The baculovirus/insect cell system as an alternative to Xenopus oocytes. First characterization of the AKT1 K+ channel from Arabidopsis thaliana

Frédéric Gaymard, Martine Cerutti, Christèle Horeau, Guy Lemailliet, Serge Urbach, Marc Ravallec, Gerard Devauchelle, Hervé Sentenac, Jean-Baptiste Thibaud

To cite this version:
Frédéric Gaymard, Martine Cerutti, Christèle Horeau, Guy Lemailliet, Serge Urbach, et al.. The baculovirus/insect cell system as an alternative to Xenopus oocytes. First characterization of the AKT1 K+ channel from Arabidopsis thaliana. Journal of Biological Chemistry, American Society for Biochemistry and Molecular Biology, 1996, 271 (37), pp.22863-22870. 10.1074/jbc.271.37.22863 . hal-02695991

HAL Id: hal-02695991
https://hal.inrae.fr/hal-02695991
Submitted on 1 Jun 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
The Baculovirus/Insect Cell System as an Alternative to Xenopus Oocytes

FIRST CHARACTERIZATION OF THE AKT1 K⁺ CHANNEL FROM ARABIDOPSIS THALIANA*

(Received for publication, February 13, 1996, and in revised form, May 31, 1996)

Frederic Gaymard‡§, Martine Cerutti¶, Christelle Horeau‡, Guy Lemailllet‡, Serge Urbach‡, Marc Ravallec‡, Gerard Devauchelle‡, Herve Sentenac‡, and Jean-Baptiste Thibaud‡

From the ‡Laboratoire de Biochimie et Physiologie Moleculaire des Plantes, Ecole Nationale Superieure Agronomique de Montpellier, Institut National de la Recherche Agronomique, CNRS URA 2133, 34060 Montpellier Cedex 1 and the §Laboratoire de Pathologie Comparee, Institut National de la Recherche Agronomique, CNRS URA 1184, 30380 Saint-Christol-les-Ales, France

Two plant (Arabidopsis thaliana) K⁺ transport systems, KAT1 and AKT1, have been expressed in insect cells (Sf9 cell line) using recombinant baculoviruses. Microscopic observation after immunogold staining revealed that the expressed AKT1 and KAT1 polypeptides were mainly associated with internal membranes, but that a minute fraction was targeted to the cell membrane. AKT1 was known, from earlier electrophysiological characterization in Xenopus oocytes, to be an inwardly rectifying voltage-gated channel highly selective for K⁺, while similar experiments had failed to characterize AKT1. Insect cells expressing AKT1 displayed an exogenous inwardly rectifying K⁺ conductance reminiscent of that described previously in Xenopus oocytes expressing AKT1. Under similar conditions, cells expressing AKT1 showed a disturbed cell membrane electrical stability that precluded electrophysiological analysis. Use of a baculovirus transfer vector designed so as to decrease the expression level allowed the first electrophysiological characterization of AKT1. The baculovirus system can thus be used as an alternative method when expression in Xenopus oocytes is unsuccessful for electrophysiological characterization of the ion channel of interest. The plant AKT1 protein has been shown in this way to be an inwardly rectifying voltage-gated channel highly selective for K⁺ ions and sensitive to cGMP.

In plants, inwardly rectifying potassium channel activity is involved in long-term K⁺ uptake and in related functions at the cell or whole plant level, e.g. turgor regulation, stomatal guard cell movements, or cell expansion and plant growth (1–3). The first plant K⁺ channels characterized at the molecular level, AKT1 (4) and KAT1 (5) from Arabidopsis thaliana, were cloned by functional complementation of yeast strains defective in K⁺ transport. Several K⁺ channels have since been identified using probes from AKT1 or KAT1 cDNAs (Refs. 6–8 and sequences found in the EMBL Data Bank). These channels share strong homologies (~60% identity) and show structural and sequence homologies with K⁺ channels of the Shaker family found in insects and mammals (4, 5, 9). They display the characteristic hydrophobic domain consisting of six transmembrane segments, named S1 to S6, with a pore-forming region located between S5 and S6. A putative cyclic nucleotide-binding domain is present downstream of S6, as found in cyclic nucleotide-gated channels of the Shaker superfamily (4–8). Two subfamilies can be defined according to the presence or absence (channels of the AKT1 or KAT1 type, respectively) of an ankyrin domain in the polypeptidic chain downstream of the putative cyclic nucleotide-binding domain (3, 4).

