receptor <sup>a</sup>	Suramin	PPADS	P5P	RB2	NF023	References <sup>k</sup>
Rat vas deferens	P2X (P2X <sub>1</sub> )	pK <sub>B</sub> 5.5 K <sub>d</sub> 3.9	iso-PPADS <sup>b</sup>	pK <sub>B</sub> 5.3–5.8	pK <sub>B</sub> 5.8 <sup>c</sup>	pA <sub>2</sub> 5.9 K <sub>d</sub> 1.0	1,2 3
Rabbit vas deferens	P2X (P2X <sub>1</sub> )	pA <sub>2</sub> 5.1	pA <sub>2</sub> 6.3	pA <sub>2</sub> 5.2		pA <sub>2</sub> 5.7	4,5
Guinea-pig vas deferens	P2X (P2X <sub>1</sub> )	Yes (NC)	pK <sub>B</sub> 5.6				6,7
Rat mesenteric bed	P2X (P2X <sub>1</sub> )	pA <sub>2</sub> 5.0	pK <sub>B</sub> 6.4	pA <sub>2</sub> 5.4		pA <sub>2</sub> 5.5	5,8
Hamster mesenteric bed	P2X (P2X <sub>1</sub> )	pA <sub>2</sub> 5.3				pA <sub>2</sub> 5.6	9
Rabbit ear artery	P2X (P2X <sub>1</sub> )	pK <sub>B</sub> 4.8	pA <sub>2</sub> 6.4			N.D.	10–12
Rabbit saphenous artery	P2X (P2X <sub>1</sub> )	pA <sub>2</sub> 4.8	pA <sub>2</sub> 6.0			pA <sub>2</sub> 5.7	9,11,12
Rat renal vascular bed	P2X (P2X <sub>1</sub> )	Yes	pK <sub>B</sub> 6.0		Yes		13
Guinea-pig ileum submucosal arterioles	P2X (P2X <sub>1</sub> )	pK <sub>B</sub> 5.5	pK <sub>B</sub> 6.3				14
Rabbit urinary bladder	P2X (P2X <sub>1</sub> )		pA <sub>2</sub> 6.3				15
Guinea-pig urinary bladder	P2X (P2X <sub>1</sub> )	pA <sub>2</sub> 5.1	pA <sub>2</sub> 6.7				16
Human urinary bladder	P2X (P2X <sub>1</sub> )	pK <sub>B</sub> 5.9 <sup>d</sup>					17
Human saphenous vein	P2X (P2X <sub>1</sub> )	pK <sub>B</sub> 4.8					18
Rat vagus nerve	P2X	pA <sub>2</sub> 5.9	iso-PPADS <sup>e</sup>	pK <sub>B</sub> 5.3–5.4	pK <sub>B</sub> 4.96 <sup>e</sup>		19,20
Guinea-pig taenia coli	P2Y (P2Y <sub>1</sub> )	pA <sub>2</sub> 5.0 K <sub>d</sub> 10.1	pA <sub>2</sub> 4.6–5.3			pA <sub>2</sub> 4.2 K <sub>d</sub> 22–34	9,21,22 3
Rat duodenum	P2Y (P2Y <sub>1</sub> )	pA <sub>2</sub> 5.0	pA <sub>2</sub> 5.1	pA <sub>2</sub> 5.4		pA <sub>2</sub> 4.3	5,11
Rat mesenteric bed	P2Y (P2Y <sub>1</sub> )	pA <sub>2</sub> 5.3	pA <sub>2</sub> 5.5–6.0			pA <sub>2</sub> 4.9	9,11,22,23
Bovine aorta	P2Y (P2Y <sub>1</sub> )	pK <sub>B</sub> 5.5					24
Rat aorta	P2Y (P2Y <sub>1</sub> )	K <sub>d</sub> 2–6	K <sub>d</sub> 0.2–0.4		K <sub>d</sub> 0.5–0.8		25
Turkey erythrocytes	P2Y (P2Y <sub>1</sub> )	Yes (NC)	pA <sub>2</sub> 5.9		Yes (NC)		26
Bovine pulmonary artery EC	P2Y (P2Y <sub>1</sub> )	pA <sub>2</sub> 5.5			pA <sub>2</sub> 6.3		27
Rabbit thoracic aorta							9
+EC <sub>(ATP)</sub>	P2Y (P2Y <sub>1</sub> )	pA <sub>2</sub> 3.2–4.4				Inactive	
-EC <sub>(ATP)</sub>	P2Y	Inactive				Inactive	
C6 glioma cells							26,28
↑IP <sub>3</sub>	P2Y (P2Y <sub>1</sub> )	pA <sub>2</sub> 4.4			Yes (NC)		
↓cAMP	P2Y (P2Y <sub>1</sub> )	Slight at 100 μM	Inactive at <100 μM		pA <sub>2</sub> 6.3		
Rat astrocytes	P2Y	Yes	IC <sub>50</sub> 0.9				29
Mouse vas deferens	P2Y-like <sup>f</sup>				pK <sub>B</sub> 5.3		30
Rat atria	P2Y-like <sup>g</sup>				pK <sub>B</sub> 5.1		31
Rat mesenteric bed	P2Y (P2Y <sub>2</sub> )	Inactive	Inactive			Inactive	9,23
Hamster mesenteric bed	P2Y (P2Y <sub>2</sub> )	pA <sub>2</sub> 4.9				Inactive	9
Bovine aorta	P2Y (P2Y <sub>2</sub> )	Inactive					24
Rat aorta	P2Y (P2Y <sub>2</sub> )	K <sub>d</sub> 26–37			K <sub>d</sub> 6.5		25
Bovine pulmonary artery EC	P2Y (P2Y <sub>2</sub> )	pA <sub>2</sub> 4.4			pA <sub>2</sub> 5.7		27
C6 glioma	P2Y (P2Y <sub>2</sub> )	pA <sub>2</sub> 4.4					26
C2C12 myotubes	P2Y (P2Y <sub>2</sub> )	pA <sub>2</sub> 4.4					32
Rat astrocytes	P2Y (P2Y <sub>2</sub> )	Yes	IC <sub>50</sub> 7.2				29
Rat neuroblastoma × glioma cells	P2Y (P2Y <sub>2</sub> )	IC <sub>50</sub> 40–60	IC <sub>50</sub> 20–30				33
RAW 264.7 macrophages	P2Y (pyrimidinoceptor)	pA <sub>2</sub> 4.8	Inactive		pA <sub>2</sub> 5.8		34
Rat mesenteric arteries	P2Y (pyrimidinoceptor) <sup>h</sup>	Inactive	Inactive		Inactive		22,23,35
Rat superior cervical ganglion	P2Y (pyrimidinoceptor) <sup>i</sup>	Inactive					36
Human platelets	P2Y (P <sub>2T</sub> )	pA <sub>2</sub> 4.6	Yes <sup>j</sup>				37,38

P2X<sub>1</sub>-like receptor-mediated responses were determined against the effects of  $\alpha,\beta$ -meATP; P2Y<sub>1</sub>-like receptor-mediated responses were determined against the effects of ADP $\beta$ S or 2MeSATP; P2Y<sub>2</sub>-like receptor-mediated responses were determined against the effects of UTP (in tissues in which ATP is approximately equipotent with UTP). NC, noncompetitive; +EC, with endothelium; -EC, without endothelium.

<sup>a</sup> The likely cloned receptor counterparts of endogenous responses are indicated in parentheses.

<sup>b</sup> pK<sub>B</sub> 6.6 for iso-PPADS (Khakh *et al.*, 1994).

<sup>c</sup> Cibacron blue.

<sup>d</sup> Suramin antagonized only the lower part of the  $\alpha,\beta$ -meATP response curve (Paea *et al.*, 1995).

<sup>e</sup> pK<sub>B</sub> 6.0 for iso-PPADS (Trezise *et al.*, 1994c).

<sup>f</sup> Antagonism of ATP $\gamma$ S inhibition of [<sup>3</sup>H]NA overflow.

<sup>g</sup> Antagonism of ATP- and ATP $\gamma$ S-mediated inhibition of evoked [<sup>3</sup>H]NA overflow.

<sup>h</sup> Tested against contractions to UTP.

<sup>i</sup> Tested against depolarizations to UDP and UTP; responses to  $\alpha,\beta$ -meATP and ATP were blocked.

<sup>j</sup> At high concentrations (>100 μM).

<sup>k</sup> References: 1, Khakh *et al.*, 1994; 2, Trezise *et al.*, 1994b; 3, Bültmann *et al.*, 1996b; 4, Lambrecht *et al.*, 1992; 5, Lambrecht *et al.*, 1996; 6, McLaren *et al.*, 1994; 7, Bailey and Hourani, 1995; 8, Windscheif *et al.*, 1994; 9, Ziyal, 1997; 10, Leff *et al.*, 1990; 11, Lambrecht, 1996; 12, Ziganshin *et al.*, 1994b; 13, Eltze and Ullrich, 1996; 14, Galligan *et al.*, 1995; 15, Ziganshin *et al.*, 1993; 16, Usune *et al.*, 1996; 17, Paea *et al.*, 1995; 18, von Kügelgen *et al.*, 1995; 19, Trezise *et al.*, 1994b; 20, Trezise *et al.*, 1994c; 21, Hoyle *et al.*, 1990; 22, Windscheif *et al.*, 1995a; 23, Ralevic and Burnstock, 1996a; 24, Wilkinson *et al.*, 1994; 25, Hansmann *et al.*, 1997; 26, Boyer *et al.*, 1994; 27, Chen *et al.*, 1996a; 28, Lin and Chuang, 1994; 29, Ho *et al.*, 1995; 30, von Kügelgen *et al.*, 1994; 31, von Kügelgen *et al.*, 1995b; 32, Henning *et al.*, 1993; 33, Reiser, 1995; 34, Chen *et al.*, 1996c; 35, Lagaud *et al.*, 1996; 36, Connolly and Harrison, 1995; 37, Hourani *et al.*, 1992; 38, Windscheif *et al.*, 1995b.

based compound which is moderately selective as an antagonist of P2X receptors. NF023 is about 30-fold selective for P2X<sub>1</sub>-like receptors in the rat vas deferens versus P2Y<sub>1</sub>-like receptors in the guinea-pig taenia coli

(Bültmann *et al.*, 1996b). It has 79-fold selectivity for endogenous P2X<sub>1</sub>-like receptors in rabbit vas deferens versus P2Y<sub>1</sub>-like receptors in turkey erythrocytes; pA<sub>2</sub> values of 5.5 to 5.7 at P2X<sub>1</sub>-like receptors in rabbit

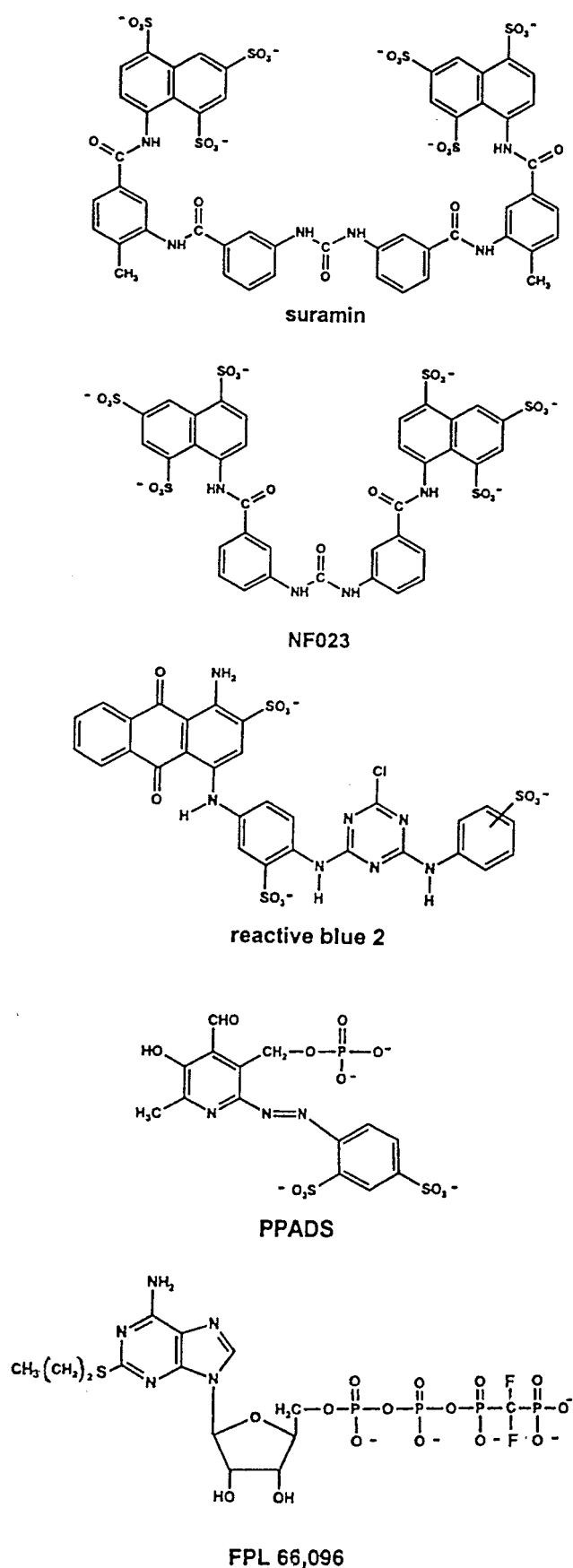


FIG. 7. The chemical structures of some P2 receptor antagonists. (Adapted from Windscheif, 1996).

isolated blood vessels, rabbit vas deferens, and rat and hamster mesenteric arterial beds; and  $\text{pA}_2$  values of 4.6 to 5.5 at vascular and nonvascular smooth muscle  $\text{P2Y}_1$ -like receptors (Lambrecht *et al.*, 1996; Ziyal, 1997; Ziyal *et al.*, 1997). Its effects at the other P2X (and P2Y) receptor subtypes have not been reported. Antagonism is competitive and reversible. Like the parent compound suramin, NF023 inhibits ecto-nucleotidase activity, but unlike suramin, it has high  $\text{P2X}_1$ -like versus ecto-nucleotidase-selectivity (Beukers *et al.*, 1995; Bültmann *et al.*, 1996b).

3. *NF279*. NF279 (8, 8'-(carbonylbis(imino-4,1-phenylenecarbonylimino))bis(1,3,5-naphthalenetrisulfonic acid) is a suramin analog that is about 10-fold more potent than NF023 in blocking  $\alpha, \beta$ -meATP-mediated contractions at  $\text{P2X}_1$ -like receptors in rat vas deferens,  $\text{pIC}_{50}$  5.7 (Damer *et al.*, 1998). With a  $\text{pA}_2$  value of 4.3 at  $\text{P2Y}_1$ -like receptors in the guinea-pig taenia coli, it has the highest P2X- versus P2Y- and ecto-nucleotidase-selectivity so far reported (Damer *et al.*, 1998).

4. *Pyridoxal-5-phosphate (P5P)*. P5P is a non-selective P2 receptor antagonist, but has proved useful as a starting compound for the synthesis of more P2X-selective antagonists (Lambrecht *et al.*, 1996). Antagonism by P5P is, however, selective versus non-purine receptors and seems to be competitive at  $\text{P2X}_1$ -like receptors in vas deferens of rabbit (Lambrecht *et al.*, 1996) and rat (Trezise *et al.*, 1994b), and at  $\alpha, \beta$ -meATP-mediated depolarization of rat vagus nerve (Trezise *et al.*, 1994b). P5P non-competitively inhibits responses mediated by recombinant receptors  $\text{P2X}_1$  and  $\text{P2X}_2$  but is less potent than its derivative pyridoxalphosphate-6-azophenyl-2',4'-disulfonic acid (PPADS) (Evans *et al.*, 1995). P5P inhibits  $\alpha, \beta$ -meATP-induced depolarization of rat superior cervical ganglion (Connolly, 1995).

5. *PPADS*. Although originally put forward as a P2X-selective antagonist, unfortunately it must now be accepted that PPADS is a non-selective (but non-universal) P2 receptor antagonist. PPADS is a slowly-equilibrating and slowly-reversible antagonist with  $\text{pA}_2$  values of approximately 6 to 6.7 at endogenous  $\text{P2X}_1$ -like receptors in a variety of smooth muscle preparations (table 8; Lambrecht *et al.*, 1996; Ziganshin *et al.*, 1993, 1994b; Bültmann and Starke, 1994a; McLaren *et al.*, 1994; Windscheif *et al.*, 1994; Galligan *et al.*, 1995; Von Kügelgen *et al.*, 1995a; Eltze and Ullrich, 1996; Ralevic and Burnstock, 1996b; Usune *et al.*, 1996). It also blocks recombinant  $\text{P2X}_1$ ,  $\text{P2X}_2$ ,  $\text{P2X}_3$ , and  $\text{P2X}_5$  receptors with  $\text{IC}_{50}$  values of 1 to 2.6  $\mu\text{M}$  (Collo *et al.*, 1996). A lysine residue in receptors  $\text{P2X}_1$ ,  $\text{P2X}_2$ , and  $\text{P2X}_5$  (amino acid 249 in  $\text{P2X}_1$ ) seems to be involved in the slowly reversible component of block by PPADS, probably involving formation of a Schiff's base (Buell *et al.*, 1996b). Rat recombinant  $\text{P2X}_4$  and  $\text{P2X}_6$  receptors are not blocked by PPADS (Buell *et al.*, 1996b; Collo *et al.*, 1996; Soto *et al.*, 1996a,b; Garcia-Guzman *et al.*, 1997a), but interestingly, the human homolog of the  $\text{P2X}_4$  receptor is

blocked by PPADS with an  $IC_{50}$  of 28  $\mu M$  (Garcia-Guzman *et al.*, 1997a). PPADS antagonizes depolarizations induced by  $\alpha, \beta$ -meATP in rat superior cervical ganglion (Connolly, 1995).

PPADS generally blocks endogenous P2Y<sub>1</sub>-like and recombinant P2Y<sub>1</sub> receptors coupled to PLC (Boyer *et al.*, 1994; Brown *et al.*, 1995; Charlton *et al.*, 1996a; Schachter *et al.*, 1996) but not those coupled to inhibition of adenylate cyclase (Boyer *et al.*, 1994; Webb *et al.*, 1996c). PPADS has been reported to be inactive at P2Y<sub>1</sub>-like receptors in smooth muscle of rabbit mesenteric artery and endothelium of rabbit aorta (Ziganshin *et al.*, 1994b), but blocks those in rat duodenum, guinea-pig taenia coli ( $pA_2$  values 5.1 and 5.3, respectively) (Windscheif *et al.*, 1995a), and rat mesenteric arterial bed ( $pA_2$  value 6.0) (Ralevic and Burnstock, 1996b). PPADS blocks P2Y<sub>2</sub>-like receptors in astrocytes from the dorsal horn of the spinal cord ( $IC_{50}$  approximately 0.9  $\mu M$ ) (Ho *et al.*, 1995) but not P2Y<sub>2</sub>-like receptors on rat mesenteric arterial endothelium (Windscheif *et al.*, 1994; Ralevic and Burnstock, 1996a), or those on cultured bovine aortic endothelial cells (Brown *et al.*, 1995). PPADS antagonizes responses to UTP at the recombinant P2Y<sub>4</sub> receptor ( $IC_{50}$  value approximately 15  $\mu M$ ) (Communi *et al.*, 1996a). At high concentrations PPADS blocks P2Y<sub>ADP</sub> receptor-mediated ADP-induced platelet aggregation and inhibits ecto-nucleotidase activity (Windscheif *et al.*, 1995b; Chen *et al.*, 1996c). At concentrations greater than 10  $\mu M$ , non-specific effects of PPADS have been reported involving inhibition of IP<sub>3</sub>-induced  $[Ca^{2+}]_i$  mobilization (Vigne *et al.*, 1996).

6. *Iso-PPADS*. An isomer of PPADS, pyridoxalphosphate-6-azophenyl-2',5'-disulfonic acid (iso-PPADS) is a slowly-equilibrating and slowly-reversible antagonist of responses at P2X receptors with similar potency to PPADS (Trezise *et al.*, 1994c) and competes for [<sup>3</sup>H] $\alpha, \beta$ -meATP binding sites in the rat vas deferens (Khakh *et al.*, 1994). Iso-PPADS blocks depolarizations evoked by  $\alpha, \beta$ -meATP, but not those to UTP in rat superior cervical ganglion, but in contrast to PPADS also blocks depolarizations to muscarine (Connolly, 1995).

7. *Reactive blue 2*. The anthraquinone-sulfonic acid derivative reactive blue 2 (synonymous with cibacron blue) is a non-competitive P2 receptor antagonist which does not discriminate adequately between P2X and P2Y subtypes. In the vasculature, it has micromolar affinity and some selectivity for endothelial P2Y<sub>1</sub> and smooth muscle P2Y<sub>1</sub>-like receptors versus other vascular P2X and P2Y receptors; however, selectivity versus the smooth muscle P2X<sub>1</sub>-like receptor is low, and its use is limited by a narrow effective concentration range and time of exposure (Burnstock and Warland, 1987a; Hopwood and Burnstock, 1987; Houston *et al.*, 1987). Reactive blue 2 antagonism of P2Y receptors includes block of the recombinant P2Y<sub>6</sub> receptor (Chang *et al.*, 1995) and some endogenous P2Y<sub>2</sub>-like and uridine nucleotide-specific receptors (Nakaoka and Yamashita, 1995; Chen *et*

*al.*, 1996c). Reactive blue 2 blocks selectively contractile responses to ADP $\beta$ S at a P2Y-like receptor, but enhances P2X receptor-mediated contractions to  $\alpha, \beta$ -meATP and ATP in rat anococcygeus smooth muscle (Najbar *et al.*, 1996)

Reactive blue 2 also has been shown to block responses mediated by endogenous P2X receptors in adult rat superior cervical and nodose ganglia, and guinea-pig coeliac ganglion (Silinsky and Gerzanich, 1993; Connolly and Harrison, 1994; Khakh *et al.*, 1995a), rat vagus nerve (Trezise *et al.*, 1994c), urinary bladder and vas deferens (Choo, 1981; Bo *et al.*, 1994; Bültmann and Starke, 1994a; Suzuki and Kokubun, 1994), endogenous P2X<sub>7</sub>-like receptors (McMillian *et al.*, 1993; Wiley *et al.*, 1993), and recombinant P2X<sub>2</sub> (Brake *et al.*, 1994) and P2X<sub>4</sub> (Bo *et al.*, 1995; Séguéla *et al.*, 1996) receptors. Thus, this compound does not discriminate adequately between P2X and P2Y receptors, although it may be useful in discriminating between subtypes of coexisting P2 receptors. Inhibition by reactive blue 2 of GABA and glutamate receptors (Motin and Bennett, 1995; Nakazawa *et al.*, 1995), and NMDA-gated ion channels (Peoples and Li, 1998) further advises caution in the use of this compound. Inhibition of ectoATPase activity by reactive blue 2 also has been reported (Stout and Kirley, 1995).

8. *Reactive red*. Reactive red is at least 350 times more potent than reactive blue 2 as a competitive antagonist at the P2Y<sub>1</sub>-like receptor of guinea-pig taenia coli ( $K_d$ , 28 nM); however, it is only 15-fold selective versus the P2X<sub>1</sub>-like receptor in rat vas deferens, and has ecto-nucleotidase activity (Bültmann and Starke, 1995). Its effects at other P2X and P2Y subtypes are largely unknown.

9. *Trypan blue*. Trypan blue blocks selectively (versus K<sup>+</sup> and noradrenaline)  $\alpha, \beta$ -meATP-mediated contractions at the P2X<sub>1</sub>-like receptor in rat vas deferens but is also an inhibitor of ADP $\beta$ S-mediated relaxations via P2Y<sub>1</sub>-like receptors in guinea-pig taenia coli and an inhibitor of ecto-nucleotidase activity (Bültmann *et al.*, 1994; Wittenburg *et al.*, 1996).

10. *Evans blue*. Evans blue blocks selectively responses to  $\alpha, \beta$ -meATP in the rat vas deferens versus those mediated by ADP $\beta$ S in the guinea-pig taenia coli, but potentiates contraction to ATP, ADP, and 2MeSATP in a manner attributable in part to ecto-nucleotidase inhibition; it also has non-specific potentiating effects (Bültmann and Starke, 1993; Bültmann *et al.*, 1995; Wittenburg *et al.*, 1996). The desmethyl derivative of Evans blue, NH01, is highly selective for the P2X<sub>1</sub>-like receptor in vas deferens versus the P2Y<sub>1</sub>-like receptor in guinea-pig taenia coli ( $K_d$  values 0.8 and > 100  $\mu M$ , respectively), but is only moderately selective for the P2X<sub>1</sub> receptor versus inhibition of ecto-nucleotidase activity (Wittenburg *et al.*, 1996).

11. *DIDS*. The Cl<sup>-</sup> transport blocker 4,4'-diisothiocyanatostilbene-2,2'-disulfonate (DIDS) is a noncompetitive, pseudo-irreversible antagonist of P2X<sub>1</sub>-like recep-



tor-mediated contractions to  $\alpha,\beta$ -meATP and of the purinergic component of the neurogenic contractile response in guinea-pig and rat vas deferens, and is selective versus the P2Y<sub>1</sub>-like receptor of guinea-pig taenia coli (Fedan and Lamport, 1990; Bültmann and Starke, 1994b; Bültmann *et al.*, 1996a). However, it is nonselective versus inhibition of ecto-nucleotidase activity (Bültmann *et al.*, 1996a). DIDS discriminates between subtypes of P2X receptors, being a potent inhibitor of responses mediated at the P2X<sub>1</sub> receptor cloned from human bladder (IC<sub>50</sub> 3  $\mu$ M), but less than 40% effective at recombinant P2X<sub>2</sub> receptors from PC12 cells at concentrations of up to 300  $\mu$ M (Evans *et al.*, 1995). DIDS blocks depolarization to  $\alpha,\beta$ -meATP in rat superior cervical ganglia, but has no effect on depolarization to UTP or potassium, or hyperpolarization to adenosine (Connolly and Harrison, 1995a). DIDS and some analogs of DIDS also block endogenous P2X<sub>7</sub>-like receptors (el-Moatassim and Dubyak, 1993; McMillian *et al.*, 1993; Soltoff *et al.*, 1993). DIDS, PPADS, and dextran sulfate discriminate between recombinant human P2X<sub>1</sub> and rat P2X<sub>2</sub> receptors in displacement of binding studies, having 7- to 33-fold higher affinity for P2X<sub>1</sub> receptors (Michel *et al.*, 1996).

12. *Arylazidoaminopropionyl ATP (ANAPP<sub>3</sub>)*. ANAPP<sub>3</sub>, a photo-affinity analog of ATP, activates and desensitizes endogenous smooth muscle P2X<sub>1</sub>-like receptors, irreversibly so after exposure to light, and selectively versus non-purine receptors (Hogaboom *et al.*, 1980; Fedan *et al.*, 1985; Venkova and Krier, 1993). Its effects at other P2X receptor subtypes have not been determined. However, ANAPP<sub>3</sub> also weakly antagonizes relaxations to ATP, ADP, and adenosine in the guinea-pig taenia coli (Westfall *et al.*, 1982).

13. *2-Alkylthio derivatives of ATP*. 2-Alkylthio derivatives of ATP are potent P2Y<sub>1</sub> receptor antagonists: both base modifications, leading to 8-(6-aminohexylamino)-ATP and N-oxide ATP, and ribose modifications, leading to 2',3'-isopropylidene-AMP, result in derivatives that display selectivity for endothelial P2Y<sub>1</sub>-like receptors and are virtually inactive at smooth muscle P2Y<sub>1</sub>-like and P2X<sub>1</sub>-like receptors (Burnstock *et al.*, 1994).

14. *5'-p-Fluorosulfonyl benzoyladenine*. This is an irreversible inhibitor of ATP-induced Ba<sup>2+</sup> influx via the P2X<sub>7</sub> receptor in human lymphocytes, although maximal inhibition does not exceed 90% (Wiley *et al.*, 1994).

