Adenosine Triphosphate Activates a Noninactivating K⁺ Current in Adrenal Cortical Cells through Nonhydrolytic Binding

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Abstract Bovine adrenal zona fasciculata (AZF) cells express a noninactivating K⁺ current (I_{AC}) that is inhibited by adrenocorticotropic hormone and angiotensin II at subnanomolar concentrations. Since I_{AC} appears to set the membrane potential of AZF cells, these channels may function critically in coupling peptide receptors to membrane depolarization, Ca²⁺ entry, and cortisol secretion. I_{AC} channel activity may be tightly linked to the metabolic state of the cell. In whole cell patch clamp recordings, MgATP applied intracellularly through the patch electrode at concentrations above 1 mM dramatically enhanced the expression of I_{AC} K⁺ current. The maximum I_{AC} current density varied from a low of 8.45 ± 2.74 pA/pF (n = 17) to a high of 109.2 ± 26.3 pA/pF (n = 6) at pipette MgATP concentrations of 0.1 and 10 mM, respectively. In the presence of 5 mM MgATP, I_{AC} K⁺ channels were tonically active over a wide range of membrane potentials, and voltage-dependent open probability increased by only ~30% between −40 and +40 mV. ATP (5 mM) in the absence of Mg²⁺ and the nonhydrolyzable ATP analog AMP-PNP (5 mM) were also effective at enhancing the expression of I_{AC} K⁺ channels. At 1 mM ATP, the unitary I_{AC} current amplitude did not vary with the ATP concentration or substitution with AMP-PNP. In addition to ATP and AMP-PNP, a number of other nucleotides including GTP, UTP, GDP, and UDP all increased the outwardly rectifying I_{AC} current with an apparent order of effectiveness: MgATP > ATP = AMP-PNP > GTP = UTP > ADP >> GDP > AMP and ATP-γ-S. Although ATP, GTP, and UTP all enhanced I_{AC} amplitude with similar effectiveness, inhibition of I_{AC} by ACTH (200 pM) occurred only in the presence of ATP. As little as 50 μM MgATP restored complete inhibition of I_{AC} which had been activated by 5 mM UTP. Although the opening of I_{AC} channels may require only ATP binding, its inhibition by ACTH appears to involve a mechanism other than hydrolysis of this nucleotide. These findings describe a novel form of K⁺ channel modulation by which I_{AC} channels are activated through the nonhydrolytic binding of ATP. Because they are activated rather than inhibited by ATP binding, I_{AC} K⁺ channels may represent a distinctive new variety of K⁺ channel. The combined features of I_{AC} channels that allow it to sense and respond to changing ATP levels and to set the resting potential of AZF cells, suggest a mechanism where membrane potential, Ca²⁺ entry, and cortisol secretion could be tightly coupled to the metabolic state of the cell through the activity of I_{AC} K⁺ channels.

Key words: adenosine triphosphate • potassium channel • adrenocorticotropic hormone • nucleotide

Introduction

I_{AC} is a novel noninactivating K⁺ current that may set the resting potential of bovine adrenal zona fasciculata (AZF) cells. Angiotensin II (AII) and adrenocorticotropic hormone (ACTH) inhibit I_{AC} and depolarize AZF cells at concentrations identical to those that stimulate cortisol production (Mlinar et al., 1993a). This K⁺ channel appears to act pivotally in coupling these peptide hormone receptors to depolarization-dependent Ca²⁺ entry and corticosteroid production (Enyeart et al., 1993).

I_{AC} K⁺ channel activity may be regulated by the complex interaction of biochemical factors and membrane voltage. In whole-cell patch clamp recordings from AZF cells, we found that I_{AC} K⁺ current measured during depolarizing voltage steps increases dramatically (10–100-fold) over a period of many minutes (Mlinar et al., 1993a). Inhibitory factors present in the cytoplasm may be diluted during dialysis of the cell by pipette solution, allowing the functional expression of the I_{AC} current. In this regard, the time-dependent growth of I_{AC} is suppressed by including the nonhydrolyzable GTP analog GTP-γ-S in the recording pipette, indicating the presence of an inhibitory mechanism requiring a GTP-binding protein (Mlinar et al., 1993a). Accordingly, inhibition of I_{AC} by both ACTH and AII require G-pro-
tein intermediates (Mlinar et al., 1995; Enyeart et al., 1996b).

ACTH receptors are coupled to adenylate cyclase through Gs. Although most cAMP-dependent actions of ACTH are mediated through cAMP-dependent protein kinase, inhibition of IAC by both ACTH and cAMP occur through an A-kinase–independent mechanism requiring ATP hydrolysis (Enyeart et al., 1996b). This result suggests that opening and closing of IAC K+ channels could be coupled to an ATP hydrolysis cycle, similar to that which controls the activity of the cystic fibrosis transmembrane conductance regulator (CFTR) Cl– channels (Hwang et al., 1994; Baukrowitz et al., 1994; Quinton and Reddy, 1992). If so, then IAC K+ channels could be activated by the hydrolytic or nonhydrolytic binding of ATP to these channels or associated proteins.

A large number of ATP-sensitive K+ channels are expressed by a variety of cells ranging from cardiac and skeletal muscle cells to neurons and insulin-secreting pancreatic β cells (Ashcroft, 1988a; Hilgemann, 1997; Terzic et al., 1994; Takano and Noma, 1993). However, these inwardly rectifying channels are uniformly inhibited by ATP through nonhydrolytic binding to the channel or an associated protein. In contrast, whole-cell and single channel patch clamp recordings from bovine AZF cells showed that ATP, over a physiological range of concentrations, dramatically enhanced IAC K+ current.

MATERIALS AND METHODS

Tissue culture media, antibiotics, fibronectin, and fetal bovine sera were obtained from Gibco Laboratories (Grand Island, NY). Culture dishes were purchased from Corning Glass Works (Corning, NY). Coverslips were from Belco Glass, Inc. (Vineland, NJ). Enzymes, ACTH (1-24), NaATP, MgATP, KATP, KADP, AMP, 5'-adenylyl-imidodiphosphate (AMP-PNP, lithium salt), adenosine 5'-O-(3-thio-triphosphate) (ATP-gS, tria-lithium salt), EDTA, NaGTP, NaGDP, NaUTP, and NaUDP were obtained from Sigma Chemical Co. (St. Louis, MO). Pinacidil was obtained from Research Biochemicals International (Natick, MA).