Electrophysiological characterization by heterologous expression in Xenopus laevis oocytes or yeast indicated that AKT1 is an inwardly rectifying voltage-gated K⁺ channel highly selective for K⁺ (10–15). It is expressed in guard cells and thought to mediate long-term K⁺ influx leading to stomatal opening (16). Northern blot analysis indicated that AKT1 is expressed mainly in roots (17). Studies of its tissue-specific expression using the GUS reporter gene revealed that its promoter directs preferential expression in the peripheral cell layers of the mature region of roots (18), suggesting a role in K⁺ uptake from the soil solution. Injection of AKT1 cRNA in Xenopus oocytes did not, however, affect the membrane conductance. The K⁺ channel activity of the encoded polypeptide thus awaited characterization.

The insect cell line Sf9 can express high levels of foreign proteins when infected by a recombinant baculovirus. This expression system has been shown to be capable of performing most eukaryotic post-translational modifications (19, 20). It has been used, in particular, for expressing the Drosophila Shaker K⁺ channel in a functional form (21–23). In this study, functional expression of AKT1 and KAT1 polypeptides has been achieved using the baculovirus/Sf9 system.

EXPERIMENTAL PROCEDURES

Antibodies—Polyclonal antibodies were raised against the ankyrin domain of AKT1 and the C-terminal region of KAT1 (see Fig. 1A). Nucleotide sequences coding for these domains were cloned into the pET-3c vector designed for expression in Escherichia coli (24). The required restriction sites (Ndel and BamHI) were introduced in AKT1 and KAT1 cDNAs as described below.

The ankyrin domain of AKT1 was amplified by polymerase chain reaction using a 5’-primer (5’-TTCATATGGATCTTCCTCCT) introducing a TAA stop codon at position 2218, just before the unique BamHI site present in AKT1. The Ndel-BamHI fragment was sequenced on both strands. KAT1 cDNA was introduced into pBluescript® so that the BamHI polylinker site was present downstream of the KAT1 stop codon. The

* This work was supported in part by the Bio Avenir Programme funded by Rhône-Poulenc and the Ministry in Charge of Research and Industry and by the European Community BIOTECH Program as part of the Project of Technological Priority 1993–1996. The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

† To whom correspondence should be addressed. Tel.: 33-67612518; Fax: 33-67525737; E-mail: gaymard@ensam.inra.fr.
Expression of Plant \( K^+\) Channels in Insect Cells

\( NsI-bamH\) fragment encoding the C-terminal part of \( KAT1\) was cloned into the SD184 vector (25), introducing a NdeI site just up-stream of the \( NsI\) site. The \( NdeI-bamH\) fragment was thereafter introduced into the pET3c vector.

The recombinant pET-3c vectors were introduced in \( E.\ coli \) strain BL21(DE3) (24). Protein expression was induced by adding isopropyl-1-thio-b-D-galactopyranoside (final concentration of 0.4 mM) and lasted 3 h at 37°C. Cell-free extracts were purified by nickel affinity chromatography using the 

\( NsI\) enzyme of the \( NsI-bamH\) fragment was thereafter introduced into the pET3c vector.

Recombinant Baculoviruses—Two baculovirus transfer vectors (see Fig. 1B) were used, pGmA34T (27) and pGmA217. In the pGmA34T vector, a 244-bp HI fragment encoding the C-terminal part of \( KAT1\) was cloned into the pJRD184 vector (25), introducing a 

\( NdeI-bamHI\) fragment was thereafter introduced into the pET3c vector.

