A2 Adenosine Receptors Inhibit Calcium Influx Through L-Type Calcium Channels in Rod Photoreceptors of the Salamander Retina

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Stella, Salvatore L. Jr., Eric J. Bryson, and Wallace B. Thoreson. A2 adenosine receptors inhibit calcium influx through L-type calcium channels in rod photoreceptors of the salamander retina. J Neurophysiol 87: 351–360, 2002; 10.1152/jn.00010.2001. Presynaptic inhibition is a major mechanism for regulating synaptic transmission in the CNS and adenosine inhibits Ca2+ currents (ICa) to reduce transmitter release at several synapses. Rod photoreceptors possess L-type Ca2+ channels that regulate the release of L-glutamate. In the retina, adenosine is released in the dark when L-glutamate release is maximal. We tested whether adenosine inhibits ICa and intracellular Ca2+ increases in rod photoreceptors in retinal slice and isolated cell preparations. Adenosine inhibited both ICa and the [Ca2+]i increase evoked by depolarization in a dose-dependent manner with ~25% inhibition at 50 μM. An A2-selective agonist, (N6-[2-(3,5-dimethoxyphenyl)-2-(2-methylphenyl)-ethyl]adenosine) (DPMA), but not the A1- or A3-selective agonists, (R)-N6-(1-methyl-2-phenylethyl)adenosine and N6-2-(4-aminophenyl)ethyladenosine, also inhibited ICa and depolarization-induced [Ca2+]i increases. An inhibitor of protein kinase A (PKA), Rp-cAMPS, blocked the effects of DPMA on both ICa, and the depolarization-evoked [Ca2+]i increase in rods. The results suggest that activation of A2 receptors stimulates PKA to inhibit L-type Ca2+ channels in rods resulting in a decreased Ca2+ influx that should suppress glutamate release.

INTRODUCTION

Adenosine is a potent neuromodulatory substance that is widely distributed throughout the CNS. Adenosine (or P1) receptors are divided into four known molecular and pharmacological subtypes: A1, A2A, A2B, and A3 receptors (Ralevic and Burnstock 1998). Adenosine is well characterized as an inhibitory transmitter in the CNS (Ribeiro 1995), but excitatory actions of adenosine have also been observed (Sebastiao and Ribeiro 1996). Inhibitory actions of adenosine are commonly mediated by the A1 receptor that couples negatively to adenylyl cyclase via a Gi protein to reduce cAMP levels in the cell (Dolphin et al. 1986; Ralevic and Burnstock 1998; van Calker et al. 1979). A2 receptors have been considered to mediate excitatory effects in the brain because they couple positively to adenylyl cyclase through a Gi protein to increase cAMP levels (Ralevic and Burnstock 1998; Sebastiao and Ribeiro 1996; van Calker et al. 1979). However, synaptic activation of A2 receptors is not always associated with an increase in ICa or transmitter release. A2 receptor activation enhances P-type but not other Ca2+ channel subtypes in neurons (Satoh et al. 1997; Umemiya and Berger 1994). Adenosine acting at A2 receptors has been shown to inhibit both N- and L-type Ca2+ channels in PC12 cells via stimulation of cAMP and protein kinase A (PKA) (Kobayashi et al. 1998; Park et al. 1998). A2 receptor activation also inhibits ICa, and thus GABA release in supra-chiasmatic and arcuate nuclei neurons (Chen and van den Pol 1997). It has thus been suggested that the increased excitability associated with A2 receptor activation arises from inhibition of ICa and the resulting decrease in release of inhibitory transmitter (reviewed in Edwards and Robertson 1999).

Adenosine is released in darkness from the retina (Blazynski and Perez 1991; Paes de Carvalho et al. 1990; Perez et al. 1986). Adenosine is present in human photoreceptors (Braas et al. 1987), and [3H]adenosine is taken up into photoreceptors and horizontal cells via transporters for adenosine (Paes de Carvalho et al. 1990; Studholme and Yazulla 1997), suggesting that adenosine is removed from the extracellular space following release. The presence of A2 receptors in the outer retina and particularly photoreceptors has been demonstrated by autoradiography and in situ hybridization (Blazynski 1990; Kvanta et al. 1997). Adenosine acting on A2 receptors stimulates melanin synthesis (Valenciano et al. 1998) and myoid elongation in cone photoreceptors (Rey and Burnside 1999), providing evidence for a physiological role for A2 receptors on photoreceptors.


The purpose of the present study was to examine the effect of adenosine on ICa and Ca2+ influx in rod photoreceptors.

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Driven by evidence that adenosine inhibits $I_{Ca}$ in many other preparations, adenosine is released from retinal neurons in the dark, $A_2$ receptors are located on photoreceptors, and an uptake system for adenosine is present at the photoreceptor synapse, we hypothesized that adenosine acting on $A_2$ receptors may inhibit $I_{Ca}$ and thus decrease $Ca^{2+}$ influx into rods, which would in turn reduce transmitter release. Whole cell perforated patch-clamp recordings and $Ca^{2+}$-imaging experiments with fura-2 were performed on rods in retinal slice and isolated cell preparations. Our results indicate that adenosine inhibits both $I_{Ca}$ and the depolarization-evoked $Ca^{2+}$ influx in a dose-dependent manner and that this inhibition is mediated by $A_2$ receptor activation coupled to a PKA pathway. To our knowledge, this is the first report of inhibition of presynaptic $I_{Ca}$ by $A_2$ receptors at a glutamatergic synapse. Abstracts describing some of these results have previously been presented (Stella and Thoreson 1999; Stella et al. 1999).

