Adrenocorticotropic Hormone and cAMP Inhibit Noninactivating K+ Current in Adrenocortical Cells by an A-kinase-independent Mechanism Requiring ATP Hydrolysis

JOHN J. ENYEART,*1 BORIS MLINAR,† and JUDITH A. ENYEART*

From the *Department of Pharmacology, The Ohio State University, College of Medicine, Columbus, Ohio 43210-1239; and †The Neuroscience Program, The Ohio State University, College of Medicine, Columbus, Ohio 43210-1239

ABSTRACT Bovine adrenal zona fasciculata (AZF) cells express a noninactivating K+ current (IAC) that is inhibited by adrenocorticotropic hormone (ACTH) at picomolar concentrations. Inhibition of IAC may be a critical step in depolarization-dependent Ca2+ entry leading to cortisol secretion. In whole-cell patch clamp recordings from AZF cells, we have characterized properties of IAC and identified its activating and inactivating pathways by which ACTH inhibits this current. IAC was identified as a voltage-gated, outwardly rectifying, K+-selective current whose inhibition by ACTH required activation of a pertussis toxin-insensitive GTP binding protein. IAC was selectively inhibited by the cAMP analogue 8-(4-chlorophenylthio)-adenosine 3',5'-cyclic monophosphate (8-pcpt-cAMP) with an IC50 of 160 μM. The adenylate cyclase activator forskolin (2.5 μM) also reduced IAC by 92 ± 4.7%. Inhibition of IAC by ACTH and 8-pcpt-cAMP for forskolin was not prevented by the cAMP-dependent protein kinase inhibitors H-89 (5 μM), cAMP-dependent protein kinase inhibitor peptide (PKI[5-24]) (2 μM), (Rp)-cAMPS (500 μM), or by the nonspecific protein kinase inhibitor staurosporine (100 nM) applied externally or intracellularly through the patch pipette. At the same concentrations, these kinase inhibitors abolished 8-pcpt-cAMP-stimulated A-kinase activity in AZF cell extracts. In intact AZF cells, 8-pcpt-cAMP activated A-kinase with an EC50 of 77 nM, a concentration 2,000-fold lower than that inhibiting IAC half maximally. The active catalytic subunit of A-kinase applied intracellularly through the recording pipette failed to alter functional expression of IAC. The inhibition of IAC by ACTH and 8-pcpt-cAMP was eliminated by substituting the nonhydrolyzable ATP analogue AMP-PNP for ATP in the pipette solution. Penfluridol, an antagonist of T-type Ca2+ channels inhibited 8-pcpt-cAMP-induced cortisol secretion with an IC50 of 0.33 μM, a concentration that effectively blocks Ca2+ channel in these cells. These results demonstrate that IAC is a K+-selective current whose gating is controlled by an unusual combination of metabolic factors and membrane voltage. IAC may be the first example of an ionic current that is inhibited by cAMP through an A-kinase-independent mechanism. The A-kinase-independent inhibition of IAC by ACTH and cAMP through a mechanism requiring ATP hydrolysis appears to be a unique form of channel modulation. These findings suggest a model for cortisol secretion in which cAMP combines with two separate effectors to activate parallel steroidogenic signalling pathways. These include the traditional A-kinase-dependent signalling cascade and a novel pathway wherein cAMP binding to IAC K+ channels leads to membrane depolarization and Ca2+ entry. The simultaneous activation of A-kinase- and Ca2+-dependent pathways produces the full steroidogenic response.

KEY WORDS: potassium channel • adrenal cortex • cortisol • protein kinase

INTRODUCTION Cortisol secretion by zona fasciculata cells of the adrenal cortex occurs in a diurnal pattern under the control of the pituitary peptide adrenocorticotropic hormone (ACTH)1 (Bondy, 1985; Simpson and Waterman, 1988). The cellular mechanisms that couple ACTH receptor activation to cortisol production are incompletely understood. Early studies have shown that ACTH stimulates the synthesis of cAMP by adrenocortical cells (Lefkowitz, et al., 1971; Moyle et al., 1973). Cyclic AMP, in turn, mimics many of the actions of ACTH: activating steroidogenic enzymes, inducing their synthesis, and stimulating cortisol secretion. Consequently, cAMP has long been considered to be the primary intracellular messenger for ACTH. It has also been widely accepted that the steroidogenic actions of cAMP are mediated by activation of a cAMP-dependent protein kinase signalling cascade (Simpson and Waterman, 1988; Parker and Schimmer, 1995), even though several steroid hydroxylases lack consensus cAMP response elements in their 5' flanking region (Parker and Schimmer, 1995).
In addition to cAMP, a requirement for Ca\(^{2+}\) in ACTH-stimulated steroidogenesis by cells of the adrenal cortex is well established (Capponi et al., 1984; Quinn et al., 1991; Enyeart et al., 1993). Transmitter and hormone release by many secretory cells is tightly coupled to depolarization-dependent Ca\(^{2+}\) entry. Recently, we identified a novel K\(^+\) current (I\(_{AC}\)) in bovine adrenal fasciculata (AZF) cells that may contribute to the resting potential (Mlinar et al., 1993a). Importantly, ACTH inhibits I\(_{AC}\) with a temporal pattern and potency that parallel membrane depolarization and cortisol secretion. ACTH-stimulated cortisol secretion is inhibited by antagonists of T-type Ca\(^{2+}\) channels, the primary Ca\(^{2+}\) channel subtype expressed by these cells (Enyeart et al., 1993; Mlinar et al., 1993b). These results establish the importance of electrical events and depolarization-dependent Ca\(^{2+}\) entry in ACTH-stimulated cortisol secretion. They also suggest a model whereby ACTH receptor activation is coupled to membrane depolarization through inhibition of I\(_{AC}\), K\(^+\) channels. The molecular components of the signalling pathway that link ACTH receptors to I\(_{AC}\) K\(^+\) channel inhibition have not been identified. However, the suppression of I\(_{AC}\) expression by GTP-\(\gamma\)-S as well as cholera toxin suggest that these K\(^+\) channels are under the inhibitory control of G\(_s\), the GTP-binding protein that couples ACTH receptors to adenylyl cyclase (Mlinar et al., 1995a). In the present study, we have further characterized I\(_{AC}\) current with respect to its biophysical properties and inhibition by ACTH and cyclic nucleotides.