Insect Cell Culture—The \( Sf9\) cell line was maintained in monolayer culture at 28°C in TC-100 medium (Life Technologies, Inc.) supplemented with 0.37 g/liter \( \alpha\)-ketoglutaric acid, 0.4 g/liter \( \beta\)-nicotinic acid, 0.055 g/liter fumaric acid, 0.67 g/liter malic acid, 0.06 g/liter succinic acid, 2.7 g/liter sucrose, 0.2 g/liter choline chloride, 0.2 g/liter \( \beta\)-alanine, 0.35 g/liter NaHCO\(_3\), 3.33 g/liter lactalbumin (Difco), 0.05 g/liter streptomycin sulfate, 0.125 g/liter penicillin, and 10% fetal calf serum. Cells were split every 4 days to maintain a density ranging from \( 4 \times 10^7\) to \( 7 \times 10^8\) cells/ml.

Recombinant transfer vectors, named p34T-AKT1, p34T-KAT1, and p217-AKT1, were obtained as described in the legend to Fig. 1B by cloning \( AKT1\) and \( KAT1\) cDNAs into pGmA34T and pGmA217 cDNA into pGmA217, respectively. \( Sf9\) cells were transfected with wild-type baculovirus or with viruses recombinant for \( KAT1\) or \( AKT1\) (see "Experimental Procedures" and Fig. 1).

RESULTS

Expression of \( KAT1\) and \( AKT1\)—After 2 days of incubation at 28°C, cells were harvested and centrifuged at 500 \( \times \) \( g\) for 5 min. The pellet was washed with ice-cold PBS. The cells were centrifuged for 5 min at 500 \( \times \) \( g\) and resuspended at \( 10^7\) cells/ml in a grinding medium containing 10 mM Tris-HCl (pH 7.5), 1 mM EDTA, 250 mM NaCl, 10% glycerol, 1 mM dithiobisethyl, 2 mM phenylmethylsulfon fluoride, 2 \( \mu\)g/ml aprotinin, 1 \( \mu\)g/ml leupeptin, 1 \( \mu\)g/ml pepstatin, and 1 \( \mu\)g/ml antipain. The suspension was frozen in liquid nitrogen, quickly thawed at room temperature, and sonicated three times for 10 s with a probe sonicator. The homogenate (referred to as total extract) was centrifuged twice at 13,000 \( \times \) \( g\) for 20 min. The supernatant was collected and centrifuged at 100,000 \( \times \) \( g\) for 1 h. The crude membrane pellet was suspended in 2 mM Tris-HCl (pH 7.5), 1 mM dithiobisethyl, 2 mM phenylmethylsulfon fluoride, and 10% glycerol and stored in liquid nitrogen. Proteins were assayed according to Schaffner and Weissman (29) using bovine serum albumin as a standard.

Immunoblot—Proteins were separated by SDS-PAGE according to Laemmli (30) and electroblotted onto a nitrocellulose membrane (Schleicher & Schuell). Blots were blocked in PBS containing 5% low fat milk for 3 h at room temperature. Primary antibody diluted in PBS containing 0.1% Tween 20 (PBS-T) was bound overnight at room temperature. After three 10-min washes in PBS-T, goat anti-rabbit IgG secondary antibody coupled to peroxidase (Sigma) diluted in PBS-T was added. Blots were incubated for 2 h at room temperature and washed as described above. Peroxidase activity was detected using a 0.5 mg/ml 4-chloronaphthol solution prepared in PBS, 20% glycerol, and 0.01% H\(_2\)O\(_2\).

Immunogold Staining and Microscopy—\( Sf9\) cells were infected with recombinant baculoviruses as described above (see "Membrane Purification") and harvested 2 days later by pelleting at 500 \( \times \) \( g\) for 5 min. They were fixed for 1 h in 4% paraformaldehyde in PBS at 4°C. Following dehydration (increasing ethanol concentration up to 100%), cells were embedded in LR white resin (Taab). Thin sections were made and immunostaining was performed as described (31). Observations were made with a Zeiss (Jena) EM 10C/CR electron microscope.

Patch-clamp Experiments—\( Sf9\) cells were plated in 3-cm diameter cell culture dishes and infected as described above (see "Membrane Purification"). Prior to electrophysiological recordings, culture medium was replaced by a bath solution containing 10 mM KCl or 100 mM KCl, 4 mM CaCl\(_2\), 5 mM MgCl\(_2\), 5 mM glucose, 10 mM MES/Tris (pH 6.3), and NaCl (to give an osmolality of 0.28). Standard voltage-clamp protocols (see "Results") allowed macroscopic current recording in the whole cell configuration of patch-clamp (32).