## IX. P2X Receptors

P2X receptors are ATP-gated ion channels which mediate rapid (within 10 ms) and selective permeability to cations (Na<sup>+</sup>, K<sup>+</sup> and Ca<sup>2+</sup>) (Bean, 1992; Dubyak and el-Moatassim, 1993; North, 1996). This is appropriate given their distribution on excitable cells (smooth muscle cells, neurons, and glial cells) and role as mediators of fast excitatory neurotransmission to ATP in both the central and peripheral nervous systems. This contrasts with the slower onset of response (less than 100 ms) to

ATP acting at metabotropic P<sub>2Y</sub> receptors, which involves coupling to G proteins and second-messenger systems. Seven P2X receptor proteins (P2X<sub>1</sub> to P2X<sub>7</sub>) have been cloned and the ion channels formed from homomeric association of the subunits when expressed in *Xenopus* oocytes or in mammalian cells have been functionally characterized and show distinct pharmacological profiles (table 9). The P2X<sub>7</sub> receptor is considered separately below (see Section X.) because it is functionally unique among P2X receptors in being able to act as a non-selective pore.

### A. Structure

Structural features of P2X receptors have been predicted from the amino acid sequences of cloned P2X receptor subunits. It is important to bear in mind that the P2X proteins that have been cloned are receptor subunits, not actual receptors; a single 2 transmembrane subunit alone cannot form an ion channel. The proteins have 379 to 472 amino acids and are believed to insert into the cell membrane to form a pore comprising two hydrophobic transmembrane domains, with much of the protein occurring extracellularly as an intervening hydrophilic loop (fig. 8). The overall structure of the receptor most closely resembles that of amiloride-sensitive epithelial Na<sup>+</sup> channels. The putative extracellular loop of cloned receptors P2X<sub>1</sub> to P2X<sub>7</sub> has 10 conserved cysteine residues, 14 conserved glycine residues and 2 to 6 potential N-linked glycosylation sites. It is believed that disulfide bridges may form the structural constraints needed to couple the ATP-binding site to the ion pore. Most of the conserved regions are in the extracellular loop, with the transmembrane domains being less well-conserved.

The quaternary structures of classical ligand-gated channels, for example, those of the nicotinic ACh receptor and the epithelial Na<sup>+</sup> channel, generally take the form of heteromeric complexes of structurally related subunits. P2X receptors are believed to complex in a similar way in biological tissues. Their subunit stoichiometry is unknown, but may involve three subunits (or multiples of three subunits) based on SDS polyacrylamide gel electrophoresis estimates of the relative molecular mass of the recombinant P2X<sub>1</sub> and P2X<sub>3</sub> receptors determined under non-denaturing conditions (Nicke *et al.*, 1998).

The pharmacological properties of endogenous P2X receptors in smooth muscle and PC12 cells correlate well with those of the recombinant receptors cloned from these tissues, P2X<sub>1</sub> and P2X<sub>2</sub> receptors, respectively; both native and recombinant P2X<sub>1</sub> receptors are sensitive to  $\alpha,\beta$ -meATP and rapidly desensitize, whereas P2X<sub>2</sub> receptors are insensitive to  $\alpha,\beta$ -meATP and do not desensitize. A good correlation is also seen between the properties of endogenous P2X receptors in neonatal dorsal root ganglion and the recombinant P2X<sub>3</sub> receptor (cloned from and expressed predominantly or exclu-

TABLE 9  
Cloned P2X receptors

Receptor	Number of amino acids	cDNA library source	Agonist activity	References
P2X <sub>1</sub>	399	Human urinary bladder Rat vas deferens Mouse urinary bladder	ATP > $\alpha,\beta$ -meATP 2MeSATP > ATP > $\alpha,\beta$ -meATP —	Valera <i>et al.</i> , 1995; Longhurst <i>et al.</i> , 1996 Valera <i>et al.</i> , 1994 Valera <i>et al.</i> , 1996
P2X <sub>2</sub>	472	Rat PC12 cells	2MeSATP > ATP; $\alpha,\beta$ -meATP inactive	Brake <i>et al.</i> , 1994
P2X <sub>2(b)</sub> <sup>a</sup>	401	Rat cerebellum	2MeSATP = ATP = $\alpha,\beta$ -meATP	Brändle <i>et al.</i> , 1997; Simon <i>et al.</i> , 1997
P2X <sub>3</sub>	397	Human heart, spinal cord Rat DRG cells Rat DRG cells	2MeSATP > ATP > $\alpha,\beta$ -meATP 2MeSATP > ATP > $\alpha,\beta$ -meATP > UTP ATP > 2MeSATP > $\alpha,\beta$ -meATP	Garcia-Guzman <i>et al.</i> , 1997b Chen <i>et al.</i> , 1995a Lewis <i>et al.</i> , 1995
P2X <sub>4</sub>	388	Human brain Rat brain Rat brain Rat hippocampus Rat SCG Rat pancreatic islet	ATP $\gg$ 2MeSATP $\geq$ CTP > $\alpha,\beta$ -meATP ATP $\gg$ 2MeSATP $\geq$ CTP > $\alpha,\beta$ -meATP ATP > 2MeSATP $\gg$ $\alpha,\beta$ -meATP ATP > 2MeSATP $\gg$ $\alpha,\beta$ -meATP ATP; $\alpha,\beta$ -meATP inactive ATP, ADP, 2MeSATP $\gg$ $\alpha,\beta$ -meATP	Garcia-Guzman <i>et al.</i> , 1997a Soto <i>et al.</i> , 1996a Séguéla <i>et al.</i> , 1996 Bo <i>et al.</i> , 1995 Buell <i>et al.</i> , 1996b Wang <i>et al.</i> , 1996
P2X <sub>5</sub>	417	Rat ganglia	ATP > 2MeSATP > ADP $\alpha,\beta$ -meATP inactive	Collo <i>et al.</i> , 1996
	455	Rat heart	ATP > 2MeSATP > ADP	Garcia-Guzman <i>et al.</i> , 1996
P2X <sub>6</sub>	379	Rat superior cervical ganglion Rat brain	ATP > 2MeSATP > ADP; $\alpha,\beta$ -meATP inactive —	Collo <i>et al.</i> , 1996 Soto <i>et al.</i> , 1996b
P2X <sub>7</sub>	595	Mouse macrophage	BzATP > ATP > UTP ATP > UTP > BzATP	Nuttall <i>et al.</i> , 1993
		Rat macrophage and brain	BzATP > ATP > 2MeSATP > ADP; UTP inactive	Surprenant <i>et al.</i> , 1996
	595	Human monocytes	BzATP > ATP	Rassendren <i>et al.</i> , 1997

<sup>a</sup> Splice variant, also termed P2X<sub>2.2</sub>.

sively in sensory neurons); both are sensitive to  $\alpha,\beta$ -meATP and rapidly desensitize (Evans and Surprenant, 1996). Thus, there is good reason to believe that the native P2X receptors in these tissues are predominantly homomers formed by the association of a single type of subunit.

However, this is not always the case. ATP-gated currents at endogenous P2X receptors in rat nodose neurons are mimicked by  $\alpha,\beta$ -meATP and do not desensitize (Lewis *et al.*, 1995), a pharmacological profile that does not correspond to any of the homomeric P2X receptors cloned to date; all are expressed in sensory ganglia except P2X<sub>7</sub>. Although P2X<sub>3</sub> is expressed preferentially in sensory neurons, currents evoked by ATP and  $\alpha,\beta$ -meATP at the recombinant P2X<sub>3</sub> receptor rapidly desensitize. However, when P2X<sub>3</sub> is coexpressed in HEK293 cells with P2X<sub>2</sub> (but not with other subtypes), a non-desensitizing response to ATP is observed which mimics that seen in rat nodose neurons and which cannot be explained by additive effects of the two homomeric channels (Lewis *et al.*, 1995). It was suggested that a new heteromeric receptor, P2X<sub>2</sub>P2X<sub>3</sub>, is formed from the P2X<sub>3</sub> and P2X<sub>2</sub> subunits (Lewis *et al.*, 1995). This hypothesis is supported by the observation of a high level of colocalization of P2X<sub>2</sub>- and P2X<sub>3</sub>-immunoreactivity in rat nodose and dorsal root ganglia (Vulchanova *et al.*, 1997). Direct evidence for the formation of a P2X<sub>2</sub>P2X<sub>3</sub> heteromer comes from a study showing that in cells

coinfecting with P2X<sub>2</sub> and P2X<sub>3</sub> receptors, the two proteins can be cross-immunoprecipitated with antibodies specific for either of the epitope tags introduced at the C terminal of the proteins (Radford *et al.*, 1997). Electrophysiological studies showing sensitivity to  $\alpha,\beta$ -meATP and a slowly desensitizing response is consistent with formation of heteromeric receptors because this is distinct from responses mediated by homomeric P2X<sub>2</sub> and P2X<sub>3</sub> receptors (Radford *et al.*, 1997).

Further evidence for the existence of P2X<sub>2</sub>P2X<sub>3</sub> heteromers in sensory neurons is suggested by electrophysiological studies in cultured neurons of adult rat dorsal root (Robertson *et al.*, 1996) and trigeminal ganglion neurons (Cook *et al.*, 1997). However, heterogeneity within populations of sensory neurons has been identified in the form of single labeling for P2X<sub>2</sub> or P2X<sub>3</sub> of some rat nodose and dorsal root neurons (possibly coexisting with other P2X proteins) (Vulchanova *et al.*, 1997), and by the demonstration of two types of inward current to ATP (transient and slowly desensitizing) in tooth-pulp nociceptors (Cook and McCleskey, 1997). This raises interesting questions about the patterns of P2X receptor subtype expression and the physiological properties of different neurons.

The likely formation of P2X<sub>2</sub>P2X<sub>3</sub> heteromers in sensory neurons has important implications for the subunit organization of P2X receptors in other biological tissues, because the different P2X proteins have widespread and

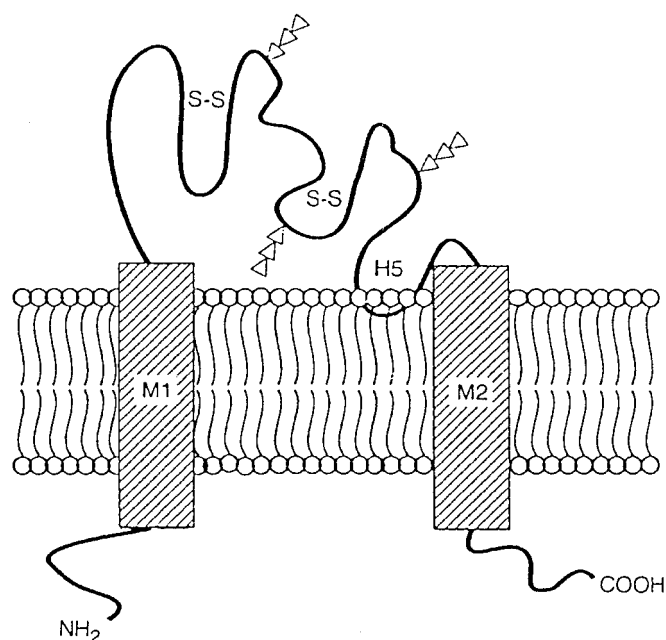


FIG. 8. Diagram depicting a proposed transmembrane topology for P2X<sub>2</sub> protein showing both N- and C-terminals in the cytoplasm. Two putative membrane spanning segments (M<sub>1</sub> and M<sub>2</sub>) traverse the lipid bilayer of the plasma membrane and are connected by a hydrophilic segment of 270 amino acids. This putative extracellular domain is shown containing two disulfide-bonded loops (S-S) and three N-linked glycosyl chains (triangles). The P2X<sub>2</sub> cDNA was sequenced on both strands using Sequanase. (From Brake *et al.*, 1994).

overlapping distributions. However, it seems that not all combinations are possible; for example, cotransfected P2X<sub>1</sub> and P2X<sub>2</sub> subunits do not combine to form heteromeric receptors (Surprenant, 1996). Figure 9 shows examples of ATP-gated currents in native cells and how these correlate with recombinant P2X receptors.

Alternative splicing of P2X pre-messenger RNA has been shown for the P2X<sub>2</sub> receptor (Brändle *et al.*, 1997; Simon *et al.*, 1997). The splice variant exhibits a different pharmacology to the native receptor, suggesting that there may be heterogeneity in responses of tissues expressing the different proteins.

### B. Cloned P2X Receptors

1. *P2X<sub>1</sub> receptor.* The P2X<sub>1</sub> receptor has been cloned from rat vas deferens and human and mouse urinary bladder (Valera *et al.*, 1994, 1995, 1996) (table 9). The recombinant receptor is activated by 2MeSATP  $\geq$  ATP  $>$   $\alpha,\beta$ -meATP  $\gg$  ADP, and inward currents evoked by these compounds are reversibly blocked by suramin and PPADS (Valera *et al.*, 1994). The receptor desensitizes very rapidly (in hundreds of milliseconds).

P2X<sub>1</sub> receptor mRNA is expressed in urinary bladder, smooth muscle layers of small arteries and arterioles, and vas deferens, with lower levels in lung and spleen (Valera *et al.*, 1994; Collo *et al.*, 1996). P2X<sub>1</sub> receptor mRNA is also expressed in dorsal root ganglia, trigeminal ganglia, coeliac ganglia, spinal cord, and rat brain (Valera *et al.*, 1994; Webb *et al.*, 1995; Collo *et al.*, 1996).

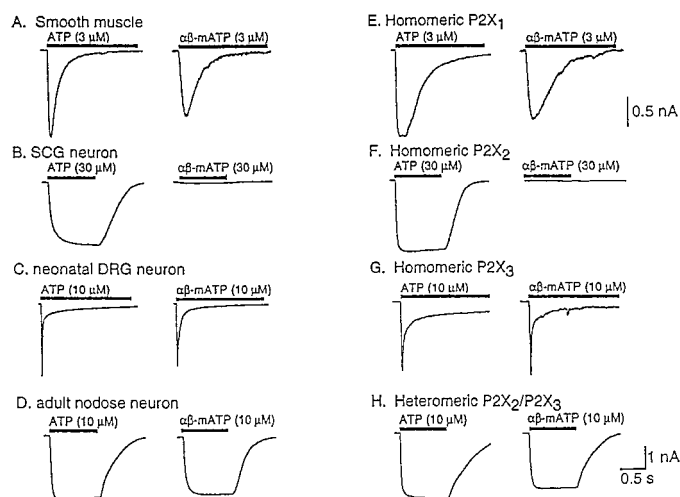


FIG. 9. Examples of ATP-gated currents evoked in native cells (A-D) and in HEK293 cells expressing homomeric (E-G) or heteromeric (H) P2X receptors. Bars above each trace refer to the duration of agonist application. All recordings are at holding potential of  $-70$  mV. Traces shown in C from neonatal dorsal root ganglion neurons are unpublished records kindly supplied by M. Rae, S. Robertson, E. Rowan, and C. Kennedy, University of Strathclyde; all other traces from authors unpublished records. (From Evans and Surprenant, 1996.)

The P2X<sub>1</sub> receptor seems to be the most significant P2X subtype in vascular smooth muscle, although P2X<sub>4</sub> receptors may also be expressed (Soto *et al.*, 1996a). The similar pharmacological profiles and desensitization of the recombinant P2X<sub>1</sub> receptor and its native counterpart is consistent with the concept that the vascular smooth muscle P2X receptor is a P2X<sub>1</sub> receptor homomer. ATP-gated ion channels in platelets and megakaryocytes have a similar pharmacology to the recombinant P2X<sub>1</sub> receptor, which has led to the suggestion that these ion channels are P2X<sub>1</sub> receptors (Somasundaram and Mahaut-Smith, 1994; MacKenzie *et al.*, 1996).

2. *P2X<sub>2</sub> receptor.* The P2X<sub>2</sub> receptor first cloned from rat pheochromocytoma PC12 cells (originally called P2XR1) (Brake *et al.*, 1994) displays only 41% amino acid homology with the rat vas deferens P2X<sub>1</sub> receptor. At the recombinant P2X<sub>2</sub> receptor ATP, adenosine 5'-O-(3-thiotriphosphate) (ATP $\gamma$ S) and 2MeSATP are approximately equipotent at eliciting non-selective inward cation currents, whereas  $\alpha,\beta$ -meATP and  $\beta,\gamma$ -meATP are inactive as agonists or antagonists (Brake *et al.*, 1994). This receptor undergoes little or no desensitization. It also differs from the P2X<sub>1</sub> receptor in that it is less permeable to Ca<sup>2+</sup> and shows much higher sensitivity to inhibition by extracellular Ca<sup>2+</sup> (Evans *et al.*, 1996).

P2X<sub>2</sub> receptor mRNA is distributed in bladder, brain, spinal cord, superior cervical ganglia, adrenal medulla, intestine, and vas deferens, with highest levels found in the pituitary gland and vas deferens (Brake *et al.*, 1994). Distinct but restricted patterns of distribution of P2X<sub>2</sub> mRNA have been described within rat brain (Collo *et al.*, 1996). P2X<sub>2</sub> receptor mRNA is the only P2X mRNA



observed in the adrenal medulla (Collo *et al.*, 1996). P2X<sub>2</sub> mRNA is absent from skeletal muscle, and several organs including heart, liver, kidney, lung, and spleen. Immunohistochemical detection shows a widespread distribution of the P2X<sub>2</sub> receptor in brain and spinal cord (Vulchanova *et al.*, 1996). The pharmacological profile of the P2X response in PC12 cells, namely insensitivity to  $\alpha,\beta$ -meATP and lack of desensitization, is consistent with the concept that this is an endogenous counterpart of the P2X<sub>2</sub> receptor.

Sequence homology (about 40%) between P2X<sub>2</sub> and a partial cDNA called RP-2 encoding for a protein activated in thymocytes undergoing programmed cell death, has led to the suggestion that RP-2 may encode an ion channel subunit activated by ATP released during apoptosis (Brake *et al.*, 1994).

A splice variant of a P2X<sub>2</sub> receptor has been isolated from rat cerebellum and characterized pharmacologically (Brändle *et al.*, 1997; Simon *et al.*, 1997). The protein, termed P2X<sub>2(b)</sub> or P2X<sub>2-2</sub>, has a 69 amino acid deletion of the carboxyl-terminal, shows a similar distribution in the rat central and peripheral nervous system as the original P2X<sub>2</sub> receptor (distinguished by the terminology P2X<sub>2(a)</sub>), and forms a homomeric receptor mediating inward currents to ATP (Brändle *et al.*, 1997; Simon *et al.*, 1997). Although the P2X<sub>2(b)</sub> receptor was equally sensitive to agonists as the P2X<sub>2(a)</sub> receptor, it showed significantly lower antagonist sensitivity and a faster rate of desensitization. Two other splice variants were also identified, and designated p2X<sub>2(c)</sub> and p2X<sub>2(d)</sub> to indicate that their functional significance remains to be determined (Simon *et al.*, 1997).

A truncated form of the P2X<sub>2</sub> receptor (360 amino acids compared with the 472 of P2X<sub>2</sub>), P2X<sub>2-1</sub> (originally called P2xR1), has been isolated from the pituitary gland and secretory epithelial tissue of rat cochlea (Housley *et al.*, 1995).

3. *P2X<sub>3</sub> receptor.* The P2X<sub>3</sub> receptor cloned from rat dorsal root ganglion (Chen *et al.*, 1995a; Lewis *et al.*, 1995) shows only 43% amino acid sequence homology with the P2X<sub>1</sub> receptor and 47% identity to the P2X<sub>2</sub> receptor. The P2X<sub>3</sub> receptor is activated by agonists with a potency order of 2MeSATP  $\gg$  ATP  $>$   $\alpha,\beta$ -meATP and undergoes rapid desensitization (in less than 100 ms).

The P2X<sub>3</sub> receptor has a very restricted distribution; it is expressed only by a subset of sensory neurons (trigeminal, nodose, and dorsal root ganglia), and is absent from sympathetic, enteric and central nervous system neurons, and smooth muscle (Chen *et al.*, 1995a; Lewis *et al.*, 1995; Collo *et al.*, 1996). All of the other cloned P2X receptors also have been localized in sensory neurons. The human P2X<sub>3</sub> receptor transcript is limited to spinal cord and heart (Garcia-Guzman *et al.*, 1997b). Interestingly, whereas the homomeric P2X<sub>3</sub> receptor accounts for rapidly desensitizing currents to ATP and  $\alpha,\beta$ -meATP in neonatal sensory neurons (Krishtal *et al.*, 1988a, 1988b; Li *et al.*, 1993; Robertson *et al.*, 1996), a

heteromeric P2X<sub>2</sub>P2X<sub>3</sub> receptor seems to account for the nondesensitizing response in adult sensory neurons (Lewis *et al.*, 1995), suggesting that there may be differential expression of P2X subunits in sensory neurons in development.

4. *P2X<sub>4</sub> receptor.* The P2X<sub>4</sub> receptor protein has been cloned from rat hippocampus (Bo *et al.*, 1995), DRG cells (Buell *et al.*, 1996b), rat (Séguéla *et al.*, 1996; Garcia-Guzman *et al.*, 1997a) and human brain (Soto *et al.*, 1996a; Garcia-Guzman *et al.*, 1997a), as well as rat endocrine tissue (Wang *et al.*, 1996). The P2X receptor cloned from rat brain by Séguéla *et al.* (1996) was referred to as P<sub>2x3</sub> in their paper, but a comparison of the receptor sequence with known subtypes identifies it as P2X<sub>4</sub>. A sequence homology of 87% between the human and rat P2X<sub>4</sub> receptors is sufficiently different to produce subtle differences in antagonist binding and desensitization. The recombinant P2X<sub>4</sub> receptor is most potently activated by 2MeSATP, but  $\alpha,\beta$ -meATP is weak or inactive (Bo *et al.*, 1995; Séguéla *et al.*, 1996). P2X<sub>4</sub> is relatively insensitive to the antagonists suramin and PPADS; high concentrations ( $>100 \mu\text{M}$ ) are required to block ATP-evoked currents (Bo *et al.*, 1995; Séguéla *et al.*, 1996), although the human receptor shows a higher sensitivity for suramin and PPADS (Garcia-Guzman *et al.*, 1997a). A lysine residue present in the P2X<sub>1</sub> and P2X<sub>2</sub> receptors, but absent in the P2X<sub>4</sub> receptor, is critical for the binding of antagonists but not agonists (Buell *et al.*, 1996a). The P2X<sub>4</sub> receptor does not desensitize rapidly, although reversible rundown of the current occurs during prolonged exposure to ATP (Séguéla *et al.*, 1996). More rapid desensitization of the human P2X<sub>4</sub> receptor (Garcia-Guzman *et al.*, 1997a) compared with the rat P2X<sub>4</sub> receptor (Buell *et al.*, 1996a) has been described. P2X<sub>4</sub> ATP-gated currents are potentiated by coapplication of Zn<sup>2+</sup> (Séguéla *et al.*, 1996; Garcia-Guzman *et al.*, 1997a).

P2X<sub>4</sub> receptor mRNA is expressed in brain, spinal cord, sensory ganglia, superior cervical ganglion, lung, bronchial epithelium, thymus, bladder, acinar cells of the salivary gland, adrenal gland, testis, and vas deferens (Bo *et al.*, 1995; Buell *et al.*, 1996b; Collo *et al.*, 1996; Séguéla *et al.*, 1996). Within the brain and spinal cord, the distribution of P2X<sub>4</sub> mRNA is very similar to, but not identical with, that of the P2X<sub>6</sub> receptor (Collo *et al.*, 1996). P2X<sub>4</sub> receptor mRNA is unique in that it is the only type expressed by acinar cells of the salivary gland (Collo *et al.*, 1996).

5. *P2X<sub>5</sub> receptor.* This P2X receptor was first cloned from rat coeliac ganglia (Collo *et al.*, 1996). Human homologs of the P2X<sub>5</sub> receptor have tentatively been identified (Tokuyama *et al.*, 1996a, 1996b). Rapid inward currents are activated by ATP  $>$  2MeSATP  $>$  ADP, whereas  $\alpha,\beta$ -meATP is ineffective as an agonist. The receptor does not readily desensitize. Currents are readily inhibited by suramin and PPADS. In situ hybridization shows P2X<sub>5</sub> mRNA in motoneurons of the ven-

tral horn of the cervical spinal cord, and in neurons in the trigeminal and dorsal root ganglia. With the exception of the mesencephalic nucleus of the trigeminal nerve, the brain does not express P2X<sub>5</sub> mRNA (Collo *et al.*, 1996). Appropriately, functional studies have identified P2X receptors in rat trigeminal mesencephalic nucleus neurons with a profile most similar to that of P2X<sub>5</sub> receptors (Khakh *et al.*, 1997)

6. *P2X<sub>6</sub> receptor.* This clone was isolated from a rat superior cervical ganglion cDNA library (Collo *et al.*, 1996). Rapid currents are mediated by ATP > 2MeSATP > ADP, but  $\alpha,\beta$ -meATP has no effect. Currents are only partially inhibited by suramin or PPADS. P2X<sub>6</sub> mRNA is heavily expressed in the CNS, with heaviest staining in cerebellar Purkinje cells and ependyma (Collo *et al.*, 1996). Staining is also detected in the cervical spinal cord, notably in spinal motoneurons of lamina IX, and the superficial dorsal horn neurons of lamina II. P2X<sub>6</sub> mRNA is also present in trigeminal, dorsal root, and coeliac ganglia; and in gland cells of the uterus, granulosa cells of the ovary, and bronchial epithelia, but is absent from salivary epithelia, adrenal medulla, and bladder smooth muscle (Collo *et al.*, 1996).

7. *P2X<sub>7</sub> receptor.* This receptor is considered in detail in Section X.

### C. Signal Transduction Mechanisms

P2X receptors mediate the rapid (onset within 10 ms) non-selective passage of cations (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>) across the cell membrane resulting in an increase in intracellular Ca<sup>2+</sup> and depolarization (Bean, 1992; Dubyak and el-Moatassim, 1993). The direct flux of extracellular Ca<sup>2+</sup> through the channel constitutes a significant source of the increase in intracellular Ca<sup>2+</sup>. However, membrane depolarization leads to the secondary activation of voltage-dependent Ca<sup>2+</sup> channels, which probably make the primary contribution to Ca<sup>2+</sup> influx and to the increase in intracellular Ca<sup>2+</sup>. Because this transduction mechanism does not depend on the production and diffusion of second-messengers within the cytosol or cell membrane, the response time is very rapid, and appropriately plays an important role in fast neuronal signaling and regulation of muscle contractility. P2X channels often show considerable current fluctuation, or "flickery bursts," in the open state that may represent unresolved closures or rapid transition between states (Evans and Surprenant, 1996). Selectivity for Ca<sup>2+</sup> permeability between P2X receptors on sensory versus autonomic nerves and smooth muscle has been suggested, but the patterns are not entirely clear (see Evans and Surprenant, 1996). The kinetics of ATP-gated currents have been reviewed (Surprenant, 1996).

Cations can modulate ATP-activated currents in native and endogenous P2X receptors. Mg<sup>2+</sup> and Ca<sup>2+</sup> generally inhibit P2X receptor currents, probably by decreasing the affinity of the ATP binding site by an allosteric change in the receptor (Honoré *et al.*, 1989;

Nakazawa *et al.*, 1990; Li *et al.*, 1997a). However, an increase in the transient ATP response (but not the slowly-desensitizing ATP response) has been observed when Ca<sup>2+</sup> replaces Na<sup>+</sup> in the extracellular solution in rat trigeminal sensory neurons (Cook and McCleskey, 1997). Interestingly, the recombinant P2X<sub>2</sub> receptor seems to be more susceptible than the P2X<sub>1</sub> receptor to inhibition by increases in extracellular Ca<sup>2+</sup> (Evans *et al.*, 1996). Allosteric interactions may also be responsible for the ability of monovalent cations to negatively modulate binding to recombinant P2X<sub>4</sub> receptors (Michel *et al.*, 1997), and trivalent cations to negatively modulate the binding site of recombinant P2X<sub>1</sub> and P2X<sub>2</sub> receptors and the endogenous receptor of PC12 cells (Nakazawa *et al.*, 1997).