**MATERIALS AND METHODS**

Tissue culture media, antibiotics, fibronectin, and fetal bovine sera were obtained from Gibco BRL (Grand Island, NY). Culture dishes were purchased from Corning (Corning, N.Y.) Coverslips were from Bellico (Vineland, NJ). Enzymes, ACTH (1-24), angiotensin II (AII), 8-pCPT-AMP (8-[4-chlorophenylthio]-adenosine 3'-5'-cyclic monophosphate), guanosine 5'-O-2-(thio)diphosphate (GDP-\(\beta\)-S), cAMP, cGMP, MgATP, 5'-adenyl-imido-diphosphate (AMP-PNP), and the catalytic subunit of cAMP-dependent protein kinase (bovine heart) were from Sigma Chemical Co. (St. Louis, MO). Pertussis toxin, PKI peptide (5-24), and (Rp)-adenosine-3',5'-cyclic monophosphorothiate ((Rp)-cAMPS) were from Calbiochem Corp. (San Diego, CA). H-89 and staurosporine were from Biomol (Plymouth Meeting, PA). Cortisol secretion was determined using a solid phase radioimmunoassay kit (Diagnostic Products Corp., Los Angeles, CA). Protein kinase A (cAMP-dependent protein kinase) assay system was from Gibco BRL. [\(^{32}\)P]ATP for use with the kit was from Amersham Life Science (Arlington Heights, IL).

**Isolation and Culture of AZF Cells**

Bovine adrenal glands were obtained from steers (age range 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 (Gospodarowicz et al., 1977) with some modifications. In a sterile tissue culture hood, the adrenals were cut in half lengthwise and the lighter medulla tissue trimmed away from the cortex and discarded. The capsule with attached glomerulosa and thicker fasciculata-reticularis layers were then dissected into large pieces approximately 1.0 x 1.0 x 0.5 cm. A Stadie-Riggs tissue slicer (Thomas Scientific) 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. The fasciculata/glomerulosa margin (~0.5 mm) was discarded. The remaining glomerulosa tissue with attached capsule was saved for isolation of AZG cells. Fasciculata tissue slices were then diced into 0.5-mm pieces and dissociated with 2 mg/ml (~200-300 U/ml) of Type I collagenase, 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 2 layers of sterile cheesecloth, then centrifuged to pellet cells at 100 g for 5 min. The cells were washed twice with DMEM/0.2% BSA, centrifuging as before to pellet. 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, 0.1 mg/ml streptomycin, and plated for immediate use or resuspended in FBS/5% DMSO, divided into 1-ml aliquots each containing ~2 x 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 then rinsed with warm, sterile PBS immediately before adding cells. Dishes were maintained at 37°C in a humidified atmosphere of 95% air and 5% CO₂.

**Patch Clamp Experiments**

Patch clamp recordings of K\(^+\) channel currents were made in the whole-cell configuration. The standard pipette solution was 120 mM KCl, 2 mM MgCl₂, 1 mM CaCl₂, 10 mM HEPES, 11 mM BAPTA, 200 μM GTP, 2 mM MgATP with pH buffered to 7.2 using KOH. Pipette [Ca\(^{2+}\)] was determined using the “Bound and Determined” program (Brooks and Storey, 1992). The external solution consisted of 140 mM NaCl, 5 mM KCl, 2 mM CaCl₂, 2 mM MgCl₂, 10 mM HEPES, and 5 mM glucose, pH 7.4, using NaOH. Deviations from these solutions are noted in the text. 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 15-20 μm and capacitances of 10-15 pF were selected. Coverslips were transferred from 35-mm culture dishes to the recording chamber (volume, 1.5 ml) which was continuously perfused by gravity at a rate of 5-5 ml/min. Patch electrodes with resistances of 1.0-2.0 megohms were fabricated from Corning 7052 or 0010 glass (Garner Scientific) and coated with 3-5% agarose before adding cells. Dishes were maintained at 37°C in a humidified atmosphere of 95% air and 5% CO₂.

© 2017 American Physiological Society. All rights reserved. doi: 10.1152/ajpcell.00187.2015
AZF cells were cultured on fibronectin-treated 35-mm plates at a density of ~4 × 10⁴ per dish in DMEM/F12 (1:1) containing 10% FBS, 100 U/ml penicillin, 0.1 mg/ml streptomycin, and the antioxidants 1 μM tocopherol, 20 nM selenite, and 100 μM ascorbic acid (DMEM/F12+). After 24 h, the media was aspirated and changed to defined media consisting of DMEM/F12 (1:1), 50 μg/ml BSA, 100 μM ascorbic acid, 1 μM tocopherol, 10 nM insulin, and 10 μg/ml transferrin. The Ca²⁺ antagonist penfluridol was added at this time for a 1 h preincubation before switching to media containing this antagonist as well as 8-pcpt-cAMP as required. 200-μL samples of media were collected at selected times and frozen at -20°C and later assayed for cortisol using a solid phase RIA kit (Diagnostic Products Corp., Los Angeles, CA). All experiments were performed on triplicate 35-mm dishes, and hormone assays were performed in duplicate at several dilutions.

**Protein Kinase A Assay**

AZF cells were cultured on fibronectin-coated 60-mm plates at a density of 3-5 × 10⁴ cells per plate in DMEM/F12+. After 24 h, the media was aspirated and changed to defined media (control) or the same media containing 8-pcpt-cAMP. After 15 min, the media was aspirated and cells harvested in 700 μL extraction buffer (5 mM EDTA, 50 mM Tris, pH 7.5). Cells in extract were homogenized using Qiashredder columns (Qiagen, Chatsworth, CA), and 10 μL supernatant from lysate was either assayed directly or incubated with the protein kinase antagonists for 15 min before measuring activity with the Protein Kinase A Assay System from Gibco BRL. All experiments were performed on duplicate 60-mm plates, and enzyme assays were performed in duplicate.

**RESULTS**

**Iₖc; Kinetics, K⁺ Selectivity, and Specific Inhibition by ACTH**

In whole-cell patch clamp recordings on bovine AZF cells, two distinct components of K⁺ current were expressed by nearly every cell. As previously reported, these include a rapidly inactivating A-type K⁺ current (Mlinar and Enyeart, 1993) and a noninactivating K⁺ current (Iₖc) which was present upon initiating whole-cell recording and which grew by an average of ~10-fold over a period of many minutes (Mlinar et al., 1993a) (Fig. 1 A, left).