Isolation and Culture of AZF Cells

Bovine adrenal glands were obtained from steers (age 1–3 yr) within 15 min of slaughter at a local slaughterhouse. Fatty tissue was removed immediately and the glands were transported to the laboratory in ice-cold PBS containing 0.2% dextrose. Isolated AZF cells were prepared as previously described with some modifications (Gospodarowicz et al., 1977). In a sterile tissue culture hood, the adrenals were cut in half lengthwise and the lighter capsule with attached glomerulosa and thicker fasciculata-reticularis layers were then dissected into large pieces (~1.0 × 1.0 × 0.5 cm). A Stadie-Riggs tissue slicer (Thomas Scientific, Swedesboro, NJ) was used to slice fasciculata-reticularis tissue from the glomerulosa layers by slicing 0.3–0.5 mm slices from the larger pieces. The first medulla/fasciculata slices were discarded. One to two subsequent fasciculata slices were saved in cold sterile PBS/0.2% dextrose. Fasciculata tissue slices were then diced into 0.5 mm³ pieces and dissociated with 2 mg/ml (~200–300 U/ml) of Type I collagenase (neutral protease activity not exceeding 100 U/mg of solid), 0.2 mg/ml deoxyribonuclease in DMEM/F12 for ~1 h at 37°C, triturating after 30 and 45 min with a sterile plastic transfer pipette. After incubating, the suspension was filtered through two layers of sterile cheesecloth, and then centrifuged to pellet cells at 100 g for 5 min. Undigested tissue remaining in the cheesecloth was collagenase treated for an additional hour. Pelleted cells were washed twice with DMEM/0.2% BSA, centrifuging as before. Cells were filtered through 200-μm stainless steel mesh to remove clumps after resuspending in DMEM. Dispersed cells were again centrifuged and either resuspended in DMEM/F12 (1:1) with 10% FBS, 100 U/ml penicillin, and 0.1 mg/ml streptomycin, and plated for immediate use, or resuspended in FBS/5% DMSO, divided into 1-ml aliquots, each containing ~2 × 10⁶ cells and stored in liquid nitrogen for future use. Cells were plated in 35-mm dishes containing 9-mm² glass coverslips that had been treated with fibronectin (10 μg/ml) at 37°C for 30 min, and then rinsed with warm, sterile PBS immediately before adding cells. Dishes were maintained at 37°C in a humidified atmosphere of 95% air/5% CO₂.

To minimize variability in IAC currents, all of the cells used in experiments measuring current density (~200 cells) were obtained in a single isolation from six bovine adrenal glands and stored in liquid N₂, as described above, in ~70 vials. For each experiment, cells were plated on coverslips from a single vial. Experimental results reported in this paper were obtained in recordings made over an 8-mo period. Cells stored in liquid N₂, as described above, retained electrophysiological and biochemical properties for at least 1 yr from freezing date. Specifically, AZF cells stored in this way expressed IAC K+ current as well as I₃ K+ current with no obvious deterioration during the course of this study. Further, as previously reported, ACTH and All both inhibited IAC K+ current in these cells with a potency not distinguishable from that observed in freshly isolated cells (Enyeart et al., 1996b; Mlinar et al., 1993a, 1995). After months in liquid N₂, cultured AZF cells responded to ACTH and All with large increases in cortisol secretion, and expression of orphan receptor mRNAs (Enyeart et al., 1993, 1996a, 1996b; Mlinar et al., 1995).

Patch Clamp Experiments

Patch clamp recordings of K+ channel currents were made in the whole-cell and outside-out patch configurations. For both recording configurations, the standard pipette solution was 120 mM KCl, 2 mM MgCl₂, 1 mM CaCl₂, 10 mM HEPES, 11 mM BaPTA (1,2-bis(2-aminophenoxy)ethane-N,N',N,N''-tetraacetic acid), and 200 μM GTP, with pH buffered to 7.2 using KOH. Addition of various nucleotides and other deviations from the standard solution are described in the text. Pipette (Ca²⁺) was determined using the “Bound and Determined” program (Brooks and Storey, 1992). The external solution consisted of (mM): 140 NaCl, 5 KCl, 2 CaCl₂, 2 MgCl₂, 10 HEPES, and 5 glucose, pH 7.4 using NaOH. All solutions were filtered through 0.22-μm cellulose acetate filters. AZF cells were used for patch clamp experiments 2–12 h after plating. Typically, cells with diameters of <15 μm and capacitances of 8–12 pF were selected, Coverslips were transferred from 35-mm culture dishes to the recording chamber (1.5 ml vol) that was continuously perfused by gravity at a rate of 3–5 ml/min. For whole cell recordings, patch electrodes with resistances of 1.0–2.0 MΩ were fabricated from Corning glass (7052 or 0010; Garner Glass Co., Claremont, CA). These routinely yielded access resistances of 1.5–4 MΩ and voltage clamp time constants of <100 μs. For single channel recordings, patch electrodes with higher resistances of 3–5 MΩ were used. K+ currents were recorded at room temperature (22–25°C).
following the procedure of Hamill et al. (1981) using an EPC-7 patch clamp amplifier (List Electronic, Darmstadt, Germany).

Pulse generation and data acquisition were done using a personal computer and PCLAMP software with an Axolab interface (Axon Instruments, Inc., Burlingame, CA). Currents were digitized at 1–20 kHz after filtering with an 8-pole Bessel filter (Frequency Devices Inc., Haverhill, MA). Linear leak and capacity currents were subtracted from current records using scaled hyperpolarizing steps of 1/3–1/4 amplitude. Data were analyzed and plotted using PCLAMP 5.5 and 6.02 (CLAMPAN, CLAMPFIT, FETCHAN, and PSTAT) and GraphPAD InPLOT. Drugs were applied by bath perfusion, controlled manually by a six-way rotary valve. Series resistance compensation was not used in experiments where the $I_{AC}$ currents were <1 nA. A current of this size in combination with a 4 MΩ access resistance produces a voltage error of only 4 mV that was not corrected.