Zn<sup>2+</sup> potentiates the cation conductance induced by ATP at most P2X receptors, including those in rat superior cervical ganglion (Cloues *et al.*, 1993; Cloues, 1995), nodose and coeliac ganglion neurons (Li *et al.*, 1993, 1996), PC12 cells (Koizumi *et al.*, 1995a), and recombinant P2X<sub>1</sub> (Brake *et al.*, 1994) and P2X<sub>4</sub> receptors (Séguela *et al.*, 1996). The P2X<sub>7</sub> receptor is an exception in this respect because it is inhibited by Zn<sup>2+</sup> and Cu<sup>2+</sup> (Virginio *et al.*, 1997). Ni<sup>2+</sup> enhances ATP-activated currents in rat superior cervical ganglia (Cloues *et al.*, 1993) and Cd<sup>2+</sup> potentiates ATP-evoked inward currents and dopamine release in rat pheochromocytoma cells (Ikeda *et al.*, 1996).

Modulation of the affinity of the ATP-binding site occurs by extracellular protons; acid pH causes an increase, and alkaline pH causes a decrease in currents, as shown for the recombinant P2X<sub>2</sub> receptor and endogenous P2X receptors in rat dorsal root and nodose ganglion cells (King *et al.*, 1996b; Li *et al.*, 1996, 1997b; Wildman *et al.*, 1997). This may be particularly significant for P2X receptor-mediated signaling in pathophysiological conditions where injury or inflammation can profoundly alter extracellular pH.

### D. Desensitization

P2X receptors can be divided into two broad groups according to whether they desensitize rapidly, that is, within 100 to 300 ms, or slowly if at all (table 10). This subdivision hinges critically on the time to desensitization; "rapid" desensitization should not be confused with desensitization which occurs over a few seconds, and thus is a phenomenon which is difficult to identify in other than studies of single channel activity. As a general rule, all rapidly desensitizing P2X receptors are activated by  $\alpha,\beta$ -meATP as well as by 2MeSATP and ATP. These include: recombinant P2X<sub>1</sub> and P2X<sub>3</sub> receptors; their endogenous counterparts, namely P2X<sub>1</sub>-like receptors of smooth muscle (with some exceptions, indicated below); P2X<sub>1</sub>-like receptors of promyelocyte HL60 cells (Buell *et al.*, 1996b); and platelets (MacKenzie *et al.*, 1996) and P2X<sub>3</sub>-like receptors of neonatal sensory neurons (dorsal root ganglion and nodose ganglion)

TABLE 10  
Distinguishing pharmacological characteristics of P2 receptors

P2X receptors	Desensitization	$\alpha,\beta$ -meATP sensitivity	PPADS sensitivity	Suramin sensitivity
P2X <sub>1</sub>	Rapid	Yes	Yes	Yes
P2X <sub>2</sub>	Slow	—	Yes	Yes
P2X <sub>3</sub>	Rapid	Yes	Yes	Yes
P2X <sub>4</sub>	Slow	—	—	—
P2X <sub>5</sub>	Slow	—	Yes	Yes
P2X <sub>6</sub>	Slow	—	—	—
P2X <sub>7</sub> (P <sub>2Z</sub> )	Slow	—	N.D.	Yes
P2X <sub>2</sub> P2X <sub>3</sub>	Slow	Yes	N.D.	N.D.

P2Y receptors	Agonist sensitivity				
	2MeSATP	ATP	UTP	ADP	UDP
P2Y <sub>1</sub>	Yes	Yes	—	Yes	—
P2Y <sub>2</sub>	—	Yes	Yes	—	—
p2y <sub>3</sub>	—	—	Yes	Yes	Yes
P2Y <sub>4</sub>	—	Yes <sup>a</sup>	Yes	—	—
P2Y <sub>6</sub>	—	—	—	—	Yes
P2Y <sub>11</sub>	Yes	Yes	—	—	—
P2Y <sub>ADP</sub>	—	— <sup>b</sup>	—	Yes	—
Endogenous uridine nucleotide-specific	—	—	Yes	—	Yes

—, weak or inactive; N.D., not determined.

<sup>a</sup> Rat, but not human. P2Y<sub>4</sub> receptor is sensitive to ATP = UTP.

<sup>b</sup> ATP is a competitive antagonist.

Lower case is used to designate the p2y3 receptor in recognition that it is a nonmammalian (chick) receptor and may be the homolog of the mammalian P2Y<sub>6</sub> receptor.

(Krishtal *et al.*, 1988a,b; Li *et al.*, 1993; Robertson *et al.*, 1996). Desensitization of P2X<sub>3</sub>-like receptors of neonatal sensory neurons, but not P2X<sub>1</sub>-like receptors of smooth muscle, is concentration-dependent (Evans and Surprenant, 1996; Robertson *et al.*, 1996). Desensitization will clearly serve to terminate the purinergic response even though ATP release may still be ongoing, but exactly why this is more important in some tissues remains to be determined.

P2X receptors which do not desensitize rapidly, desensitize slowly or not at all. These “non-desensitizing” P2X receptors are defined as receptors for which the currents are maintained for at least a few seconds in the continuous presence of agonist. Non-desensitizing P2X receptors can be further subdivided into two groups: 1) those that are sensitive to  $\alpha,\beta$ -meATP, and 2) those that are insensitive or only weakly sensitive to  $\alpha,\beta$ -meATP (Evans and Surprenant, 1996). Non-desensitizing  $\alpha,\beta$ -meATP-sensitive P2X receptors are those in adult sensory ganglia (nodose and dorsal root ganglion) (Krishtal *et al.*, 1988a, 1988b; Li *et al.*, 1993; Khakh *et al.*, 1995a; Wright and Li, 1995), and guinea-pig coeliac ganglion (Evans *et al.*, 1992; Khakh *et al.*, 1995a). It has been suggested that these receptors may be heteromers of P2X<sub>2</sub> and P2X<sub>3</sub> subunits (P2X<sub>2</sub>P2X<sub>3</sub> receptors) (Lewis *et al.*, 1995) (fig. 9). Non-desensitizing  $\alpha,\beta$ -meATP-sensitive responses have also been shown in some smooth muscle, namely in the arterial vasculature of human placenta (Dobronyi *et al.*, 1997; Ralevic *et al.*, 1997), and intestine of the three-spined stickleback *Gasterosteus aculeatus* L (Knight and Burnstock, 1993), and similarly may be caused by actions at P2X heteromers. Non-desensitizing  $\alpha,\beta$ -meATP-sensitive P2X receptors have also been described in the CNS, on rat locus coeruleus neurons (Tschöpl *et al.*, 1992; Shen and North, 1993),

and some rostral ventrolateral medulla neurons (Ralevic *et al.*, 1996).

Non-desensitizing  $\alpha,\beta$ -meATP-insensitive P2X receptors are cloned P2X<sub>2</sub>, P2X<sub>4</sub>, P2X<sub>5</sub>, and P2X<sub>6</sub> receptors (table 10a), as well as native P2X receptors on most autonomic neurons, including rat superior cervical ganglia (Cloues *et al.*, 1993; Nakazawa and Inoue, 1993; Khakh *et al.*, 1995a), guinea-pig submucosal enteric neurons (Barajas-Lopez *et al.*, 1994), PC12 cells (Nakazawa *et al.*, 1990; Nakazawa and Hess, 1993; Kim and Rabin, 1994), rat cardiac parasympathetic ganglia (Fieber and Adams, 1991), and chick ciliary ganglion neurons (Abe *et al.*, 1995). Non-desensitizing  $\alpha,\beta$ -meATP-insensitive receptors have also been described in the CNS in nucleus tractus solitarius neurons (Ueno *et al.*, 1992; Nabekura *et al.*, 1995) and trigeminal mesencephalic nucleus neurons (Khakh *et al.*, 1997); these may correspond to P2X<sub>4</sub>, P2X<sub>5</sub>, or P2X<sub>6</sub> receptors, or to combinations of these subunits, given the rich expression of these proteins in the brain. ATP-gated  $\alpha,\beta$ -meATP-insensitive currents in myometrial smooth muscle cells from pregnant rats have been reported to be resistant to desensitization (Honoré *et al.*, 1989).

The mechanism of P2X receptor desensitization is not well understood. For the rapidly desensitizing P2X<sub>1</sub> receptor, this may involve the hydrophobic domains of the receptor because transfer to the P2X<sub>2</sub> receptor of both of the hydrophobic domains, but not the extracellular loop, of the P2X<sub>1</sub> receptor changes the phenotype of the P2X<sub>2</sub> receptor from non-desensitizing to rapidly-desensitizing (Werner *et al.*, 1996). Amino acid deletions of the carboxyl terminal of the P2X<sub>2</sub> receptor produces splice variants that desensitize more rapidly than the original receptor (Brändle *et al.*, 1997; Simon *et al.*, 1997). On the other hand, the N-terminal region of the receptor has



been suggested to be important in desensitization of the P2X<sub>3</sub> receptor (King *et al.*, 1997). Desensitization of the P2X<sub>3</sub> receptor seems to involve the activation of calcineurin through the entry of extracellular calcium (King *et al.*, 1997).

### E. Agonists and Antagonists

There are no universal or subtype-selective P2X receptor agonists. ATP and diadenosine polyphosphates with a phosphate chain length greater than or equal to three are naturally-occurring agonists at P2X receptors (Hoyle *et al.*, 1989; Hoyle, 1990; Bo *et al.*, 1994; Schlüter *et al.*, 1994; Bailey and Hourani, 1995; Ralevic *et al.*, 1995a; Usune *et al.*, 1996). The greater potency of the longer chain diadenosine polyphosphates (Ap<sub>4</sub>A-Ap<sub>6</sub>A) compared with ATP at endogenous P2X<sub>1</sub>-like receptors may be caused by their greater resistance to breakdown (Hoyle, 1990; Ogilvie, 1992; Ralevic *et al.*, 1995a). UTP is a weak agonist of P2X<sub>3</sub> receptors (Chen *et al.*, 1995a; Robertson *et al.*, 1996) and may interact with P2X<sub>1</sub>-like receptors in rat urinary bladder (Hashimoto and Kokubun, 1995) as well as mouse vas deferens (Von Kügelgen *et al.*, 1990).

In physiological solution, Ca<sup>2+</sup> and Mg<sup>2+</sup> ions form complexes with the free acid ATP<sup>4-</sup>, such that the solution contains a mixture of ATP<sup>4-</sup>, MgATP<sup>2-</sup>, and CaATP<sup>2-</sup> (together with lower concentrations of the species variants MgHATP<sup>-</sup>, CaHATP<sup>-</sup>, and Ca<sub>2</sub>ATP). Under physiological conditions, ATP<sup>4-</sup> is a minor component of the total ATP concentration (approximately 1 to 10% depending on temperature, pH, and divalent cation concentration). The concentration of ATP<sup>4-</sup> decreases with increasing cation concentration and with acidic pH (that results in conversion of ATP<sup>4-</sup> to HATP<sup>3-</sup>, which has proved useful in studies aimed at investigating the identity of the active form of ATP). Cockcroft and Gomperts (1980) raised the question of which was the active form of ATP with their suggestion that ATP<sup>4-</sup> causes an increase in mast cell plasma membrane permeability. It has since been shown that this form of the ligand is likely to be responsible for pore-forming actions in mast cells, macrophages, and lymphocytes as well as a number of other cell types expressing a receptor termed the P<sub>2Z</sub> or P2X<sub>7</sub> receptor. Addition of Mg<sup>2+</sup> forms the inactive species MaATP<sup>2-</sup> and thereby reduces the concentration of ATP<sup>4-</sup>, rapidly closing the cation channel (Greenberg *et al.*, 1988; el-Moatassim and Dubyak, 1993; Gargett *et al.*, 1996; Lin and Lee, 1996). Similarly, 3'-O-(4-benzoyl)benzoyl ATP (BzATP<sup>4-</sup>), and not the complex MgBzATP<sup>2-</sup>, seems to be the active species in P<sub>2Z</sub> or P2X<sub>7</sub>-mediated pore formation.

The idea that ATP<sup>4-</sup> is the active form of ATP has been extended to P2X receptors other than the P<sub>2Z</sub> or P2X<sub>7</sub> receptor. Hence, ATP<sup>4-</sup> has been suggested to be the ligand that activates P2X receptors in guinea-pig vas deferens smooth muscle (Fedan *et al.*, 1990), rat parotid acinar cells (McMillian *et al.*, 1993), and PC12 cells (Kim

and Rabin, 1994; Choi and Kim, 1996); it also mediates ATP-gated currents in pregnant rat myometrial smooth muscle cells (Honoré *et al.*, 1989). The P2X receptors expressed by these tissues do not form nonspecific membrane pores. In these studies, suggestion of a role for ATP<sup>4-</sup> as the active ligand is based primarily on the fact that responses are inhibited by elevation of extracellular Mg<sup>2+</sup> or other cations which chelate with ATP, and because responses correlate well with the calculated ATP<sup>4-</sup> concentration and not with the total ATP concentration or with the concentration of Mg<sup>2+</sup> in solution. However, this alone does not seem to be sufficient evidence in light of more recent studies which show that divalent cations can influence agonist potency by effects other than by changes in the relative concentrations of the ATP species in solution.

It is now apparent that interpretation of the effects of removal of Mg<sup>2+</sup> and Ca<sup>2+</sup> from solution on agonist potency is complicated by additional inhibition of ectonucleotidase activity, disinhibition of single channel conductance of P2X receptors, and possibly membrane depolarization. These effects seem to have a greater influence on the end response than does a shift in the concentration of the active species of ATP. Inhibition of ecto-nucleotidase activity seems to be the overriding effect of Ca<sup>2+</sup> and Mg<sup>2+</sup> removal on agonist potency in the rat isolated vagus nerve, where the potency of responses to ATP and 2MeSATP was increased, but that of the stable analog  $\alpha,\beta$ -meATP was unchanged (Trezise *et al.*, 1994a). Studies on single channel conductance of native P2 receptors in rat nodose ganglion, PC12 cells, and recombinant P2X<sub>1</sub> and P2X<sub>2</sub> receptors, in which consideration of ecto-nucleotidase activity is effectively bypassed in conditions of concentration clamp, have confirmed that raising Ca<sup>2+</sup> or Mg<sup>2+</sup> decreases the potency of ATP (Nakazawa and Hess, 1993; Evans *et al.*, 1996; Li *et al.*, 1997a; Virginio *et al.*, 1997). However, the mechanism seems to involve a decrease in the affinity of the agonist binding site by allosteric effects on the receptor (although direct cation block of the channels is also possible) (Nakazawa and Hess, 1993; Evans *et al.*, 1996; Li *et al.*, 1997a). The fact that recombinant P2X<sub>2</sub> receptors show a higher sensitivity than P2X<sub>1</sub> receptors to inhibition by extracellular Ca<sup>2+</sup> (Evans *et al.*, 1996) is further consistent with the hypothesis that cation modulation of P2X receptors is due to changes occurring at the level of the receptor, and can be influenced by the intrinsic properties of that receptor, rather than a change in the relative concentrations of ATP species in the extracellular solution. Because of these complicating factors, the identity of the active species of ATP acting at P2X receptors is currently unclear.

$\alpha,\beta$ -MeATP is an agonist at recombinant P2X<sub>1</sub>, P2X<sub>3</sub>, and heteromeric P2X<sub>2</sub>P2X<sub>3</sub> receptors; endogenous P2X<sub>1</sub>-like receptors in smooth muscle, platelets, and HL60 cells; P2X<sub>3</sub>-like receptors in neonatal nodose and dorsal root ganglia; and P2X receptors in guinea-pig coeliac

TABLE 11  
P2 receptors in the central nervous system

Region of neurone isolation/ recording	Agonist	Antagonist/inhibitor	Receptor	Effect	Desensitization	Reference
Cerebellum	2MeSATP > ADP > ATP > ADO > $\alpha,\beta$ -meATP > AMP > UTP	GDP $\beta$ S	P2Y	K <sup>+</sup> channel	—	Ikeuchi and Nishizaki, 1996a
Inferior colliculus	2MeSATP > ADP > ATP > AMP > $\alpha,\beta$ -meATP	GDP $\beta$ S	P2Y	K <sup>+</sup> channel	—	Ikeuchi and Nishizaki, 1995b
Superior colliculus	2MeSATP > ADP > ADO > ATP > AMP (UTP, $\alpha,\beta$ -meATP inactive)	—	P2Y	K <sup>+</sup> channel	—	Ikeuchi <i>et al.</i> , 1995b
Dorsal motor nucleus of vagus	ATP ( $\alpha,\beta$ -meATP inactive)	Suramin, RB2	P2X	Rapid inward current	No	Nabekura <i>et al.</i> , 1995
Hippocampus	ATP	GDP $\beta$ S-insensitive Suramin	—	Slow inward currents <sup>a</sup>	No	Inoue <i>et al.</i> , 1992
Hippocampus	2MeSATP > ATP > ADP > ADP $\approx$ 2MeSATP > ATP > ADO > AMP (UTP, $\alpha,\beta$ -meATP inactive)	Suramin	—	Inward currents	—	Balachandran and Bennett, 1996
Hippocampus	ATP = ADP $\gg$ AMP > $\alpha,\beta$ -meATP	GDP $\beta$ S	P2Y	K <sup>+</sup> channel, $\uparrow$ [Ca <sup>2+</sup> ] <sub>i</sub>	—	Ikeuchi <i>et al.</i> , 1996a,b
Hypoglossal nucleus	ATP inactive ATP, ATP $\gamma$ S > $\alpha,\beta$ -meATP (ADP inactive)	$\uparrow$ [Ca <sup>2+</sup> ] <sub>i</sub> via PKC Suramin, PPADS	P2Y P2	$\uparrow$ [Ca <sup>2+</sup> ] <sub>i</sub> Excitation of hypoglossal nerve	—	Mironov, 1994 Funk <i>et al.</i> , 1997
Hypothalamus	ATP, ATP $\gamma$ S > $\alpha,\beta$ -meATP (ADP inactive)	Suramin	— P2X	No inward currents Rapid $\uparrow$ [Ca <sup>2+</sup> ] <sub>i</sub>	— Slow (>100 s)	Nabekura <i>et al.</i> , 1995 Chen <i>et al.</i> , 1994a
Locus ceruleus	ATP, $\alpha,\beta$ -meATP	—	P2X	$\uparrow$ Firing, depolarization	No	Harms <i>et al.</i> , 1992
Locus ceruleus	$\alpha,\beta$ -meATP, 2MeSATP	Suramin, $\alpha,\beta$ -meATP	P2X	$\uparrow$ Firing, depolarization	No	Tschöpl <i>et al.</i> , 1992
Locus ceruleus	2MeSATP > ATP = ADP > $\alpha,\beta$ -meATP	—	—	$\uparrow$ Conductance; depolarization	Slow	Shen and North, 1993
Locus ceruleus	$\alpha,\beta$ -meATP	Suramin, PPADS	P2X	Rapid depolarization	No	Nieber <i>et al.</i> , 1997
Medial habenula	ATP, $\alpha,\beta$ -meATP	Suramin, PPADS	P2X	Block of synaptic potentials	—	Edwards <i>et al.</i> , 1992
Medial vestibular nucleus	$\alpha,\beta$ -meATP	Suramin, $\alpha,\beta$ -meATP	P2X	Inward currents Block of synaptic potentials	Yes (>100 ms)	Chessell <i>et al.</i> , 1997
Medulla	ADP $\beta$ S 2MeSATP > ADP > ATP $\approx$ $\alpha,\beta$ -meATP $\approx$ AMP > UTP ATP inactive	PPADS (not suramin) GDP $\beta$ S	P2Y P2Y	$\uparrow$ Firing K <sup>+</sup> channel	Slow	Ikeuchi <i>et al.</i> , 1995a
Mesencephalic nucleus	ATP, ATP $\gamma$ S, $\alpha,\beta$ -meATP	—	—	Ineffective at evoking inward currents	—	Shen and North, 1993
Mesencephalic nucleus Nucleus tractus solitarius	ATP	Suramin	P2X	Inward currents Inward currents	Slow No	Khakh <i>et al.</i> , 1997 Ueno <i>et al.</i> , 1992, Nabekura <i>et al.</i> , 1995
Parabrachial nucleus	ATP inactive	—	—	No inward currents	—	Shen and North, 1993
Rostral ventrolateral medulla	ATP, $\alpha,\beta$ -meATP	Suramin	P2X	$\uparrow$ Firing	No	Sun <i>et al.</i> , 1992
Striatum	2MeSATP > ATP $\approx$ $\alpha,\beta$ -meATP ATP $\gg$ 2MeSATP $\approx$ ADP > ADO > AMP	Suramin, RB2, PTX	P2Y	Dopamine release	No, Yes <sup>b</sup>	Ralevic <i>et al.</i> , 1996 Zhang <i>et al.</i> , 1995
Striatum	ATP, $\alpha,\beta$ -meATP	—	—	K <sup>+</sup> channel	—	Ikeuchi and Nishizaki, 1995a

Substantia nigra	ATP	—	—	Inward currents at 1 in 12 neurones	—	Nabekura <i>et al.</i> , 1995
Supraoptic vasopressin neurones	ATP = $\alpha, \beta$ -meATP	Suramin Suramin	P2X P2	$\uparrow$ Firing Block of excitation to vagus nerve stimulation	No <sup>c</sup>	Day <i>et al.</i> , 1993
Supraoptic magnocellular neurosecretory cells (hypothalamic)	$\alpha, \beta$ -meATP > ATP > UTP > 2MeSATP > $\beta\gamma$ -meATP	PPADS	P2X	Depolarization, $\uparrow$ input conductance	No	Hiruma and Bourque, 1995
Tuberomammillary nucleus	ATP $\approx$ 2MeSATP $\gg$ $\alpha, \beta$ -meATP $\approx$ ADP	—	P2X	Rapid inward cation current	No	Furukawa <i>et al.</i> , 1994
Dorsal horn of spinal cord	ATP ATP ATP, ATP- $\gamma$ S	— — Suramin	P2X — P2X	Inward currents $\uparrow$ Excitability Rapid inward currents	Yes — Partial	Jahr and Jessel, 1983 Fyffe and Perl, 1984 Li and Perl, 1995
Spinal cord neurones	2MeSATP $\approx$ ATP $\approx$ ADP $\gg$ AMP, UTP, $\alpha, \beta$ -meATP (inactive)	GDP $\beta$ S	P2Y	K <sup>+</sup> currents	—	Ikeuchi and Nishizaki, 1996b

<sup>a</sup> A rapid inward current is also observed, but is blocked by a non-NMDA receptor antagonist.

<sup>b</sup> Desensitization observed in a subpopulation of  $\alpha, \beta$ -meATP-sensitive neurones.

<sup>c</sup> Reproducible responses to ATP on rapid application at <1 min intervals.

GDP $\beta$ S, guanosine-5'-O-(2-thiodiphosphate); G, protein inhibitor; PTX, pertussis toxin; RB2, reactive blue 2.

ganglion.  $\alpha, \beta$ -meATP generally does not bind to P2Y receptors; it is weak or inactive (EC<sub>50</sub> values 100  $\mu$ M) at recombinant receptors P2X<sub>2</sub> and P2X<sub>4-7</sub> and at the likely endogenous P2X receptor counterparts (Collo *et al.*, 1996; Evans and Surprenant, 1996).  $\alpha, \beta$ -meATP-sensitive P2X receptors are sensitive to ATP, 2MeSATP, and  $\alpha, \beta$ -meATP with EC<sub>50</sub> values of approximately 0.5 to 5  $\mu$ M, whereas  $\alpha, \beta$ -meATP-insensitive P2X receptors are generally less sensitive to ATP and 2MeSATP (EC<sub>50</sub> values 8 to 50  $\mu$ M) (Collo *et al.*, 1996; Evans and Surprenant, 1996).

P2X receptors that are sensitive to  $\alpha, \beta$ -meATP can be divided into two groups according to whether they are (rapidly) desensitizing or are non-desensitizing (see also Section IX.D., Desensitization).  $\alpha, \beta$ -MeATP-sensitive desensitizing P2X receptors are cloned P2X<sub>1</sub> and P2X<sub>3</sub> receptors and their likely endogenous counterparts.  $\alpha, \beta$ -MeATP-sensitive non-desensitizing P2X receptors include some smooth muscle P2X receptors (Knight and Burnstock, 1993; Dobronyi *et al.*, 1997; Relevic *et al.*, 1997), P2X receptors on adult dorsal root ganglion and nodose ganglion, and guinea-pig coeliac neurons as well as heteromeric P2X<sub>2</sub>P2X<sub>3</sub> receptors (Krishtal *et al.*, 1988a,b; Evans *et al.*, 1992; Li *et al.*, 1993; Khakh *et al.*, 1995a; Lewis *et al.*, 1995; Wright and Li, 1995).

Notably, L- $\beta, \gamma$ -meATP is active at P2X but not at P2Y receptors. It can discriminate between  $\alpha, \beta$ -meATP-sensitive P2X receptors on smooth muscle of vas deferens and those on neurons. It is approximately equipotent with  $\alpha, \beta$ -meATP and ATP at vas deferens and at the recombinant P2X<sub>1</sub> receptor when ecto-nucleotidase activity is suppressed, but ineffective at P2X receptors of rat vagal neurons, rat nodose ganglion neurons, and guinea-pig coeliac neurons (Trezise *et al.*, 1995; Surprenant, 1996).

ATP $\gamma$ S is an agonist at recombinant P2X<sub>2</sub> and P2X<sub>4</sub> receptors (Brake *et al.*, 1994; Bo *et al.*, 1995). It is a partial agonist at recombinant P2X<sub>1</sub> and P2X<sub>2</sub> receptors, as well as at endogenous receptors in vas deferens, PC12 cells, and nodose and coeliac ganglia (Surprenant, 1996) with potency generally less than that of ATP.

PPADS, NF023, and NF279 show selectivity as antagonists at P2X *versus* P2Y receptors (see Section VIII.C.).

#### F. Distribution and Biological Effects

Tissue distributions of the different cloned P2X receptor proteins are detailed in the section on cloned receptors (see Section IX.B.). Most of the receptor proteins have widespread distributions and most tissues express more than one subtype of P2X receptor, which may lead to heteropolymerization. Exceptions are P2X<sub>3</sub>, which is only expressed in sensory ganglia (Chen *et al.*, 1995a; Lewis *et al.*, 1995), P2X<sub>1</sub>, which is the principal subtype expressed in smooth muscle (Valera *et al.*, 1994; Collo *et al.*, 1996), and P2X<sub>4</sub>, which is the only subtype expressed by acinar cells of salivary glands (Buell *et al.*, 1996b). The principal distribution of P2X receptors is on excit-



able tissue such as smooth muscle and nerves, although they have also been cloned from, or have been shown to be expressed by, endocrine tissues (P2X<sub>4</sub>; Wang *et al.*, 1996), platelets (P2X<sub>1</sub>-like; MacKenzie *et al.*, 1996), and promyelocyte HL60 cells (P2X<sub>1</sub>-like; Buell *et al.*, 1996a).

Autoradiography using [<sup>3</sup>H]- $\alpha$ , $\beta$ -meATP, which labels P2X<sub>1</sub> and P2X<sub>3</sub> receptors, has shown high and low affinity binding sites in vascular smooth muscle, urinary bladder, brain, spinal cord, heart, liver, spleen, and cochlea (Bo and Burnstock, 1990, 1993, 1994; Michel and Humphrey, 1993; Balcar *et al.*, 1995; Mockett *et al.*, 1995). The significance of the two binding sites is not clear, and may represent distinct P2X subtypes, although [<sup>3</sup>H] $\alpha$ , $\beta$ -meATP binding to nucleotide-binding proteins cannot be excluded. At least two high affinity binding sites for [<sup>3</sup>H] $\alpha$ , $\beta$ -meATP were described in a rat aortic endothelial cell line, one of which was suggested to correspond to labeling of 5'-nucleotidase, advising caution in the use of this radioligand (Michel *et al.*, 1995).