The Iₖc K⁺ current could be studied in isolation at holding potentials positive to -40 mV where the A-type K⁺ current had completely inactivated. Iₖc recorded in response to a voltage step to +40 mV from a holding potential of -35 mV consisted of an apparent instantaneous component and second time-dependent component (Fig. 1 A, right). Currents could be fit with a single exponential of the form: I = Iₖmax[1 - exp(T/τₐ)] + C, where τₐ is the activation time constant and C is the time-independent component. In the example illustrated, the time-dependent component, which comprised 66% of the total current, activated with a time constant of 3.30 ms.

![Figure 1](https://example.com/image.png)

**FIGURE 1.** Properties of Iₖc K⁺ current. (A, left) Time-dependent expression. K⁺ currents were activated by voltage steps to +20 mV applied at 30-s intervals from a holding potential of -80 mV. Current records recorded at the indicated time after initiating whole-cell recording. (A, right) Iₖc activation kinetics. Iₖc was selectively activated by 20-ms voltage steps to +40 mV from a holding potential of -35 mV. Current record is average of three traces. Iₖc current was fit with a function of the form: I = Iₖmax[1 - exp(T/τₐ)] + C, where τₐ = 3.30 ms and C = 525 pA. (B) Voltage clamp protocols and specific inhibition of Iₖc by ACTH. K⁺ currents were recorded using two different protocols before and after exposing the cell in A to 10 pM ACTH. (left) K⁺ currents were activated by voltage steps to +20 mV applied at 30-s intervals from a holding potential of -80 mV. (right) 300-ms voltage clamp steps to +20 mV were preceded by 10-s prepulse to -20 mV which inactivated A-type K⁺ current. (C) Voltage-independent block and K⁺ selectivity of ACTH-inhibited current. (left) Voltage ramp of 100 mV/s was applied from a holding potential of 0 mV to voltages between +60 and -140 mV (trace 1). A second voltage ramp was applied after steady-state block with 100 pM ACTH (trace 2). Trace 2 was digitally subtracted from trace 1 to give the ACTH-inhibited current (trace 3). (right) Experiment illustrated in left panel repeated in a different cell in saline where external [K⁺] was raised to 50 mM by substitution for Na⁺. Numbered traces are as in left panel.
Besides revealing unusual activation kinetics for a voltage-gated channel, recordings such as these indicate that a substantial fraction of $I_{AC}$ channels remain open at membrane potentials negative to $-35$ mV, as would be anticipated for a channel that contributes to the resting potential in AZF cells. In other experiments, we found that $I_{AC}$ is an outwardly rectifying current that is weakly voltage-dependent at potentials from $-30$ to $+40$ mV. Over this range, the relative open probability increased approximately e-fold per 50 mV (data not shown).

The absence of time-dependent inactivation of the slowly developing $I_{AC}$ K$^+$ current component allowed it to be easily isolated and measured in whole-cell recordings using either of two voltage clamp protocols. When voltage steps of 300-ms duration were applied from a holding potential of $-80$ mV to a test potential of $+20$ mV, $I_{AC}$ could be measured in isolation near the end of the test pulse at a point where the A-type K$^+$ current had inactivated entirely (Fig. 1 B, left).

Using the second protocol, $I_{AC}$ was activated with an identical voltage step after a 10-s prepulse to $-20$ mV had fully inactivated the A-type current (Fig. 1 B, right). $I_{AC}$ measured by either method provided nearly identical results. Fig. 1 B also illustrates the selective inhibition of $I_{AC}$ by ACTH in the same cell using these two protocols. After a 6-min exposure to ACTH, voltage steps from $-80$ to $+20$ mV activate only the residual rapidly inactivating $I_{A}$ K$^+$ current (left). As expected, when the $I_{A}$ current had been inactivated by a prepulse, ACTH inhibited the remaining $I_{AC}$ current almost completely (right).

Ramp voltage clamp steps applied in 5 and 50 mM external KCl showed that $I_{AC}$ is an outwardly rectifying current with a reversal potential that varies as predicted by the Nernst equation for a channel selectively permeable to K$^+$ (Fig. 1 C, left). Moreover, the K$^+$ current component inhibited by ACTH also displayed these identical properties. After $I_{AC}$ had reached a stable amplitude, ramp voltage clamp steps were applied from a holding potential of 0 mV over a range from $+60$ to $-140$ mV (trace I). The cell was then superfused with 100 pM ACTH, and the ramp voltage protocol was repeated after a steady-state block was achieved (trace 2). Digital subtraction of trace 2 from trace 1 showed that the ACTH-inhibited current (trace 3) approached zero at potentials negative to $-80$ mV, almost identical to the control current, and close to the reversal potential predicted by the Nernst equation for a channel selectively permeable to K$^+$. Repeating this same experiment on a second cell where external KCl had been raised to 50 mM (right) showed that the reversal potential for the control and ACTH-inhibited currents shifted to $-27$ and $-25$ mV, respectively, values close to $-29$ mV as predicted by the Nernst equation.

**ACTH and GTP-Binding Proteins**

ACTH receptors in adrenal cortical cells are coupled to adenylate cyclase through a G-protein intermediate $G_s$. To determine whether ACTH-mediated inhibition of $I_{AC}$ also involved a G-protein, GTP in the patch pipette was replaced with the inactive guanine nucleotide GDP-$\beta$-S. With standard pipette solution (200 µM GTP), 100 pM ACTH inhibited $I_{AC}$ by 95.3 ± 1.3% ($n = 12$). When 1 mM GDP-$\beta$-S replaced GTP in the pipette, ACTH (100 pM) inhibited $I_{AC}$ by only 30.0 ± 12.7% ($n = 9$). Raising the ACTH concentration to 500 pM enhanced block to only 40.5 ± 16.8% ($n = 6$) (Table I).

Experiments with GDP-$\beta$-S suggested that ACTH-mediated inhibition of $I_{AC}$ occurred through a G-protein intermediate. To determine if either $G_i$ or $G_o$, mediated this inhibition, AZF cells were preincubated before patch clamping with pertussis toxin (Ptx) which suppresses activation of $G_i$ or $G_o$. Ptx had no significant effect on the time-dependent growth of $I_{AC}$ or its inhibition by ACTH (Table I). In cells pretreated for 9–12 h with Ptx (200 ng/ml), ACTH (100 pM) inhibited $I_{AC}$ by 95.5 ± 1.6% ($n = 6$). Results with guanine nucleotide and Ptx indicated that ACTH-mediated inhibition of $I_{AC}$ requires activation of a G protein but not $G_i$ or $G_o$.