**RESULTS**

**Effects of ATP and Analogs on $I_{AC}$ K$^+$ Current**

Bovine AZF cells express two types of K$^+$ currents that are easily distinguished in whole cell recordings. These include a rapidly inactivating A type K$^+$ current and a noninactivating K$^+$ current that grows continually over a period of many minutes in whole cell recordings (Mlinar et al., 1993a; Enyeart et al., 1996b). The absence of time-dependent inactivation of the $I_{AC}$ K$^+$ current allowed it to be easily isolated for measurement in whole cell recordings using either of two voltage clamp protocols. When voltage steps of 300-ms duration were ap-

**Figure 1.** MgATP enhances time-dependent expression of $I_{AC}$ K$^+$ current. (A) Current records showing K$^+$ currents at indicated times after initiating whole-cell recording with patch pipettes containing standard pipette solution (see METHODS) supplemented with 2, 5, or 10 mM MgATP as indicated. (top) K$^+$ currents were activated by voltage steps to +20 mV from a holding potential of −80 mV applied at 30-s intervals. (bottom) Voltage clamp steps to +20 mV were preceded by 10-s prepulses to −20 mV, inactivating the A-type K$^+$ current. (B) $I_{AC}$ currents activated at 30-s intervals by either of the above voltage protocols were measured and plotted against time for three representative cells in which the pipette contained 2 (●), 5 (■), or 10 (●) mM MgATP. Open symbols show current amplitudes after inactivating prepulse. (C) Max $I_{AC}$ current density (expressed as pA/pF) was obtained by dividing the maximum $I_{AC}$ current amplitude obtained in experiments such as those illustrated in A and B by the cell capacitance determined from transient cancellation controls of patch clamp amplifier. $I_{AC}$ current density is plotted against pipette MgATP concentration. Results are mean ± SEM for the indicated number of cells.
plied from a holding potential of −80 mV to a test potential of +20 mV, IAC could be selectively measured near the end of a step, at a point where the A type K+ current had inactivated entirely (Fig. 1 A, top traces). Using the second protocol, IAC was selectively activated with an identical voltage step, after a 10-s prepulse to −20 mV had fully inactivated the A type current (Fig. 1 A, bottom traces).

The time-dependent increase in IAC amplitude observed in whole-cell recordings depended on the concentration of ATP in the pipette solution. At concentrations >1 mM, MgATP dramatically increased the maximum IAC amplitude attained (Fig. 1). At lower concentrations, MgATP was much less effective. With MgATP present in the pipette at 0.1 and 0.4 mM, IAC reached maximum current densities of 8.4 ± 2.7 (n = 7) and 12.2 ± 4.9 pA/pF (n = 10), respectively. In contrast, at concentrations of 5 and 10 mM MgATP, IAC reached, after 10−25 min, maximums of 78.0 ± 8.9 (n = 26) and 109.2 ± 26.3 nA/pF (n = 6), respectively (Fig. 1 C).

The dramatic enhancement of IAC current by MgATP observed in whole-cell recordings could have several explanations. Modulation of ion channel function by protein kinases is widespread, while ion channel modulation through an ATP hydrolysis cycle involving ATPases is more recently been reported (Baukrowitz et al., 1994; Levitan, 1994). Alternatively, MgATP−S is a poorly hydrolyzable ATP analog that is, like AMP−PNP, a poor substrate for cellular ATPases. In contrast to AMP−PNP, MgATP−S is a good substrate for many protein kinases, while the transferred phosphothioate group is resistant to hydrolysis by phosphatases (Eckstein, 1985). MgATP−S produced effects on K+ currents in AZF cells that were dramatically different from those observed with AMP−PNP. Specifically, with 2 mM ATP−γ−S in the pipette, IAC did not grow in whole-cell recordings. Instead, any noninactivating IAC current that was present upon initiating whole-cell recording was inhibited over a period of several minutes (Fig. 3 A). At the same time, the decay kinetics of the rapidly inactivating A type K+ current often slowed dramatically in the presence of ATP−γ−S. In the experiment illustrated in Fig. 3 B, 4 min after commencing whole-cell recording, IAC inactivated with a time constant (τi) of 26.1 ns. By 13 min, τi had slowed to 254 ns. In spite of the slowed inactivation kinetics, a 10-s prepulse to −20 mV was effective at inactivating nearly all of the Ia current (Fig. 3 C). Overall, with 2 mM ATP−γ−S in the recording pipette, IAC was not clearly detectable in any of 20 cells at any time between 5 and 30 min. In nine of these cells, Ia inactivation kinetics slowed dramatically during the recordings.

**ATP and Unitary IAC Currents**

Single channel recordings made from AZF cells in the outside-out configuration showed that, in contrast to whole-cell currents, unitary IAC current amplitudes were not increased by raising the “intracellular” MgATP concentration from 2 to 5 mM. In these experiments, IAC currents were first recorded in the whole-cell configuration to allow IAC to reach a stable amplitude. After obtaining an outside-out patch, the holding potential was set to −40 mV, a potential where nearly all Ia channels are inactivated (Milnar and Enyeart, 1993b). Under these conditions, a single type of K+ channel was typically present in the patch membrane. Fig. 4 A shows unitary currents activated by voltage steps to +30 mV from a holding potential of −40 mV in the presence of either 2 or 5 mM MgATP. Histogram analysis of unitary current amplitudes showed a single major peak for the lower and higher MgATP concentrations with respective means of 3.81 ± 0.62 pA and 3.92 ± 0.81 pA (Fig. 4 A). A second minor peak, with a mean of approximately twice the unitary amplitude, was also present (data not shown).