1. **CNS.** P2X receptors are widely distributed in the CNS; excitation and activation of cation channels by ATP and/or  $\alpha$ , $\beta$ -meATP have been described throughout the brain and spinal cord (table 11). However, despite the widespread distribution of P2X receptors, evidence that ATP acts as a fast excitatory transmitter in the brain has so far been convincingly provided only for the medial habenulla (Edwards *et al.*, 1992; Edwards and Gibb, 1993) and locus coeruleus (Nieber *et al.*, 1997). In these regions, synaptic currents are blocked by suramin and by desensitization with  $\alpha$ , $\beta$ -meATP, and are mimicked by ATP and  $\alpha$ , $\beta$ -meATP. Interestingly, the non-desensitizing receptors P2X<sub>2</sub>, P2X<sub>4</sub>, and P2X<sub>6</sub> are the most abundantly expressed P2X receptors in the brain (Kidd *et al.*, 1995; Collo *et al.*, 1996), which correlates well with the majority of functional studies that show a lack of desensitization of P2X receptors in the CNS (table 11).

Activation of P2X receptors increases the activity of neurons in the rostral ventrolateral medulla and the pre-Bötzing region, areas within the brainstem that contribute specifically to central regulation of the cardiovascular system and respiratory drive (Sun *et al.*, 1992; Ralevic *et al.*, 1996, 1998). Pronounced effects on blood pressure and respiratory drive observed on micro-injection of ATP and  $\alpha$ , $\beta$ -meATP into these regions indicates a potential role for P2X receptors in central modulation of the cardiovascular and respiratory systems (Sun *et al.*, 1992; Ralevic *et al.*, 1996, 1998). Clarification of the physiological significance of these findings awaits identification of the specific pathways and release of endogenous ATP acting as a mediator of these effects.

There are marked regional differences in excitation by ATP of neurons throughout the brain. For instance, in rat brain, responses to ATP are elicited in 100% of neurons in the locus coeruleus, 96% of neurons in the dorsal motor nucleus, and 25% of neurons in the nucleus trac-

tus solitarius, while neurons in the mesencephalic and parabrachial nuclei are insensitive to ATP (Shen and North, 1993; Nabekura *et al.*, 1995). The functional significance of this is not clear. These values correlate poorly with the reported densities of [<sup>3</sup>H] $\alpha$ , $\beta$ -meATP binding in rat brain (Bo and Burnstock, 1994), probably because [<sup>3</sup>H] $\alpha$ , $\beta$ -meATP binds most strongly to P2X<sub>1</sub> and P2X<sub>3</sub> receptors and does not reflect adequately the distribution of other P2X subtypes. A strong correlation between the percentage of cells responding to ATP and ACh/nicotine suggests colocalization of P2X and nicotinic ACh receptors (Nabekura *et al.*, 1995).

2. **Sensory nerves.** Rapid inward currents are mediated by ATP in the dorsal horn of the spinal cord (Li and Perl, 1995; Li *et al.*, 1997b), and there is evidence for P2X receptor-mediated fast synaptic transmission via ATP in a small subset of dorsal horn neurons (Bardoni *et al.*, 1997). Glutamate evoked release after activation of P2X receptors on dorsal root ganglion neurons indicates a role for presynaptic P2X receptors (Gu and MacDermott, 1997). ATP-gated currents have also been shown on many sensory ganglion neurons (Krishtal *et al.*, 1988a,b; Khakh *et al.*, 1995a; Wright and Li, 1995; Robertson *et al.*, 1996; Li *et al.*, 1993, 1997a,b). P2X<sub>2</sub>P2X<sub>3</sub> heteropolymeric receptors have been suggested to account for non-desensitizing ATP-gated currents in adult sensory ganglia (Lewis *et al.*, 1995). P2X receptors also been shown in peripheral sensory nerve terminals, on capsaicin-sensitive sensory nerve terminals in canine lung (Pelleg and Hurt, 1996) and rat hindpaw (Bland-Ward and Humphrey, 1997), and in rat tooth pulp sensory neurons (Cook *et al.*, 1997), where they may be involved in nociception. Immunohistochemical studies indicate the involvement of P2X<sub>3</sub>-like receptors in ATP responses in sensory nerves of tooth pulp (Cook *et al.*, 1997). Together, these findings are consistent with the concept that ATP may be involved in the generation of pain signals via P2X receptors

3. **PNS.** ATP may act via P2X receptors to mediate transmission between neurons, as first shown by suramin-mediated block of synaptic currents between cultured coeliac ganglion cells (Evans *et al.*, 1992; Silinsky *et al.*, 1992). ATP-gated currents also have been shown on many sympathetic (Cloues *et al.*, 1993; Cloues, 1995; Khakh *et al.*, 1995a) and parasympathetic ganglia (Fieber and Adams, 1991; Abe *et al.*, 1995; Sun and Stanley, 1996)

The presynaptic P2 receptors on postganglionic sympathetic neurons may belong to the P2X receptor family. These include P2 receptors on cultured rat sympathetic neurons that mediate NA release (Boehm, 1994; Boehm *et al.*, 1995), P2 receptors in chick cultured sympathetic neurons that facilitate electrically-evoked [<sup>3</sup>H]NA release (Allgaier *et al.*, 1994a,b, 1995a,b), and P2X (P2X<sub>2</sub>-like) receptors in pheochromocytoma cells that mediate NA and dopamine release (Inoue *et al.*, 1991; Majid *et al.*, 1992, 1993; Nakazawa and Inoue, 1992; Ikeda *et al.*,

1996).  $\alpha,\beta$ -MeATP acts at presynaptic P2X-like receptors on cholinergic and nonadrenergic axons of guinea-pig ileum to enhance electrically-evoked release of [ $^3$ H]choline and [ $^3$ H]NA, respectively (Sperlagh and Vizi, 1991). Activation of cholinergic nerves in guinea-pig ileum via P2X-like receptors has been proposed (Kennedy and Humphrey, 1994). Multiple P2X receptors, predominantly P2X<sub>2</sub>-like receptors and rapidly desensitizing P2X receptors (P2X<sub>1</sub>- or P2X<sub>3</sub>-like), have been described on guinea-pig myenteric neurons (Zhou and Galligan, 1996). In rat isolated vagus nerve, responses to high, but not low, concentrations of  $\alpha,\beta$ -meATP are resistant to antagonism by suramin and reactive blue 2, but are attenuated by iso-PPADS, suggesting heterogeneity of endogenous P2X receptors (Trezise *et al.*, 1994c). An ATP-gated channel sensitive to suramin and insensitive to UTP mediates NA release from a subpopulation of adrenal chromaffin cells (Castro *et al.*, 1995).

4. *Smooth muscle.* ATP neurotransmission in the PNS identifies a physiological role for P2X receptors on smooth muscle, and as mediators of excitatory junction potentials (EJPs), depolarization, and constriction (Burnstock, 1990; Burnstock and Ralevic, 1996). The postjunctional response of the vas deferens, and most blood vessels to sympathetic nerve stimulation, is a rapid EJP that is blocked by tetrodotoxin, guanethidine, P2 receptor antagonists, and by desensitization of the P2X<sub>1</sub>-like receptor with  $\alpha,\beta$ -meATP, but is resistant to  $\alpha$ -adrenoceptor blockade (Burnstock, 1990; Von Kügelgen and Starke, 1991). Longer periods of stimulation result in summation of the EJPs and the membrane depolarizes allowing the opening of voltage-dependent Ca<sup>2+</sup> channels, Ca<sup>2+</sup> entry, and contraction. The P2X<sub>1</sub> protein is the predominant subtype expressed in vascular smooth muscle, although P2X<sub>4</sub> transcripts have been shown to be expressed in rat aorta and vena cava (Soto *et al.*, 1996a). This correlates well with the rapid desensitization of ATP and  $\alpha,\beta$ -meATP-mediated contractile responses observed in most smooth muscle preparations (Burnstock and Kennedy, 1985; Ralevic and Burnstock, 1988, 1991a,b).

The rabbit saphenous artery provides a classic example of a vessel in which pharmacological manipulations have been used to identify the relative contributions of NA and ATP to sympathetic neurotransmission (Burnstock and Warland, 1987b; Warland and Burnstock, 1987). In this vessel, sympathetic nerve stimulation produces a contractile response of which less than 30% is blocked by the  $\alpha_1$ -adrenoceptor antagonist prazosin, whereas the remainder, the purinergic component, is abolished by  $\alpha,\beta$ -meATP (Burnstock and Warland, 1987b) (fig. 10). The sympathetic origin of the purinergic response is confirmed by the fact that reserpine treatment, which depletes sympathetic nerves of their catecholamine content, fails to abolish nerve-mediated con-

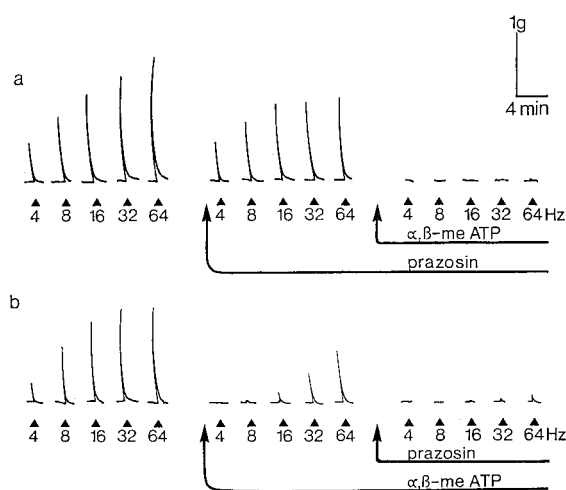


FIG. 10. Contractions produced in the isolated saphenous artery of the rabbit on neurogenic transmural stimulation (0.08–0.1 msec; supramaximal voltage) for 1 sec (a,b) at the frequencies (Hz) indicated (▲). Nerve stimulations were repeated in the presence of 10 μM prazosin added before (a) or after (b) desensitization of the P<sub>2</sub>-purinoceptor with  $\alpha,\beta$ -methylene ATP ( $\alpha,\beta$ -meATP) as indicated on the figure by the arrowed lines. The horizontal bar signifies 4 min and the vertical bar 1 g. (From Burnstock and Warland, 1987b, *Br J Pharmacol* 90:111–120; with permission from McMillan Press Limited.)

tractions despite a greater than 95% reduction in tissue NA content.

It can be envisaged that rapid desensitization of the P2X response in smooth muscle may result in attenuation of sympathetic contraction both by effectively eliminating the purinergic component of the response, as well as by removing the potential for synergistic augmentation of the response by postjunctional interactions involving P2X receptors and adrenoceptors (see Ralevic and Burnstock, 1990, 1991a). The physiological significance of rapid desensitization of the smooth muscle P2X receptor is currently unclear, although a role in negative modulation of the sympathetic response during repetitive or prolonged neurogenic stimulation seems to be indicated. The contractile response mediated by P2X receptors in the perfused arterial vasculature of human placental cotyledons is a rare example of a vascular smooth muscle P2X response that does not desensitize (Dobronyi *et al.*, 1997; Ralevic *et al.*, 1997); it may be significant that placental blood vessels are also unique in that they are not innervated.

The expression of more than one functionally-coupled P2X receptor in a single tissue is suggested in the rat vas deferens where three distinct contraction-mediating receptors for ATP were proposed based on differential functional antagonism by PPADS, suramin and reactive blue 2, and different susceptibility to desensitization (Bültmann and Starke, 1994a). Suramin-resistant components of the contractile response to ATP, which may be caused by actions at suramin-insensitive P2X<sub>4</sub> and P2X<sub>6</sub> receptors, have been described in vas deferens of mouse (Von Kügelgen *et al.*, 1990), rat (Bültmann and Starke, 1994a), and guinea pig (Bailey and Hourani,

1994, 1995), and in frog aorta (Knight and Burnstock, 1996), as well as human urinary bladder (Palea *et al.*, 1995). Where this was examined, the suramin-resistant contractile response to ATP does not appear to be caused by actions at a P2Y<sub>2</sub>-like receptor, or to ecto-nucleotidase inhibition by suramin (Von Kügelgen *et al.*, 1990; Bailey and Hourani, 1994, 1995; Knight and Burnstock, 1996). A suramin-resistant component of constriction to ATP in cat colon circular muscle also cannot be explained by the ectoATPase activity of suramin (Venkova and Krier, 1993).

Differences in pharmacological profiles have been reported for smooth muscle P2X<sub>1</sub>-like receptors of urinary bladder, vas deferens, and blood vessels (Abbracchio and Burnstock, 1994; Burnstock *et al.*, 1994). Notably, 2MeSATP and derivatives of ATP are inactive in rabbit saphenous artery but are agonists at P2X<sub>1</sub>-like receptors in guinea-pig vas deferens and bladder (Burnstock *et al.*, 1994). Non-desensitizing responses of smooth muscle to  $\alpha,\beta$ -meATP have been described in human placental arteries (Dobronyi *et al.*, 1997; Ralevic *et al.*, 1997), and stickleback intestine (Knight and Burnstock, 1993), which is different from the rapidly desensitizing P2X<sub>1</sub>-like response to  $\alpha,\beta$ -meATP typical of other smooth muscle preparations. It is possible that the non-desensitizing response is mediated by heteromeric P2X receptors with subunits conferring both sensitivity to  $\alpha,\beta$ -meATP and resistance to desensitization.

In rat and human urinary bladder, but not in dog bladder,  $\alpha,\beta$ -meATP mediates contraction, suggesting species heterogeneity with respect to expression of P2X receptors in this issue (Palea *et al.*, 1994; Suzuki and Kokubun, 1994).  $\beta,\gamma$ -MeATP is a potent constrictor of human saphenous vein, but is weak or inactive in human extrarenal veins and arteries (Von Kügelgen *et al.*, 1995a), suggesting that P2X receptor proteins are differentially distributed among vessels.

5. *Blood cells.* ATP and  $\alpha,\beta$ -meATP activate cation channels in human platelets that have been suggested to be P2X<sub>1</sub> receptors (MacKenzie *et al.*, 1996). The currents are mimicked by the spontaneous activation of single channel currents in platelets, suggested to be caused by autocrine activation following release of endogenous ADP and ATP from the platelets. In rat megakaryocytes, ATP and ATP $\gamma$ S activate a rapid (100 ms) nonselective cation channel that rapidly desensitizes (Somasundaram and Mahaut-Smith, 1994), and may also be mediated by a P2X<sub>1</sub> receptor. Currents elicited by exogenous ATP or  $\alpha,\beta$ -meATP at P2X<sub>1</sub>-like receptors in HL60 cells can only be observed when the ongoing desensitization by ATP released from these cells is removed (Buell *et al.*, 1996a), suggesting that P2X<sub>1</sub> receptors may be more widely distributed than currently anticipated.

Interactions between P2X and nicotinic ACh receptors, or possibly direct activation by ATP of ACh receptors (possibly by actions on different subunits), have

been described in PC12 cells (Nakazawa *et al.*, 1990; Nakazawa, 1994), cultured *Xenopus* myotomal muscle cells (Igusa, 1988), membranes of rat superior cervical ganglion (SCG) cells (Nakazawa and Inoue, 1993; Nakazawa, 1994), and postjunctional ACh receptors in rat cultured flexor digitorum brevis muscle fibers (Mozzrymas and Ruzzier, 1992). ATP-induced [<sup>3</sup>H]NA release from chick sympathetic neurons is blocked by nicotinic receptor antagonists (Allgaier *et al.*, 1995b). However, ATP does not act at nicotinic receptors in guinea-pig coeliac ganglion (Evans *et al.*, 1992), rat intracardiac neurons (Fieber and Adams, 1991), or, controversially, rat SCG neurons (Cloues *et al.*, 1993; Boehm, 1994).

## X. P2X<sub>7</sub> and Endogenous P2X<sub>7</sub>-Like (or P<sub>2Z</sub>) Receptors

The P2X<sub>7</sub> receptor cloned from rat macrophages and brain by Surprenant *et al.* in 1996 is the cytolytic "P<sub>2Z</sub> receptor" previously described in mast cells, macrophages, fibroblasts, lymphocytes, erythrocytes, and erythroleukemia cells. In line with the main aim of this review, "P2X<sub>7</sub>-like receptor" is used for the endogenous receptor counterpart of the P2X<sub>7</sub> receptor in preference to "P<sub>2Z</sub> receptor". A unique feature of cloned P2X<sub>7</sub> and endogenous P2X<sub>7</sub>-like receptors is that, whereas under physiological conditions these function like other P2X receptors in that they are selectively permeable to small cations only, in the continued presence of ATP and when divalent cation levels are low, the cation channel can convert to a pore, permeable to small molecules as well as ions.

### A. Structure

The P2X<sub>7</sub> receptor and its endogenous counterpart is structurally similar to other P2X receptors (see Section IX A), except for the fact that it has a significantly longer intracellular C-terminal (240 amino acids) than other P2X receptors, of which at least the last 177 amino acids are crucial for the induction of the non-selective pore (Surprenant *et al.*, 1996).

### B. Cloned P2X<sub>7</sub> Receptors

The P2X<sub>7</sub> receptor was first cloned from rat brain and macrophages (Surprenant *et al.*, 1996). The recombinant receptor has an agonist potency order for eliciting inward currents of 3'-O-(4-benzoyl)benzoyl ATP (BzATP)  $\gg$  ATP  $\gg$  2MeSATP > ATP $\gamma$ S > ADP (Surprenant *et al.*, 1996) (table 9). The human homolog has been cloned and shows a lower sensitivity to agonists (Rassendren *et al.*, 1997). In low divalent cation solution, agonists induce sustained currents and the channel becomes permeable to molecules of up to 900 daltons, although in normal solution selectivity for small cations is observed (Surprenant *et al.*, 1996). As with other P2X receptors, this receptor is inhibited by divalent cations (Rassendren *et al.*, 1997; Virginio *et al.*, 1997).



### C. Signal Transduction Mechanisms

Brief activation of the recombinant P2X<sub>7</sub> receptor and its endogenous counterpart causes rapid membrane depolarization and cation influx and is a reversible process. However, sustained activation causes an increase in permeability by allowing bidirectional transport of a variety of ions including Na<sup>+</sup>, K<sup>+</sup>, and Ca<sup>2+</sup> and small molecules with a molecular weight of less than or equal to 900 daltons, except in lymphocytes where the limit is 200–300 daltons. This effect is associated with cytotoxicity. Permeabilization involves the cytoplasmic C terminus of the protein because it does not occur with a truncated P2X<sub>7</sub> receptor lacking the last 177 residues, although cation function of the receptor is retained. The different upper size limit of the pore for P2X<sub>7</sub>-like receptors in different cells may represent isoforms of the receptor or different conductance states.

In murine and human macrophages (el-Moatassim and Dubyak, 1992, 1993; Humphreys and Dubyak, 1996) and human leukaemic lymphocytes (Gargett *et al.*, 1996; Gargett and Wiley, 1997), activation of P2X<sub>7</sub>-like receptors causes activation of phospholipase D, although the mechanism is unknown. In lymphocytes this has been suggested to be coupled to the influx of bivalent cations (Gargett *et al.*, 1996), whereas in murine macrophages it is suggested to occur distinct from P2X<sub>7</sub>-like pore formation (el-Moatassim and Dubyak, 1993). In murine macrophages BzATP-induced activation of phospholipase D is not mimicked by Ca<sup>2+</sup>-mobilizing agonists or by activators of protein kinase C (el-Moatassim and Dubyak, 1992), and in a human monocyte cell line it is blocked by calcium-calmodulin kinase II inhibition (Humphreys and Dubyak 1996).

Activation of the P2X<sub>7</sub>-like receptor of human macrophages triggers the release of the inflammatory cytokine IL-1 $\beta$ , which may provide a clue to the physiological and/or pathophysiological role of this receptor (Griffiths *et al.*, 1995; Ferrari *et al.*, 1997).

### D. Desensitization

Currents evoked at recombinant P2X<sub>7</sub> and endogenous P2X<sub>7</sub>-like receptors do not readily desensitize. However, species differences in the time for which the current flows caused by brief application of agonist have been described. Currents elicited by BzATP at the recombinant rat P2X<sub>7</sub> receptor decline slowly, particularly in low divalent cation solution, leading to sustained currents (10–20 min) even by very brief agonist application (1–3s) (Surprenant *et al.*, 1996). By contrast, currents evoked at the human P2X<sub>7</sub> receptor decline to baseline within 10–20 sec of discontinuing agonist application (Rassendren *et al.*, 1997).

### E. Agonists

The recombinant P2X<sub>7</sub> receptors and its endogenous counterpart have high selectivity for ATP, with most

other purine compounds having little or no activity. The active ligand is suggested to be the tetrabasic acid ATP<sup>4-</sup> (Cockcroft and Gomperts, 1980), which is present as approximately 1% of the relatively high concentration (100  $\mu$ M) of ATP that is required to activate this receptor. Thus, reducing the extracellular cation concentration increases agonist potency. Increasing the concentration of Mg<sup>2+</sup> rapidly closes the cation channel, although it is not clear to what extent this is due to the formation of the inactive MgATP<sup>2-</sup> complex, caused by direct block of the ion channel, or caused by a decrease in affinity caused by allosteric modulation of the receptor (Virginio *et al.*, 1997). By contrast with other P2X receptors, the P2X<sub>7</sub>-like receptor is inhibited by Cu<sup>2+</sup> and Zn<sup>2+</sup> (Virginio *et al.*, 1997). P<sup>1</sup>,P<sup>4</sup>-diadenosine tetraphosphate (Ap<sub>4</sub>A) can activate the P2X<sub>7</sub>-like receptor of mast cells, possibly because of its quadruple negative charge (Tatham *et al.*, 1988).

BzATP is currently the most potent agonist at the endogenous P2X<sub>7</sub>-like receptor; it is 10 to 100 times more potent than ATP in activating P2X<sub>7</sub>-like receptors in a number of cells (Gonzalez *et al.*, 1989a; Erb *et al.*, 1990; el-Moatassim and Dubyak, 1992; Soltoff *et al.*, 1992; McMillian *et al.*, 1993; Nuttle *et al.*, 1993), although it is only twice as potent as ATP in eliciting cytolysis of hepatocytes (Zoetewij *et al.*, 1996). Species differences between human and murine macrophage P2X<sub>7</sub>-like receptors have been suggested, based on different sensitivities to permeabilization by ATP, BzATP, and ATP $\gamma$ S (Hickman *et al.*, 1994).

### F. Antagonists

KN-62 (1-[N,O-bis(5-isoquinolinesulfonyl)-N-methyl-L-tyrosyl]-4-phenylpiperazine) has been described as a potent antagonist at the P2X<sub>7</sub>-like receptor of human lymphocytes with an IC<sub>50</sub> of approximately 12 nM (Gargett and Wiley, 1997).

2',3'-Dialdehyde ATP (oxidized ATP) is an antagonist at the P2X<sub>7</sub>-like receptor, but is irreversible and requires prolonged exposure of cells to high concentrations of inhibitor (Murgia *et al.*, 1993; Wiley *et al.*, 1994; Falzoni *et al.*, 1995; Humphreys and Dubyak, 1996; Zoetewij *et al.*, 1996; Surprenant *et al.*, 1996).

### G. Distribution and Biological Effects

P2X<sub>7</sub> mRNA and protein are distributed in bone marrow cells, including granulocytes, monocytes/macrophages and B lymphocytes, and in macrophages in brain, as shown by evidence from functional studies on these cell types (Collo *et al.*, 1997).

Functional studies have shown that P2X<sub>7</sub>-like receptor distribution is generally limited to cells of hemopoietic origin including mast cells (Cockcroft and Gomperts, 1980; Tatham *et al.*, 1988; Tatham and Lindau, 1990), macrophages (Steinberg *et al.*, 1987; Greenberg *et al.*, 1988; el-Moatassim and Dubyak, 1992, 1993; Murgia *et al.*, 1992, 1993; Hickman *et al.*, 1994; Falzoni *et al.*,

1995), the human monocyte cell line THP-1 (Humphreys and Dubyak, 1996), fibroblasts (Weisman *et al.*, 1989; Erb *et al.*, 1990; Pizzo *et al.*, 1992), erythrocytes (Parker and Snow, 1972), erythroleukaemia cells (Chahwala and Cantley, 1984), and lymphocytes (Wiley *et al.*, 1994; Gargett *et al.*, 1996; Jamieson *et al.*, 1996; Markwardt *et al.*, 1997). P2X<sub>7</sub>-like receptors are also present on hepatocytes (Zoetewij *et al.*, 1996) and parotid and salivary gland acinar cells (Sasaki and Gallacher, 1990; McMillian *et al.*, 1993; Soltoff *et al.*, 1992, 1993).

Although several roles for the P2X<sub>7</sub> receptor have been proposed, its physiological significance is largely unknown. The increased permeability caused by activation of the P2X<sub>7</sub>-like receptor results in large ion fluxes and leakage of small metabolites. On prolonged stimulation it may cause cell swelling, vacuolization, and cell death by necrosis or apoptosis (Dubyak and el-Moatassim, 1993). The biological significance of this cytotoxic effect of ATP is not clear, but may have a role in the elimination of unwanted cells during physiological or pathological cell and tissue turnover. There is increasing evidence to support suggestions that the P2X<sub>7</sub> receptor is involved in signaling between macrophages or other cells involved in the immune response and target cells (Steinberg and Di Virgilio, 1991; Dubyak and el-Moatassim, 1993); the P2X<sub>7</sub>-like receptor is involved in fusion of macrophages to form multinucleated giant cells that die shortly after fusion, a process that is inhibited by oxidized ATP (Chiozzi *et al.*, 1997). Furthermore, ATP causes the release of the inflammatory cytokine IL-1 $\beta$  via the P2Y<sub>7</sub>-like receptor of human macrophages (Griffiths *et al.*, 1995; Ferrari *et al.*, 1997).

Loss of the adhesion molecule L-selectin from leukocytes after activation of P2X<sub>7</sub>-like receptors implicates a role for these receptors in modulation of leukocyte binding to endothelial cells and migration through the vascular wall (Jamieson *et al.*, 1996; Wiley *et al.*, 1996).

## XI. P2Y Receptors

P2Y receptors are purine and pyrimidine nucleotide receptors that are coupled to G proteins. Currently this includes the cloned mammalian receptors P2Y<sub>1</sub>, P2Y<sub>2</sub>, P2Y<sub>4</sub>, P2Y<sub>6</sub>, and P2Y<sub>11</sub>, and the P2Y<sub>ADP</sub> (or P<sub>2T</sub>) receptor (that has not yet been cloned), and endogenous uridine nucleotide-specific receptors (that show some pharmacological similarities with cloned P2Y<sub>4</sub> and P2Y<sub>6</sub> receptors) (tables 10 and 12). The chick p2y3 receptor may be the homolog of the human P2Y<sub>6</sub> receptor (hence lower case lettering). Putative P2Y<sub>5</sub>, P2Y<sub>7</sub>, P2Y<sub>9</sub>, and P2Y<sub>10</sub> receptors are not included in the definitive P2Y receptor family after convincing evidence that these are not P2Y receptors. A receptor claimed as P2Y<sub>Ap4A</sub> (or P<sub>2D</sub>) has not yet been cloned, but may belong to the P2Y receptor family. A P2Y receptor has been cloned from *Xenopus* neural plate (Bogdanov *et al.*, 1997).

Receptors for pyrimidines that are activated specifically by uridine nucleotides, but not by adenine nucleotides

or nucleotides, were first proposed by Seifert and Schultz in 1989. This proposal has been confirmed by the cloning of two uridine nucleotide-specific receptors, P2Y<sub>4</sub> (human) and P2Y<sub>6</sub>, showing preference for UTP and UDP, respectively (Communi *et al.*, 1996b, c) (but see Section XV). Subsequent to Seifert and Schultz's proposal, but before the cloning of P2Y<sub>4</sub> and P2Y<sub>6</sub> receptors, some confusion in the literature was caused by the identification of "P<sub>2U</sub>-purinoceptors", activated equipotently by UTP and ATP (O'Connor *et al.*, 1991), because P<sub>2U</sub> receptors were often loosely termed "pyrimidinoceptors" and separate identity of these and receptors activated preferentially by UTP or UDP (but weakly or not at all by ATP) was often indistinct. The cloning of the P2Y<sub>2</sub> receptor and its characterization as a receptor activated by ATP, as well as UTP, helped to reinforce the concept that this receptor is distinct from receptors that are activated selectively by pyrimidines.