 METHODS

Tissue preparation

Larval tiger salamanders (*Ambystoma tigrinum*, Kons, German-town, WI or Charles Sullivan, TN; 7–10 in) were cared for according to institutional guidelines. Retinal slices were prepared according to the methods of Werblin (1978) and Wu (1987); exact procedures are described in further detail by Thoreson et al. (1997). Briefly, salamanders were killed by decapitation and pithed, the eyes were enucleated, and the anterior portion of an eye including the lens was removed. The resulting eyecup was cut into sections and placed vitreal side down onto a piece of filter paper, the sclera, choroid, and retinal pigment epithelium were removed under chilled amphibian superfusate. The isolated retina was then cut into 100- to 150-$\mu$m slices using a razor-blade tissue chopper (Stoelting). Retinal slices were rotated 90° for viewing of the retinal layers when placed under a water immersion objective (X40, 0.7 NA or X60, 1.0 NA) and viewed on an upright fixed stage microscope (Olympus BHWI or Nikon E600FN). All procedures were performed under dim light or under infrared illumination using Gen III image intensifiers (Nitemate NavIII, Litton Industries).

Solitary retinal neurons were prepared by isolating retina from the eyecup and finely mincing it using half of a double-edged razor blade. The minced retina was then gently triturated in amphibian superfusate with a large-bore fire-polished Pasteur pipette. Isolated cells were plated on slides coated with a salamander-specific antibody, Sal-1 (kindly provided by Peter MacLeish). Prior to beginning an experiment, cells were allowed to adhere to the slides for 15 min at 4°C.

Solutions and perfusion

Solutions were applied by a single-pass, gravity-fed perfusion system that delivered medium to the slice chamber (chamber volume: ~0.5 ml) at a rate of 1.0 ml/min. The normal amphibian superfusate that bathed the slices contained (in mM) 111 NaCl, 2.5 KCl, 1.8 CaCl$_2$, 0.5 MgCl$_2$, 10 N-2-hydroxyethylpiperazine-N’-2-ethanesulfonic acid (HEPES), and 5 glucose. After obtaining a photoreceptor recording, the superfusate was switched to a Ba$^{2+}$ solution to enhance Ca$^{2+}$ currents. The Ba$^{2+}$ solution contained (in mM) 99 NaCl, 2.5 KCl, 10 BaCl$_2$, 0.5 MgCl$_2$, 10 HEPES, 5 glucose, 0.1 picrotoxin, and 0.1 nitric acid. The pH of all solutions was adjusted to 7.8 with NaOH. The osmolarity measured with a vapor pressure osmometer (Wescor) was 242 ± 5 mOsm. Solutions were continuously bubbled with 100% O$_2$.

Electrophysiology

Patch pipettes were pulled on a Narashige PB-7 vertical puller from borosilicate glass pipettes (1.2 mm OD, 0.95 mm ID, omega dot) and had tips of ~1 μm OD with tip resistances of 10–15 MΩ.

Pipettes were filled with a solution containing (in mM) 54 CsCl, 61.5 CsCH$_3$SO$_4$, 3.5 NaCH$_3$SO$_4$, and 10 HEPES. The pH was adjusted to 7.2 with CsOH and the osmolarity was adjusted, if necessary, to 242 ± 5 mOsm. To maintain endogenous second-messenger signaling pathways and avoid the rundown that accompanies conventional whole cell recording of $I_{Ca}$, we used the perforated patch method of whole cell recording with the pore forming antibiotic, nystatin (Rae et al. 1991). Nystatin was dissolved in dimethylsulfoxide (DMSO) at a concentration of 120 mg/ml and then diluted into the pipette electrolyte solution to achieve a final concentration of 480 μg/ml. The final working solution was vortexed vigorously for 20–30 s and stored in the refrigerator. Fresh antibiotic solutions were made every 3 h. In successful recordings, seals >1 GΩ were obtained in ≤30 s and cells were usually fully perforated within 5 min of sealing.

Rods were identified by their long, rod-shaped outer segments. For electrophysiology, electrode placement was performed under infrared illumination using either Gen III image intensifiers mounted over the microscope eyepieces or with an infrared-sensitive video camera mounted on the trinocular head of the microscope.

The input resistance ($R_m$) of rods in the slice averaged 659.3 ± 48.9 (SE) MΩ (n = 22). $R_m$ of isolated rods averaged 2.4 ± 0.3 GΩ (n = 5). Access resistance, clamp speed, and membrane capacitance were measured by analyzing capacitive transients evoked by hyperpolarizing steps from a holding potential of ~70 mV. The time constant of the capacitative transient indicated a voltage-clamp speed of 0.97 ± 0.07 ms and a membrane capacitance for rods in the slice of 36.5 ± 3.7 pF (n = 22). For isolated rods, the clamp speed and capacitance determined from the capacitative transient averaged 2.4 ± 0.42 ms and 13.5 ± 1.8 pF (n = 5), respectively. Access resistance was typically between 22 and 30 MΩ; recordings were considered acceptable only when the access resistance was <40 MΩ. Estimates of the voltage errors introduced by the access resistance are included in the legends of figures showing examples of $I_{Ca}$.