In whole-cell recordings, MgATP and AMP-PNP both induced expression of noninactivating outward currents presumed to be IAC. Single channel current−voltage (IV) relationships recorded in the presence of the hydrolyzable and nonhydrolyzable nucleotides showed that the corresponding unitary K+ currents were identical. Single channel IVs for IAC K+ channels were obtained by applying voltage steps in 10-mV increments to outside-out patches from a holding potential of −40 mV. The single channel IV relationship obtained with 5 mM MgCl2 and MgATP, respectively, was nearly identical (Fig. 4 B). In each case, with otherwise standard pipette and external solutions, IAC channel currents displayed a unitary conductance of ~70 pS, estimated between potentials of 0 and +40 mV. Thus, the unitary currents activated by low and high concentrations of MgATP or a nonhydrolyzable ATP analog, appear to flow through the same IAC channel.
Figure 2. Effect of K\textsuperscript{+} ATP and AMP-PNP on I\textsubscript{AC} expression. The time-dependent increase of I\textsubscript{AC} K\textsuperscript{+} current was monitored using patch pipettes containing standard solution supplemented with AMP-PNP, or a modified pipette solution containing no MgCl\textsubscript{2} with ATP added as a K\textsuperscript{+} salt. (A and B) K\textsuperscript{+} currents were activated at 30s intervals from a holding potential of −80 mV using patch electrodes containing 5 mM KATP (A) or 5 mM AMP-PNP (B). K\textsuperscript{+} current records at the indicated times after obtaining the whole-cell configuration with (middle) and without (left) inactivating prepulses as described in Fig. 1. I\textsubscript{AC} current amplitude is plotted against time at right. (C) Effect of KATP and AMP-PNP on maximum I\textsubscript{AC} current density. Maximum I\textsubscript{AC} current density in the presence of 5 mM KATP and 5 mM AMP-PNP was 48.5 ± 9.8 pA/pF (n = 11) and 67.3 ± 23.2 pA/pF (n = 6), respectively, compared with 78.0 ± 8.9 pA/pF (n = 26) with 5 mM MgATP in the pipette solution. Maximum I\textsubscript{AC} current density was calculated from experiments as in A and B above. MgATP, KATP, and AMP-PNP were applied intracellularly through the pipette solution at either 0.1 or 5.0 mM. Results are mean ± SEM for the indicated number of individual determinations.
Experiments with KATP and AMP-PNP indicated that nonhydrolytic binding of ATP was sufficient to convert $I_{AC}$ channels to an active or activatable form. To determine whether other adenine nucleotides would increase $I_{AC}$ amplitude in whole cell recordings, we compared MgATP with ADP and AMP. A time-dependent increase in $I_{AC}$ amplitude occurred in the presence of ADP but not AMP (Fig. 5, A and C). When the pipette contained 5 mM AMP, $I_{AC}$ failed to grow above the control amplitude measured immediately after initiating whole-cell recording (Fig. 5, B and C). Further, in each of five cells, the rapidly inactivating A type $K_1$ current was observed to decrease with time in the presence of AMP (Fig. 5 B). Overall, when the pipette contained 5 mM ADP, $I_{AC}$ grew to a maximum current density of 36.1 ± 10.8 pA/pF ($n = 12$), compared with 78.0 ± 8.9 pA/pF ($n = 26$) observed with 5 mM MgATP in the patch electrode (Fig. 5 D). When the patch electrode contained 0.1 mM ADP, $I_{AC}$ reached a maximum of only 10.7 ± 2.4 pA/pF ($n = 4$), a value not significantly different from that observed with 0.1 mM MgATP.

In addition to ATP, we found that other nucleotide triphosphates, including GTP and UTP, were also effective in promoting $I_{AC}$ activity in whole cell recordings. In these experiments, sodium salts of ATP, UTP, or GTP were added to the pipette solution at a concentration of 5 mM. With each of these agents, a time-dependent increase in $I_{AC}$ amplitude, which usually reached a maximum value in 10–25 min, was observed (Fig. 6). Overall, these three nucleotides produced similar effects on $I_{AC}$ current densities with maximum values of 72.0 ± 27.5 (n = 5), 57.7 ± 23.8 (n = 7), and 53.7 ± 18.0 pA/pF (n = 8), for ATP, GTP, and UTP respectively (Fig. 6 B). The nucleotide diphosphates GDP and UDP were much less effective than the nucleotide triphosphates at enhancing $I_{AC}$, but both did significantly increase $I_{AC}$ over the control value observed in the absence of nucleotides (Fig. 6 B).

**Current–Voltage Characteristics of Nucleotide-activated $K_1$ Current**

The IV relationships for the noninactivating $K_1$ currents induced by ATP, GTP, and UTP were similar and indicated that, regardless of the nucleotide, a large fraction of $I_{AC}$ channels are open at membrane potentials at least as negative as –40 mV. In these experiments, $I_{AC}$ was selectively activated by applying voltage steps of varying size from a holding potential of –40 mV. Fig. 7, A and B illustrates typical IV relationships obtained with 5 mM ATP and 5 mM UTP. Sustained outward currents were present at the holding potential. The $K_1$ current observed in response to depolarizing steps consisted of an apparently instantaneous component and a time-dependent fraction that became more prominent with stronger depolarizations (Fig. 7 B). Similar outwardly rectifying currents were observed with all three nucleotide triphosphates.

The characteristics of $I_{AC}$ currents observed in current–voltage relationships suggested that $I_{AC}$ $K_1$ channels are at most weakly voltage dependent over potentials ranging from –40 to +40 mV. In an effort to determine to what extent the outwardly rectifying properties of $I_{AC}$ were due to the conductance properties of open channels as opposed to voltage-dependent activation, we compared the steady state IV for the $I_{AC}$ current to the instantaneous current–voltage relationship. The open channel IV (IV) provides a measure of the open channel conductance properties.

The IV for $I_{AC}$ was obtained by selectively activating this current from a holding potential of –40 mV with.
150-s depolarizing steps to +50 mV, after which the membrane potential was stepped to new levels between +40 and −120 mV. The IAC “tail current” was measured after 1 ms, before a significant change in the number of open channels occurred (Fig. 7C).