**Inhibition of $I_{AC}$ by Cyclic Nucleotides**

If the inhibitory actions of ACTH on $I_{AC}$ are mediated by cAMP then membrane-permeable cAMP analogues should mimic ACTH in whole-cell patch clamp experiments. 8-pcpt-cAMP inhibited $I_{AC}$ in a concentration-dependent manner. Fig. 2 A shows that 8-pcpt-cAMP, like ACTH, selectively inhibited $I_{AC}$, without reducing the rapidly inactivating A-type current. Typically, 8-pcpt-cAMP-mediated inhibition occurred after a delay of 1 to 2 min, and required several additional minutes to reach a maximum (Fig. 2 B). In experiments where 8-pcpt-cAMP was superfused at concentrations ranging from 50 µM to 2 mM, $I_{AC}$ was inhibited with an IC50 of

<table>
<thead>
<tr>
<th>Treatment</th>
<th>% Inhibition of $I_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 pM ACTH</td>
<td>95.3 ± 1.3 ($n = 12$)</td>
</tr>
<tr>
<td>100 pM ACTH + PTX</td>
<td>95.5 ± 1.6 ($n = 6$)</td>
</tr>
<tr>
<td>100 pM ACTH + GDPβS</td>
<td>30.0 ± 12.7 ($n = 9$)</td>
</tr>
<tr>
<td>500 pM ACTH + GDPβS</td>
<td>40.4 ± 16.8 ($n = 6$)</td>
</tr>
</tbody>
</table>

$I_A$ amplitude was measured at 30-s intervals using the two protocols shown in Fig. 1 B with pipette solutions containing 200 pM GTP or no added GTP with 1 mM GDP-β-S. Alternatively, cells were pretreated for 9–12 h with 200 ng/ml Ptx before recording currents using control pipette solution. Cells were superfused with ACTH at 100 or 500 pM as indicated. Results are mean ± SEM.
Inhibition of I_{AC} by 8-pcpt-cAMP. K^+ currents were activated at 30-s intervals by the two voltage clamp protocols described in the legend of Fig. 1. When I_{AC} had reached a stable amplitude, 8-pcpt-cAMP was superfused at various concentrations between 50 μM and 2 mM. (A) Selective inhibition of I_{AC} by 8-pcpt-cAMP. K^+ currents were recorded using two protocols before and after superfusing cell with 500 μM 8-pcpt-cAMP. (left) current records in response to voltage steps from −80 to +20 mV in control saline and after block by 8-pcpt-cAMP. (right) current records from same cell, recorded with inactivating pre-pulse. (B) Time-dependent block of I_{AC} by 8-pcpt-cAMP. I_{AC} current amplitude, measured as in A above, plotted against time before and after superfusion of 8-pcpt-cAMP. (C) Inhibition curve. Fraction of unblocked I_{AC} is plotted against 8-pcpt-cAMP concentration. Data was fit with an equation of the form \( I/I_{\text{max}} = 1/[1 + (B/K_i)] \) where \( B \) is 8-pcpt-cAMP concentration and \( K_i \) is the equilibrium dissociation constant.

160 μM (Fig. 2 C). Although considerably less lipophilic than 8-pcpt-cAMP, cAMP (0.2–2 mM) also inhibited I_{AC} but less potently. At a concentration of 2 mM, cAMP inhibited I_{AC} by 65.9 ± 4.8% (n = 3). In contrast, cGMP had no effect on I_{AC} at this concentration.

The inhibition of I_{AC} by the relatively membrane-impermeant cAMP raised the possibility that cAMP could be acting on I_{AC} through a receptor present on the extracellular surface of AZF cells. To determine whether intracellularly-generated cAMP suppressed I_{AC} K^+ channel activity, we exposed cells to the diterpene adenylate cyclase activator forskolin. Forskolin selectively and reversibly inhibited I_{AC} (Fig. 3, A and B). At a concentration of 2.5 μM forskolin reduced I_{AC} by 92.0 ± 4.7% (n = 4).

The addition of cAMP to the recording pipette (allowing intracellular cAMP to rapidly increase upon establishment of the whole-cell configuration) was effective in completely suppressing the time-dependent expression of I_{AC} typically observed in whole-cell recordings from AZF cells. The maximum I_{AC} current densities recorded in cells where 0.2 and 2 mM cAMP were added to the pipette were 3.80 ± 0.85 (n = 4) and 2.33 ± 0.95 pA/pF (n = 7), respectively. By comparison, maximum current density recorded with control pipette solution was 11.80 ± 2.06 pA/pF (n = 28) (Fig. 3 C). Exposing cells to 100 μM ACTH immediately upon initiating whole-cell recording also eliminated I_{AC} expression completely (data not shown).

**Protein Kinases and I_{AC} Modulation**

In many cells where cAMP regulates K^+ channel function, modulation proceeds through an A-kinase–dependent phosphorylation (Pedrazzani and Storm, 1993; Drain et al., 1994; Levitan, 1994). Two selective A-kinase antagonists were used to determine whether this enzyme was the effector of I_{AC} inhibition by ACTH, cAMP, and forskolin. H-89 is an isoquinoline sulfonamide which has been reported to inhibit cAMP-dependent protein kinase with an IC_{50} of <50 nM (Hidaka et al., 1991). When included in the recording pipette at a concentration of 5 μM, H-89 failed to significantly alter suppression of I_{AC} by any of the three agents (Fig. 4, A and C). In the presence of the A-kinase antagonist, ACTH (200 pM), 8-pcpt-cAMP (500 μM), and forskolin (2.5 μM) inhibited I_{AC} by 91.5 ± 3.0% (n = 3), 79.8 ± 4.8% (n = 6), and 88.8 ± 1.9% (n = 3), respectively. By comparison, under control conditions, these same three agents inhibited I_{AC} by 96.1 ± 1.7% (n = 6), 79.8 ± 7.4% (n = 8), and 92.0 ± 4.7% (n = 4), respectively.