Once whole cell access was achieved, light responses were obtained to determine the spectral sensitivity of the cell. Light-evoked responses in rods were generated by light from a tungsten light source that passed through a filter wheel containing interference filters of four different wavelengths (380, 480, 580, and 680 nm). The light stimulus was reflected into the microscope condenser using a beam splitter. Light intensity was controlled by neutral density filters (Wratten gel).

The intensity of unattenuated light measurement with a laser power meter (Metrologic) was ~1.1 × 10$^8$ photon s$^{-1}$ μm$^{-2}$ at 680 nm, 1.3 × 10$^7$ photon s$^{-1}$ μm$^{-2}$ at 580 nm, and 2.1 × 10$^5$ photon s$^{-1}$ μm$^{-2}$ at 480 nm (the power meter was not accurate at 380 nm). Generally, a flash of 1-s duration was used. The protocol for identifying the spectral sensitivity of a single photoreceptor involved successive flashes of increasing intensity (usually encompassing 2 log units of intensity) at the four wavelengths.

After superfusion with the 10 mM BaCl$_2$ solution was started, voltage ramps (0.5 mV/ms) from ~90 to ~60 mV were used to assess $I_{Ca}$ every 30 s. Voltage ramps yield a similar current-voltage profile as a step protocol but cause less rundown or inactivation of the current and provide more data points for fitting for analysis (Stella and Thoreson 2000). Drug solutions were applied after $I_{Ca}$ appeared stable for ≥90 s.

Cells were voltage clamped at ~70 mV using an Axopatch 200B patch-clamp amplifier (Axon Instruments, Foster City, CA). Currents were acquired and analyzed using Clampex 7.0 software (Axon Instruments). The leak conductance was assumed to be ohmic and equal to the minimum conductance between ~75 and ~55 mV and then
Measuring $[\text{Ca}^{2+}]_o$, transients

Intracellular $\text{Ca}^{2+}$ changes were assessed using the ratiometric dye fura-2 (Gryniewicz et al. 1985). Retinal slices were incubated for 45 min in the dark with 0.5 ml of 10 $\mu \text{M}$ fura-2/AM + 0.02% pluronic F-127 (Molecular Probes, Eugene, OR) in a slice chamber at 4°C. This was followed by an additional incubation in fura-2/AM alone for 1.5 h.

Digital fluorescent images were recorded with a cooled CCD camera (SensiCam, Cooke) on an upright fixed stage microscope (Nikon E600FN) equipped with a $\times 60$ (1.0 NA) water-immersion objective. A 150-W Xe bulb (Opti-Quip) was mounted on a Sutter Lambda 10–2 filter wheel with 340- and 380-nm interference filters and coupled to the microscope by a liquid light guide (Sutter). The 380-nm intensity was attenuated with a 0.5-neutral density filter to balance the intensity of emissions evoked by 340 and 380 nm. The fluorescence emitted by the cells on stimulation with 340- or 380-nm light was filtered through a 510 ± 20-nm band-pass emission filter. Axon Imaging Workbench (AIW 2.2) was used to control the camera, filter wheel, and image acquisition. Pixel binning (2 × 2) of the images was used to decrease acquisition rate (acquisition time: 0.5–1 s). Images were subtracted for background camera noise but no averaging or masking was performed.

To activate voltage-dependent $\text{Ca}^{2+}$ channels, cells were depolarized by increasing $[\text{K}^+]_o$ from 2.5 to 50 mM for 1 min. Elevated KCl applications were performed at 15 min intervals to reduce any $\text{Ca}^{2+}$-dependent inactivation. Images were acquired at 5- to 10-s intervals during elevated $[\text{K}^+]_o$ applications. All experiments were performed at room temperature. For analysis, a region of interest was drawn over the rod inner segment and a change in the ratio values for control conditions were determined by comparing the ratio changed produced in control superfusate with 0.5 ml of 10 $\mu \text{M}$ fura-2/AM + 0.02% pluronic F-127 (Molecular Probes, Eugene, OR) in a slice chamber at 4°C. This was followed by an additional incubation in fura-2/AM alone for 1.5 h.