Micropipettes were two-step pulled from soft glass (Modulohm A/S, Herleu, Denmark) and displayed typically a 2-megohm resistance in bath solution when filled with 80 mM KF, 50 mM KCl, 1 mM MgCl\(_2\), 10 mM EGTA, 10 mM MOPS/NaOH (pH 7.2), and NaCl (osmolality set to 0.20). Reference and measuring electrodes were connected to an Axopatch 200 A amplifier that was controlled by pClamp software (Axon Instruments, Inc.). Linear leak current was digitally subtracted from recorded whole cell current. Most capacitive currents could usually be compensated by using built-in features of the amplifier. Residual capacitive currents were removed and digitally subtracted from whole cell currents using the method described by Zitlau and Walther (33). Digitized data were analyzed using pClamp and Sigmaplot (Jandel Scientific, Erkrath, Germany) software.

RESULTS

Expression of \( KAT1\) and \( AKT1\)—\( Sf9\) cells were infected either with wild-type baculovirus or with viruses recombinant for \( KAT1\) or \( AKT1\) cDNA: RB34T-KAT1, RB34T-AKT1, and RB217A-AKT1 (see "Experimental Procedures" and Fig. 1). RB217A-AKT1 was obtained using a transfer vector designed (deletion in the polyhedrin promoter) (Fig. 1) so as to decrease the level of expression of the foreign sequence.

Infection of \( Sf9\) cells with wild-type baculovirus resulted in the appearance of many extra bands following SDS-PAGE of total cell extract (Fig. 2A). The major one, present at 31 kDa, corresponds to the virus polyhedrin gene product. When \( Sf9\) cells were infected with viruses recombinant for \( KAT1\) or \( AKT1\) cDNA, the polyhedrin band was no longer present, while an extra major band was clearly visible. The relative molecular mass of this band was close to that expected for the corresponding plant channel: \( 70\) kDa for \( KAT1\) (predicted molecular mass of \( 78\) kDa) and \( 95\) kDa for \( AKT1\) (predicted molecular mass of \( 97\) kDa) (Fig. 2A). Antibodies raised against \( KAT1\) or \( AKT1\) detected a 70-kDa band (Fig. 2B) and a 95-kDa band (lanes 34T-AKT1 and 217A-AKT1), respectively. This confirmed that both plant channels were expressed in \( Sf9\) cells. The level of expression of \( AKT1\) was lower in RB217A-AKT1-infected cells than in RB34T-AKT1-infected cells, as expected from the use of an 8 base pair-deleted polyhedrin promoter (28).

Plant Channel Targeting in \( Sf9\) Cells—In a preliminary biochemical approach, the cellular localization of plant channels expressed in \( Sf9\) cells was investigated by preparing soluble and membrane protein fractions and analyzing their polypeptide composition by SDS-PAGE. Polypeptide bands of the size expected for \( AKT1\) and \( KAT1\) were detected in the membrane protein fraction (Fig. 3). Western blotting performed with the corresponding antisera failed to detect the channels in the soluble protein fraction (Fig. 3B). Cellular distribution of \( AKT1\) in \( Sf9\) cells was further investigated by immunogold staining. Infection with \( AKT1\) and \( KAT1\) recombinant viruses dramatically increased the amount of intracellular membrane (Fig. 4) when compared with that of
Strong staining was observed in both RB34T-AKT1- and RB217Δ-AKT1-infected cells (Fig. 4, A–D), in contrast to control cells. Additionally, KAT1-expressing cells (RB34T-KAT1-infected) probed with the serum raised against the AKT1 ankyrin domain (Fig. 4E) also showed little staining, equivalent to that observed with the other controls. High magnification micrographs (Fig. 4, C–D) indicated that most AKT1 proteins had an intracellular localization in both cells and that only a minute fraction of the expressed polypeptide was targeted to the plasma membrane. The intracellular pool of AKT1 was associated with internal membranes. Counting of gold particles was performed on nine different cells of each type. While internal membrane staining in RB217Δ-AKT1-infected cells was 35% lower than in RB34T-AKT1-infected cells (24 and 37 particles/μm², respectively; S.D. 20% of mean values), plasma membrane staining was similar in both cell types (~2.7 ± 0.8 particles/μm² of plasma membrane) (data not shown).
Electrophysiological Evidence for Functional Channel Expression—From a holding potential of -10 mV, membrane potential was clamped for 800-ms periods to values ranging from 0 to -160 mV. Negligible currents were usually recorded in cells infected with wild-type virus as shown in Fig. 5A. In some cell batches, however, randomly activating currents could be recorded at membrane potential values negative to -120 mV (data not shown). Cell batches that exhibited this behavior were discarded.