### A. Structure

P2Y receptors are 308 to 377 amino acid proteins with a mass of 41 to 53 kDa after glycosylation. The seven transmembrane domain tertiary structure of P2Y receptors is common to that of other G protein-coupled receptors, general features of which have been described for adenosine P1 receptors (see Section.II.B.). A model of the P2Y receptor, based on the primary sequence of the P2Y<sub>1</sub> receptor and using the structural homolog rhodopsin as a G protein-coupled receptor template, has identified positively charged amino acid residues in transmembrane regions 3, 6, and 7 that may be involved in ligand binding by electrostatic interactions with the phosphates of ATP (Van Rhee *et al.*, 1995). Several of these amino acids are conserved in other G protein-coupled receptors. Site-directed mutagenesis of the P2Y<sub>2</sub> receptor to convert positively charged amino acids in transmembrane regions 6 and 7 to neutral amino acids causes a 100- to 850-fold decrease in the potency of ATP and UTP, which suggests a role for these amino acids in binding purines and pyrimidines (Erb *et al.*, 1995). By contrast, the most critical residues for ATP binding at the human P2Y<sub>1</sub> receptor are in transmembrane regions 3 and 7 on the exofacial side of the receptor (Jiang *et al.*, 1997).

Most P2Y receptors act via G protein coupling to activate PLC leading to the formation of IP<sub>3</sub> and mobilization of intracellular Ca<sup>2+</sup>. Coupling to adenylate cyclase by some P2Y receptors has also been described. The response time of P2Y receptors is longer than that of the rapid responses mediated by P2X receptors because it involves second-messenger systems and/or ionic conductances mediated by G protein coupling. Signaling pathways for the P2Y receptor subtypes are considered in detail in the sections for each of these receptors.

## XII. P2Y<sub>1</sub> and Endogenous P2Y<sub>1</sub>-Like Receptors

The P2Y<sub>1</sub> receptor, and its endogenous counterpart termed P2Y<sub>1</sub>-like, is a receptor for the endogenous ligands ADP, ATP, and certain diadenosine polyphosphates; it is not activated by UDP and UTP. It seems to be more sensitive to adenine nucleotide diphosphates than to triphosphates. Sensitivity to ATP seems to be variable; many P2Y<sub>1</sub> and P2Y<sub>1</sub>-like receptors are relatively insensitive to ATP (ATP may act as a partial agonist), but are strongly activated by ADP (see Heterogeneity of P2Y<sub>1</sub>-like receptors, Section XII.F.). Characteristically, among all other P2Y subtypes, the P2Y<sub>1</sub> receptor and its endogenous counterpart are strongly activated by 2MeSATP, ADP, ADPβS, and adenosine-5'-O-(2-fluoro)-diphosphate (ADPβF) (table 10b). In the present review, evidence for G protein coupling, and evidence that 2MeSATP and ADP or ADPβS or ADPβF are full and potent agonists, is taken as provisional evidence for an endogenous P2Y<sub>1</sub>-like receptor, although this remains to be confirmed with the development and use of selective agonists and antagonists.

### A. Cloned P2Y<sub>1</sub> Receptors

The first cloned P2Y<sub>1</sub> receptor was from chick brain (Webb *et al.*, 1993b) (table 12). The recombinant receptor

is activated by agonists with a potency order of 2MeSATP ≥ ATP ≫ ADP, although α,β-meATP, β,γ-meATP, and UTP are inactive (Webb *et al.*, 1993b). Responses to ATP and 2MeSATP are antagonized by suramin and reactive blue 2. Activation of the recombinant P2Y<sub>1</sub> receptor mediates IP<sub>3</sub> formation and an increase in intracellular Ca<sup>2+</sup>, but no change in cAMP levels (Simon *et al.*, 1995). Homologs of the chick brain P2Y<sub>1</sub> receptor have been cloned from a variety of species (table 12). Notably, the relative potency of ATP and ADP differs widely between recombinant P2Y<sub>1</sub> and endogenous P2Y<sub>1</sub>-like receptors. Although it is possible that for recombinant receptors this is because of differences in assay conditions, the unequivocal insensitivity to ATP of some endogenous P2Y<sub>1</sub>-like receptors (Dixon *et al.*, 1995; Ralevic and Burnstock, 1996a; Webb *et al.*, 1996b) suggests that this is likely to be due to inherent differences in receptor structure.

### B. Signal Transduction Mechanisms

The main signal transduction pathway of recombinant P2Y<sub>1</sub> and endogenous P2Y<sub>1</sub>-like receptors is activation of PLC. From studies of the P2Y<sub>1</sub>-like receptor in turkey erythrocytes, the G protein has been identified as a G<sub>q</sub> protein, G<sub>11</sub>, and is insensitive to pertussis and cholera

TABLE 12  
Cloned P2Y receptors

Receptor	Number of amino acids	cDNA library source	Agonist activity	References
P2Y <sub>1</sub>	362	Human brain	2MeSATP > ATP ≫ UTP	Schachter <i>et al.</i> , 1996
		Human prostate and ovary	2MeSATP > ATP = ADP	Janssens <i>et al.</i> , 1996
		Human placenta	—	Léon <i>et al.</i> , 1995, 1997
		Human HEL cells	—	Ayyanathan <i>et al.</i> , 1996
		Bovine endothelium	2MeSATP = ADP > ATP ≫ UTP	Henderson <i>et al.</i> , 1995
		Rat insulinoma cells	2MeSATP > 2Cl-ATP > ATP (α,β-meATP inactive)	Tokuyama <i>et al.</i> , 1995
		Rat ileal myocytes	2MeSATP = 2ClATP > ADP > ATP (UTP inactive)	Pacaud <i>et al.</i> , 1996
		Mouse insulinoma cells	—	Tokuyama <i>et al.</i> , 1995
		Turkey brain	2MeSATP > ADP > ATP (UTP inactive)	Filtz <i>et al.</i> , 1994
		Chick brain	2MeSATP > ATP > ADP (UTP inactive)	Webb <i>et al.</i> , 1993b
P2Y <sub>2</sub>	373	Human CF/T43 epithelial cells	ATP = UTP ≫ 2MeSATP	Parr <i>et al.</i> , 1995
		Human bone	—	Bowler <i>et al.</i> , 1995
		Rat microvascular coronary EC	—	Gödecke <i>et al.</i> , 1996
		Rat alveolar type II cells	ATP = UTP	Rice <i>et al.</i> , 1995
		Rat pituitary	ATP = UTP > ADP = UDP > GTP	Chen <i>et al.</i> , 1996b
		Wistar Kyoto rat <sup>a</sup>	—	Seye <i>et al.</i> , 1996
		Mouse NG108-15 neuroblastoma cells	ATP = UTP > ATPγS ≫ 2MeSATP	Lustig <i>et al.</i> , 1993
p2y3 <sup>b</sup>	328	Chick brain	UDP > UTP > ADP > 2MeSATP > ATP	Webb <i>et al.</i> , 1995, 1996a
P2Y <sub>4</sub>	352	Human placenta	UTP > ATP = ADP <sup>c</sup>	Communi <i>et al.</i> , 1996b
		Human placenta	—	Stam <i>et al.</i> , 1996
		Human chromosome X	UTP > UDP (ATP inactive)	Nguyen <i>et al.</i> , 1996
		Rat heart	ATP = UTP = ADP = ITP = ATPγS = 2MeSATP = Ap <sub>4</sub> A > UDP	Bogdanov <i>et al.</i> , 1998
P2Y <sub>6</sub>	379	Human placenta and spleen	UDP > UTP > ADP > 2MeSATP ≫ ATP	Communi <i>et al.</i> , 1996b
		Rat aortic smooth muscle	UTP > ADP = 2MeSATP > ATP	Chang <i>et al.</i> , 1995
		Activated T-cells	—	Southey <i>et al.</i> , 1996
P2Y <sub>11</sub>	371	Human placenta	ATP > 2MeSATP ≫≫ ADP (UTP, UDP inactive)	Communi <i>et al.</i> , 1997

<sup>a</sup> Tissue not specified.

<sup>b</sup> p2y3 may be the chick homologue of the mammalian P2Y<sub>6</sub> receptor.

<sup>c</sup> The reported activity of UDP at the P2Y<sub>4</sub> receptor has been shown to be caused by UTP present as a contaminant.



toxin, which activates PLC $\beta$  isoenzymes via its  $\alpha$  subunit (Waldo *et al.*, 1991a, 1991b; Maurice *et al.*, 1993). Insensitivity or partial sensitivity to pertussis toxin is characteristic of most endogenous P2Y<sub>1</sub>-like receptors coupled to PLC, indicating the involvement of G<sub>q/11</sub> proteins. In contrast, P2Y<sub>1</sub>-like receptors coupled to inhibition of adenylate cyclase are typically blocked by pertussis toxin, indicating an involvement of G<sub>i</sub> proteins (Boyer *et al.*, 1995; Berti-Mattera *et al.*, 1996; Webb *et al.*, 1996c).

IP<sub>3</sub> formation and Ca<sup>2+</sup> mobilization can stimulate a variety of signaling pathways including PKC, PLA<sub>2</sub>, Ca<sup>2+</sup>-dependent K<sup>+</sup> channels, NOS and subsequent endothelium-derived relaxing factor (EDRF) formation, and can generate endothelium-derived hyperpolarizing factor (EDHF). The main physiological target of DAG is stimulation of PKC, which in turn may stimulate phosphatidyl choline-specific PLC, PLD, the MAPK pathway, and Ca<sup>2+</sup> influx via voltage-operated Ca<sup>2+</sup> channels. Generation of PKC (with no detectable elevations in IP<sub>3</sub> or cytosolic Ca<sup>2+</sup>) and subsequent rapid tyrosine phosphorylation of MAPK seems to be the pathway by which P2Y<sub>1</sub>-like (and P2Y<sub>2</sub>-like) receptors on endothelial cells mediate prostacyclin production (Bowden *et al.*, 1995; Patel *et al.*, 1996). This pathway is involved in cell metabolism, secretion, gene expression, and growth. P2Y<sub>1</sub>-like receptor activation of a phosphatidyl choline-specific PLC, and of PLD, has been reported (Martin and Michaelis, 1989; Piroton *et al.*, 1990; Purkiss and Boarder, 1992), although activation may occur downstream of PKC.

A second signaling pathway of endogenous P2Y<sub>1</sub>-like receptors may be inhibition of adenylate cyclase. This has been described for P2Y<sub>1</sub>-like receptors in a clonal population of rat brain capillary endothelial cells (B10 cells) (Webb *et al.*, 1996c). The two pathways are expressed independently, that is, P2Y<sub>1</sub>-like activation of PLC does not coincide with P2Y<sub>1</sub>-like inhibition of adenylate cyclase. It is not yet clear whether this involves differential G protein-coupling or is caused by heterogeneity of P2Y<sub>1</sub>-like receptors (Webb *et al.*, 1996c). P2Y receptor-mediated adenylate cyclase inhibition was originally described for P2Y<sub>1</sub>-like receptors in rat C6 glioma cells and the clonal cell line C6-2B (Pianet *et al.*, 1989; Valeins *et al.*, 1992; Lin and Chuang, 1993; Boyer *et al.*, 1993, 1994, 1995). However, the decrease in cAMP in C6 cells is not blocked by selective antagonists of the P2Y<sub>1</sub> receptor, which suggests that these receptors are distinct from P2Y<sub>1</sub> receptors coupled to activation of PLC (Boyer *et al.*, 1996). P2Y<sub>1</sub>-like receptor-mediated inhibition of adenylate cyclase activity has also been described in Schwann cells (Berti-Mattera *et al.*, 1996). Inhibition of adenylate cyclase is pertussis toxin-sensitive, indicating an involvement of G<sub>i</sub> proteins, but it is unclear whether activation is mediated by  $\alpha$ ,  $\beta$ , or  $\gamma$  subunits (Boyer *et al.*, 1995; Harden *et al.*, 1995; Webb *et al.*, 1996c).

P2Y<sub>1</sub>-like receptors may mediate membrane-delimited G protein regulation of ion channels, that is, lack the involvement of cytosolic second-messenger systems. Although membrane-delimited regulation is frequently assumed to imply a direct physical interaction between the active G protein subunit and the ion channel, some ion channels may be regulated by lipid-soluble second-messengers such as arachidonic acid and metabolites (Wickman and Clapham, 1995). In rat cerebellar neurons, the opening of an outwardly rectifying, pertussis toxin-insensitive GDP $\beta$ S-sensitive K<sup>+</sup> current by 2MeSATP > ADP > ATP activation of a P2Y<sub>1</sub>-like receptor was suggested via coupling of the  $\beta$ ,  $\gamma$  subunits of the G protein to a K<sup>+</sup> channel (Ikeuchi and Nishizaki, 1996a). The single channel currents induced by 2MeSATP were without latency, suggesting that the channel was activated only by plasma membrane factors without the involvement of intracellular components (Ikeuchi and Nishizaki, 1996a). An ADP-sensitive K<sup>+</sup> channel in inferior colliculus (Ikeuchi and Nishizaki, 1995b) and medullar (Ikeuchi *et al.*, 1995a) neurons was also suggested to be activated by direct action of the  $\beta\gamma$  subunits of the G protein. In contrast, 2MeSATP and ATP activation of a K<sup>+</sup> channel in striatal neurons seems to be mediated via PKC (Ikeuchi and Nishizaki, 1995a).

In some cells, P2Y<sub>1</sub>-like receptors are colocalized with P2Y<sub>2</sub>-like receptors. The biological significance of this is not clear, particularly where ATP is a common agonist, but makes more sense where the P2Y<sub>1</sub>-like receptor is selective for ADP, and ATP acts only at the P2Y<sub>2</sub>-like receptor (as has shown to be the case for coexisting P2Y<sub>1</sub>- and P2Y<sub>2</sub>-like receptors on some endothelial cells). The receptors have similar signaling pathways, although the P2Y<sub>1</sub>-like receptor seems to be more sensitive than the P2Y<sub>2</sub>-like receptor to manipulations of PKC activity. This is likely to be related to the important role of PKC as a negative feedback regulator of PLC activity to allow finely tuned regulation of this signaling pathway. Thus, stimulation of PKC with 12-O-tetradecanoyl- $\beta$ -phorbol 13-acetate (TPA) causes a greater inhibition of P2Y<sub>1</sub>- than of P2Y<sub>2</sub>-like receptor mediated responses in rat osteoblastic cells (Gallinaro *et al.*, 1995). The IP<sub>3</sub> response of the endothelial P2Y<sub>1</sub>-like receptor is attenuated by stimulation of PKC with phorbol 12-myristate 13-acetate and enhanced by PKC inhibition with Ro 31-8220, but the P2Y<sub>2</sub>-like response is less affected or is unaffected (Purkiss *et al.*, 1994; Communi *et al.*, 1995; Chen *et al.*, 1996a). Discrimination between the signaling pathways of P2Y<sub>1</sub>- and P2Y<sub>2</sub>-like receptors, and the ways in which these may be differentially modulated, might provide some clues about the biological significance of their colocalization.

### C. Desensitization

In general, P2Y<sub>1</sub> and P2Y<sub>1</sub>-like receptors do not readily desensitize. When this does occur, as with other G protein-coupled receptors, desensitization may in-

involve receptor phosphorylation by protein kinases and uncoupling from the associated G protein. Studies of the P2Y<sub>1</sub>-like receptor in turkey erythrocyte membranes showed that desensitization ( $t_{1/2}$  15 min) is heterologous, involves multiple mechanisms, and does not involve PKC or intracellular Ca<sup>2+</sup> (Galas and Harden, 1995). In cultured bovine aortic endothelial cells, preexposure to 2MeSATP or UTP causes homologous partial desensitization of IP<sub>3</sub> formation by P2Y<sub>1</sub>- and P2Y<sub>2</sub>-like receptors, respectively, and heterologous partial desensitization of the 2MeSATP response by UTP (Wilkinson *et al.*, 1994). P2Y<sub>1</sub>-like receptor desensitization has also been observed in rat colon muscularis mucosae (Hourani *et al.*, 1993) and rabbit mesenteric arterial smooth muscle (Ziganshin *et al.*, 1994b).

#### D. Agonists

The P2Y<sub>1</sub> and P2Y<sub>1</sub>-like receptor is generally more sensitive to adenine nucleotide diphosphates than to triphosphates. ADPβS, ADPβF, and 3'-deoxyATPαS (dATPαS) are potent agonists at P2Y<sub>1</sub> receptors. 2MeSATP is a potent and selective agonist at the P2Y<sub>1</sub> and P2Y<sub>1</sub>-like receptor *versus* other cloned P2Y receptors (but see P2Y<sub>11</sub> receptor, Section XVII.), but is also a potent agonist at most P2X receptors. α,β-meATP, β,γ-meATP, and UTP are inactive and thus are useful as negative evidence in the characterization of this receptor. Certain of the diadenosine polyphosphates (particularly those with a phosphate chain of three phosphates or less) may be natural, albeit non-selective, agonists at P2Y<sub>1</sub>-like receptors (Ralevic *et al.*, 1995a; Pintor *et al.*, 1996). The potency of ATP differs widely among endogenous P2Y<sub>1</sub>-like receptors, and the lack of effect of ATP at some endogenous P2Y<sub>1</sub>-like receptors is unequivocal (Dixon *et al.*, 1995; Ralevic and Burnstock, 1996a; Webb *et al.*, 1996b). This would tend to rule out the possibility that this heterogeneity is caused by contamination of solutions of ADP and ATP caused by purine interconversion and metabolism. However, molecular evidence does not support a subdivision of the P2Y<sub>1</sub> receptor, and heterogeneity of ADP/ATP relative potencies is also apparent for recombinant P2Y<sub>1</sub> receptors (table 12).

The charge carried by the molecule may influence agonist potency; it has been suggested that ATP uncomplexed with divalent cations, ATP<sup>4-</sup>, is the preferred agonist of the P2Y<sub>1</sub>-like receptor expressed on bovine aortic endothelial cells (Motte *et al.*, 1993b). In the guinea-pig taenia coli, the order of potency for relaxation at the P2Y<sub>1</sub>-like receptor by non-hydrolysable analogs of β,γ-meATP reflects the order of electronegativity, with the more acidic analogs being more potent: AMP-PCF<sub>2</sub>P > AMP-CCl<sub>2</sub>P > β,γ-meATP (Cusack *et al.*, 1987).

2-Thioether derivatives of adenine nucleotides, including 2-hexylthio ATP and 2-cyclohexylthio ATP, are potent agonists at P2Y<sub>1</sub>-like receptors coupled to adenylate cyclase (EC<sub>50</sub> values 28 and 58 pM respectively),

but are significantly less potent at PLC-coupled P2Y<sub>1</sub> receptors (Boyer *et al.*, 1995). N<sup>6</sup>-Methyl ATP is selective for P2Y<sub>1</sub>-like receptors in the taenia coli versus vascular P2Y<sub>1</sub>-like receptors (Fischer *et al.*, 1993; Burnstock *et al.*, 1994).

#### E. Antagonists

Adenosine 3',5'- and 2',5'-bisphosphates act as competitive antagonists at the P2Y<sub>1</sub> receptor coupled to PLC; adenosine-3'-phosphate-5'-phosphosulfate (A3P5PS) and adenosine-3'-phosphate-5'-phosphate (A3P5P) block responses at the recombinant P2Y<sub>1</sub> receptor with pK<sub>B</sub> values of 6.5 and 5.7, respectively (Boyer *et al.*, 1996). These compounds are inactive at the adenylate cyclase-coupled P2Y<sub>1</sub>-like receptor of C6 glioma cells and at recombinant P2Y<sub>2</sub>, P2Y<sub>4</sub>, or P2Y<sub>6</sub> receptors (Boyer *et al.*, 1996). Interestingly, A3P5PS and A3P5P are partial agonists at the turkey but not the human recombinant P2Y<sub>1</sub> receptor. N<sup>6</sup>-methyl modification of 2'-deoxyadenosine 3'5'-bisphosphate, to produce the compound MRS 2179, enhanced antagonist potency (IC<sub>50</sub> value 330 nM) by 17-fold and eliminated the partial agonist properties observed with the lead compound, resulting in the most potent P2Y<sub>1</sub> receptor antagonist reported to date (Camaioni *et al.*, 1998).

#### F. Heterogeneity of P2Y<sub>1</sub> and Endogenous P2Y<sub>1</sub>-Like Receptors

Although endogenous P2Y<sub>1</sub>-like receptors couple to different signal transduction pathways and there may be profound differences in their ligand binding profiles, molecular evidence does not support the subdivision of this receptor. It seems most likely that this heterogeneity may arise from small differences in structure. Sequence homology of only 84% between turkey and human P2Y<sub>1</sub> receptors may explain why A3P5PS and A3P5P are partial agonists at the turkey P2Y<sub>1</sub> receptor but not its human homolog (Boyer *et al.*, 1996). These receptors were expressed in the same cell type and assayed under the same conditions.

Heterogeneity in ligand binding at P2Y<sub>1</sub> receptors includes both agonist and antagonist binding profiles. Recombinant P2Y<sub>1</sub> receptors cloned from different species and tissues show different relative potencies to ATP and ADP (table 12), as do their endogenous counterparts. Although the true potency of ATP at endogenous P2Y<sub>1</sub>-like receptors is difficult to assess because of actions at coexisting receptors and rapid breakdown by ecto-nucleotidases, ADP-specific P2Y<sub>1</sub>-like receptors that are activated potently by ADP and 2MeSATP, but weakly or not at all by ATP, have been described in a number of isolated cells and tissues, including rat hepatocytes (Keppens and deWulf, 1991; Keppens *et al.*, 1992; Dixon *et al.*, 1995), endothelium of rat mesenteric arteries (Ralevic and Burnstock, 1996a,) and rat brain capillary endothelial cells (Feolde *et al.*, 1995; Webb *et al.*, 1996c). The P2 receptor antagonist PPADS has been shown to block vasodilatation mediated by ADP and

2MeSATP (at a P2Y<sub>1</sub>-like receptor) but not to ATP and UTP (at a P2Y<sub>2</sub>-like receptor), which implies that at least in rat mesenteric arteries, ATP does not act at P2Y<sub>1</sub>-like receptors, although it does act at P2Y<sub>2</sub>-like receptors (Ralevic and Burnstock, 1996a). This has important implications for the agonist selectivity of P2Y<sub>1</sub> receptors in other tissues.

ADP-specific P2Y<sub>1</sub>-like receptors may account for some of the ambiguities in the literature concerning classification of P2Y receptors. Thus, ADP-activated P2Y receptors identified as "P<sub>2T</sub>" (P2Y<sub>ADP</sub>) receptors in osteoblasts (Sistare *et al.*, 1994, 1995) are likely to be ADP-specific P2Y<sub>1</sub> receptors because 2MeSATP and ADP are equipotent agonists (Reimer and Dixon, 1992; Sistare *et al.*, 1994, 1995; Dixon *et al.*, 1997b). A "P<sub>2T</sub>" receptor coexisting with the P2Y<sub>2</sub> receptor in porcine ovarian granulosa cells may also be an ADP-specific P2Y<sub>1</sub> receptor (Kamada *et al.*, 1994).

PPADS is able to discriminate between some P2Y<sub>1</sub> receptors; it generally blocks recombinant P2Y<sub>1</sub> receptors and endogenous P2Y<sub>1</sub>-like receptors coupled to PLC (Boyer *et al.*, 1994; Brown *et al.*, 1995; Charlton *et al.*, 1996a; Schachter *et al.*, 1996) but has no effect at P2Y<sub>1</sub>-like receptors coupled to inhibition of adenylate cyclase (Boyer *et al.*, 1994; Webb *et al.*, 1996c). On the other hand, PPADS is ineffective at rabbit aortic endothelial P2Y<sub>1</sub>-like receptors, where PLC coupling might be expected (Ziganshin *et al.*, 1994b). Block of P2Y<sub>1</sub>-like receptors with different pA<sub>2</sub> values also implies receptor heterogeneity: pA<sub>2</sub> values 5.1 and 5.3 in rat duodenum and guinea-pig taenia coli, respectively, (Windscheif *et al.*, 1995a); pA<sub>2</sub> values 6.0 in rat mesenteric arterial endothelium (Ralevic and Burnstock, 1996a) and at recombinant turkey brain (Charlton *et al.*, 1996a) P2Y<sub>1</sub> receptors. PPADS is ineffective as an antagonist at rabbit mesenteric arterial smooth muscle P2Y<sub>1</sub>-like receptors (Ziganshin *et al.*, 1994b).

Different sensitivities to ATP and analogs of ATP have been shown for P2Y<sub>1</sub>-like receptors in guinea-pig taenia coli, and in vascular endothelium and smooth muscle (Fischer *et al.*, 1993; Burnstock *et al.*, 1994; Abbraccio and Burnstock, 1994). Among other differences, N<sup>6</sup>-methylATP is a selective agonist at guinea-pig taenia coli P2Y<sub>1</sub>-like receptors, but is inactive at vascular P2Y<sub>1</sub>-like receptors (Fischer *et al.*, 1993; Burnstock *et al.*, 1994). Relaxation by  $\alpha,\beta$ -meATP of the guinea-pig taenia coli seems to be via a P2Y receptor of undetermined subtype as this response is not blocked by the P2X-selective antagonist Evans blue (Bültmann *et al.*, 1996). 2-Thioether derivatives of adenine nucleotides are potent agonists at adenylyl cyclase-linked P2Y<sub>1</sub>-like receptors in C6 rat glioma cells, but not at PLC-linked P2Y<sub>1</sub>-like receptors of turkey erythrocytes (Boyer *et al.*, 1995). Interestingly, ATP seems to be a partial agonist at adenylate cyclase-coupled P2Y receptors. At the endothelial P2Y<sub>1</sub>-like receptor, P<sup>1</sup>,P<sup>3</sup>-diadenosine triphosphate (Ap<sub>3</sub>A) is the most potent ligand and P<sup>1</sup>,P<sup>5</sup>-diadenosine

pentaphosphate (Ap<sub>5</sub>A) is inactive (Ralevic *et al.*, 1995a).

### G. Distribution and Biological Effects

P2Y<sub>1</sub> and P2Y<sub>1</sub>-like receptors are widely distributed having been described in heart, vascular, connective, immune, and neural tissues. The transcript for chick brain P2Y<sub>1</sub> mRNA is distributed in brain, spinal cord, gastrointestinal tract, spleen, and skeletal muscle, but not in heart, liver, stomach, lung, or kidney (Webb *et al.*, 1993b). In the rat, P2Y<sub>1</sub> receptor mRNA is expressed at variable levels in many tissues including heart, brain, spleen, lung, liver, skeletal muscle, and kidney, but is not detected in testis (Tokuyama *et al.*, 1995). Within the brain, P2Y<sub>1</sub> mRNA has a widespread but specific distribution, being particularly rich in various nuclei of the telencephalon, diencephalon, and mesencephalon as well as in the external granule, Purkinje, and internal granule cells of the cerebellum (Webb *et al.*, 1994).

Receptors with the pharmacological profile of a P2Y<sub>1</sub> receptor have been identified in functional studies in a wide variety of cells including rat astrocytes (Pearce *et al.*, 1989; Pearce and Langley, 1994), frog glial cells (Robitaille, 1995), avian erythrocytes (Berrie *et al.*, 1989; Boyer *et al.*, 1989), rat osteoblasts (Reimer and Dixon, 1992; Gallinaro *et al.*, 1995), pancreatic  $\beta$  cells (Petit *et al.*, 1988), rat mast cells (Osipchuk and Cahalan, 1992), rat alveolar type II cells (Rice and Singleton, 1987), human T-leukemia cells (Biffen and Alexander, 1994), rat cochlear lateral wall (Ogawa and Schacht, 1995), and rat cochlear lateral wall epithelial cells (Ikeda *et al.*, 1995). The physiological significance of these receptors is still largely undetermined. Diverse P2Y<sub>1</sub>-like receptor-mediated metabolic effects include insulin secretion from pancreatic  $\beta$ -cells (Bertrand *et al.*, 1987; Hillaire-Buys *et al.*, 1991, 1993, 1994), renin secretion in renal cortical slices (Churchill and Ellis, 1993a, 1993b), gluconeogenesis in renal cortical tubules (Cha *et al.*, 1995), and glycogenolysis in rat hepatocytes (Keppens and De Wulf, 1991).