Drug solutions

Adenosine, ATP, (R)-N^6-(1-methyl-2-phenylethyl)adenosine (R-PIA), N^6-[2-(3,5-dimethoxyphenyl)-2-(2-methylphenyl)-ethyl]adenosine (DPMA), N^6-2-(4-aminophenyl)ethyladenosine (APNEA), and Rp-adenosine 3',5'-cyclic monophosphothioate triethylamine (Rp-cAMPS) were obtained from Sigma Chemical (St. Louis, MO). Solutions containing (−)Bay K 8644 (Research Biochemicals International) or nisoldipine (Zeneca Pharmaceuticals) were prepared by diluting 10,000× DMSO stock solutions into the superfusate. R-PIA, DPMA, and APNEA stocks were dissolved in DMSO as 50 mM stock solutions. All other stock solutions (1,000×) were prepared in distilled water or superfusate. Superfusion with 0.1% DMSO alone did not produce a significant change in ratiometric recordings. The following drugs were obtained from other sources: Rp-adenosine 3',5'-cyclic monophosphothioate triethylamine (Rp-cAMPS), 8-sulfinyladenosine (8SA), and 6-[(2,2-dimethyl-1-pyrrolidinyl)ethyl]adenosine (DPMA). Thiophosphorylated nucleotides were prepared as described previously (Hauri et al. 1986). Adenosine 5'-(bis-)phosphorylcholine (APPC), 6-[2-(3,5-dimethoxyphenyl)-2-(2-methylphenyl)-ethyl]adenosine (APNEA), and 6-[2-(3,5-dimethoxyphenyl)-2-(2,5-dimethylphenyl)-ethyl]adenosine (APNEA) were obtained from Sigma Chemical (St. Louis, MO). Solutions containing (−)-Bay K 8644 (Research Biochemicals International) or nisoldipine (Zeneca Pharmaceuticals) were prepared by diluting 10,000× DMSO stock solutions into the superfusate. R-PIA, DPMA, and APNEA stocks were dissolved in DMSO as 50 mM stock solutions. All other stock solutions (1,000×) were prepared in distilled water or superfusate. Superfusion with 0.1% DMSO alone did not produce a significant change in ratiometric recordings.
not affect any of the properties of \( I_{Ca} \) or Ca\(^{2+}\) imaging responses that we studied.

**RESULTS**

**Characterization of L-type calcium currents in rod photoreceptors**

We will refer to the inward current evoked by a depolarizing voltage ramp in rods in the presence of 10 mM Ba\(^{2+}\) as \( I_{Ca} \). In the presence of 10 mM Ba\(^{2+}\), a slowly developing U-shaped current-voltage relationship appeared above \(-50\) mV that peaked between \(-25\) and \(-10\) mV and then diminished at more positive potentials. The current typically reversed between \(+50\) and \(+60\) mV. The peak amplitude of \( I_{Ca} \) in rods averaged \(-371.7 \pm 31.7\) pA (\(n = 23\)) and the voltage at which the current was half-maximal (\(V_{50}\)) averaged \(-31.0 \pm 1.6\) mV (\(n = 23\)).

Figure 1 illustrates an example of the effects of the DHP agonist, Bay K 8644 (1 \(\mu\)M), and the DHP antagonist, nisoldipine (5 \(\mu\)M), on \( I_{Ca} \) recorded in a rod. In agreement with other studies on photoreceptors, \( I_{Ca} \) was enhanced by Bay K 8644 and incompletely blocked by a high concentration of nisoldipine (Kourennyi and Barnes 2000; Wilkinson and Barnes 1996). In addition to suppressing the peak current, nisoldipine produced a positive shift in the current/voltage relationship for \( I_{Ca} \) similar to that shown by Wilkinson and Barnes for cone \( I_{Ca} \) (Wilkinson and Barnes 1996). Three millivolts of the rightward shift shown in Fig. 1 can be accounted for by a decrease in \( I_{Ca} \) flowing across the access resistance. The remainder of this positive shift may arise from the more potent block of L-type \( I_{Ca} \) by nisoldipine at more negative potentials (Albillos et al. 1994). The residual \( I_{Ca} \) in photoreceptors recorded in the presence of nisoldipine has been shown to arise largely from unblocked L-type Ca\(^{2+}\) channels and not from a second channel type (Kourennyi and Barnes 2000; Wilkinson and Barnes 1996).

**Adenosine inhibits rod \( I_{Ca} \)**

The effect of adenosine on rod \( I_{Ca} \) is shown in Fig. 2. Figure 2A illustrates current-voltage profiles of \( I_{Ca} \) in control conditions (Fig. 2B, 1) and in the presence of adenosine (Fig. 2B, 2). Figure 2B plots the amplitude of \( I_{Ca} \) measured with voltage ramps every 30 s. As illustrated in Fig. 2A, adenosine (50 \(\mu\)M) inhibited \( I_{Ca} \) in rods without shifting the current-voltage relationship along the voltage axis. The mean reduction in \( I_{Ca} \), by 50 \(\mu\)M adenosine was 22.8 \(\pm\) 3.3% (\(n = 9, P = 0.0001\)). All of the rods tested at this concentration displayed a similar degree of inhibition in the presence of adenosine. Typically, inhibition of the rod \( I_{Ca} \) began within 30 to 60 s, the time required for complete solution exchange in the recording chamber. Full inhibition was observed after 2 min, and currents recovered after \(-5\) min washout of adenosine (Fig. 2B). As the concentration of adenosine was increased from 1 to 50 \(\mu\)M, a significant inhibition of rod \( I_{Ca} \) was seen at concentrations 10 \(\mu\)M, implying that there is a concentration-dependent effect of adenosine on rod \( I_{Ca} \) (Fig. 3).

To test whether an intermediary cell type might be involved in adenosine modulation of rod \( I_{Ca} \), solitary rods were mechanically isolated by gentle trituration and tested with 50 \(\mu\)M adenosine. As in retinal slices, adenosine significantly inhibited \( I_{Ca} \) in isolated rods by 19.0 \(\pm\) 5.5% (\(n = 5, P = 0.026\)), suggesting that adenosine acts directly on rod photoreceptors to modulate \( I_{Ca} \).