A synthetic 20 amino acid peptide, PKI(5-24), patterned after a portion of the naturally occurring cAMP-dependent protein kinase inhibitory peptide (PKI) in-
hibits A-kinase with an IC₅₀ of 2 nM (Van Haastert et al., 1984; Cheng et al., 1985). Adding PKI(5-24) to the recording pipette at a concentration of 1 or 2 μM (500-1,000 times the IC₅₀) failed to significantly blunt Iₐc inhibition by ACTH or 8-pcpt-cAMP. In the experiment illustrated in Fig. 4 B, the cell was sequentially exposed to 500 μM 8-pcpt-cAMP and 200 μM ACTH. The 65% inhibition of Iₐc observed upon exposure to 8-pcpt-cAMP was fully reversed upon switching to normal saline. Subsequent infusion of 200 μM ACTH produced near complete inhibition of Iₐc. Overall, with 2 μM PKI(5-24) in the recording pipette, ACTH (200 μM) and 8-pcpt-cAMP (500 μM) reduced Iₐc by 85.2 ± 2.5% (n = 8) and 64.5 ± 7.5% (n = 8), respectively. Since none of the three agents that inhibit Iₐc was superfused until at least 10 min after commencing whole-cell recording in these experiments, it is likely that the intracellular concentrations of PKI(5-24) and H-89 approached that in the pipette solution for many minutes before ACTH, 8-pcpt-cAMP, or forskolin reached the cell (Pusch and Neher, 1988).

Patch clamp experiments with H-89 and PKI(5-24) indicated that inhibition of Iₐc by either ACTH or 8-pcpt-cAMP did not require the activation of cAMP-dependent protein kinase. To further test this hypothesis and to determine whether other protein kinases function in suppressing this current, Iₐc inhibition by ACTH and 8-pcpt-cAMP was measured in cells that had been exposed to the potent nonselective protein kinase inhibitor staurosporine. Staurosporine, a microbial alkaloid, inhibits protein kinase A with an IC₅₀ of 8.2 nM while C kinase and Ca²⁺/CaM kinase II are inhibited with IC₅₀ of 2.7 and 20 nM, respectively (Tamaoki, 1991).

Staurosporine (100 nM) was applied to cells through bath perfusion, by including it in the pipette solution, or through these two routes in combination. For external delivery, AZF cells were perfused for 5-20 min with saline containing the membrane-permeable staurosporine before superfusing saline containing this antagonist as well as ACTH (100 or 200 pM) or 8-pcpt-cAMP (500 μM). At concentrations of 100 or 200 pM, ACTH produced nearly identical maximal inhibition of Iₐc (95.3 ± 1.3% [n = 12] and 96.1 ± 1.7% [n = 6], respectively). Regardless of the route of application, staurosporine only slightly blunted the responses to ACTH. When staurosporine was applied externally, through the pipette or simultaneously through both routes, ACTH (100 or 200 pM) inhibited Iₐc by 87.6 ± 3.6% (n = 5), 80.4 ± 0.8% (n = 3), and 78.4 ± 10.7% (n = 3) (Fig. 5 B).

Staurosporine had no effect on Iₐc inhibition by 8-pcpt-cAMP. Alone, 500 μM 8-pcpt-cAMP reduced Iₐc by 73.8 ± 7.4% (n = 8). When cells were exposed to staurosporine by bath perfusion and pipette in combination, 8-pcpt-cAMP inhibited Iₐc by 78.4 ± 10.7% (n = 3) (Fig. 5, A and B). In many experiments where cells...
were superfused with ACTH or 8-pcpt-cAMP in the presence of an A-kinase inhibitor, a typically small (<20%) transient increase in IAC amplitude preceded the prolonged inhibition (Figs. 5 A and 4 B).

The phosphorothioate derivative of cAMP, (Rp)-cAMPS, competitively antagonizes A-kinase activation by cAMP with an estimated inhibition constant of <10 μM (Van Haastert et al., 1984; Botelho et al., 1988). Like the other A-kinase inhibitors, (Rp)-cAMPS failed to suppress inhibition of IAC by ACTH. When 500 μM (Rp)-cAMPS was applied through the patch electrode, AGTH inhibited IAC by 88 ± 3.2% (n = 3) (data not shown).

A-Kinase Activation and Inhibition

In whole-cell patch clamp experiments, the protein kinase inhibitors H-89, PKI(5-24), and staurosporine were applied intracellularly to the cytoplasm through the patch pipette for 10–20 min before superfusing 8-pcpt-cAMP. To establish that the three kinase antagonists ef-
effectively inhibited A-kinase under conditions similar to those of our experiments, we measured 8-pcpt-cAMP-stimulated A-kinase activity in cytoplasmic extracts from AZF cells in untreated extracts and in extracts which were pretreated for 15 min with the kinase inhibitors at the identical concentrations used in patch clamp experiments. In the experiment illustrated in Fig. 6 A, 8-pcpt-cAMP (200 μM) increased A-kinase activity 62-fold over control. H-89, and staurosporine inhibited this increase by 97–100%.

If inhibition of I_{AC} by 8-pcpt-cAMP required activation of A-kinase then 8-pcpt-cAMP-mediated activation of A-kinase in intact AZF cells and inhibition of I_{AC} current should occur over a similar range of concentrations. 8-pcpt-cAMP activated A-kinase in AZF cells with an E_{C50} of 77 nM, a concentration ~2,000-fold lower than that needed to inhibit I_{AC} half maximally (Fig. 6 B). Consequently, 8-pcpt-cAMP maximally activated A-kinase at concentrations which did not measurably inhibit I_{AC}. Further, in these experiments application of 8-pcpt-cAMP to intact AZF cells at maximally effective concentrations activated virtually all (95.1 ± 4.8%, n = 5) of the A-kinase in these cells. Application of 10 μM cAMP (100× the E_{C50}) directly to cellular extracts from cells treated with 8-pcpt-cAMP did not further increase A-kinase activity.

Measurements of A-kinase activity in AZF cells clearly indicated that A-kinase activation was neither necessary nor sufficient for cAMP-mediated inhibition of I_{AC}. In another series of experiments, we added the catalytic subunit of cAMP-dependent protein kinase (5 μg/ml) to the patch pipette solution and measured I_{AC} at 30-s intervals. As illustrated in Fig. 7, the active catalytic subunit did not prevent the time-dependent expression of I_{AC}, nor did it alter inhibition of this current by ACTH. Similar results were obtained in each of three cells.