An estimate of the voltage dependence of IAC activation over the range of potentials from −40 to +40 mV was obtained by dividing current amplitudes taken from the steady state IV relationship by corresponding amplitudes from the IIVs. Dividing the steady state IV values obtained with ATP in Fig. 7B by the IIV values from Fig. 7C indicated that the open probability of IAC channels increased by only 30% over this 80-mV range of potentials.

The weak voltage dependence of IAC open probability indicated that the current–voltage characteristics of IAC are due to the conductance properties of open channels. Accordingly, in a previous study using elevated external K+, we have shown IAC to be an outwardly rectifying current (Enyeart et al., 1996b).

Effect of Other Agents on IAC

Each of the nucleotides that activated IAC is a polyvalent anion that can bind polyvalent metal cations. Nucleotide binding of polyvalent trace metals may activate a calcium-activated chloride current in Xenopus oocytes (Hilgemann, 1997). It is unlikely that nucleotide chelation of metals activates IAC in AZF cells since EDTA, a nonspecific metal ion chelator, failed to activate this K+ current when included in the pipette solution. When whole cell recordings were made with standard pipette solution supplemented with 0.1 mM MgATP, IAC reached a maximum density of 8.45 ± 2.74 pA/pF.
Adenosine Triphosphate–activated K⁺ Current

The addition of EDTA (1 mM) to this pipette solution did not increase $I_{AC}$. In the presence of 1 mM EDTA, $I_{AC}$ reached a maximum density of 6.24 ± 4.56 pA/pF ($n = 6$).

Although $I_{AC}$ channels are activated rather than inhibited by ATP, modulation by this nucleotide could indicate that $I_{AC}$ channels are structurally similar to ATP-sensitive K⁺ channels. Inwardly rectifying ATP-sensitive K⁺ channels such as those found in pancreatic β cells display a distinctive pharmacology. K⁺ channel activators such as pinacidil dramatically enhance the activity of these channels (Takano and Noma, 1993). However, pinacidil at concentrations of 30 ($n = 4$) and 100 ($n = 2$) μM failed to measurably increase $I_{AC}$ amplitude in whole-cell recordings.

**ACTH and ATP Hydrolysis**

The activity of $I_{AC}$ K⁺ channels is promoted by a number of nucleotide triphosphates including the nonhydrolyzable ATP analog AMP-PNP. Apparently, activation of $I_{AC}$ channels by these nucleotides requires only binding to the channel or an associated protein. Relatedly, ACTH and its primary intracellular messenger, cAMP, can both inhibit $I_{AC}$ by an A-kinase–independent mechanism requiring ATP hydrolysis (Enyeart et al., 1996b). These results are consistent with a model in which $I_{AC}$ opening and closing are controlled through an ATP hydrolysis cycle involving ATP binding and metabolism via an ATPase.

To test this model and clarify the mechanism of...
ACTH, we took advantage of our finding that UTP (and GTP) could activate $I_{AC}$ almost as effectively as ATP. However, unlike ATP, UTP is not a substrate for enzymes including adenylate cyclase, protein kinases, and most ATPases. As previously reported (Mlinar et al., 1993; Enyeart et al., 1996), when the pipette contains standard solution (CONTROL) supplemented with either NaATP, NaGTP, or NaUTP at a concentration of 5 mM. Current traces and corresponding plots of $I_{AC}$ amplitude against time for four representative cells are shown. (B) Maximum $I_{AC}$ current density (expressed as pA/pF) was obtained by dividing the maximum $I_{AC}$ current by cell capacitance in experiments such as those illustrated in A. Results are mean ± SEM for the indicated number of cells for each nucleotide.

The central finding of this study is that over a physiological range of concentrations, ATP, in hydrolyzable or nonhydrolyzable forms, dramatically increases $I_{AC}$ current in bovine AZF cells through a mechanism.

These results indicate that ACTH does not close $I_{AC}$ channels through ATPase-catalyzed hydrolysis of ATP at the nucleotide binding site since the activating site presumably remained occupied by UTP. The findings also convincingly demonstrate that the outwardly rectifying, noninactivating $K^+$ current activated by ATP and UTP in AZF cells are the identical ACTH-inhibited $I_{AC}$ current.

**Discussion**

The central finding of this study is that over a physiological range of concentrations, ATP, in hydrolyzable or nonhydrolyzable forms, dramatically increases $I_{AC}$ $K^+$ current in bovine AZF cells through a mechanism.
Adenosine Triphosphate–activated K\textsuperscript{1} Current

that presumably requires only the binding of this nucleotide to the channel or a related protein. A number of other nucleotides, including ADP, UTP, and GTP were also effective at enhancing I\textsubscript{AC} activity. With any of these nucleotides in the pipette, a significant fraction of I\textsubscript{AC} channels remained tonically active at membrane potentials at least as negative as \(-40\) mV and the open probability increased little between \(-40\) and \(+40\) mV. Although the opening of I\textsubscript{AC} K\textsuperscript{+} channels under physiological conditions may require only the binding of ATP to the I\textsubscript{AC} channel, its inhibition by ACTH appears to proceed through a mechanism other than the hydrolysis of this nucleotide. Due to their capacity to sense cellular ATP levels and set the membrane potential of AZF cells, I\textsubscript{AC} K\textsuperscript{+} channels may act as transducers that couple metabolic signals to membrane depolarization and cortisol secretion.

Modulation of I\textsubscript{AC} K\textsuperscript{+} Current by Adenine Nucleotides

The activation of I\textsubscript{AC} K\textsuperscript{+} channels by both hydrolyzable and nonhydrolyzable forms of ATP clearly distinguishes these channels from the ATP-sensitive K\textsuperscript{+} channels described in many other cells. These inwardly rectifying channels are uniformly inhibited by the nonhydrolytic binding of ATP and analogs (Ashcroft, 1988\textsuperscript{a}). However, in a number of ATP-inhibited K\textsuperscript{+} channels, low concentrations of MgATP (<100 \muM) are actually required to maintain K\textsuperscript{+} channel activity. Phosphorylation of the channel by a protein kinase is the mechanism involved (Lederer and Nichols, 1989; Terzic et al., 1994; Levitan, 1994). Regardless, when ATP concentrations are raised to the millimolar range, inwardly rectifying ATP-sensitive K\textsuperscript{+} channels are uniformly inhibited. In contrast, outwardly rectifying I\textsubscript{AC} channels are activated.