**Adenosine reduces depolarization-evoked Ca\(^{2+}\) influx in rods**

Ca\(^{2+}\)-imaging experiments were performed on retinal slices to test whether adenosine reduced depolarization-evoked [Ca\(^{2+}\)]\(_i\) increases in rod photoreceptors. Slices were incubated with fura-2/AM. Rods were depolarized by elevating [K\(^+\)]\(_o\) from 2.5 to 50 mM for 1 min. Figure 4A shows a brightfield Nomarski image of rod photoreceptors in the retinal slice. Corresponding paired pseudocolor images of fluorescence from the same cells are displayed in Fig. 4B (340, 380, and 340/380 nm), showing cells in both normal (2.5 mM) and elevated (50 mM) [K\(^+\)]\(_o\) amphibian superfusate. Figure 4C shows a plot of the [Ca\(^{2+}\)]\(_i\) response measured in a rod photoreceptor before, during, and after the application of adenosine (50 \(\mu\)M). Adenosine produced a reversible inhibition of the depolarization-evoked [Ca\(^{2+}\)]\(_i\) increase. On average, adenosine (50 \(\mu\)M) caused a 25.9 \(\pm\) 3.4% (\(n = 14, P < 0.0001\)) reduction in the K\(^+\)-evoked 340/380 ratio change in rod photoreceptors in the slice. Significant inhibition of the K\(^+\)-evoked [Ca\(^{2+}\)]\(_i\) increase was seen at concentrations as low as 1 \(\mu\)M (4.9 \(\pm\) 1.4%, \(n = 11, P = 0.005\)), and inhibition increased in a dose-dependent fashion with concentrations \(\leq 50\) \(\mu\)M (Fig. 5).

**A\(_2\) receptor agonists inhibit rod \( I_{Ca} \) and Ca\(^{2+}\) influx**

Adenosine can interact with P2 (purinergic) receptors (Ralevic and Burnstock 1998) that have been shown to modulate Ca\(^{2+}\) channels in various neurons (Brown et al. 2000; Dave and Mogul 1996). To test whether a P2 receptor may be involved in the modulation of voltage-gated Ca\(^{2+}\) channels in rods, ATP was bath applied to rod photoreceptors in the retinal slice preparation and examined with perforated patch recording of rod \( I_{Ca} \) and [Ca\(^{2+}\)]\(_i\), imaging using fura 2. ATP did not significantly inhibit \( I_{Ca} \) (50 \(\mu\)M ATP: +7.1 \(\pm\) 11.3%, \(n = 7, P = 0.549\)) or the K\(^+\)-evoked Ca\(^{2+}\) increase in rod photoreceptors (75 \(\mu\)M ATP: +11.9 \(\pm\) 7.3%, \(n = 15, P = 0.1296\)), suggesting that P2 receptors do not mediate the observed inhibition by adenosine.

The absence of an ATP effect suggests that adenosine acts at an adenosine receptor. There are four major subtypes of adenosine receptors: A\(_1\), A\(_2A\), A\(_2B\), and A\(_3\). R-PIA is an A\(_3\)-selective receptor agonist, DPMA is an A\(_3\)-selective receptor agonist that interacts with both A\(_2A\) and A\(_2B\) receptors, and APNEA is an A\(_3\)-selective receptor agonist (Bridges et al. 1988; Ralevic and Burnstock 1998). To characterize the adeno-
adenosine receptor subtype that mediates inhibition of $I_{Ca}$, we tested the effects of these three agonists on the rod $I_{Ca}$. As shown in Fig. 6B, only the A$_2$-selective agonist, DPMA (2 µM), significantly inhibited the rod $I_{Ca}$. Like adenosine, DPMA did not cause a significant shift in the current-voltage relationship along the voltage axis (Fig. 6B, mean shift in $V_{50}$ = 0.8 ± 0.63 mV, $n$ = 6, $P$ = 0.1563). The A$_1$-selective agonist, R-PIA (2 µM), and A$_3$-selective agonist, APNEA (2 µM), did not significantly inhibit rod $I_{Ca}$ (Fig. 6A, 6B, and 6C). Adenosine receptor agonists were tested at 2 or 10 µM. Figure 6D illustrates the overall results with R-PIA (2 µM), DPMA (2 µM), and APNEA (10 µM) on rod $I_{Ca}$. DPMA at concentrations of 2 and 10 µM inhibited $I_{Ca}$ in rods by 15.1 ± 3.4% ($n$ = 12, $P$ < 0.0001) and 31.0 ± 3.1% ($n$ = 12, $P$ = 0.003; 25.3 µM: -25.9 ± 3.4%, $n$ = 14, $P$ < 0.0001).