Slowly activating inward currents could be recorded in cells infected with each of the recombinant viruses (Fig. 5, B–D). During double-pulse protocols, the above three cell types displayed tail currents that reversed at potential values close to the equilibrium potential for K+ ions (data not shown, but see Fig. 6 and Table I regarding RB217Δ-AKT1-infected cells), indicating that the inward currents shown in Fig. 5 were mainly carried by K+ ions. As current recording was much more reproducible in cells expressing AKT1 from RB217Δ-AKT1 (Fig. 5D) than from RB34T-AKT1 (Fig. 5C), AKT1 channel activity was further characterized using the former virus.

AKT1 Channel Voltage Gating—Inward currents were recorded during hyperpolarizing pulses in cells bathed first in 10 mM K+ and thereafter in 100 mM K+. These currents activated slowly with a multiexponential time course (Fig. 7, A and B). Steady-state activation was virtually achieved within the 1100-ms hyperpolarizing pulses. Half-activation time was clearly voltage-dependent: 40 ms at -180 mV and 160 ms at -120 mV in the 10 mM K+ bath (36 and 140 ms, respectively, in 100 mM K+). Plotting steady-state current versus voltage (Fig. 7C) revealed a strong inward rectification. Due to the presence of a Shaker S4-like voltage sensor in AKT1 (4), we hypothesized that this rectification was due mainly to a voltage-dependent G/Gmax ratio and determined whether the steady-state IV curves shown in Fig. 7C could be fitted by a simplified voltage-gating model. As described previously for the KAT1 channel (12), the steady-state current was assumed to be predicted by the Goldman equation, multiplied by a voltage-dependent G/Gmax ratio changing from 0 to 1 upon hyperpolarization. The G/Gmax voltage dependence was described using a simple two-state Boltzmann equation, assuming it was independent of the K+ concentration in the bath (10 or 100 mM). The calculated steady-state IV curve was drawn in full line in Fig. 7C for each bath condition. The single Boltzmann curve corresponding to both fits is shown in Fig. 7D. The half-activa-
Effect of ATP and cGMP on AKT1 Activation—In most cases, a rapid decrease in AKT1 current was observed when the pipette solution contained no ATP (Fig. 8A). This decrease could generally be prevented by including 2 mM ATP in the pipette solution (Fig. 8B). The standard pipette solution thus contained 2 mM MgATP. In some cases, this ATP concentration caused an increase in the current recorded at a given potential. This was due to a slight positive shift in the activation potential (Fig. 8B). When the clamped cell was perfused with a bath solution supplemented with 0.1 mM 8-bromo-cGMP, the current decreased. This was due to a negative shift in the activation potential, as shown in Fig. 8C (example representative of six independent recordings). This shift in AKT1 activation potential was time-dependent; the maximal value was reached within ~15 min and was in the ~25 to ~40 mV range.

DISCUSSION

Our current knowledge of the structure/function relationship of voltage-gated animal Shaker channels originates mainly from the literature reporting the functional characterization of wild-type and mutant channels expressed in Xenopus oocytes. This expression system is popular for electrophysiologists as it is readily amenable to current recordings. However, in some unpublished experiments aimed at characterizing new putative animal channels, no functional expression has been obtained from cRNA injection in oocytes. Similarly, although the KAT1 channel was expressed and characterized in Xenopus oocytes (10–14), similar attempts for AKT1 have failed up until now.