![Figure 6](image-url)  
**FIGURE 6.** Effect of 8-pcpt-cAMP and kinase inhibitors on A-kinase activity. (A) AZF cells were cultured on duplicate fibronectin-coated 60-mm plates at a density of 3–5 × 10⁶ cells/plate in serum-supplemented DMEM/F12. After 24 h, media was replaced with serum-free DMEM/F12 (CONTROL) or this same media containing 8-pcpt-cAMP. After 15 min, cells were harvested and extracts prepared as described in MATERIALS AND METHODS for measurement of A-kinase activity. Aliquots of extracts from cells were treated with 5 μM H-89 or 100 nM staurosporine for 15 min before measuring A-kinase activity. A-kinase (PKA) activity is expressed as pmol of [γ-32P] incorporated into substrate per min per million AZF cells. (B) Concentration-dependent stimulation of A-kinase activity by 8-pcpt-cAMP. AZF cells were cultured as described above in A. After 24 h, media was replaced with serum-free DMEM/F12 containing no further additions or 8-pcpt-cAMP at various concentrations ranging from 20 nM to 200 μM. After 15 min, cells were harvested for measurement of A-kinase activity. Protein kinase activity, expressed as percentage of maximum activity, is plotted against 8-pcpt-cAMP concentration (closed circles). For comparison, the concentration-dependent inhibition of I_{AC} by 8-pcpt-cAMP is plotted on the same graph (open circles). Data is the same as that shown in Fig. 2 C. Both sets of data were fit with an equation of the form: y = 1/(1 + [B]/[B]), where y is the percent maximal response, B is the 8-pcpt-cAMP concentration, and K_{i} is the equilibrium dissociation constant.

![Figure 7](image-url)  
**FIGURE 7.** A-kinase catalytic subunit and I_{AC} inhibition. K⁺ currents were recorded with a patch electrode containing 5 μg/ml of A-kinase catalytic subunit (bovine heart) with phosphorylating activity of 46 picomolar U/μg of protein. AZF cell was superfused with 200 μM of ACTH at the indicated time. Voltage clamp steps were applied from −80 mV to a test potential of +20 mV with (open circles) or without (closed circles) inactivating prepulses as described in the legend of Fig. 1. I_{AC} amplitude is plotted against time. (Inset) I_{AC} currents recorded immediately before and after maximum inhibition by ACTH.
IAc Inhibition by ACTH and 8-pcpt-cAMP Requires ATP Hydrolysis

Experiments with protein kinase inhibitors indicated that IAc inhibition by both ACTH and cAMP did not require phosphorylation by A kinase or other common serine/threonine kinases. However, IAc inhibition by both ACTH and cAMP was dependent on the hydrolysis of ATP. When the nonhydrolyzable ATP analogue AMP-PNP (1 mM) replace ATP in the pipette solution, ACTH and 8-pcpt-cAMP were ineffective at inhibiting IAc. In the presence of AMP-PNP, ACTH (100 nM) inhibited IAc by only 10.9 ± 6.2% (n = 7) compared to 95.3 ± 1.8% (n = 12) observed in the presence of ATP (Fig. 8 B).

Similarly, with AMP-PNP in the recording pipette, 200 μM 8-pcpt-cAMP inhibited IAc by only 4.0 ± 4.2% (n = 5) compared with 58.8 ± 7.8% (n = 8) in the control pipette solution (Fig. 8 A and B). As shown in Fig. 8 A, substituting AMP-PNP for ATP in the recording pipette did not alter the time-dependent expression of IAc typically observed in whole-cell recordings, but eliminated inhibition by 200 μM 8-pcpt-cAMP. Inhibition of IAc by ACTH, 8-pcpt-cAMP, and forskolin was also prevented in a total of six cells when recordings were made using pipette solutions that contained neither ATP nor AMP-PNP (data not shown).

Ca²⁺ Dependence

ACTH-stimulated activation of adenylate cyclases in AZF cells requires the presence of extracellular Ca²⁺ (Lefkowitz et al., 1970; Lefkowitz et al., 1971). To determine if inhibition of IAc by ACTH shared this Ca²⁺ dependence, we exposed cells to the peptide in Ca²⁺-free saline containing 0.1 mM EGTA. The time-dependent growth of IAc was not suppressed in the “0” Ca²⁺ saline, but the inhibition of this current by ACTH was prevented completely (Fig. 9). In each of three cells, 100 pM ACTH produced no inhibition of IAc in the absence of external Ca²⁺. This effect was specific to ACTH. Inhibition of IAc by forskolin was not affected. Fig. 9 A shows the results of an experiment performed in Ca²⁺-free external solution, in which the cell was sequentially superfused with ACTH and forskolin. ACTH was ineffective, while forskolin inhibited IAc almost completely. In three experiments performed in “0” Ca²⁺, forskolin inhibited IAc by 95.1 ± 5% (Fig. 9 C). A second peptide hormone, AII, retained its ability to inhibit IAc in the absence of extracellular Ca²⁺ (Fig. 9, B and C). Thus, the removal of extracellular Ca²⁺ did not result in a nonspecific inhibition of adenylate-cyclase activation or peptide hormone binding. It is unlikely that the ineffectiveness of ACTH in zero external Ca²⁺ resulted from a secondary reduction in intracellular Ca²⁺. When the internal pipette solution was reduced to nominally zero by raising BAPTA from 11 to 20 mM with no Ca²⁺ added to the pipette, ACTH inhibited IAc by 91% in two cells.

T-type Ca²⁺ Channels and 8-pcpt-cAMP-stimulated Cortisol Secretion

It is well established that cAMP-induced steroidogenesis is obligatorily dependent on the cAMP-dependent protein kinase signalling cascade. In addition, the results of the present study suggest that cAMP may inhibit IAc, K⁺ current through a separate A-kinase-independent pathway. Previously, we proposed a model for ACTH-stimulated cortisol secretion whereby IAc inhibition leads to membrane depolarization and Ca²⁺ entry.
through T-type Ca^{2+} channels (Enyeart et al., 1993; Mlinar et al., 1993a). Accordingly, the diphenylbutylpiperidine penfluridol inhibits T-type Ca^{2+} channels and ACTH-stimulated cortisol secretion in bovine AZF cells with similar potency and IC_{50}s of 0.3 and 0.16 µM, respectively (Enyeart et al., 1993). We used penfluridol to determine whether 8-pcpt-cAMP-stimulated cortisol secretion might also require Ca^{2+} entry through T-type Ca^{2+} channels. 8-pcpt-cAMP stimulated large (>50-fold) increases in cortisol-secreted by AZF cells. Penfluridol inhibited 8-pcpt-cAMP-stimulated cortisol secretion measured after 24 h with an IC_{50} of 0.33 µM (Fig. 10). Cortisol secreted during a 4 h exposure to 8-pcpt-CAMP was also inhibited with similar potency.