Using Ca$^{2+}$ imaging techniques, we tested the effects of the same three adenosine receptor agonists on depolarization-evoked [Ca$^{2+}$]$_i$ increases. Figure 7A displays responses to a series of K$^+$-evoked depolarizations measured in the inner segment of a rod photoreceptor in the presence of R-PIA (10 µM), DPMA (10 µM), and APNEA (10 µM). Only the A$_2$-selective agonist, DPMA, inhibited the depolarization-evoked [Ca$^{2+}$]$_i$ increase in rods. Figure 7B shows the overall results of adenosine receptor agonists on the depolarization-induced [Ca$^{2+}$]$_i$ increases in rods. In agreement with the effects of these agonists on rod $I_{Ca}$, DPMA (10 µM) reduced the K$^+$-evoked [Ca$^{2+}$]$_i$ increase in rods by 30.9 ± 4.9% ($n$ = 12, $P$ < 0.0001), while R-PIA (10 µM) and APNEA (10 µM) did not significantly alter the K$^+$-evoked [Ca$^{2+}$]$_i$ increase (R-PIA, +3.0 ± 3.3%, $n$ = 12, $P$ = 0.355; APNEA, -4.4 ± 2.7%, $n$ = 12, $P$ = 0.129).

A$_2$ receptors inhibit rod $I_{Ca}$ and Ca$^{2+}$ influx through a PKA-dependent pathway

The primary signaling mechanism by which A$_2$ receptors transduce their signals intracellularly is to couple positively to adenylyl cyclase and thus stimulate the production of cAMP, which in turn activates PKA to phosphorylate various proteins that can include Ca$^{2+}$ channels subunits (Alexander et al. 1994; De Jongh et al. 1996; Gubitz et al. 1996; Mogul et al. 1993). Similar to the effects of the A$_2$ receptor agonist DPMA, stimulation of cAMP production with forskolin or activation of PKA with Sp-cAMPS inhibits $I_{Ca}$ in rods (Stella and Thoreson 2000). We therefore tested whether Rp-cAMPS, a cell-permeant analogue of cAMP known to inhibit PKA activity (Chik et al. 1997; Dolphin 1995), could block the effects of DPMA. Rp-cAMPS (10 µM) was applied to retinal slices prior to application of DPMA (2 µM). As illustrated in Fig. 8A, DPMA did not inhibit rod $I_{Ca}$ while in the presence of Rp-cAMPS. Figure 8B shows current-voltage profiles of rod $I_{Ca}$ obtained in control conditions (Fig. 8A, 1), in the presence of Rp-cAMPS (Fig. 8A, 2), and in the presence of both Rp-cAMPS and DPMA (Fig. 8A, 3). The bar graph in Fig. 8C shows that $I_{Ca}$ recorded in the presence of DPMA was significantly larger when Rp-cAMPS (10 µM) was also present. The increase in $I_{Ca}$ above the baseline in the presence of Rp-cAMPS and DPMA may reflect ability of Rp-cAMPS to enhance $I_{Ca}$ in rods (Stella and Thoreson 2000).

Figure 9 shows effects of Rp-cAMPS on [Ca$^{2+}$]$_i$ increases produced by application of elevated [K$^+$]$_o$ on rod photoreceptors in the slice. Similar to rod $I_{Ca}$, application of Rp-cAMPS (10 µM) prevented DPMA from inhibiting the K$^+$-evoked Ca$^{2+}$ increase (Fig. 9A, +3.6 ± 10.8% $n$ = 8, $P$ = 0.7499). To confirm the efficacy of DPMA, DPMA (2 µM) was reapplied after washout of Rp-cAMPS and found to inhibit the K$^+$-evoked Ca$^{2+}$ increase (Fig. 9A, -36.1 ± 3.9%, $n$ = 8, $P$ < 0.0001). In agreement with the $I_{Ca}$ results of Fig. 8, Rp-cAMPS (10 µM), significantly reduced the ability of DPMA (2 µM) to inhibit the depolarization-evoked [Ca$^{2+}$]$_i$ increase (Fig. 9B, DPMA (2 µM) versus DPMA (2 µM) + Rp-cAMPS (10 µM): paired t-test, $n$ = 8, $P$ = 0.0212). The results of these experiments suggest that stimulation of PKA activity is primarily responsible for A$_2$ receptor modulation of voltage-dependent L-type Ca$^{2+}$ channels in rods.

**DISCUSSION**

The present study indicates that activation of A$_2$ receptors by adenosine stimulates PKA activity, which in turn inhibits voltage-gated L-type Ca$^{2+}$ channels in rod photoreceptors. Similar concentrations of adenosine also produced a comparable inhibition of depolarization-evoked [Ca$^{2+}$]$_i$ increases. Adenosine released in the retina in darkness (Blazynski and Perez 1991; Paes de Carvalho et al. 1990; Perez et al. 1986) may therefore inhibit $I_{Ca}$ and reduce Ca$^{2+}$ entry into rods that would likely inhibit their release of glutamate.