The distribution of P2Y<sub>1</sub>-like receptors on vascular endothelium and smooth muscle cells implies a role in the regulation of vascular tone. In most blood vessels, P2Y<sub>1</sub>-like receptors are present on the endothelium and mediate vasodilatation by Ca<sup>2+</sup>-dependent activation of endothelial NOS and generation of EDRF and by generation of EDHF. Endothelial prostacyclin production is also stimulated by the P2Y<sub>1</sub>-like receptor, but this seems to play a minimal role in vasodilatation, at least under physiological conditions. The fact that ATP and ADP are released locally from endothelial cells during shear stress and hypoxia and from platelets during aggregation, identifies a possible role for endothelial P2Y<sub>1</sub>-like receptors in modulation of vascular tone under normal conditions and during thrombosis. P2Y<sub>1</sub>-like receptors on pulmonary artery endothelium may be involved in stimulation of leukocyte adhesion (Dawicki *et al.*, 1995).



P2Y<sub>1</sub>-like receptors are present on the smooth muscle of a number of blood vessels and, like their endothelial counterparts, mediate vasodilatation (Kennedy and Burnstock, 1985; Mathieson and Burnstock, 1985; Burnstock and Warland, 1987a; Liu *et al.*, 1989; Brizzolara and Burnstock, 1991; Keefe *et al.*, 1992; Corr and Burnstock, 1994; Qasabian *et al.*, 1997; Simonsen *et al.*, 1997). P2Y<sub>1</sub>-like receptors (and P2Y<sub>2</sub>-like receptors) are expressed by human coronary artery smooth muscle cells in culture (Strøbæk *et al.*, 1996). The mechanism underlying relaxation by smooth muscle P2Y<sub>1</sub>-like receptors is not known but may involve activation of K<sup>+</sup> channels. In rabbit mesenteric arteries and skeletal muscle-resistance arteries, glibenclamide partially blocks smooth muscle hyperpolarization and relaxation to ADP, indicating a role for K<sub>ATP</sub> channels (Brayden, 1991). The smooth muscle P2Y<sub>1</sub>-like receptor of rabbit pulmonary artery mediates relaxation independently of mobilization of intracellular Ca<sup>2+</sup> (in contrast with that mediated by coexisting P2Y<sub>2</sub>-like receptors) implying lack of involvement of the PLC pathway (Qasabian *et al.*, 1997). The biological significance of P2Y<sub>1</sub>-like receptors expressed by the smooth muscle of rabbit portal vein (Brizzolara *et al.*, 1993) (fig. 11), guinea-pig pulmonary artery (Liu *et al.*, 1992), and lamb small coronary arteries (Simonsen *et al.*, 1997) may be in mediation of the neurogenic, purinergic (non-adrenergic non-cholinergic) relaxation shown in these vessels. It is possible that vascular smooth muscle P2Y<sub>1</sub>-like receptors mediate relaxation to ATP released as a neurotransmitter from sensory-motor nerves. A P2Y<sub>1</sub>-like receptor on cultured aortic smooth muscle cells has been reported to mediate the mitogenic effect of ATP via activation of PKC, and then Raf-1 and MAPK (Yu *et al.*, 1996); it has also been reported to cause induction of immediate early genes (Malam-Souley *et al.*, 1996), which indicates a role in vascular smooth muscle proliferation.

Interestingly, autocatalytic release of ATP (ATP-mediated release of ATP) has been described in guinea-pig cardiac endothelial cells, which may involve P2Y<sub>1</sub>-like receptors (Yang *et al.*, 1994). A P2Y<sub>1</sub>-like receptor on rat basophilic leukocyte cells is suggested to amplify intracellular Ca<sup>2+</sup> signaling and secretory responses to antigen stimulation, and to propagate the response to neighboring cells partly by the release of additional stores of ATP from secretory granules (Osipchuk and Cahalan, 1992).

Activation of the P2Y<sub>1</sub>-like receptor expressed on platelets leads to platelet shape change, aggregation, and intracellular calcium rise, with no effect on adenylate cyclase (Daniel *et al.*, 1998; Hechler *et al.*, 1998; Jin *et al.*, 1998). This effect is blocked by the selective P2Y<sub>1</sub> receptor antagonists A2P5P and A3P5P. The P2Y<sub>1</sub> receptor seems to be crucial for triggering the ADP-induced shape change, whereas aggregation is mediated by cooperative effects with platelet P2Y<sub>ADP</sub> (or P2<sub>T</sub>) re-

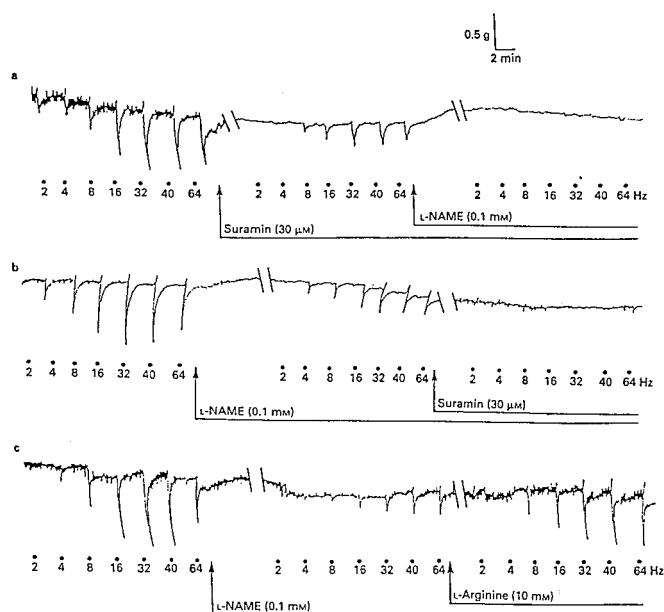


FIG. 11. Relaxations of the rabbit portal vein to neurogenic transmural stimulation for 10 sec (2 to 64 Hz, 0.7 ms, 100 V) at 5 min intervals. Guanethidine (3.4 μM) and atropine (0.114 μM) were present throughout to block adrenergic and cholinergic neurotransmission respectively. Tone was induced with ergotamine (8.6 μM). Panel (a) shows that preincubation with suramin (30 μM) for 20 min reduced the nerve-mediated relaxations compared with controls and that suramin-resistant neurogenic relaxations were abolished 20 min after the addition of the nitric oxide synthase inhibitor, N<sup>G</sup>-nitro-L-arginine methyl ester (L-NAME, 0.1 mM). Panel (b) shows that neurogenic relaxations remaining after 20 min pretreatment of the tissue with L-NAME (0.1 mM) were abolished 20 min after the addition of suramin (30 μM). In (c), the effect of adding L-NAME (0.1 mM) to the tissue is shown; there was an additional rise in tone and inhibition of the response to nerve stimulation after a 20 min incubation period. The subsequent treatment of tissues with L-arginine (10 mM) for 20 min reversed this effect. Each of the traces in (a), (b), and (c) is representative of similar results in six separate experiments. (From Brizzolara *et al.*, 1993, *Br J Pharmacol* 109:606–608; with permission from McMillan Press Limited).

ceptor-mediated inhibition of adenylate cyclase (Daniel *et al.*, 1998; Hechler *et al.*, 1998; Jin *et al.*, 1998).

P2Y<sub>1</sub> receptor mRNA is selectively expressed by large diameter sensory neurons and when expressed in oocytes was shown to be mechano-sensitive and to exhibit inward currents (Nakamura and Strittmatter, 1996). A functional correlate may be ATP-triggered Ca<sup>2+</sup> release from IP<sub>3</sub>-sensitive Ca<sup>2+</sup> stores in large DGR neurons; [Ca<sup>2+</sup>]<sub>i</sub> transients were not elicited by small neurons (Svichar *et al.*, 1997).

ATP inhibits the light-evoked release of ACh from rabbit retinal cholinergic neurons in a DPCPX-insensitive manner, although the receptor subtype is not clear (Neal and Cunningham, 1994). A P2Y<sub>1</sub>-like receptor may mediate inhibition by ATP and 2MeSATP (but not α,β-meATP) of excitatory postsynaptic potentials in guinea-pig submucosal neurons, and although it is suggested that it is a P3-like receptor, it is not activated by adenosine (Barajas-López *et al.*, 1995).

P2Y<sub>1</sub>-like receptors mediate the opening of K<sup>+</sup> channels in rat cultured cerebellar neurons, striatal neurons, superior and inferior colliculus neurons, medullar neu-

rons, hippocampal neurons, and spinal neurons (Ikeuchi *et al.*, 1995a,b; 1996a,b; Ikeuchi and Nishizaki, 1995b; 1996a,b). The transduction mechanism seems to be a pertussis toxin-insensitive G protein which directly opens the potassium channels via its  $\beta\gamma$  subunit. Adenosine seems to be an agonist at P2Y<sub>1</sub>-like receptors in hippocampal neurons (Ikeuchi *et al.*, 1996a) and neurons of the superior colliculus (Ikeuchi *et al.*, 1995b), raising the possibility that these are P1 or P3 receptors. A P2Y<sub>1</sub>-like receptor mediates dopamine release in rat striatum (Zhang *et al.*, 1995). An increase in the firing rate of rat medial vestibular nucleus neurons by ADP $\beta$ S has been attributed to activation of P2Y receptors (Chesell *et al.*, 1997).

### XIII. P2Y<sub>2</sub> and Endogenous P2Y<sub>2</sub>-Like Receptors

The P2Y<sub>2</sub> receptor (and its endogenous counterpart, formerly called the P<sub>2U</sub> receptor) is activated by ATP and UTP with approximately equal potency and is insensitive or is only weakly activated by ADP and other nucleoside diphosphates, 2MeSATP and  $\alpha,\beta$ -meATP (table 10b). In this review, endogenous receptors exhibiting this pharmacological profile have provisionally been termed P2Y<sub>2</sub>-like (but see Section XV.).

#### A. Cloned P2Y<sub>2</sub> Receptors

The first cloned P2Y<sub>2</sub> receptor was from mouse NG108–15 neuroblastoma cells (Lustig *et al.*, 1993). Species homologs have been cloned from rat, cat, and human (table 12).

#### B. Signal Transduction Mechanisms

Cloned P2Y<sub>2</sub> and endogenous P2Y<sub>2</sub>-like receptors couple via both G<sub>i/o</sub> and G<sub>q/11</sub> proteins to mediate phospholipid breakdown and phosphoinositides as well as Ca<sup>2+</sup> mobilization via PLC $\beta$ , an effect which may accordingly be pertussis toxin-sensitive, -partially sensitive, or -insensitive (see Dubyak and el-Moatassim, 1993). P2Y<sub>2</sub>-like receptor coupling to G<sub>i</sub> proteins involves the  $\beta\gamma$  G<sub>i</sub> protein subunits, which stimulate phospholipase C- $\beta$ <sub>2</sub>. IP<sub>3</sub> formation, Ca<sup>2+</sup> mobilization, and a variety of signaling pathways including PKC, PLA<sub>2</sub>, Ca<sup>2+</sup>-dependent K<sup>+</sup> channels, and EDRF and EDHF formation. The specific downstream involvement of a given signaling pathway seems to be partially dependent on the cell type in which the P2Y<sub>2</sub>-like receptor is expressed.

Activation of PLD and stimulation of phosphatidylcholine breakdown by P2Y<sub>2</sub>-like receptors has been reported (Purkiss and Boarder, 1992; Pfeilschifter and Merriweather, 1993; Balboa *et al.*, 1994; Gerwins and Fredholm, 1995a,b). The mechanism of activation of PLD is unclear but may involve the combined actions of PKC, Ca<sup>2+</sup>, and G proteins, as suggested for P2Y<sub>2</sub>-mediated pertussis toxin-insensitive activation of PLD in DDT<sub>1</sub> MF2 cells (Gerwins and Fredholm, 1995b). As with the P2Y<sub>1</sub>-like receptor, protein tyrosine phosphorylation

and MAPK activation seems to be the major route for P2Y<sub>2</sub>-like receptor-mediated prostacyclin production in endothelial cells (Bowden *et al.*, 1995; Patel *et al.*, 1996). This occurs subsequent to activation of PKC and does not involve IP<sub>3</sub> or cytosolic Ca<sup>2+</sup> (Patel *et al.*, 1996). Stress-activated protein kinases, independent of PKC activation, have been shown to be activated by ATP and UTP in rat renal mesangial cells (Huwiler *et al.*, 1997).

Secondary to activation of PLC and mobilization of Ca<sup>2+</sup>, the P2Y<sub>2</sub>-like receptor mediates the opening of Ca<sup>2+</sup>-sensitive Cl<sup>-</sup> channels in airway epithelia (Clarke and Boucher, 1992; Stutts *et al.*, 1992), intrahepatic biliary epithelial cell lines (Wolkoff *et al.*, 1995), and avian exocrine salt gland cells (Martin and Shuttleworth, 1995), which drives fluid secretion. Activation of P2Y<sub>2</sub>-like receptors stimulates cation and K<sup>+</sup> currents via Ca<sup>2+</sup>-dependent signaling mechanisms in HTC cells from a rat liver tumor cell line (Fitz and Sostman, 1994). UTP and ATP mediate depolarization of supraoptic neurosecretory cells in rat hypothalamus by the opening of a non-selective cation channel (Hiruma and Bourque, 1995).

A P2Y<sub>2</sub>-like receptor has been shown to mediate inhibition of adenylate cyclase in some cells, although as shown in C6–2B rat glioma cells, this may occur secondary to an increase in cytosolic free Ca<sup>2+</sup> (Munshi *et al.*, 1993). Inhibition of cAMP accumulation by UTP and ATP at a P2Y<sub>2</sub>-like receptor in NCB-20 cells is accompanied by an elevation in intracellular Ca<sup>2+</sup> (Garritsen *et al.*, 1992). A pertussis toxin-sensitive G protein mediates P2Y<sub>2</sub>-like inhibition of cAMP accumulation in cultured renal mesangial cells (Schulze-Lohoff *et al.*, 1995). In the renal epithelial cell line, MDCK-D1 cells UTP and ATP mediate an increase in cAMP that is blocked by indomethacin identifying a cyclooxygenase-dependent mechanism; this suggests the involvement of PGE<sub>2</sub> (Post *et al.*, 1996). An increase in cGMP levels mediated by P2Y<sub>2</sub>-like receptors in mouse neuroblastoma  $\times$  rat glioma hybrid cells occurs secondary to mobilization of intracellular Ca<sup>2+</sup> (Reiser, 1995).

Inhibition of N-type calcium currents by P2Y<sub>2</sub>-like receptors expressed in sympathetic neurons has been reported (Filippov *et al.*, 1997).

P2Y<sub>2</sub>-like receptors are colocalized with P2Y<sub>1</sub>-like receptors on many cells and have a common signaling pathway in PLC. P2Y<sub>2</sub>-like responses are less sensitive to manipulations of the PKC pathway (Purkiss *et al.*, 1994; Communi *et al.*, 1995; Gallinaro *et al.*, 1995; Chen *et al.*, 1996a) (see also Section XII.B., on P2Y<sub>1</sub> and P2Y<sub>1</sub>-like receptor signal transduction mechanisms).

#### C. Desensitization

P2Y<sub>2</sub> and endogenous P2Y<sub>2</sub>-like receptors do not readily desensitize. However, tachyphylaxis of a P2Y<sub>2</sub>-like response has been reported in UMR-106 rat osteoblasts (Sistare *et al.*, 1994), human term placental (trophoblastic) cells (Petit and Belisle, 1995), rat cultured

pituitary cells (gonadotropes) (Chen *et al.*, 1994b, 1995b), C6–2B rat glioma cells (Munshi *et al.*, 1993), and in cultured endothelial cells (Motte *et al.*, 1993a; Wilkinson *et al.*, 1994; Nobles *et al.*, 1995). Maximum desensitization of the P2Y<sub>2</sub> receptor in mouse epithelial cells was observed at 5 to 10 min after UTP exposure, and full receptor responsiveness recovered at the same time after removal of agonist (Garrard *et al.*, 1998). The mechanism of desensitization is not well understood, but as with many G protein-coupled receptors may involve phosphorylation of the intracellular regions of the receptor. The C terminal may be important because progressively larger truncations of this region of the P2Y<sub>2</sub> receptor decreased the rate and magnitude of desensitization (Garrard *et al.*, 1998).

Plasticity of expression of the P2Y<sub>2</sub> receptor during *in vitro* differentiation and inflammatory activation of HL-60 human promyelocytic leukocytes has been described (Martin *et al.*, 1997a). When HL-60 cells differentiate into neutrophils, P2Y<sub>2</sub> receptor mRNA levels and receptor function are largely preserved. In contrast, differentiation of HL-60 cells into monocytes/macrophages is associated with a complete loss of P2Y<sub>2</sub> receptor-mediated function and a 10-fold reduction of P2Y<sub>2</sub> mRNA levels; this suggests receptor down-regulation (Martin *et al.*, 1997a). It was suggested that down-regulation of the P2Y<sub>2</sub>-like receptor might be related to inflammatory activation rather than differentiation.

#### D. Up-Regulation

P2Y<sub>2</sub>-like receptor activity and P2Y<sub>2</sub> receptor mRNA levels were increased in rat submandibular gland after ligation of the main excretory duct but not in the contralateral nonligated gland, indicating that changes in expression of the P2Y<sub>2</sub> receptor may occur during pathological conditions (Turner *et al.*, 1997).

#### E. Agonists and Antagonists

UTP and ATP are natural ligands at P2Y<sub>2</sub> and P2Y<sub>2</sub>-like receptors, and are approximately equipotent. 2Me-SATP and  $\alpha,\beta$ -meATP are weak or inactive, which provides useful negative evidence in the characterization of this receptor. UTP $\gamma$ S is equipotent with UTP and ATP at recombinant P2Y<sub>2</sub> and endogenous P2Y<sub>2</sub>-like receptors, but has the advantage of being resistant to hydrolysis (Lazarowski *et al.*, 1996). ATP $\gamma$ S has been shown to be an agonist at recombinant P2Y<sub>2</sub> receptors, but is less potent than UTP and ATP (Lustig *et al.*, 1993; Lazarowski *et al.*, 1995). Ap<sub>4</sub>A is a potent agonist at recombinant P2Y<sub>2</sub> receptors with a potency greater than ATP $\gamma$ S and is within the same range as UTP and ATP, raising the possibility that it is an endogenous regulator of these receptors (Lazarowski *et al.*, 1995).

It has been suggested that endogenous P2Y<sub>2</sub>-like receptors are preferentially activated by the fully ionized forms of ATP and UTP, ATP<sup>4-</sup>, and UTP<sup>4-</sup> in bovine aortic endothelial cells (Lustig *et al.*, 1992; Motte *et al.*,

1993b), human neutrophils (Walker *et al.*, 1991), a cultured neuroblastoma-glioma hybrid cell line (NG108–15 cells) (Lin *et al.*, 1993), rat lactotrophs (Carew *et al.*, 1994), mouse pineal gland tumor cells (Suh *et al.*, 1997), and MDCK cells (Yang *et al.*, 1997). The UTP and ATP responses were shown to correlate with the concentration of the fully ionized form of these agonists and not with the concentration of their cation complexes or other ionized forms. Although both UTP and ATP are rapidly degraded and augmentation of responses in Mg<sup>2+</sup>-free medium by ecto-nucleotidases must be considered, this seems not to be involved because potentiation of responses was also observed for the stable agonist ATP $\gamma$ S (Yang *et al.*, 1997). Direct effects of cations on the receptor are also possible.

There are no selective antagonists at P2Y<sub>2</sub> and P2Y<sub>2</sub>-like receptors. Suramin and PPADS are nonselective antagonists at subpopulations of P2Y<sub>2</sub>-like receptors (see Section XIII.F., Heterogeneity of P2Y<sub>2</sub> and Endogenous P2Y<sub>2</sub>-Like Receptors).

#### F. Heterogeneity of P2Y<sub>2</sub> and Endogenous P2Y<sub>2</sub>-Like Receptors

Endogenous P2Y<sub>2</sub>-like receptors show two phenotypes of response with respect to antagonism by suramin and PPADS. However, there is no molecular evidence to support a subdivision of P2Y<sub>2</sub> receptors. The differences in sensitivities to antagonists do not correspond to species differences or to the apparent division according to differences in G protein coupling. Suramin-insensitive P2Y<sub>2</sub>-like receptors are those on bovine aortic endothelial cells (Wilkinson *et al.*, 1994), rat duodenum muscularis mucosae (Johnson *et al.*, 1996), rabbit aortic endothelium (Chinellato *et al.*, 1994), and rat mesenteric arterial endothelium (Ziyal, 1997). PPADS-insensitivity is also reported for P2Y<sub>2</sub>-like receptors on rat mesenteric arterial endothelium (Ralevic and Burnstock, 1996a), as well as for P2Y<sub>2</sub>-like receptors on rat renal artery smooth muscle (Eltze and Ullrich, 1996) and bovine aortic endothelial cells (Brown *et al.*, 1995).

Suramin-sensitive endogenous P2Y<sub>2</sub>-like receptors include those on mouse C2C12 myotubes (Henning *et al.*, 1992, 1993), rat pituitary gonadotrophs (Chen *et al.*, 1994b), mouse cortical thick ascending limb segments (Paulais *et al.*, 1995), rat lactotrophs (Carew *et al.*, 1994), hamster mesenteric endothelium (Ziyal, 1997), rat PC12 cells (Murrin and Boarder, 1992), DDT MF-2 cells (Hoiting *et al.*, 1990; Sipma *et al.*, 1994), rat astrocytes (Ho *et al.*, 1995), early embryonic chick neural retina (Sugioka *et al.*, 1996; but also see Section XVII. on Endogenous Uridine Nucleotide-Specific Receptors), rat brain endothelial cells (Nobles *et al.*, 1995), rabbit pulmonary artery endothelium and cultured smooth muscle cells (Qasabian *et al.*, 1997), bovine pulmonary artery endothelium (Chen *et al.*, 1996c), mouse mammary tumor epithelial cells (Enomoto *et al.*, 1994), and mouse neuroblastoma and rat glioma hybrid cells (Reiser, 1995). PPADS is also an inhibitor of P2Y<sub>2</sub>-like receptors



in mouse neuroblastoma and rat glioma hybrid cells (Reiser, 1995), as well as of P2Y<sub>2</sub>-like receptors in rat astrocytes (Ho *et al.*, 1995).

### G. Distribution and Biological Effects

P2Y<sub>2</sub> and endogenous P2Y<sub>2</sub>-like receptors are widely distributed, but relatively little is known about their physiological significance. Particularly intriguing is the functional significance of a receptor that can be activated equally by purines and pyrimidines; to establish the physiological relevance of this it is important to know more about whether there are different sources or differential release of UTP and ATP. Some of these questions may be answered in the not too distant future as a result of the recent development of a radiometric assay based on the nucleotide specificity of UDP-glucose pyrophosphohydrolase, which is capable of detecting nanomolar concentrations of UTP (Lazarowski *et al.*, 1997a). UTP has been shown to be released from endothelial cells by increased flow (Saiag *et al.*, 1995) and is released from epithelial and astrocytoma cells by perturbation of the bathing medium (mechanical stimulation) (Enomoto *et al.*, 1994; Lazarowski *et al.*, 1997a). ATP is also released from these cells under these conditions, although whether its release is independent of that of UTP is unclear. UTP is stored in platelets (Goetz *et al.*, 1971), which may be significant in modulation of vascular contractility during platelet aggregation in pathophysiological conditions.

Northern blot analysis revealed distribution of P2Y<sub>2</sub> receptor mRNA in spleen, testes, kidney, liver, lung, heart, and brain (Lustig *et al.*, 1993; Parr *et al.*, 1995). Alveolar type II cell P2Y<sub>2</sub> receptor mRNA is expressed in rat heart, kidney, lung, spleen, and testis, but not in brain or liver (Rice *et al.*, 1995). The P2Y<sub>2</sub> receptor cloned from human osteoclastoma is expressed in osteoclastoma, bone, and osteoblasts (Bowler *et al.*, 1995). P2Y<sub>2</sub> receptor mRNA has been localized in primary cultures of rat aortic smooth muscle cells (Chang *et al.*, 1995) and in cardiac myocytes and fibroblasts (Webb *et al.*, 1996d).

As shown in functional studies, receptors exhibiting the pharmacological properties of the P2Y<sub>2</sub> receptor are present in a wide variety of cells and tissues including astrocytes, different types of blood cells, chromaffin cells, endothelial cells, epithelial cells, fibroblasts, glial cells, hepatocytes, keratinocytes, myocytes, osteoblasts, pancreatic  $\beta$ -cells, pheochromocytoma PC12 cells, pituitary cells, thymocytes, and tumor cells (table 13).

In the vasculature, P2Y<sub>2</sub>-like receptors are generally present on the endothelium where they stimulate the synthesis and release of prostacyclin and NO, leading to vasodilatation (Ralevic and Burnstock, 1991a, 1991b; 1996a, 1996b). Smooth muscle contraction mediated equipotently by UTP and ATP may indicate P2Y<sub>2</sub>-like receptors, although the G protein coupling of these receptors remains to be confirmed. These receptors have

been described in rat pulmonary vasculature (Rubino and Burnstock, 1996), rat renal vasculature (Eltze and Ullrich, 1996), bovine middle cerebral artery (Miyagi *et al.*, 1996a), and rat duodenum (Johnson *et al.*, 1996). Interestingly, Ca<sup>2+</sup>-mobilizing P2Y<sub>2</sub>-like receptors described on cultured smooth muscle cells of rabbit pulmonary artery are not coupled to a functional response (Qasabian *et al.*, 1997). A clue to their role may lie in the demonstration that P2Y<sub>2</sub>-like receptors mediate an increase in expression of immediate-early and delayed-early cell cycle-dependent genes in cultured aortic smooth muscle cells, in contrast with the induction only of immediate-early genes by 2MeSATP in the same cells (Malam-Souley *et al.*, 1996).

Enhanced leukocyte adherence to cultured pulmonary artery endothelial cells by P2Y<sub>2</sub>-like receptors has been shown (Dawicki *et al.*, 1995). P2Y<sub>2</sub> receptors on neutrophils stimulate degranulation, potentiate N-formyl-methionyl-leucyl-phenylalanine (FMLP)-induced superoxide formation, and induce aggregation (Kuroki *et al.*, 1989; Seifert *et al.*, 1989a,b; Walker *et al.*, 1991). P2Y<sub>2</sub>-like receptors on HL-60 cells mediate activation of NADPH oxidase and superoxide generation and mediate potentiation of FMLP-induced superoxide formation (Seifert *et al.*, 1989a), while those on neutrophils and HL-60 cells induce chemotaxis and actin polymerization (Verghese *et al.*, 1996). P2Y<sub>2</sub>-like receptors on gonadotrophs mediate the release of luteinizing hormone (Chen *et al.*, 1995b). P2Y<sub>2</sub>-like receptors are Cl<sup>-</sup> secretagogues in human nasal mucosa, probably via activation of Ca<sup>2+</sup>-dependent Cl<sup>-</sup> channels (Mason *et al.*, 1991; Stutts *et al.*, 1992); this is an effect which has been explored for its potential in the pharmacological control of cystic fibrosis, a disease characterized by a failure to secrete Cl<sup>-</sup> ions into the airway lumen leading to dehydration of airway secretions.

Coupling of P2Y<sub>2</sub>-like receptors to catecholamine secretion in PC12 cells is controversial, having been reported by some researchers (Majid *et al.*, 1993; Koizumi *et al.*, 1995b), but not by others (Barry and Cheek, 1994; Nikodijevic *et al.*, 1994; de Souza *et al.*, 1995). It is intriguing that while there is no good evidence for UTP release as a neurotransmitter, it is able to modulate the release of other substance from nerves.

It has been shown recently (Bogdanov *et al.*, 1998) that, unlike the human P2Y<sub>4</sub> receptor (see Section XV.), which is selective for UTP, the rat P2Y<sub>4</sub> homolog is equisensitive to ATP and UTP; that is, in agonist profile it is identical with rat P2Y<sub>2</sub>. Therefore, it seems likely that the endogenous receptor called P2Y<sub>2</sub>-like in this section may be a P2Y<sub>2</sub> or a P2Y<sub>4</sub> receptor, at least where rat tissue is concerned. However, since there is a differential sensitivity to widely used antagonists, it should be possible to distinguish which receptor is operating in a particular tissue. In view of this new data, it is now clear that the former P<sub>2U</sub> receptor cannot be equated with a single P2Y subtype.