The baculovirus/insect cell system has often been used to express functional membrane proteins (20). The Drosophila Shaker K+ channel was shown to be expressed in Sf9 cells and targeted to the plasma membrane in a functional state (21). KAT1 and AKT1 are the first ion channels from the plant kingdom to be expressed using this system. Both plant chan-

### Table I

<table>
<thead>
<tr>
<th>Bath/pipette K conc</th>
<th>10/110 mM</th>
<th>100/110 mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reversal potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AKT1 current</td>
<td>−63 ± 9 (10)</td>
<td>−5 ± 4 (7)</td>
</tr>
<tr>
<td>Theoretical K+</td>
<td>−62</td>
<td>−2</td>
</tr>
</tbody>
</table>

## References

1. O. Pongs, personal communication.
channels have been expressed in a functional form and partly targeted to the plasma membrane of the cells as revealed by whole cell current recording and immunogold staining (Figs. 4-8). This is the first report showing that the baculovirus expression system can be used in an alternative strategy for characterizing ion channels when attempts using *Xenopus* oocytes have failed. The reason why AKT1 is expressed in a functional state in the former system and not in the latter is still unknown.

The membrane of Sf9 cells was often unable to withstand hyperpolarizations beyond −100 mV. Due to this problem, Sf9 cells do not offer the ideal system for electrophysiological characterization of hyperpolarization-activated channels such as KAT1 and AKT1. Some cell batches, however, were able to withstand membrane potential as negative as −160 mV (Fig. 5A) or even −180 mV. It is worth noting that Sf9 cells infected with either RB34T-KAT1 or RB217Δ-AKT1 recombinant baculovirus withstood large hyperpolarizations (see Fig. 6 for RB217Δ-AKT1-infected cells) much more reproducibly than wild-type baculovirus-infected cells or RB34T-AKT1-infected cells.

AKT1 was highly expressed in cells infected with RB34T-AKT1 (Fig. 2); however, these cells showed membrane instability. Breakdowns occurred especially at potentials more negative than −100 to −120 mV, precluding any characterization of AKT1 channel activity using this construct (Fig. 5C). As expected, the expression level of AKT1 in cells infected with RB217Δ-AKT1 was lower than in the former cells (Fig. 2). In both types of cells, the plant channel was present in the membrane fraction (Fig. 3), although the amount of AKT1 actually targeted to the plasma membrane was small and roughly the same in both cases (Fig. 4). Most expressed polypeptides remained associated with internal membranes; their functional competence is unknown. A similar phenomenon with the expression of the *Drosophila* Shaker channel in Sf9 cells was hypothesized from the discrepancy between the magnitude of the currents recorded in the infected cells and the intensity of the Shaker polypeptide band on a Coomassie Blue-stained protein gel (21). Similarly, a liver gap junction protein expressed in Sf9 cells has been shown to remain mainly associated with the endoplasmic reticulum, with only a small fraction reaching the cell surface (34). It seems that Sf9 cells are able to synthesize large amounts of membrane proteins, but the protein export machinery is overwhelmed by the high rates of synthesis (35).

By making use of the RB217Δ-AKT1 virus instead of the RB34T-AKT1 virus, it was possible to obtain conditions allowing the functional characterization of AKT1. This work represents the first data on AKT1 channel activity. Our results demonstrated that the reversal potential for AKT1 current remained close to the equilibrium potential for K⁺ ions when the external concentration of this ion was changed (Table I), indicating that this current is mainly carried by K⁺ ions. This is in agreement with the presence in the putative selectivity filter-forming region of a GYGD motif (4) thought to be a hallmark of highly selective K⁺ channels (36).