**Adenosine receptor pharmacology and signaling pathways**

Purine and pyrimidine receptors are divided into two large families, P1 (or adenosine) receptors and P2 (or purinergic) receptors (for review, Ralevic and Burnstock 1998). ATP (50–75 µM) had no effect on the $I_{Ca}$, or the depolarization-evoked [Ca$^{2+}$]$_i$ increase in rods, indicating that P2 receptors are unlikely to contribute to the inhibition produced by adenosine. Adenosine receptor subtypes were classified originally by their effects on adenylyl cyclase activity: A$_1$ receptors...
inhibit and A\textsubscript{2} receptors stimulate adenylyl cyclase (Londos et al. 1980; van Calker et al. 1979). However, the classification has since been broadened to include a new A\textsubscript{3} receptor subtype (Zhou et al. 1992) and two subtypes of A\textsubscript{2} receptors, A\textsubscript{2A} and A\textsubscript{2B} (Furlong et al. 1992; Maenhaut et al. 1990; Pierce et al. 1992). To discriminate among A\textsubscript{1}, A\textsubscript{2}, and A\textsubscript{3} receptor subtypes, we used selective agonists for each receptor subtype: R-PIA for A\textsubscript{1} receptors, DPMA for A\textsubscript{2} receptors, and APNEA for A\textsubscript{3} receptors. The ability of the A\textsubscript{2}-selective agonist, DPMA, but not the A\textsubscript{1} or A\textsubscript{3} receptor agonists to inhibit both the depolarization-evoked Ca\textsuperscript{2+} increase and \(I_{\text{Ca}}\) in rods (Figs. 6 and 7) is consistent with binding studies that have localized A\textsubscript{2} receptors to photoreceptor inner and outer segments (McIntosh and Blazynski 1994). We did not attempt to pharmacologically discriminate between A\textsubscript{2A} and A\textsubscript{2B} receptors. However, mRNA for the A\textsubscript{2A} receptor has been shown to be expressed in the outer nuclear layer and ganglion cell layer, whereas A\textsubscript{2B} receptor mRNA is absent from the retina (Kvanta et al. 1997), suggesting that A\textsubscript{2A} receptors are likely to be responsible for the effects observed in the present study. In a

**FIG. 6.** Effect of adenosine receptor agonists on rod photoreceptor \(I_{\text{Ca}}\). A: the A\textsubscript{1}-selective adenosine receptor agonist, (R)-N\textsuperscript{6}-(1-methyl-2-phenyl-ethyl)adenosine (R-PIA, 2 \(\mu\)M), did not inhibit rod \(I_{\text{Ca}}\). Voltage error at the peak of the current due to uncompensated access resistance was estimated to be \(-9\) mV in both records. B: the A\textsubscript{2}-selective agonist, N\textsuperscript{6}-[2-(3,5-dimethoxy-phenyl)-ethyl]adenosine (DPMA, 2 \(\mu\)M), inhibited rod \(I_{\text{Ca}}\). Voltage error at the peak of the current due to uncompensated access resistance was estimated to be \(-2.6\) mV in control and \(-2.1\) mV in DPMA. C: the A\textsubscript{3}-selective adenosine receptor agonist, N\textsuperscript{6}-2-(4-aminophenyl)ethyladenosine (APNEA, 10 \(\mu\)M), did not inhibit rod \(I_{\text{Ca}}\). Voltage error at the peak of the current due to uncompensated access resistance was estimated to be \(-4\) mV in both records. Each graph shows I-V relationships of voltage ramps obtained in control superfusate (---) and test solution (- - -). D: bar graph comparing effects of R-PIA, DPMA, and APNEA on \(I_{\text{Ca}}\) in rods. Amplitude of the currents obtained in test solutions were normalized to currents obtained in the control solution (\(I_{\text{test}}/I_{\text{control}}\)). * significant changes with respect to control (\(P < 0.05\)). R-PIA, \(-0.5 \pm 4.7\%\), \(n = 6\), \(P = 0.92\); DPMA, \(-15.1 \pm 4.7\%\), \(n = 11\), \(P < 0.0001\); APNEA, \(+2.4 \pm 5.8\%\), \(n = 7\), \(P = 0.69\).
study on cone motility in teleosts, the rank order of potency for adenosine agonists was found to be consistent with A2-like receptors, but antagonist potencies did not correspond precisely to either A2A or A2B receptors (Rey and Burnside 1999). A2 receptor activation elevates cAMP levels in whole retina (Blazynski et al. 1986; Paes de Carvalho and Mello 1982). A2 receptor-mediated inhibition of Ca\(^{2+}\) influx and \(I_{ca}\) in rods is similar to the inhibition of rod \(I_{ca}\) produced by stimulation of cAMP production or activation of PKA (Stella and Thoreson 2000) and inhibition of PKA with Rp-cAMPS blocked the inhibitory effect of DPMA in rods (Figs. 8 and 9). Taken together, these results indicate that A2 receptor-mediated changes in Ca\(^{2+}\) influx from depolarization of \(I_{ca}\) in rods are likely established by stimulation of PKA.

Sources of retinal adenosine

Adenosine has been detected in photoreceptors of human, monkey, guinea pig (Braas et al. 1987), fish (Ehinger and Perez 1984), and chick retinas (Paes de Carvalho et al. 1992). Adenosine has also been localized to ganglion cells (Ehinger and Perez 1984) and cells in the inner nuclear layer (Ehinger and Perez 1984; Paes de Carvalho et al. 1992) including rod horizontal cells (Studholme and Yazulla 1997) and amacrine cells (Blazynski 1989). Adenosine is released tonically from retinas in the dark (Blazynski and Perez 1991; Paes de Carvalho et al. 1990; Perez et al. 1986) and likely results from intracellular turnover of ATP in photoreceptor inner segments. In the dark, photoreceptors are depolarized by cations (e.g., Na\(^{+}\), Ca\(^{2+}\)) entering through cyclic nucleotide channels in the outer segment (Shimazaki and Oakley 1986; Torre 1982). Increased intracellular adenosine levels are generated by the turnover of ATP from a highly active Na\(^{+}\)/K\(^{+}\)-ATPase in the inner segment that counters the cation influx in the outer segment. The increased ATP turnover and breakdown of adenine nucleotides elevates intracellular adenosine levels. Increased adenosine