#### XIV. p2y3 Receptor

This receptor has been cloned from chick brain and has nucleotide selectivity with a potency order of  $UDP > UTP > ADP > 2MeSATP > ATP$  (Webb *et al.*, 1995, 1996a). The designation p2y3 reflects the current reservations expressed by the IUPHAR nomenclature committee about its inclusion as a distinct subtype within the P2Y receptor family because no mammalian homolog has yet been identified. It has been suggested that this may be the chick homolog of the mammalian P2Y<sub>6</sub> receptor, with which it has 62% sequence homology, although this has not yet been confirmed. This receptor is activated by UDP, and to a lesser extent UTP and ADP, and couples to PLC. Its expression is rather restricted, being detected in spleen, spinal cord, kidney, and lung.

#### XV. P2Y<sub>4</sub> Receptor

This uridine nucleotide-specific receptor has been cloned from human placenta (Communi *et al.*, 1996c), human chromosome X (Nguyen *et al.*, 1996), and rat heart (Bogdanov *et al.*, 1998). The human P2Y<sub>4</sub> receptor is highly selective for UTP over ATP and is not activated by nucleoside diphosphates. ATP can act as an antagonist and partial agonist. The human P2Y<sub>4</sub> receptor seems to couple to two distinct G proteins: a G<sub>i</sub> protein at the early stage and a G<sub>q/11</sub> protein at a later stage of signaling to activate PLC and IP<sub>3</sub> formation (Communi *et al.*, 1996a). The IP<sub>3</sub> response declines within minutes of stimulation of the receptor and is not readily reproducible, indicating desensitization (Robaye *et al.*, 1997). The human P2Y<sub>4</sub> receptor is not blocked by suramin, but has been reported to be both blocked by PPADS (IC<sub>50</sub> approximately 15 μM) (Communi *et al.*, 1996a) and to be relatively insensitive to block by PPADS (used at 30 μM) (Charlton *et al.*, 1996b). P2Y<sub>4</sub> has a restricted distribution; it is expressed almost exclusively in placenta with low levels of expression in lung, and absent in most other tissues. A P2Y<sub>4</sub> receptor (initially termed P2P) has been described in rat pancreas (Stam *et al.*, 1996). P2Y<sub>4</sub> mRNA (and P2Y<sub>2</sub> mRNA, as well as barely detectable levels of P2Y<sub>6</sub> mRNA) has been detected in vascular smooth muscle (Erlinge *et al.*, 1998).

The recent cloning of a rat P2Y<sub>4</sub> receptor has shown that the recombinant receptor is activated equipotently by ATP and UTP (ADP, ATP<sub>γ</sub>S, 2MeSATP, and Ap<sub>4</sub>A are also equipotent, but are partial agonists) (Bogdanov *et al.*, 1998). Clearly, with respect to ATP and UTP sensitivity, this is identical with the profile described for the P2Y<sub>2</sub> receptor. Important implications arising from this are that some P2Y<sub>2</sub>-like responses may be mediated by a P2Y<sub>4</sub> receptor, at least in rat tissues, and that the P<sub>2U</sub> receptor cannot be equated with a single P<sub>2Y</sub> subtype.

#### XVI. P2Y<sub>6</sub> Receptor

This uridine nucleotide-specific receptor has been cloned from rat aortic smooth muscle (Chang *et al.*, 1995) and human placenta and spleen (Communi *et al.*, 1996b). The receptor is activated most potently by UDP but weakly or not at all by UTP, ATP, ADP, or 2MeSATP (Communi *et al.*, 1996b; Nicholas *et al.*, 1996). Other diphosphonucleotides are full agonists at the receptor but have lower affinities. The response is pertussis toxin insensitive, indicating the involvement of G<sub>q/11</sub> proteins in stimulation of PLC and in the formation of IP<sub>3</sub>. Interestingly, the IP<sub>3</sub> response of the human cloned P2Y<sub>6</sub> receptor decays only slowly after stimulation, remaining above baseline for more than an hour after stimulation; this is a response that is fully reproducible without the need for a long recovery period (Robaye *et al.*, 1997).

P2Y<sub>6</sub> mRNA is found abundantly in various rat tissues including placenta, thymus, lung, stomach, intestine, spleen, mesentery, heart, and aorta (Chang *et al.*, 1995; Communi *et al.*, 1996b). P2Y<sub>6</sub>, along with P2Y<sub>1</sub> and P2Y<sub>2</sub>, but not P2Y<sub>4</sub> mRNA, has been detected in adult rat cardiac myocytes (Webb *et al.*, 1996d). It has been suggested that the P2Y<sub>6</sub> receptor accounts for uridine nucleotide-specific responses in C6-2B cells (Nicholas *et al.*, 1996). A receptor activated by UDP in human nasal epithelial cells that is distinct from the P2Y<sub>2</sub> receptor may be an endogenous P2Y<sub>6</sub> receptor (Lazarowski *et al.*, 1997b). The receptor promotes [<sup>3</sup>H]inositol phosphate accumulation and an increase in [Ca<sup>2+</sup>]<sub>i</sub> and Cl<sup>-</sup> secretion, is present on the mucosal but not on the serosal surface, and desensitizes more readily than responses to UTP (Lazarowski *et al.*, 1997b). Interestingly, a uridine nucleotide-specific receptor responding to UDP in Caco-2 human intestinal epithelial cells seems to be located on the apical but not on the basolateral membrane (Inoue *et al.*, 1997). The more widespread distribution of the P2Y<sub>6</sub> receptor, compared with the P2Y<sub>4</sub> receptor, suggests that this receptor is more likely to account for endogenous uridine nucleotide-specific responses.

#### XVII. P2Y<sub>11</sub> Receptor

The P2Y<sub>11</sub> receptor was cloned from human placenta (Communi *et al.*, 1997). The receptor has 33% amino acid identity with the P2Y<sub>1</sub> receptor, its closest homolog, and 28% homology with the P2Y<sub>2</sub> receptor. The receptor couples to the stimulation of both the phosphoinositide and the adenylyl cyclase pathways; in this respect, it is unique among the P2Y family. Interestingly, this receptor seems to be the only P2Y receptor selective for ATP because it is stimulated by agonists with a rank order of potency of  $ATP > 2MeSATP \gg \gg ADP$ , with UTP and UDP inactive (Communi *et al.*, 1997). Northern blot analysis detected mRNA corresponding to the P2Y<sub>11</sub> receptor in spleen and HL-60 cells (Communi *et al.*, 1997).

TABLE 13  
Functional distribution of P2Y receptors

	P2Y <sub>1</sub> -like <sup>a</sup>	P2Y <sub>2</sub> -like <sup>b</sup>	P2Y <sub>ADP</sub> <sup>c</sup>	Uridine nucleotide-specific	References
Alveolar type II cells	Yes	Yes	—	—	Rice and Singleton, 1987; Rice <i>et al.</i> , 1995
Astrocytes	Yes	Yes	—	—	Pearce and Langley, 1994; Salter and Hicks, 1994; Ho <i>et al.</i> , 1995; Chen and Chen, 1996
Blood cells					
Erythrocytes	Yes	—	—	—	Boyer <i>et al.</i> , 1989, 1994
Erythroleukemic (human HEL megakaryocytes)	Yes	Yes	Yes	—	Shi <i>et al.</i> , 1995
Leukemic basophils (rat mast cells)	Yes	—	—	—	Osipchuk and Cahalan, 1992; Qian and McCloskey, 1993
T-leukemia cells	Yes <sup>d,e</sup>	—	Yes <sup>e</sup>	—	Biffen and Alexander, 1994
Macrophages	—	Yes	—	Yes	Greenberg <i>et al.</i> , 1988; Nuttle <i>et al.</i> , 1993; Lin and Lee, 1996
Megakaryocytes	—	—	Yes	—	Vittet <i>et al.</i> , 1992; Uneyama <i>et al.</i> , 1994
Monocytes (murine J774)	Yes	—	—	—	Fan and McCloskey, 1994
Myelomonocytic leukemic (M1)	Yes	—	—	—	Yamaguchi <i>et al.</i> , 1994
Neutrophils	—	Yes	—	—	Zhang <i>et al.</i> , 1996
Platelets	Yes	—	Yes	—	Hourani <i>et al.</i> , 1992; Hall and Hourani, 1993; Hechler <i>et al.</i> , 1998; Fagura <i>et al.</i> , 1998; Daniel <i>et al.</i> , 1998; Jin, <i>et al.</i> , 1998
CHO cells	Yes	Yes	—	—	Iredale and Hill, 1993
Chondrocytes	—	Yes	—	—	Kaplan <i>et al.</i> , 1996
Chromaffin cells	Yes	Yes	—	—	Reichsman <i>et al.</i> , 1995
Duct cells					
Pancreatic; cystic fibrosis	—	Yes	—	—	Chan <i>et al.</i> , 1996
Submandibular	—	Yes	—	—	Yu and Turner, 1991
Endothelium	Yes <sup>d</sup>	Yes	—	—	Motte <i>et al.</i> , 1993a,b; Briner and Kern, 1994; Purkiss <i>et al.</i> , 1993, 1994; Wilkinson <i>et al.</i> , 1994; Communi <i>et al.</i> , 1995; Nobles <i>et al.</i> , 1995; Miyagi <i>et al.</i> , 1996b; Ralevic and Burnstock, 1996a,b; Ralevic <i>et al.</i> , 1991b, 1997; Simonsen <i>et al.</i> , 1997
	Yes	Yes	—	Yes	Yang <i>et al.</i> , 1996
Epithelium					
Intestinal, apical; human	—	Yes	—	Yes	Inoue <i>et al.</i> , 1997
Intestinal, basolateral; human	Yes	Yes	—	—	Inoue <i>et al.</i> , 1997
Intrahepatic biliary; human	—	Yes	—	—	Wolkoff <i>et al.</i> , 1995
Mammary tumour; mouse	—	Yes	—	—	Enomoto <i>et al.</i> , 1994
Mammary tumour; human	Yes	Yes	—	—	Flezar and Heisler, 1993
MDCK cells; canine	Yes	Yes	—	—	Zegarra-Moran <i>et al.</i> , 1995; Firestein <i>et al.</i> , 1996; Yang <i>et al.</i> , 1997
Nasal mucosa; human	—	?	—	Yes	Lazarowski <i>et al.</i> , 1997b
Ocular ciliary; human	—	Yes	—	—	Wax <i>et al.</i> , 1993
Otocyst; embryonic chick	Yes	—	—	—	Nakaoka and Yamashita, 1995
Pancreatic; human cystic fibrosis	—	Yes	—	—	Chan <i>et al.</i> , 1996; Montserrat <i>et al.</i> , 1996
Retinal pigment epithelium	—	Yes <sup>d</sup>	—	—	Peterson <i>et al.</i> , 1997
Tracheal; hamster	—	Yes	—	—	Abdullah <i>et al.</i> , 1996; Kim <i>et al.</i> , 1996
Tracheal; rabbit	Yes	Yes	—	—	Aksoy <i>et al.</i> , 1995
Thymic; rat	?	?	—	?	Liu <i>et al.</i> , 1995
Submandibular salivary; mouse	Yes	Yes	—	—	Gibb <i>et al.</i> , 1994
Sweat gland; equine	Yes	Yes	—	—	Ko <i>et al.</i> , 1994
Fibroblasts	—	Yes	—	—	Fine <i>et al.</i> , 1989; Gonzalez <i>et al.</i> , 1989b,c; Marsault <i>et al.</i> , 1992; Grierson and Meldolesi, 1995a,b
Glial cells					
Enteric glia	—	Yes	—	—	Kimball and Mulholland, 1996
Bergmann glia (cerebellar)	Yes	—	—	—	Kirischuk <i>et al.</i> , 1995b
Microglia	Yes	—	—	Yes	Nörenberg <i>et al.</i> , 1997
Oligodendrocytes; cortical	Yes	—	—	—	Kirischuk <i>et al.</i> , 1995a
Oligodendrocytes; retinal	—	Yes	—	—	Kirischuk <i>et al.</i> , 1995a
Glioma					
C6/C6-2B glioma cells	Yes	Yes	—	Yes <sup>i</sup>	Boyer <i>et al.</i> , 1994, 1995, 1996; Munshi <i>et al.</i> , 1993; Lin and Chuang, 1994; Nicholas <i>et al.</i> , 1996; Schachter <i>et al.</i> , 1996
Neuroblastoma × glioma hybrid	Yes	Yes	—	—	Lin <i>et al.</i> , 1993; Filippov <i>et al.</i> , 1994; Reiser <i>et al.</i> , 1995
Goblet (tracheal SPOC1) cells	—	Yes	—	—	Abdullah <i>et al.</i> , 1996
Hepatocytes	Yes <sup>d</sup>	Yes	—	—	Charest <i>et al.</i> , 1985; Keppens and DeWulf, 1991; Keppens <i>et al.</i> , 1992; Dixon <i>et al.</i> , 1995
Keratinocytes	—	Yes	—	—	Pillai and Bikle, 1992
Kidney tubules					
Cortical thick ascending limbs	—	Yes	—	—	Paulais <i>et al.</i> , 1995
Cortical tubules	Yes	—	—	—	Cha <i>et al.</i> , 1995
Terminal inner medullary collecting duct	—	Yes	—	—	Ecelbarger <i>et al.</i> , 1994
Mesangial cells (renal)	Yes	Yes	—	—	Huwiler and Pfeilschifter, 1994; Schulze-Lohoff <i>et al.</i> , 1992, 1995; Takeda <i>et al.</i> , 1996



TABLE 13  
(Continued)

	P2Y <sub>1</sub> -like <sup>a</sup>	P2Y <sub>2</sub> -like <sup>b</sup>	P2Y <sub>ADP</sub> <sup>c</sup>	Uridine nucleotide-specific	References
Myocytes					
Cardiac	Yes	—	—	—	Qu <i>et al.</i> , 1993; Scamps and Vassort, 1994
Gastrointestinal	Yes	Yes	—	—	Blottière <i>et al.</i> , 1996; Pacaud <i>et al.</i> , 1996
Vascular	—	Yes	—	—	Erlinge <i>et al.</i> , 1995; Pacaud <i>et al.</i> , 1995; Guibert <i>et al.</i> , 1996; Malam-Souley <i>et al.</i> , 1996; Strøbæk <i>et al.</i> , 1996; Qasabian <i>et al.</i> , 1997
Osteoblasts	Yes <sup>d</sup>	Yes	—	—	Bowler <i>et al.</i> , 1992; Sistare <i>et al.</i> , 1994, 1995; Reimer and Dixon, 1992; Gallinaro <i>et al.</i> , 1995; Dixon <i>et al.</i> , 1997b
Ovarian granulosa cells					
Human	—	Yes	—	—	Kamada <i>et al.</i> , 1994; Lee <i>et al.</i> , 1996
Porcine	Yes <sup>d</sup>	Yes	—	—	Kamada <i>et al.</i> , 1994
Ovarian CHO cells	Yes	Yes	—	—	Iredale and Hill, 1993
Pancreatic $\beta$ cells	Yes	—	—	—	Bertrand <i>et al.</i> , 1987; Hillaire-Buys <i>et al.</i> , 1994
Pheochromocytoma PC12 cells	Yes	Yes	—	—	Murrin and Boarder, 1992; Majid <i>et al.</i> , 1992, 1993; Barry and Cheek, 1994; Nikodijevic <i>et al.</i> , 1994; de Souza <i>et al.</i> , 1995; Koizumi <i>et al.</i> , 1995b
Pituitary cells					
Gonadotrophs	—	Yes	—	—	Chen <i>et al.</i> , 1994b, 1995b
Lactotrophs	—	Yes	—	—	Carew <i>et al.</i> , 1994
Salt gland cells	Yes	Yes	—	—	Martin and Shuttleworth, 1995
Schwann cells	Yes	Yes	—	—	Berti Mattera <i>et al.</i> , 1996; Ansselin <i>et al.</i> , 1997; Green <i>et al.</i> , 1997
Smooth muscle					
Gastrointestinal	—	Yes	—	—	Johnson <i>et al.</i> , 1996
Vascular	Yes	—	—	—	Kennedy and Burnstock, 1985; Mathieson and Burnstock, 1985; Burnstock and Warland, 1987; Liu <i>et al.</i> , 1989; Brizzolara and Burnstock, 1991; Keef <i>et al.</i> , 1992; Corr and Burnstock, 1994; Simonsen <i>et al.</i> , 1997
	—	Yes	—	—	Eltze and Ullrich, 1996; Miyagi <i>et al.</i> , 1996a; Malam-Souley <i>et al.</i> , 1996; Rubino and Burnstock, 1996; Qasabian <i>et al.</i> , 1997
	—	—	—	Yes	Von Kùgelgen <i>et al.</i> , 1987, 1990; Saiag <i>et al.</i> , 1990, 1992; Ralevic and Burnstock, 1991b; Juul <i>et al.</i> , 1992; Lagaud <i>et al.</i> , 1996; Matsumoto <i>et al.</i> , 1997
Thyocytes	—	Yes	—	—	Schöfl <i>et al.</i> , 1995
Trophoblastic cells (placental)	—	Yes	—	—	Petit and Belisle, 1995
Tumor cells					
Ehrlich ascites	—	Yes	—	—	Dubyak and De Young, 1985
HTC liver cell line	—	Yes	—	—	Fitz and Sostman, 1994
Osteosarcoma	Yes	—	—	—	Kumagai <i>et al.</i> , 1991

<sup>a</sup> P2Y<sub>1</sub>-like, P2Y receptors other than P2Y<sub>2</sub>, P2Y<sub>4</sub>, P2Y<sub>6</sub>, P2Y<sub>ADP</sub>, and endogenous uridine nucleotide-specific receptors; probably P2Y<sub>1</sub> receptors (based on sensitivities to 2MeSATP and/or ADP, and signalling pathways), although other P2Y subtypes cannot be excluded.

<sup>b</sup> P2Y<sub>2</sub>-like, activated by ATP = UTP suggesting a possible identity as P2Y<sub>2</sub> receptors, although at least in rat tissues a P2Y<sub>4</sub> subtype identity cannot be excluded (as rat P2Y<sub>4</sub> receptors are activated by ATP = UTP). The possible presence of uridine nucleotide-specific receptors cannot be excluded in tissues responding to UTP.

<sup>c</sup> ADP-specific P2Y receptors, activated by ADP but not by ATP.

<sup>d</sup> Denotes ADP-specific P2Y receptors (ATP weak or inactive); note that this is also the agonist profile of P2Y<sub>ADP</sub> receptors.

<sup>e</sup> These may be the same P2Y<sub>1</sub>-like receptor.

<sup>f</sup> The response to UTP was distinct from that to UDP, but it is not clear whether this is via actions at a P2Y<sub>2</sub>- or P2Y<sub>4</sub>-like receptor.

<sup>g</sup> UTP was five-fold more potent than ATP, thus uridine-nucleotide-specific receptors are possible.

<sup>h</sup> Subtype(s) not clear: stimulation of PGE<sub>2</sub> production by ATP $\gamma$ S  $\geq$  UTP > ATP.

<sup>i</sup> P2Y<sub>6</sub> (Nicholas *et al.*, 1996).

<sup>j</sup> P2Y<sub>ADP</sub> receptors have been described; however, it is likely that these are ADP-specific P2Y receptors.

## XVIII. Endogenous Uridine Nucleotide-Specific Receptors

The inclusion of this as a separate section is a reflection of the current lack of information about the correlation between cloned (P2Y<sub>4</sub> and P2Y<sub>6</sub>) and endogenous uridine nucleotide-specific receptors. It is not intended to imply that these receptors are different, although this is a possibility. The existence of P2Y<sub>2</sub>, P2Y<sub>4</sub>, and P2Y<sub>6</sub> receptors identifies two receptors that can be activated by UTP (P2Y<sub>2</sub>, P2Y<sub>4</sub>) and one that can be activated by UDP (P2Y<sub>6</sub>). Thus, it is not always clear which of these receptors mediates uridine nucleotide-mediated responses in cells and tissues. Additional complications are introduced by the coexistence of P2 receptors, the lack of selective agonists and antagonists, and the inter-

conversion and degradation of agonists leading to contamination of solutions and to the possibility of obtaining false positive as well as negative results. With hindsight, some characterization of endogenous uridine nucleotide-specific responses in many tissues might have been achieved by more complete information on agonist activity profiles, specifically giving information about their UTP/UDP selectivity. It would be worthwhile to re-evaluate the pharmacological profile of biological tissues in light of new information on these P2Y receptors.

### A. Signal Transduction Mechanisms

A uridine nucleotide-specific receptor in C6–2B rat glioma cells mediates pertussis toxin-sensitive activa-

tion of PLC and an increase in IP<sub>3</sub> by UTP and UDP, but is not activated by ATP and ADP (Lazarowski and Harden, 1994). The uridine nucleotide-specific receptor in RAW 264.7 macrophages is coupled to pertussis toxin-sensitive and -insensitive G proteins that mediate activation of phospholipase A<sub>2</sub> (PLA<sub>2</sub>) and PLC, respectively (Lin and Lee, 1996).

### B. Agonists and Antagonists

Uridine nucleotide-specific receptors are activated by UTP and/or UDP, but are not activated or only weakly activated by ATP, ADP, 2MeSATP, and  $\alpha,\beta$ -meATP.

There are no selective antagonists at uridine nucleotide-specific receptors. In general, responses are insensitive to P2 receptor antagonists. However, suramin and reactive blue 2 have been reported to block the UTP-specific inositol phosphate response of RAW 264.7 macrophages (Lin and Lee, 1996).

### C. Distribution and Biological Effects

Uridine nucleotide-specific receptors, suggested to be P2Y<sub>6</sub> receptors, have been described on C6–2B cells where they coexist with P2Y<sub>1</sub>-like and P2Y<sub>2</sub>-like receptors (Boyer *et al.*, 1993). Uridine nucleotide-specific receptors are also found on macrophages (Lin and Lee, 1996) and microglial cells (Nörenberg *et al.*, 1997a). They have been shown to mediate metabolic effects, membrane ion fluxes, and hemodynamic effects in perfused rat liver (Haussinger *et al.*, 1987). Uridine nucleotide-specific receptors mediating Cl<sup>-</sup> secretion on human nasal mucosal (Lazarowski *et al.*, 1997b) and intestinal epithelial cells (Inoue *et al.*, 1997) are activated by UDP, perhaps indicating that these are P2Y<sub>6</sub> receptors.

Uridine nucleotide-specific receptors are found on vascular endothelium and smooth muscle. A pertussis toxin-sensitive uridine nucleotide-specific receptor coexists with P2Y<sub>2</sub>-like and P2Y<sub>1</sub>-like receptors on guinea-pig cardiac endothelial cells (Yang *et al.*, 1996). Uridine nucleotide-specific receptors mediating contractile responses to UTP (but not to ATP) have been described on vascular smooth muscle (Von Kügelgen *et al.*, 1987, 1990; Saiag *et al.*, 1990, 1992; Ralevic and Burnstock, 1991b; Juul *et al.*, 1992; Lagaud *et al.*, 1996). These receptors are resistant to desensitization by  $\alpha,\beta$ -meATP and/or do not show cross-tachyphylaxis with responses to ATP and/or are unaffected by antagonists including PPADS and suramin. It is possible that these correspond to human P2Y<sub>4</sub> receptors. In canine epicardial coronary arteries, vasoconstriction mediated by UTP and UDP at P2Y receptors does not cross-desensitize and is distinct from vasoconstriction mediated by ATP (Matsumoto *et al.*, 1997); this suggests effects mediated at uridine nucleotide-specific receptors similar or identical with human P2Y<sub>4</sub> and P2Y<sub>6</sub> receptors, respectively.

A uridine nucleotide-specific receptor has been described in neurons of the rat superior cervical ganglion

(SCG) (Boehm *et al.*, 1995; Connolly, 1995; Connolly and Harrison, 1995a, b). This receptor is activated by UTP and UDP but not by ATP, causing depolarization and transmitter release. Suramin does not block this SCG receptor (Connolly and Harrison, 1995b).

The approximately 5-fold greater potency of UTP, compared with ATP in elevating intracellular Ca<sup>2+</sup> in early embryonic chick neural retina, may suggest the involvement of a uridine nucleotide-specific receptor, although the authors of this study conclude that a P2Y<sub>2</sub>-like (P<sub>2U</sub>) receptor is involved (Sugioka *et al.*, 1996). It is also possible that a combination of coexpressed P2Y receptors mediate this response. The biological significance of uridine nucleotide-specific receptors is unknown, but may imply differential release of purines and pyrimidines.

## XVIV. P2Y<sub>ADP</sub> (or P<sub>2T</sub>) Receptor

The P2Y<sub>ADP</sub> (or P<sub>2T</sub>) receptor is activated by ADP, whereas ATP is a competitive antagonist. Because this receptor has not yet been cloned from the platelets or megakaryoblastic cells in which it is expressed, the recommendation of the IUPHAR committee is that the name of this receptor is written in italics. It has been suggested that the P2Y<sub>ADP</sub> receptor is equivalent to the P2Y<sub>1</sub> receptor based on their similar pharmacological profiles and the fact that P2Y<sub>1</sub> receptor mRNA is present in platelets and megakaryoblastic cell lines (Léon *et al.*, 1997). Although this seemed an attractive hypothesis with which to explain the enigma of the P2Y<sub>ADP</sub> (or P<sub>2T</sub>) receptor, there is now convincing pharmacological evidence that the P2Y<sub>ADP</sub> (or P<sub>2T</sub>) receptor is not equivalent to the P2Y<sub>1</sub> receptor; both of these receptors are expressed on platelets and cooperate to mediate platelet shape change and aggregation (Daniel *et al.*, 1998; Fagura *et al.*, 1998; Hechler *et al.*, 1998; Jin *et al.*, 1998). Notably, 2MeSATP is a full and potent agonist at the recombinant P2Y<sub>1</sub> receptor, whereas it is a noncompetitive antagonist at the P2Y<sub>ADP</sub> (or P<sub>2T</sub>) receptor, and selective antagonists of the P2Y<sub>1</sub> receptor do not block ADP-induced inhibition of adenylate cyclase in platelets.

### A. Signal Transduction Mechanisms

The P2Y<sub>ADP</sub> (or P<sub>2T</sub>) receptor couples to a G<sub>i2</sub> protein to mediate inhibition of adenylate cyclase activity (Hall and Hourani, 1993; Hourani and Hall, 1996). Conflicting reports that the P2Y<sub>ADP</sub> (or P<sub>2T</sub>) receptor may or may not also activate PLC, generating IP<sub>3</sub> and elevating levels of intracellular Ca<sup>2+</sup>, most likely came from observed effects of ADP at coexisting platelet P2Y<sub>1</sub> receptors. Platelet P2Y<sub>1</sub> receptors coupled to activation of PLC are now known to play a significant role in platelet shape change and cooperative aggregation with P2Y<sub>ADP</sub> (or P<sub>2T</sub>) receptors (Daniel *et al.*, 1998; Hechler *et al.*, 1998; Jin *et al.*, 1998).

In platelets activated by ADP, rapid influx of extracellular  $\text{Ca}^{2+}$  forms a significant component of the increase in intracellular  $\text{Ca}^{2+}$ . A component of this  $\text{Ca}^{2+}$  influx seems to be caused by ADP actions on platelet  $\text{P2X}_1$ -like receptors (coexisting with  $\text{P2Y}_{ADP}$  and  $\text{P2Y}_1$  receptors) causing the opening of these nonselective cation channels (Soslau *et al.*, 1995; MacKenzie *et al.*, 1996) (also see Section IX.F.). Platelet aggregation seems to be mediated by a combination of the above pathways stimulated by  $\text{P2Y}_{ADP}$  (or  $\text{P}_{2T}$  receptor),  $\text{P2Y}_1$ -like, and  $\text{P2X}_1$ -like receptor activation.

### B. Desensitization

Homologous desensitization of the  $\text{P2Y}_{ADP}$  (or  $\text{P}_{2T}$ ) response has been observed in human erythroleukemic cells (Shi *et al.*, 1995).