Like KAT1 current, AKT1 current activated slowly upon hyperpolarization and underwent no inactivation (Fig. 5). Comparison of traces in Fig. 5D to those in Fig. 5B reveals that AKT1 activation was slower than that of KAT1 and occurred from a more negative threshold potential. It should be noted, however, that KAT1 activation in Sf9 cells was faster (half-activation time of −15 ms at −140 mV) (Fig. 5B) than that observed in *Xenopus* oocytes (half-activation time of −200 ms at −140 mV) (11). Thus, the kinetic features of KAT1 are dependent on the expression system used. This might be due to
Boltzmann fit in Fig. 7D. The presence of ATP in the pipette solution was required to obtain routinely a stable AKT1 activation upon repeated hyperpolarizations. AKT1 current decrease in the absence of ATP was variable between cells (in the example of Fig. 8A, the decrease was particularly fast). ATP (2 mmol/liter) generally shifted the IV curve positively along the voltage axis (Fig. 8B). A shift of this curve in the opposite direction was elicited by bathing the cell with 100 µM 8-bromo-cGMP solution (Fig. 8C). All but one of these observations are reminiscent of those recently reported regarding KAT1 expressed in oocytes: while the decrease in KAT1 current was mainly due to a negative shift in the IV curve along the voltage axis (13), that of AKT1 originated from a decrease in activable channels (Fig. 8A). Previous sequence analysis indicated that a putative cyclic nucleotide-binding site sharing sequence homologies with the cyclic nucleotide-binding domain of animal cyclic nucleotide-gated channels is present in both AKT1 and KAT1 polypeptides, downstream of the membrane-spanning region (3, 4). The effect of cGMP on AKT1 and KAT1 activity may thus indicate direct modulation by cGMP, i.e. resulting from cGMP binding to the channel. An indirect effect cannot, however, be ruled out since modulation by cyclic nucleotide-dependent protein kinases is a likely means of K+ channel regulation in planta (38). Also, the hypothesis of an indirect effect is supported by the time dependence of the shift in activation potential.

The highest similarities between AKT1 and KAT1 and the animal K+ channels of the Shaker superfamily are found with the Drosophila Eag gene product. The Eag channel has been shown to be both voltage-dependent and cAMP-modulated (39). The existence of a link between strictly voltage-gated K+ channels and cyclic nucleotide-gated ion channels has been proposed (40). Eag, KAT1, and AKT1 may be members of a class of channels representing such a link.

In conclusion, we have shown that the baculovirus system can be used as an alternative method when expression in Xenopus oocytes is unsuccessful for electrophysiological characterization of the ion channel of interest. The plant AKT1 protein has been shown in this way to be a K+-selective, voltage-gated, and probably cGMP-modulated channel.

Acknowledgment—We thank Dr. David Logan for critical reading of the manuscript.

REFERENCES

18. Lagarde, D., Basset, M., Lepetit, M., Conejero, G., Gaymard, F., Astruc, S., and

FIG. 8. AKT1 channel activation is ATP-dependent and cGMP-sensitive. Voltage ramps (from 0 to −180 mV within 10 s) were applied to the membrane of RB217Δ-AKT1-infected Sf9 cells at time intervals after rupturing the patch. Pseudo steady-state current/voltage curves could be recorded. A, the absence of ATP in the pipette solution (same as given in the legend to Fig. 5, but without MgATP) caused a rapid decrease in AKT1 inward current. Zero time was at rupturing the patch. The bath contained 100 mM K+. B, a 2 mM MgATP pipette solution prevented the time-dependent decrease in current. Successive IV ramps shifted positively along the voltage axis. Zero time was at rupturing the patch. C, the addition of 100 µM 8-bromo-cGMP at zero time (upon recording the b ramp, 8 min after rupturing the patch) made the further IV ramps shift negatively along the voltage axis.

differences in expression levels in Xenopus oocytes and Sf9 cells since differences in the expression level of KAT1 within the same expression system (Xenopus oocytes) have been shown to result in changes in the kinetic features of this channel (11). Similarly, features of the Drosophila Shaker K+ channel have been shown to depend on the expression system used: the activation curves are qualitatively identical in Sf9 cells and Xenopus oocytes, but the curve obtained in the former system is shifted −15 mV to more depolarized potentials (21). Whether these kinds of differences are relevant or not to the regulation and the role of the channel in situ in the animal/plant is as yet unknown (11, 37).

As shown in steady-state IV curves (Fig. 7C), AKT1 displayed a strong inward rectification. This is likely to originate mainly from some voltage-dependent gating as shown by the
Expression of Plant K⁺ Channels in Insect Cells