![Figure 8](image) - Rp-cAMPS (10 μM) prevented inhibition of \(I_{ca}\) by DPMA (10 μM) in rods. A: time course of changes in \(I_{ca}\) amplitude during application of Rp-cAMPS and Rp-cAMPS plus DPMA. B: current-voltage relationships of voltage ramps obtained at time points 1 (control), 2 (Rp-cAMPS), and 3 (Rp-cAMPS + DPMA) from A. Control: thick solid trace. Rp-cAMPS (10 μM): thin solid trace. DPMA (2 μM) + Rp-cAMPS (10 μM): thin trace. Voltage error at the peak of the current due to uncompensated access resistance was estimated to be \(-3\) mV in all 3 records. C: bar graph summarizing relative changes in \(I_{ca}\) amplitude induced by Rp-cAMPS or Rp-cAMPS plus DPMA. Each bar represents the mean ± SE. Asterisk, \(P < 0.05\) compared with control. *DPMA significantly inhibited \(I_{ca}\) (\(-15.1 ± 4.7\%, n = 11, P < 0.0001\)) but not in the presence of Rp-cAMPS (DPMA + Rp-cAMPS \(I_{ca}\): \(+12.2 ± 6.8\%, n = 4, P = 0.14\)). DPMA produced significantly less inhibition in the presence of Rp-cAMPS (DPMA, \(n = 11\) vs. DPMA + Rp-cAMPS, unpaired t-test, \(P = 0.0001\)).

![Figure 9](image) - Rp-cAMPS (10 μM) prevented the inhibition of depolarization-evoked [Ca\(^{2+}\)] responses by DPMA (2 μM) in rod photoreceptors. A: effects of successive elevated [K\(^+\)] applications in control superfusate and in the presence of Rp-cAMPS and DPMA. DPMA reversibly inhibited depolarization-evoked [Ca\(^{2+}\)] responses in the same cell following \(-20\) min washout of Rp-cAMPS + DPMA. B: bar graph summarizing relative changes in depolarization-evoked [Ca\(^{2+}\)] responses induced by Rp-cAMPS (10 μM) and Rp-cAMPS (10 μM) plus DPMA (2 μM) in experiments similar to those illustrated in A. *DPMA (2 μM) significantly inhibited the K\(^+\)-evoked Ca increase in rods after washout of Rp-cAMPS + DPMA (\(-36.1 ± 3.9\%, n = 8, P < 0.0001\)). **DPMA (2 μM) produced significantly less inhibition in the presence of Rp-cAMPS (10 μM; paired t-test, \(n = 8, P = 0.02\)).
levels stimulate the efflux of adenosine down its concentration gradient via symmetrical adenosine transporters (Thorn and Jarvis 1996) which appear to be present on photoreceptors (Ehinger and Perez 1984).

ATP can be stored and released from vesicles (e.g., Corcoran et al. 1986; Jo and Schlachter 1999; Santos et al. 1999; von Kugelgen et al. 1994) and extracellular breakdown of ATP can be an important source of extracellular adenosine (Cunha et al. 1998). It appears unlikely that a significant amount of extracellular ATP is converted to adenosine at the photoreceptor synapse in the retinal slice preparation because application of 50–75 μM ATP did not inhibit I\textsubscript{Ca} or the depolarization-evoked Ca\textsuperscript{2+} response. However, the finding that soluble nucleotidases are co-released with ATP from sympathetic neurons suggests that they may be co-localized in synaptic vesicles (Todorov et al. 1997), and this raises the possibility that ATP might be broken down by nucleotidases in synaptic vesicles to ADP, AMP, or adenosine prior to release. Consistent with such a possibility, Blazynski and Perez (1991) have shown that K\textsuperscript{+}-evoked depolarization stimulates the release of adenosine in the retina.

Physiological significance

Previous studies have shown Ca\textsuperscript{2+} channels can be inhibited by A\textsubscript{2} receptors resulting in inhibition of transmitter release. For example, activation of A\textsubscript{2} receptors from cultured suprachiasmatic and arcuate nuclei neurons inhibit presynaptic I\textsubscript{Ca} and GABA release (Chen and van den Pol 1997). A\textsubscript{2A} activation also reduces the frequency of spontaneous and miniature inhibitory postsynaptic currents by 30% in striatal medium spiny neurons as a result of reduced GABA release (Mori et al. 1996). The present results show that A\textsubscript{2} receptor activation can also inhibit presynaptic I\textsubscript{Ca} in glutamatergic neurons. Such a mechanism might account for the decreased release of L-glutamate evoked by depolarization following activation of A\textsubscript{2A} receptors in rat striatum and cultured chick retinal neurons (Golembiowska and Zylewska 1997; Rego et al. 2000).

The results of the present study show that adenosine acting on A\textsubscript{1} receptors in rods can regulate L-type I\textsubscript{Ca} and Ca\textsuperscript{2+} influx in rods. Thus the changing levels of adenosine in the retina that accompany changing levels of illumination could serve as an autocrine or paracrine signal to regulate synaptic output from rods.

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