There are very few reports of ion channels that are directly activated by ATP binding. In human sweat glands, the CFTR Cl\textsuperscript{2} channel has been reported to be activated by both hydrolyzable and nonhydrolyzable forms of ATP at millimolar concentrations (Quinton and Reddy, 1992). However, this channel appears to differ from the I\textsubscript{AC} channel in that the CFTR channel requires A-kinase–dependent phosphorylation, as well as ATP binding, for activity. Enhanced activity of voltage-gated L-type Ca\textsuperscript{2+} channels in heart cells by nonhydrolyzable ATP analogs has also been reported (O’Rourke et al., 1992). I\textsubscript{AC} may be the first example of a K\textsuperscript{+}-selective channel that is directly activated by nonhydrolytic binding of ATP.

In a variety of cells that express ATP-sensitive K\textsuperscript{+} channels, including myocytes, pancreatic \(\beta\) cells, and neurons, the inhibitory actions of ATP are antagonized by ADP, thereby tightly coupling channel activity to the energetic state of the cell (Ashcroft, 1988\textsuperscript{a}; Takano and Noma, 1993; Terzic et al., 1994). In AZF cells, ADP and ATP each enhance the I\textsubscript{AC} K\textsuperscript{+} current, although ADP is

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**Figure 7.** I\textsubscript{AC} current–voltage relationships for ATP and UTP. (A) Whole-cell recordings were made from AZF cells using patch pipettes containing standard solution supplemented with NaATP or NaUTP, each at a concentration of 5 mM. After I\textsubscript{AC} K\textsuperscript{+} current had reached a stable amplitude, the current–voltage relationship was obtained from a holding potential of \(-40\) mV by applying voltage steps at 15-s intervals in 10-mV increments to test potentials up to \(+40\) mV. (B) I\textsubscript{AC} current amplitudes were normalized to the maximum current and plotted against test voltage. (C) Instantaneous current–voltage relationship (IV). After activation of I\textsubscript{AC} by voltage steps of 150-ms duration to \(+50\) mV from a holding potential of \(-40\) mV, the membrane potential was stepped to values between \(+40\) and \(-120\) mV, where tail currents were recorded. Maximum tail currents at each potential are expressed as a fraction of the tail current measured at 0 mV and plotted against membrane potential. Values are mean \(\pm\) SEM of measurements from three separate cells. (Inset) Tail-current records from a single cell.
less effective. Thus, in contrast to many cells where ATP and ADP exert opposing actions on ATP-sensitive K\(^+\) channels, in bovine AZF cells both nucleotides are agonists. It is possible that at some [ATP]/[ADP] ratios, the less effective ADP might antagonize the stimulatory action of ATP on I\(_{AC}\) channels.

In contrast to ATP and AMP-PNP, the poorly hydrolyzable ATP analog ATP-\(\gamma\)-S failed to enhance I\(_{AC}\) current and was actually inhibitory. While ATP-\(\gamma\)-S is a poor substrate for ATPases and phosphatases, it is a surprisingly good substrate for most kinases (Eckstein, 1985). Further, the phosphorothioate that is transferred from ATP-\(\gamma\)-S is poorly hydrolyzed. Proteins normally regulated by a phosphorylation/dephosphorylation cycle end up highly thiophosphorylated. This would suggest that phosphorylation of I\(_{AC}\) channels by an unidentified protein kinase inhibits I\(_{AC}\) and overrides enhancement of channel activity by ATP. The reduction, rather than increase, in I\(_{AC}\) K\(^+\) current observed in the first few minutes of whole-cell recording with pipettes containing ATP-\(\gamma\)-S is consistent with this model. Presumably, ATP-\(\gamma\)-S binds to the nucleotide binding site associated with enhanced I\(_{AC}\) activity. However, this action is negated by a slowly reversible phosphorylation. This model would also account for the dramatically different effects of ATP-\(\gamma\)-S and AMP-PNP on K\(^+\) current in AZF cells.

The slowing of I\(_{a}\) inactivation kinetics induced by
ATP-γ-S may also be due to the slowly hydrolyzable thiophosphorylation of the normally rapidly inactivating I_A K^+ channels. The inactivation kinetics of several A type K^+ channels are regulated by protein kinase-mediated phosphorylation that can either accelerate or slow inactivation (Covarrubias et al., 1994; Drain et al., 1994).

**Activation of I_{AC} by Other Nucleotides**

Other nucleotide triphosphates including GTP and UTP increased I_{AC} K^+ current in a manner similar to ATP. Accordingly, ATP-sensitive K^+ channels in skeletal muscle and ventricular myocytes are inhibited by GTP and UTP, although less effectively than by ATP itself (Spruce et al., 1987; Lederer and Nichols, 1989). In contrast to the inhibitory effects of nucleotide triphosphates on many ATP-sensitive channels, various nucleotide diphosphates including UDP and GDP activate these same channels (Takano and Noma, 1993; Terzic et al., 1994). Thus, while nucleotide di- and triphosphates exert opposing effects on the activity of classic ATP-sensitive channels, these nucleotides have qualitatively similar effects on I_{AC} channel activity.

Our results indicate that a diverse group of nucleotides, including purine and pyrimidine triphosphates and diphosphates, alone or complexed with Mg^{2+}, can activate I_{AC} K^+ channels through nonhydrolytic binding. Two nucleotide binding domains are present on ATP-sensitive K^+ channel-associated sulfonylurea receptors that form the β subunit of these channels in various cells (Aguilar-Bryan et al., 1995). Although the nucleotide binding sites on I_{AC} channels seem to be similar with regard to lack of nucleotide specificity, the number and location of these sites on I_{AC} channels remain to be identified.