**DISCUSSION**

In this study, I_{Ac} was identified as an outwardly rectifying K^{+}-selective current that is inhibited by both ACTH and cAMP through a novel A-kinase-independent mechanism requiring ATP hydrolysis. The results suggest a model for ACTH-stimulated cortisol secretion wherein cAMP binds to two separate effectors to activate parallel steroidogenic signalling pathways in AZF.
cells. These include the traditional A-kinase-dependent signalling cascade and a novel pathway wherein cAMP binding to Iac K⁺ channels leads to depolarization-dependent Ca²⁺ entry.

Properties of Iac and AZF Membrane Potential

Iac displayed properties that are unusual among most K⁺ currents described thus far. It is one of several outwardly rectifying K⁺ currents that have been characterized (McCloskey and Cahalan, 1990; Ketchum et al., 1995). Unlike other voltage-gated K⁺ currents, Iac activation kinetics were not marked by a sigmoidal onset but instead could be fit by a single exponential function. By comparison, activation kinetics for the A-type K⁺ current in AZF cells were classically sigmoidal and fit by an exponential function raised to a power of 4 (Mlinar and Enyeart, 1993).

The instantaneous component of Iac observed in whole-cell recordings indicated that a substantial fraction of Iac channels are active at holding potentials negative to −35 mV. Although these results demonstrate that Iac would oppose membrane depolarization and contribute to negative membrane potentials, they do not prove that Iac is primarily responsible for setting the membrane potential of AZF cells. Several lines of evidence suggest that it is. The resting potential of Iac varies with Kᵅ/Kₑ as predicted by the Nernst equation. Of the two types of K⁺ channels that can be identified in whole-cell recordings from AZF cells, only Iac is inhibited by ACTH and cAMP. ACTH inhibits Iac with a temporal pattern and concentration dependence that are nearly identical to ACTH-stimulated membrane depolarization (Mlinar et al., 1993a).

Inhibition of Iac by cAMP

The results of experiments with GDP-[β-S and Ptx were consistent with the hypothesis that ACTH-mediated inhibition of Iac required a Gₛ-dependent activation of adenylate cyclase. Accordingly, 8-pcpt-cAMP produced a concentration-dependent inhibition of Iac when applied by bath perfusion. The suppression of the time-dependent expression of Iac in whole-cell recordings made with pipettes containing cAMP and the inhibition of Iac by forskolin indicate that cAMP acts at an intracellular site rather than through a receptor located on the cell surface. This point is significant since cAMP has been reported to modulate a Na⁺ channel on cardiac myocytes through G-protein-coupled cell surface receptor (Sorbera and Morad, 1991). G-protein-coupled cAMP receptors are present on the surface of slime molds where they control development (Klein et al., 1988).

Forskolin has been reported to inhibit K⁺ currents by a cAMP-independent mechanism. However, forskolin concentrations much greater than 2.5 µM were required for significant inhibition to be observed (Zunkler et al., 1988). Further, forskolin, like cAMP, selectively inhibited Iac in AZF cells, without suppressing the transient A-type K⁺ current. Thus, it is likely that suppression of Iac by forskolin is specific and mediated by cAMP.

In nearly all reported cases, the modulation of voltage and Ca²⁺-activated K⁺ channels by cAMP occurs through phosphorylation by A-kinase (Hille, 1992; Pedarzani and Storm, 1993; Drain et al., 1994; Levitan, 1994). Iac K⁺ channels appear to be distinctive in this respect. An overwhelming body of evidence indicated that A-kinase activation was neither necessary nor sufficient for 8-pcpt-cAMP- or ACTH-mediated inhibition of Iac. The three A-kinase antagonists, H-89, PKI (5-24), (Rp)-cAMPS, and the nonspecific kinase inhibitor staurosporine applied intracellularly, externally, or by both routes at concentrations 10−1,000 times their reported IC₅₀ failed to prevent inhibition by either 8-pcpt-cAMP or ACTH. Since diffusional equilibrium between pipette and cell is reached within seconds for small molecules (Pusch and Neher, 1988), it is likely that A-kinase antagonists were present in large excess at the intended target. When applied directly to AZF cell extracts for comparable times at identical concentrations, these kinase antagonists eliminated 8-pcpt-cAMP-stimulated A-kinase activation.

Two separate lines of evidence demonstrated that A-kinase activation did not mediate Iac inhibition by 8-pcpt-cAMP. Most importantly, 8-pcpt-cAMP activated A-kinase in AZF cells with an EC₅₀ >2,000-fold lower than that necessary to inhibit Iac half maximally. Therefore, 8-pcpt-cAMP fully activated A-kinase at concentrations that had virtually no effect on Iac. Accordingly, the active catalytic subunit of bovine A-kinase applied intracellularly through the patch pipette failed to suppress expression of Iac. Although our results show that A-kinase activation is not required for Iac inhibition by cAMP, they do not exclude a role for this enzyme in Iac modulation in an undialyzed cell.

Our evidence suggests that cAMP may act directly on Iac K⁺ channels to inhibit their function. Iac K⁺ current resembles other cyclic nucleotide-gated channels with respect to its sensitivity to cAMP and weak voltage-dependent activation. A large and growing family of ion channels directly activated by cAMP has been identified, including those present in retinal and olfactory neurons. These channels are nonselective cation pores with only a weak voltage dependence (Dhallen et al., 1990; Kaupp, 1991; Hille, 1992; Yau, 1994). However, the overall sequence similarity between cyclic nucleotide-gated ion channels and voltage-activated K⁺ channels (Heginbotham et al., 1992) suggests origination from a common ancestor. In this regard, several cloned K⁺ channel genes from Drosophila and the plant Arabi-
*drosophila* larvae has been characterized with patch clamp (Delgado et al., 1991). I_{AC} may be the first ion channel directly inhibited by cAMP.

### Mechanism of ACTH Inhibition of I_{AC}

The results of patch clamp experiments were consistent with the interpretation that I_{AC} inhibition by ACTH is mediated by cAMP. Experiments with GDP-β-S and Ptx demonstrated that activation of a Ptx-insensitive G protein such as G_s was required for I_{AC} inhibition by ACTH. In AZF cells, ACTH receptors are coupled to adenylate cyclase through G_s (Mountjoy et al., 1992).