### C. Agonists

ADP is the archetypal agonist at  $\text{P2Y}_{ADP}$  receptors. The analogs 2-chloroADP and 2-MeSADP are more potent agonists at  $\text{P2Y}_{ADP}$  receptors than ADP, and  $\text{ADP}\alpha\text{S}$  and  $\text{ADP}\beta\text{S}$  are partial agonists (Hall and Hourani, 1993; Hourani and Hall, 1996).

### D. Antagonists

FPL 66096 (2-propylthio-d- $\beta,\gamma$ -difluoromethylene ATP) ( $\text{pA}_2$  8.7) (Humphries *et al.*, 1994) and ARL 67085 (formerly FPL 67085) (2-propylthio- $\beta,\gamma$ -dichloromethylene-d-ATP) (Humphries *et al.*, 1995) are potent and selective competitive antagonists at platelet  $\text{P2Y}_{ADP}$  receptors.

ATP is a competitive antagonist, with the preferred form being  $\text{ATP}^{4-}$ . The competitive effects of ATP at the  $\text{P2Y}_{ADP}$  receptor may be physiologically meaningful because degradation to ADP by platelet ecto-ATPase is slow (Beukers *et al.*, 1993). 2Cl-ATP,  $\beta,\gamma$ -meATP,  $\text{Ap}_4\text{A}$ ,  $\text{Ap}_5\text{A}$ , and  $\text{P}^1,\text{P}^6$ -diadenosine hexaphosphate ( $\text{Ap}_6\text{A}$ ) are also competitive antagonists; 2MeSATP and adenosine are non-competitive antagonists at platelet  $\text{P2Y}_{ADP}$  receptors (Harrison *et al.*, 1975; Ogilvie, 1992; Hall and Hourani, 1993). At high concentrations,  $\text{Ap}_3\text{A}$  has anti-thrombotic effects at the  $\text{P2Y}_{ADP}$  receptor. This is in contrast with its pro-thrombotic effects at low concentrations (Ogilvie, 1992), although breakdown to ADP and adenosine may be involved.  $\text{Ap}_4\text{A}$ ,  $\text{Ap}_5\text{A}$ , and  $\text{Ap}_6\text{A}$  also inhibit ADP-induced platelet aggregation, probably by competitive interaction with the  $\text{P2Y}_{ADP}$  receptor (Ogilvie *et al.*, 1996).  $\alpha,\beta$ -meATP and UTP are weak inhibitors of platelet aggregation (Hall and Hourani, 1993). Suramin is a non-selective antagonist at the  $\text{P2Y}_{ADP}$  receptor (Hourani *et al.*, 1992; Hall and Hourani, 1993).

### E. Distribution and Biological Effects

The distribution of the  $\text{P2Y}_{ADP}$  receptor seems to be limited to platelets and megakaryoblastic cell lines (Vitet *et al.*, 1992; Shi *et al.*, 1995). The lack of subtype-

specific agonists and antagonists apparently has led to erroneous descriptions of  $\text{P}_{2T}$  ( $\text{P2Y}_{ADP}$ ) receptors on a number of other cell types including osteoblasts (Sistare *et al.*, 1994, 1995) and porcine ovarian granulosa cells (Kamada *et al.*, 1994); it is likely that these are in fact ADP-specific  $\text{P2Y}_1$ -like receptors. The P2 receptor described in porcine ovarian granulosa cells, where ATP is a competitive antagonist of ADP-induced  $[\text{Ca}^{2+}]_i$  mobilization (Kamada *et al.*, 1994), may be an ADP-specific  $\text{P2Y}_1$ -like receptor, where ATP is a partial agonist.

A role for the platelet  $\text{P2Y}_{ADP}$  receptor has been clearly defined; it mediates the aggregation of platelets to ADP during thrombosis (Born, 1962; Born and Kratzer, 1984). One source of ADP activating the  $\text{P2Y}_{ADP}$  receptor may be that derived from ATP released from damaged cells in the vessel wall. The dense granules of platelets are themselves sources of high concentrations of ATP and ADP (approximately 1 M) such that platelet aggregation and degranulation leading to the release of these nucleotides is an autocatalytic process. The adenine dinucleotides  $\text{Ap}_3\text{A}$  and  $\text{Ap}_4\text{A}$  are co-stored with ADP and ATP in platelets and comprise up to 5% of the total adenine nucleotide content of the dense granules (micromolar to millimolar concentrations) (Flodgaard and Klenow, 1982; Luthje and Ogilvie, 1983; Schluter *et al.*, 1994); they are less rapidly metabolized than ATP and may have a role in the platelet aggregatory response.

Complex and cooperative signaling pathways mediated by coexisting  $\text{P2Y}_{ADP}$ ,  $\text{P2Y}_1$ , and  $\text{P2X}_1$  receptors seem to underlie the change in platelet shape, platelet aggregation, and secretion of dense granules to ADP. The  $\text{P2Y}_1$  receptor seems to be necessary to trigger platelet shape change and aggregation (Daniel *et al.*, 1998; Hechler *et al.*, 1998; Jin *et al.*, 1998). The  $\text{P2X}_1$ -like receptor mediates an initial rapid influx of  $\text{Ca}^{2+}$  in platelets (MacKenzie *et al.*, 1996), which may also contribute to initiate the change in platelet shape. This  $\text{Ca}^{2+}$  influx precedes, but is independent of, the mobilization of intracellular  $\text{Ca}^{2+}$  by the  $\text{P2Y}_{ADP}$  receptor (Hallam and Rink, 1985; Sage *et al.*, 1990). Mobilization of intracellular  $\text{Ca}^{2+}$  and adenylate cyclase by the  $\text{P2Y}_{ADP}$  receptor seems to be linked to platelet aggregation and cooperates with effects mediated by the  $\text{P2Y}_1$  receptor, such that antagonism of either receptor is sufficient to block the response. Oscillations in  $[\text{Ca}^{2+}]_i$  have been described, which seem to involve the repetitive emptying and refilling of intracellular calcium stores. The mobilization of  $[\text{Ca}^{2+}]_i$  seems to be required for activation of a secondary phase of  $\text{Ca}^{2+}$  influx (Sage *et al.*, 1990).

## XX. Other P2Y Receptors

The following G protein-coupled receptors have been cloned and proposed as members of the P2Y receptor family. Of these, the p2y5, p2y7, p2y9, and p2y10 receptors have now been shown unequivocally not to belong to the P2Y receptor family, and the inclusion of the *Xeno-*



*pus* P2Y receptor (P2Y<sub>8</sub>) does not seem likely as it lacks a mammalian homologue.

#### A. *p2y5* Receptor

A receptor expressed in activated chicken T lymphocytes was proposed as a P2Y receptor based on nucleotide binding assays (Webb *et al.*, 1996b). No functional evaluation was provided. When the turkey homolog was expressed in 1321N1 human astrocytoma cells, it was shown that no signaling responses were evoked by nucleotides; this indicates that the receptor is not a member of the P2Y receptor family (Li *et al.*, 1997c). It was noted that caution should be used when interpreting the results of binding assays in the absence of robust ligands and that a prerequisite for the identification of additional P2Y receptors should be a functional demonstration of signaling responses in an appropriate cell line (Li *et al.*, 1997c).

#### B. *p2y7*/Leukotriene B<sub>4</sub> Receptor

It was suggested that a receptor cloned from human HEL cells was a P2Y<sub>7</sub> receptor based on binding and activation by purine nucleotides when transfected in COS-7 cells (Akbar *et al.*, 1996). However, its structure, which was noted to share 30% or less homology with other cloned P2Y receptors, has been found to be identical with that of the leukotriene B<sub>4</sub> receptor cloned from HL-60 cells, and sensitivity to purines can be explained by intrinsic purinoceptors (P2Y<sub>2</sub>) in COS-7 cells (Yokomizo *et al.*, 1997). Expression of the putative P2Y<sub>7</sub> receptor in 1321N1 human astrocytoma cells has confirmed that this receptor is not activated by nucleotides and is not a member of the P2Y receptor family (Herold *et al.*, 1997).

#### C. *Xenopus* P2Y Receptor (P2Y<sub>8</sub>)

A P2Y receptor cloned from *Xenopus* neural plate is activated equipotently by purine and pyrimidine compounds with three phosphates; ATP = UTP = ITP = CTP = GTP (Bogdanov *et al.*, 1997). The cloned receptor has a particularly long C terminal of 216 amino acids (compared with approximately 16 to 67 amino acids of other P2Y receptors) that contributes to the greater length of this protein. It has been suggested that this receptor may have a role in early development of the nervous system. The receptor was tentatively named P2Y<sub>8</sub>. As a mammalian homolog of this receptor has not been identified, its inclusion as a distinct subtype of the P2Y receptor family does not seem likely.

#### D. P2Y<sub>9</sub> and P2Y<sub>10</sub> Receptors

These cloned receptors, submitted to Genbank, are not nucleotide receptors.

#### E. P2Y<sub>Ap4A</sub> (or P<sub>2D</sub>) Receptor

It has been proposed that there is a distinct class of purine receptor, originally termed P<sub>2D</sub> ("D" for dinucle-

otide), which has high affinity for the diadenosine polyphosphates (Pintor *et al.*, 1993). This receptor has not yet been cloned and thus has been given the tentative name P2Y<sub>Ap4A</sub>. It is possible that this receptor belongs to the P2Y receptor superfamily because it seems to couple to G proteins.

In rat brain synaptosomes, [<sup>3</sup>H]Ap<sub>4</sub>A and [<sup>3</sup>H]ADPβS bind to high and low affinity binding sites (Pintor *et al.*, 1993). The high affinity binding sites display an agonist potency profile that is inconsistent with that of any known subtype of P<sub>2</sub> receptor: Ap<sub>4</sub>A > ADPβS > β,γ-meATP > α,β-meATP ≫ 2MeSATP. In rat hippocampal slices, Ap<sub>4</sub>A and Ap<sub>5</sub>A activate PKC (Klishin *et al.*, 1994), which suggests the coupling of the putative P2Y<sub>Ap4A</sub> (or P<sub>2D</sub>) receptor to G proteins. However, inhibition of synaptic transmission by diadenosine polyphosphates in hippocampal slices could be inhibited by adenosine receptor antagonists (Klishin *et al.*, 1994). So far, this receptor has been described only in the CNS (Pintor *et al.*, 1993; Klishin *et al.*, 1994).

#### F. P3 Receptor

A distinct P3 receptor that is activated by both nucleosides and nucleotides, and is antagonized by both xanthines and α,β-meATP, has been proposed (Shinozuka *et al.*, 1988; Forsythe *et al.*, 1991). In aiming toward a unifying system of purine and pyrimidine receptor nomenclature, this receptor may need to be renamed according to the new system of purine receptor classification when further information on its structure, signal transduction mechanisms, and pharmacological profile become available. Responses mediated by ATP at the P3 receptor are independent of its breakdown to adenosine, and stable analogs of ATP are also agonists. In some respects this receptor is similar to those P1 receptors which bind ATP and its analogs (Bailey and Hourani, 1990; Hourani *et al.*, 1991; Von Kügelgen *et al.*, 1992; King *et al.*, 1996a; Piper and Hollingsworth, 1996).

In general, the P3 receptor is prejunctional. It is activated by agonists with a potency order of 2Cl-adenosine > β,γ-meATP > ATP = adenosine, as determined for inhibition of evoked release of NA from sympathetic nerves in rat tail artery (Shinozuka *et al.*, 1988). This receptor has also been described in rat vas deferens, and UTP was additionally shown to inhibit NA overflow (Forsythe *et al.*, 1991). A receptor activated by adenosine and ATP, which is blocked by α,β-meATP, mediates outward K<sup>+</sup> currents, and has been identified as a novel P1 receptor, may be equivalent to the P3 receptor (King *et al.*, 1996a).

Facilitation by ATP and adenosine of evoked NA release has been shown in some vascular smooth muscle. These effects are blocked by α,β-meATP and 8-SPT, but α,β-meATP is ineffective as an agonist (Miyahara and Suzuki, 1987; Zhang *et al.*, 1989; Todorov *et al.*, 1994; Ishii *et al.*, 1995); it has been suggested that this may

represent a subtype of the P3 receptor (Dalziel and Westfall, 1994).

Another distinct P3 receptor has been proposed in smooth muscle of rabbit thoracic aorta; it is activated by both adenosine and ATP, but is xanthine- and suramin-insensitive (Chinellato *et al.*, 1994).

#### G. P4/Diadenosine Polyphosphate-Specific Receptor

A novel receptor for diadenosine polyphosphates, distinct from the  $P2Y_{Ap4A}$  (or  $P_{2D}$ ) receptor, has been proposed based on a study in rat brain synaptosomes (Pintor and Miras-Portugal, 1995a). Because this receptor is not activated by ATP, the term P4 has been suggested. Increases in synaptosomal  $Ca^{2+}$  elicited by  $Ap_4A$  and  $Ap_5A$  were not blocked with suramin and methylxanthines, in contrast with the increases in  $Ca^{2+}$  evoked by ATP,  $\alpha,\beta$ -meATP, and ADP $\beta$ S. Furthermore, the actions of  $Ap_4A$  and ATP did not cross-desensitize, although there was homologous desensitization to  $Ap_5A$ . It has been suggested that this receptor may be an ion channel, or is coupled to a  $Ca^{2+}$  channel (Pintor and Miras-Portugal, 1995a). This receptor has not been cloned and its existence as a distinct subtype is controversial. The synthesis of diinosine polyphosphates as antagonists with some selectivity for the effects of  $Ap_5A$  in rat brain synaptosomes *versus* the effects mediated by ATP may prove useful in the characterization of dinucleotide receptors (Pintor *et al.*, 1998).

### XXI. Integrated Effects of P2 Receptors

Many cells express more than one type of P2 receptor. The biological significance of this is not entirely clear but allows potential regulation of multiple effectors, fine tuning of agonist-evoked responses, and/or synergy. The quite different specificities of many P2 receptors for endogenous agonists suggest that the source and local concentration of ADP, ATP, UDP, UTP, and adenine dinucleotides may be important; more detailed information on this might provide some insight into the biological significance of P2 receptor coexistence. A number of cells seem to express more than one type of P2Y receptor: for example,  $P2Y_1$ - and  $P2Y_2$ -like receptors are expressed on cortical astrocytes, osteoblasts, hepatocytes, endothelial, and epithelial cells;  $P2Y_1$ - and  $P2Y_2$ -like and uridine nucleotide-specific receptors are expressed on cardiac endothelial cells (Yang *et al.*, 1996) (also see table 13). These receptors typically have a common signaling pathway in PLC, and downstream divergence at subsequent steps of this pathway may be important. Synergism does not seem to occur.

Differential expression and coexpression of receptors among similar cells has been shown for  $P2Y_1$ -like and  $P2Y_2$ -like receptors on individual cultured human osteoblasts (Dixon *et al.*, 1997b) and for astrocytes from the dorsal spinal cord of the rat (Ho *et al.*, 1995). Coexpression may also differ among tissues: functional studies suggest that hamster mesenteric arteries have predom-

inantly  $P2Y_2$ -like receptors and few  $P2Y_1$ -like receptors (Ralevic and Burnstock, 1996b), whereas the converse seems to be true for piglet aorta (Martin *et al.*, 1985) and lamb small coronary arteries (Simonsen *et al.*, 1997) where UTP is a very weak agonist. However, it is possible that these receptors are expressed but are not coupled to a vasomotor response. The physiological significance of the differential expression of P2Y receptors at the level of single cells and tissues remains to be determined.

$P2X_1$ -like and  $P2Y_1$ -like receptors coexist on the smooth muscle in some vessels; they may reciprocally control vascular tone by acting as mediators of vasoconstriction and vasodilatation, respectively. This may occur following release of ATP from the terminals of perivascular sympathetic and sensory nerves, respectively. Cooperative effects have been shown for coexisting  $P2X_1$ -like,  $P2Y_1$ -like, and  $P2Y_{ADP}$  (or  $P_{2T}$ ) receptors on platelets, which mediate ionotropic  $Ca^{2+}$  influx and mobilization of intracellular  $Ca^{2+}$ , respectively, to bring about changes in platelet shape and aggregation (Hourani and Hall, 1996; MacKenzie *et al.*, 1996; Daniel *et al.*, 1998; Hechler *et al.*, 1998; Jin *et al.*, 1998).  $P2Y_2$ - and  $P2X_7$ -like receptors coexist on macrophages, although the functional significance of this, if any, remains to be determined.

Receptor expression may be regulated differently under different physiological and pathophysiological conditions, thereby altering patterns of coexpression. Expression of P2 receptors on mononuclear phagocytes is regulated differently by proinflammatory cytokines, which cause rapid down-regulation of  $P2X_1$ -like and  $P2Y_2$ -like receptors, but concomitant massive up-regulation of  $P2X_7$ -like receptors (Dubyak *et al.*, 1996). There also is differential functional expression during development;  $P2Y_1$ -like receptors are expressed only in early myeloid progenitor cells, whereas  $P2Y_2$ -like receptors are expressed in late stage progenitor cells, and mature monocytes and neutrophils (Dubyak *et al.*, 1996; Martin *et al.*, 1997a).

Integrated effects of P2 receptors in whole tissues are considered in the next section.

### XXII. Integrated Effects of Adenosine/P1 and P2 Receptors

P1/P2 receptor coexistence has been identified for many cell types; these include  $P2X_7$ -,  $A_{2A}$ -,  $A_{2B}$ -, and  $A_3$ -like receptors on mast cells;  $P2Y_1$ ,  $P2Y_2$ ,  $A_{2A}$ , and  $A_{2B}$  receptors on endothelial cells;  $A_1$  and  $P2X_1$ -like receptors on smooth muscle cells; and  $A_{2A}$ ,  $A_{2B}$ ,  $P2Y_2$ -, and  $P2X_2$ -like receptors on PC12 cells. The functional significance of this is not entirely clear. Among other possible interactions there may be reciprocal effects, as shown for  $A_1$  receptor-mediated inhibition and  $P2Y_1$ -like receptor-mediated stimulation of insulin secretion in pancreatic  $\beta$ -cells (Hillaire-Buys *et al.*, 1989, 1993, 1994). Activation of  $A_{2A}$  receptors inhibits ATP-induced  $Ca^{2+}$  influx

via P2X receptors in PC12 cells (Park *et al.*, 1997), indicating antagonistic interplay between these systems. Integration of purine receptor-mediated responses at the level of whole tissues is illustrated by purinergic control of blood vessel tone, which involves vasoconstrictor P2X<sub>1</sub>-like and uridine nucleotide-specific receptors on vascular smooth muscle, vasodilator P2Y<sub>1</sub>-like, P2Y<sub>2</sub>-like, A<sub>2A</sub>, and A<sub>2B</sub> receptors found on smooth muscle and endothelium, and prejunctional A<sub>1</sub> receptors that modulate the release of neurotransmitter from perivascular nerves (fig. 12).

Normal patterns of purinergic signaling may alter dramatically under pathophysiological conditions. The net effect of purine receptors may be vasodilatation if endothelial cells are intact, but vasoconstriction will predominate if the endothelium is damaged. When endothelial cells are damaged, collagen is exposed. Platelets adhere to the collagen and release ADP, ATP, UTP, and adenosine dinucleotides, together with other substances such as 5-HT. Several substances promote further aggregation via activation of platelet P2X<sub>1</sub>-like, P2Y<sub>1</sub>-like, and P2Y<sub>ADP</sub> receptors. Purines and pyrimidines released from platelets can also act on endothelial and/or vascular smooth muscle cell P2 receptors. In an inflammatory reaction, ATP may be released from sensory nerves to have effects on mast cell P2X<sub>7</sub>-like receptors, although its breakdown product adenosine may activate coexisting mast cell A<sub>3</sub> receptors, leading to further effects on vascular tone after release of mast cell mediators.

Understanding how responses mediated by purine receptors are integrated in biological systems depends on information on the sources of the natural agonists, as well as on the receptor signaling pathways. In addition, the metabolic relationship between purines, whereby extracellular ATP is rapidly catabolized to ADP and adenosine has important implications for colocalized adenosine/P1 and P2 receptors as there may be an interplay between these receptors. Notably, many of the above studies are concerned with short-term interactions between coexisting purine receptors, which represents only one aspect of purine and pyrimidine receptor signaling. Particularly for metabotropic G protein-coupled receptors, long-term trophic interactions are likely to be important (Cowen *et al.*, 1991; Abbracchio *et al.*, 1995b; Neary, 1996) and may lead to further insights into the significance of P1/P2 receptor coexistence and the cross-talk that may occur between these receptors. Further information awaits the development of selective agonists and antagonists and studies with genetic "knockout" animals.

### XXIII. Conclusions

In this review we have considered in detail the pharmacological actions and interactions of purines and pyrimidines in different cells and tissues. These are presented within a framework intended to facilitate

### Purine receptors in blood vessels

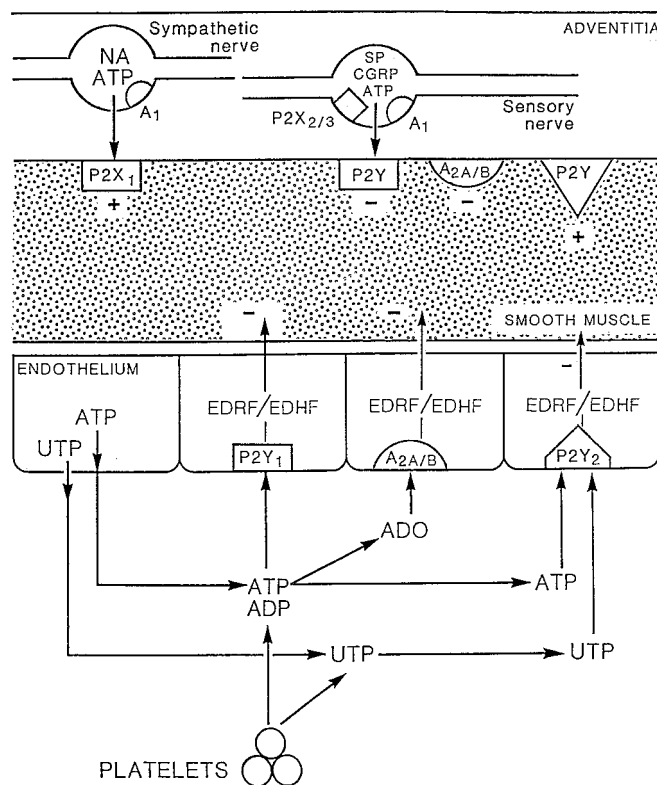


FIG. 12. Schematic of integrated effects of P1 and P2 purine receptors in the local control of vascular tone. Noradrenaline (NA), ATP, calcitonin gene-related peptide (CGRP), and substance P (SP) can be released from nerves in the adventitia to act on their respective receptors in the smooth muscle, causing vasoconstriction or vasodilatation. Prejunctional A<sub>1</sub> receptors modulate the release of neurotransmitter from sympathetic and sensory afferents. P2X<sub>2/3</sub> heteromers, possibly together with the corresponding homomeric P2X receptors, may be present on the peripheral terminals of sensory nerves where they may modulate sensory neurotransmission. Vasoconstriction following ATP release from perivascular nerves is mediated predominantly by P2X<sub>1</sub> receptors on the smooth muscle, while vasodilatation is mediated by smooth muscle P<sub>2Y</sub> receptors (P2Y<sub>1</sub>-like). P2Y receptors (possibly P2Y<sub>2</sub>, P2Y<sub>4</sub>, or P2Y<sub>6</sub>) are also present on some vascular smooth muscle and mediate vasoconstriction to purines and pyrimidines of currently undetermined source. Vasodilatation may also be mediated by smooth muscle A<sub>2A</sub> and A<sub>2B</sub> adenosine receptors. ATP and its breakdown product ADP, and UTP, can be released from endothelial cells by shear stress or hypoxia, to act on endothelial P2Y<sub>1</sub> and P2Y<sub>2</sub> receptors to mediate relaxation mainly via endothelium-derived relaxing factor (EDRF, or nitric oxide) or endothelium-derived hyperpolarizing factor (EDHF). ATP can be broken down rapidly to adenosine, which may act on endothelial and smooth muscle A<sub>2A</sub> and A<sub>2B</sub> receptors to mediate vasodilatation. (Adapted from Burnstock, 1990).

comparison between cloned and endogenous receptors and, thereby, to promote the development of the unifying system of nomenclature based on cloned receptors. For adenosine/P1 receptors, the availability of potent and selective pharmacological ligands has been crucial in the subclassification of this family into four subtypes. For P2 receptors, responses of biological tissue have been described that do not correspond well with those of any cloned P2 receptors; there are diverse reasons, including the fact that small differences in molecular structure of a receptor are commonly found between



species and tissues and may profoundly influence its properties. Other reasons include differences in assay conditions and because coexpression of different subtypes of receptors for purines and pyrimidines is common, which leads to complex pharmacological profiles. The lack of subtype-selective agonists and antagonists with which to adequately discriminate between responses is a significant handicap. Furthermore, while we have a reasonably good idea of the properties of homomeric recombinant P2X receptors, the relative contribution of individual subunits to responses mediated by heteromeric receptors is less clear. Although G protein-coupled P2Y receptors are single membrane-spanning proteins, diversity may be introduced by alternate G protein and/or second-messenger coupling.

Major advances in adenosine/P1 receptor research in the last few years include an increased understanding of the mechanisms underlying desensitization and neuro- and cardiac-protection, therefore offering novel approaches for pharmacological manipulation of receptor activity in disease. Much still needs to be learned about the A<sub>2B</sub> receptor, and the development of selective agonists and antagonists is urgently needed. As A<sub>2A</sub> and A<sub>2B</sub> receptors are often coexpressed by the same cell, this would promote investigations into short-term crosstalk and the long-term functional relationship between these subtypes. Newly developed ligands at the A<sub>3</sub> receptor will provide insights into the significance of its relatively restricted distribution and will increase our understanding of its dual protective and toxic effects. While it has long been appreciated that the different adenosine/P1 receptor subtypes have different affinities for adenosine, the fact that a single subtype can mediate opposite effects depending on its level of activation is a relatively new concept and an exciting area for further investigation. Little is known about the integrated patterns of events arising from differential activation and desensitization or up-regulation of coexisting receptors under conditions of different concentrations of adenosine, and this may be an important area for future research.

There has been a tremendous interest in the P2 receptor research in the last decade and many exciting issues have been raised. Specific questions of interest include the physiological significance of cation and pH modulation of P2X receptor activity, the true species of ATP that is the active ligand at P2 receptors, the mechanism of desensitization of P2X receptors, and the biological significance of a receptor that is activated equipotently by ATP and UTP (P2Y<sub>2</sub> and some P2Y<sub>4</sub> receptors). We expect the future will see important developments in research on receptors for pyrimidine nucleotides and investigations into the role of diadenosine polyphosphates as extracellular signaling molecules. Questions raised about the separate identity of the putative P3 receptor, and the P<sub>2D</sub> and P4 receptors claimed for adenine dinucleotides, currently identified solely by

their distinct pharmacology, are also likely to be resolved. Identification of novel splice variants may add significantly to the repertoire of P2 receptor-mediated responses. It is interesting that no receptors acting as ion channels, selective for extracellular pyrimidines, have been described, which is perhaps surprising given that some parallels exist for the putative extracellular roles of purines and pyrimidines. Given the widespread distribution of receptors responsive to UTP, characterization of the sources and conditions which mediate UTP release is important; there is no evidence for UTP release as a neurotransmitter to date, but it has been shown to modulate neurotransmission. The development of an assay for detection of nanomolar quantities of UTP is an exciting and important development in this field (Lazarowski *et al.*, 1997a).

Clearly, potent and selective agonists and antagonists are needed in purine and pyrimidine receptor research. Fortunately, groups in many universities and pharmaceutical industries are seeking to identify such ligands and, with the aid of high throughput screening, there is a good possibility that these and other questions will be answered in the not too distant future. The possibility of developing a transgenic animal model in which the animal P1 or P2 receptor subtype is replaced with the human homologue has been raised as a possible means of examining the function and pharmacology of the human receptor in biological tissue, with the intent of developing therapeutic strategies for human disease.

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