The sulfonylurea receptor-coupled ATP-sensitive K^+ channels are inwardly rectifying and, unlike most K^+ channels, include two rather than six membrane-spanning domains (Ho et al., 1993; Aguilar-Bryan et al., 1995). The structure of the novel outwardly rectifying I_{AC} channel has not been determined. However, the ineffectiveness of pinacolide in enhancing I_{AC} current does not suggest a similarity between I_{AC} and ATP-inhibited channels. Further, in other experiments, we have found that the sulfonylurea glibenclamide, which potently inhibits inwardly rectifying ATP-sensitive K^+ channels, is much less effective at inhibiting I_{AC} K^+ channels (our unpublished observations).

**ACTH and ATP Hydrolysis**

In the present study, we have demonstrated that the binding of ATP dramatically enhances the activity of I_{AC} channels measured in response to membrane depolarization. Previously, we had demonstrated that ACTH and cAMP can each inhibit I_{AC} K^+ current by a mechanism that is independent of A kinase activation while requiring ATP hydrolysis. Taken together, these results suggested that the gating of I_{AC} could be controlled through an ATP hydrolysis cycle, as has been observed for CFTR Cl^- channels of the heart (Baukrowitz et al., 1994). If ACTH-mediated hydrolysis of ATP at its binding site on the I_{AC} channel resulted in channel closing, then it is unlikely that channels activated by UTP would be effected since UTP is not a substrate for most ATPases (Azhar and Menon, 1975; Krebs and Beavo, 1979;
Edelman et al., 1987). Therefore, the effective inhibition of UTP-activated I_{AC} channels by ACTH in the presence of only 50 μM ATP argues strongly against a model for channel closing requiring hydrolysis of this nucleotide by an ATPase. However, an unusual class of ATPases that hydrolyze a variety of nucleotides including UTP has been described (Beukers et al., 1993).

In contrast to most ATPases that have K_{m}s of one to several millimolar, protein kinases are typically activated by ATP at 100–1,000-fold lower concentrations (Krebs and Beavo, 1979). ACTH may inhibit I_{AC} channels through activation of an unidentified protein kinase. The suppression of I_{AC} by ATPγS is consistent with this model.

### ATP Sensing, Membrane Potential, and Cortisol Secretion

The resting potential of bovine AZF cells approaches the Nernst equilibrium potential for K^{+} (Mlinar et al., 1993a). Of the two detectable K^{+} currents expressed by these cells, I_{AC} channels display properties consistent with one that would contribute strongly to the resting potential. The activation of I_{AC} K^{+} channels by physiological levels of ATP suggests that these membrane proteins could act as sensors coupling the metabolic state of the cell to membrane potential and ultimately, cortisol secretion (Enyeart et al., 1993).

In insulin-secreting cells of the pancreas, ATP-sensitive K^{+} channels play a key role in excitation–secretion coupling. High blood glucose levels are associated with elevated ATP, K^{+} channel inhibition, and membrane depolarization leading to Ca^{2+} entry and insulin secretion (Ashcroft, 1988a, 1988b). In bovine AZF cells where I_{AC} channels are activated rather than inhibited by ATP, elevated glucose would be associated with I_{AC} activation and membrane hyperpolarization, thereby suppressing Ca^{2+} entry and cortisol secretion (Enyeart et al., 1993). Thus, because ATP-sensitive K^{+} channel activity in AZF cells and pancreatic β cells is modulated in opposite directions by ATP, metabolic conditions inducing insulin secretion might be expected to suppress cortisol production. In this regard, cortisol is secreted under conditions of metabolic stress such as starvation, whereas insulin secretion is suppressed (Bondy, 1985).

Metabolically, the glucose-conserving hormone cortisol has effects opposing those of insulin. Cortisol stimulates gluconeogenesis and inhibits glucose uptake and use in many tissues (Bondy, 1985). Because of the antagonistic actions of these two hormones on glucose metabolism, it may then be appropriate that the cells that secrete them express ATP-sensitive K^{+} channels whose activity is regulated by ATP in opposite directions.

Although the above scheme linking cellular ATP levels to K^{+} channels and secretion of two opposing hormones is attractive, cortisol secretion occurs primarily under the control of ACTH released by the pituitary. However, in bovine AZF cells, ACTH triggers depolarization-dependent Ca^{2+} entry and cortisol secretion through inhibition of I_{AC} (Enyeart et al., 1993). It would be interesting to determine whether ACTH-mediated I_{AC} inhibition could be modulated by altering external glucose concentration. Irrespective of its function in cortisol secretion, I_{AC} is a distinctive new type of K^{+} channel that is activated rather than inhibited by ATP. Perhaps other cells that secrete hormones with antiinsulin effects (e.g., glucagon, catecholamines) also express ATP-activated K^{+} channels.

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**REFERENCES**

Aguilar-Bryan, L., C.G. Nichols, S.W. Wechsler, J.P.I. Clement, A.E. Boyd III, G. Gonzalez, H. Herrera-Sosa, K. Nguyen, J. Bryan, and D.A. Nelson. 1995. Cloning of the cell high-affinity sufonylurea receptor: a regulator of insulin secretion. Science, 268:423–429.

Ashcroft, F.M. 1988a. Adenosine 5‘-triphosphate-sensitive potassium channels. Annu. Rev. Physiol. 51:97–118.

Ashcroft, F.M., S.J.H. Ascroft, and D.E. Harrison, 1988. Properties of single potassium channels modified by glucose in rat pancreatic β-cells. J. Physiol. (Camb.). 400:501–527.

Azhar, S., and K.M. Menon. 1975. Adenosine 3′/5′-cyclic monophosphate-dependent membrane-associated protein kinase(s) from bovine corpus luteum. Biochem. J. 151:23–36.

Baukrowitz, T., T.-C. Hwang, A.C. Nairn, and D.C. Gadsby. 1994. Coupling of CFTR Cl− channel gating to an ATP hydrolysis cycle. Neuron, 12:473–482.