ACTH stimulates A-kinase and by inference cAMP synthesis at concentrations identical to those which inhibit I_{AC} (unpublished observations). The inability of ACTH to inhibit I_{AC} in the absence of extracellular Ca^{2+} supports the hypothesis that inhibition is mediated by cAMP. It had previously been demonstrated that while binding of ACTH to its receptor was not affected by removal of external Ca^{2+}, activation of adenylate cyclase was completely prevented in the absence of this divalent cation (Lefkowitz et al., 1970; Lefkowitz et al., 1971). Thus, ACTH-mediated activation of adenylate cyclase and I_{AC} inhibition share a common dependence on external Ca^{2+}. cAMP appears to be the messenger that links ACTH receptors to I_{AC} channels.

Patch clamp studies with the A-kinase antagonists failed to provide evidence that ACTH and 8-pcpt-cAMP inhibited I_{AC} by separate mechanisms. Each of the three protein kinase antagonists were ineffective at preventing I_{AC} inhibition by either agent. The complete elimination of ACTH- and 8-pcpt-cAMP-mediated inhibition of I_{AC} by AMP-PNP also suggests a common mechanism is involved.

Although all of the results in this study are consistent with the hypothesis that cAMP directly mediates inhibition of I_{AC} by ACTH, they do not exclude the possibility of a separate signalling pathway. In this regard, inhibition of I_{AC} by ACTH was more difficult to reverse than 8-pcpt-cAMP-mediated reduction of this current. However, this difference could reflect the slower dissociation of ACTH from its receptor rather than distinct inhibitory mechanisms. If ACTH at any concentration suppresses I_{AC} through a cAMP-independent mechanism, it is unlikely that activation of serine-threonine kinase is involved. Staurosporine, at concentrations of 100–200 nM, failed to significantly alter inhibition of I_{AC} by ACTH. Staurosporine inhibits some tyrosine kinases only at higher micromolar concentrations. The possibility that ACTH suppresses I_{AC} by an unknown tyrosine kinase cannot be excluded. Interestingly, we found that staurosporine does suppress AII-mediated inhibition of I_{AC} (Mlinar et al., 1995). Apparently, AII- and ACTH-mediated inhibition of this current occurs through distinct signalling pathways.

### I_{AC}. Inhibition and ATP Hydrolysis

The complete suppression of 8-pcpt-cAMP-mediated inhibition of I_{AC} observed upon substituting the nonhydrolyzable ATP analogue AMP-PNP for ATP in the recording pipette suggests that cAMP-induced channel closing is linked to an ATP hydrolysis cycle. Several channels have been discovered whose functional expression and gating are regulated by A-kinase and ATP-hydrolysis (Anderson et al., 1991; Baukrowitz et al., 1994; Fakler et al., 1994). Gating of the cystic fibrosis transmembrane conductance regulator (CFTR) Cl^- channels is coupled to an ATP hydrolysis cycle. For CFTR Cl^- channels to open they must be phosphorylated by A-kinase and then exposed to a hydrolyzable nucleoside triphosphate such as ATP (Baukrowitz et al., 1994). The functional activity of K^+ inward rectified K^+ channels also requires phosphorylation by PKA and ATP hydrolysis (Fakler et al., 1994).

cAMP-mediated inhibition of I_{AC}. K^+ channels may involve a novel mechanism that requires ATP hydrolysis but not phosphorylation by A-kinase. The results are consistent with a mechanism where the binding of cAMP to an I_{AC}. K^+ channel is coupled to the conformational change that closes the channel by a process fueled by ATP hydrolysis.

The elimination of ACTH-mediated inhibition of I_{AC} observed upon substituting AMP-PNP for ATP in the recording pipette is readily explained within the framework of a mechanism that requires both cAMP synthesis and ATP hydrolysis for channel inhibition. In addition to eliminating ATP hydrolysis, the nonhydrolyzable adenine nucleoside does not serve as a substrate for adenylate cyclase, preventing the synthesis of cAMP. Our results do not exclude the possibility that ACTH inhibition of I_{AC} occurs through a cAMP-independent mechanism such as a staurosporine-insensitive protein kinase, which would become inactive in the absence of a nonhydrolyzable substrate.

### Model for Cortisol Secretion Stimulated by ACTH and cAMP

The T-type Ca^{2+} channel antagonist penfluridol inhibited cAMP-stimulated cortisol secretion at concentrations similar to those that we previously found sup-

Downloaded from on April 2, 2017
pressed ACTH-stimulated cortisol secretion and blocked T-type Ca^{2+} channels in bovine AZF cells (Enyeart et al., 1993). The results of combined patch clamp and secretion studies suggest a model for ACTH-stimulated cortisol secretion wherein cAMP functions in a dual capacity as a second messenger to activate parallel signalling pathways (Fig. 11). Along one path, cAMP directly combines with I_{AC} K^{+} channels leading to their inhibition. This inhibition triggers the sequence of membrane depolarization T-type Ca^{2+} channel opening, and Ca^{2+}-dependent activation, and ultimately, induction of steroidogenic enzymes. cAMP activates the second pathway through the conventional interaction with A-kinase followed by activation and induction of the same steroidogenic enzymes. Although it is clear that cAMP can mediate electrical and biochemical events in cortisol secretion, the possibility remains that additional signalling pathways could be involved in ACTH-stimulated cortisol secretion.

Aside from its apparent importance in regulating cortisol secretion, I_{AC} is an extremely interesting K^{+} current whose gating is regulated by an unusual combination of voltage and metabolic factors. The cAMP-dependent inhibition of this K^{+} current through an A-kinase-independent pathway requiring ATP hydrolysis is a unique mechanism for modulating the function of ion channels. The control of I_{AC} K^{+} channel gating by metabolic factors including cAMP and ATP suggests a mechanism where the membrane potential of these secretory cells could be tightly coupled to the metabolic state of the cell and modulated by biochemical signals originating at the cell membrane.

This work was supported by National Institute of Diabetes and Digestive and Kidney Grant DK-47875 and by National American Heart Association Grant-in-aid 94011740 to J.J. Enyeart.

Original version received 23 April 1996 and accepted version received 22 July 1996.

REFERENCES


Fakler, B., U. Brandle, F. Głowaczki, H.P. Zenner, and J.P. Rup-


Pedarzani, P., and J.F. Storm. 1993. PKA mediates the effects of monamine transmitters on the K⁺ current underlying the slow spike frequency adaptation in hippocampal neurons. Neuron. 11: 1023-1035.