Beukers, M.W., I.M. Firopano, A. Van Weert, C.J. Kerkhof, A.P. Ijzerman, and W. Soudijn. 1993. Characterization of ecto-ATPase on human blood cells. A physiological role in platelet aggregation? Biochem. Pharmacol. 46:1959–1966.

Bondy, P.K. 1985. Diseases of the adrenal gland. In Williams Textbook of Endocrinology. W.B. Saunders Company, Philadelphia, PA, 816–890.

Brooks, S.P.J., and K.B. Storey. 1992. Bound and determined: a computer program for making buffers of defined ion concentrations. Anal. Biochem. 201:119–126.

Covarrubias, M., A. Wei, L. Salkoff, and T.B. Vyas. 1994. Elimination of rapid potassium channel inactivation by phosphorylation of the activation gate. Neuron, 13:1403–1412.
Drain, P., A.E. Dubin, and R.W. Aldrich. 1994. Regulation of shaker K⁺ channel inactivation gating by the cAMP-dependent protein kinase. *Neuron.* 12:1097–1109.

Eckstein, F. 1985. Nucleoside phosphorothiates. *Annu. Rev. Biochem.* 54:367–402.

Edelman, A.M., D.K. Blumenthal, and E.G. Krebs. 1987. Protein serine/threonine kinases. *Annu. Rev. Biochem.* 56:567–613.

Enyeart, J.J., R.T. Boyd, and J.A. Enyeart. 1996a. ACTH and AII differentially stimulate steroid hormone orphan receptor mRNAs in adrenal cortical cells. *Mol. Cell. Endocrinol.* 124:103–110.

Enyeart, J.J., B. Mlinar, and J.A. Enyeart. 1993. T-type Ca²⁺ are required for ACTH-stimulated cortisol synthesis by bovine adrenal zona fasciculata cells. *Mol. Endocrinol.* 7:1031–1040.

Enyeart, J.J., B. Mlinar, and J.A. Enyeart. 1996b. Adrenocorticotropic hormone and cAMP inhibit noninactivating K⁺ current in adrenocortical cells by an A-kinase-independent mechanism requiring ATP hydrolysis. *J. Gen. Physiol.* 108:251–264.

Fakler, B., U. Brandle, E. Glowaatzki, H.-P. Zenner, and J.P. Ruppersberg. 1994. Kir2.1 inward rectifier K⁺ channels are regulated independently by protein kinases and ATP hydrolysis. *Neuron.* 13:1413–1420.

Fidlon, I., and J.F. Faire. 1991. ATP-sensitive K⁺ channels in heart muscle: spare channels. *FEBS Lett.* 279:95–97.

Gospodarowicz, D., C.R. Ill, P.J. Hornsby, and G.N. Gill. 1977. Control of bovine adrenal cortical cell proliferation by fibroblast growth factor. Lack of effect of epidermal growth factor. *Endocrinology.* 100:1080–1089.

Hamill, O.P., A. Marty, E. Neher, B. Sakmann, and F.J. Sigworth. 1981. Improved patch clamp techniques for high resolution current recording from cells and cell-free membrane patches. *Pflügers Arch.* 391:85–100.

Hilgemann, D.W. 1997. Cytoplasmic ATP-dependent regulation of ion transporters and channels: mechanisms and messengers. *Annu. Rev. Physiol.* 59:193–220.

Ho, K., C.G. Nichols, W.J. Lederer, J. Lytton, P.M. Vassilev, M.V. Kanazirksa, and S.C. Hebert. 1993. Cloning and expression of an inwardly rectifying ATP-regulated potassium channel. *Nature.* 362:31–37.

Hwang, T., G. Nagel, A.C. Nairn, and D.C. Gadsby. 1994. Regulation of the gating of cystic fibrosis transmembrane conductance regulator Cl channels by phosphorylation and ATP hydrolysis. *Proc. Natl. Acad. Sci. USA.* 91:4698–4702.

Krebs, E.G., and J.A. Beavo. 1979. Phosphorylation-dephosphorylation of enzymes. *Annu. Rev. Biochem.* 48:923–959.

Lederer, W.J., and C.G. Nichols. 1989. Nucleotide modulation of the activity of rat heart ATP-sensitive K⁺ channels in isolated membrane patches. *J. Physiol. (Camb.)* 419:193–211.

Levitan, I.B. 1994. Modulation of ion channels by protein phosphorylation and dephosphorylation. *Annu. Rev. Physiol.* 56:193–212.

Mlinar, B., B.A. Biagi, and J.J. Enyeart. 1993a. A novel K⁺ current inhibited by ACTH and Angiotensin II in adrenal cortical cells. *J. Biol. Chem.* 268:8640–8644.

Mlinar, B., B.A. Biagi, and J.J. Enyeart. 1995. Losartan-sensitive AII receptors linked to depolarization-dependent cortisol secretion through a novel signaling pathway. *J. Biol. Chem.* 270:20942–20951.

Mlinar, B., and J.J. Enyeart. 1993b. Voltage-gated transient currents in bovine adrenal fasciculata cells II: A-type K⁺ current. *J. Gen. Physiol.* 102:239–255.

O’Rourke, B., P.H. Backx, and E. Marban. 1992. Phosphorylation-independent modulation of L-type calcium channels by magnesium-nucleotide complexes. *Science.* 257:245–248.

Quinton, P.M., and M.M. Reddy. 1992. Control of CFTR chloride conductance by ATP levels through non-hydrolytic binding. *Nature.* 360:79–81.

Spruce, A.E., N.B. Standen, and P.R. Stanfield. 1987. Studies of the unitary properties of adenosine-5'-triphosphate-regulated potassium channels of frog skeletal muscle. *J. Physiol. (Camb.)* 382:213–236.

Takano, M., and A. Noma. 1993. The ATP-sensitive K⁺ channel. *Prog. Neurobiol. (Oxf.)* 41:21–30.

Terzic, A., R.T. Tung, and Y. Kurachi. 1994. Nucleotide regulation of ATP sensitive potassium channels. *Cardiovasc. Res.* 28:746–753.