Feedback Control of the ATP-Sensitive K^+ Current by Cytosolic Ca^{2+} Contributes to Oscillations of the Membrane Potential in Pancreatic β-Cells

Jean-François Rolland, Jean-Claude Henquin, and Patrick Gilon

During glucose stimulation, pancreatic β-cells display membrane potential oscillations that correspond to intermittent Ca^{2+} influx, leading to oscillations of the cytosolic free calcium concentration ($[Ca^{2+}]_c$) and insulin secretion. The role of ATP-sensitive K^+ (K^+-ATP) channels in the control of these oscillations was investigated by measuring the K^+-ATP current (I_{KATP}) with the perforated mode of the patch-clamp technique. No oscillations of I_{KATP} were observed when glucose-stimulated β-cells were kept hyperpolarized, thus with low and stable $[Ca^{2+}]_c$. However, increasing $[Ca^{2+}]_c$ by Ca^{2+} influx (depolarizing pulses) or Ca^{2+} mobilization (acetylcholine) transiently augmented I_{KATP}. This effect was abolished by tolbutamide, attenuated by increasing the glucose concentration in the medium, and prevented by abrogation of the $[Ca^{2+}]_c$ rise, which demonstrates that the current is really I_{KATP} and that its increase is Ca^{2+}-dependent. Injection of a current of a similar amplitude to that of the Ca^{2+}-induced increase in I_{KATP} was sufficient to repolarize glucose-stimulated β-cells. These results suggest that, in the absence of $[Ca^{2+}]_c$ oscillations, no metabolic oscillations affect I_{KATP} in pancreatic β-cells. In contrast, $[Ca^{2+}]_c$ oscillations evoke I_{KATP} oscillations. This mechanism may constitute the feedback loop controlling the glucose-induced oscillating electrical activity in β-cells. *Diabetes* 51: 376–384, 2002

Pancreatic β-cells are electrically excitable. Their membrane potential and electrical activity are finely controlled by glucose, the most important stimulus of insulin secretion. These effects have mainly been characterized in mouse islets (1–4). In the absence of glucose or in the presence of a nonstimulating concentration of glucose (≤6 mmol/l), the membrane potential is at the resting level. When the glucose concentration increases (≥7 mmol/l), the plasma membrane depolarizes and an oscillating electrical activity starts (1). Each oscillation of the membrane potential, usually referred to as a slow wave, consists of a depolarized phase on top of which a train of action potentials appears and a repolarized phase without action potentials. Glucose modulates the duration of the slow waves that become longer, with little change in their frequency, as the glucose concentration increases (between 7 and 25 mmol/l). When this concentration exceeds 25 mmol/l, slow waves are transformed into a sustained depolarization with continuous spike activity. The changes in membrane potential are crucial for the control of β-cell function because each depolarization induces a concomitant rise in the cytosolic free Ca^{2+} concentration ($[Ca^{2+}]_c$) (5,6), which is the signal that triggers insulin secretion.

The resting membrane potential of β-cells is mainly controlled by an unknown depolarizing current and a hyperpolarizing current carried by ATP-sensitive K^+ (K^+-ATP) channels (7). When the glucose concentration is low, the ATP-to-ADP ratio is low, and many K^+-ATP channels are open; therefore, K^+-ATP current (I_{KATP}) overwhelms the depolarizing current and keeps the potential close to the equilibrium potential of K^+. When the glucose concentration increases, cell metabolism is stimulated and the ATP-to-ADP ratio rises (8), leading to closure of K^+-ATP channels (9,10). The resulting decrease in I_{KATP} permits the depolarizing current to move the membrane potential further away from the equilibrium potential of K^+. When the threshold potential of activation of voltage-dependent Ca^{2+} channels is reached, Ca^{2+} influx starts (reflected by the appearance of electrical activity), $[Ca^{2+}]_c$ increases, and insulin secretion is stimulated. Whereas it is unanimously admitted that the rise in the ATP-to-ADP ratio triggers the initial depolarization, the mechanisms driving the oscillations of the membrane potential remain incompletely understood. The opening of voltage-dependent Ca^{2+} channels undoubtedly underlies the depolarizing phase, but the mechanism(s) causing the repolarization at the end of each slow wave has escaped identification. Several hypotheses have been put forward. They include activation of Ca^{2+}-dependent K^+ channels (11–14) different from the charybdotoxin-sensitive K^+ channel (15); slow inactivation of voltage-dependent Ca^{2+} channels (3,16); decrease of cell-to-cell coupling (17) or of a store-operated current (18,19); and increase of I_{KATP} (20–22). According to this last hypothesis, cyclic closure and opening of K^+-ATP channels cause oscillations of membrane potential that, in turn, repetitively open and close Ca^{2+} channels. Theoretically, such cycles could result from intrinsic Ca^{2+}-independent metabolic oscillations

From the Unité d'Endocrinologie et Métabolisme, University of Louvain, Brussels, Belgium.

Address correspondence and reprint requests to Dr. Patrick Gilon, Unité d'Endocrinologie et Métabolisme, University of Louvain Faculty of Medicine, UCL 55.30, Av. Hippocrate 55, B-1200 Brussels, Belgium. E-mail: gilon@endo.ucl.ac.be.

Received for publication 2 July 2001 and accepted in revised form 29 October 2001.

ACh, acetylcholine; $[Ca^{2+}]_c$, cytosolic free Ca^{2+} concentration; I_{KATP}, K^+-ATP current; IP_3, Ins(1,4,5)P_3; K^+-ATP channel, ATP-sensitive K^+ channel; PIP_2, phosphatidylinositol 4,5-bisphosphate.

(23,24) or be driven by Ca^{2+} in a sort of negative feedback control (20,21,25–27).

In the present study, we used the perforated mode of the patch-clamp technique to monitor I_{KATP} in single mouse β-cells. We investigated whether oscillations of I_{KATP} exist when $[Ca^{2+}]_c$ is either kept low and stable (reflecting intrinsic metabolic oscillations) or is repetitively increased (reflecting Ca^{2+}-dependent activation of the channel). Some of the results have been presented in abstract form (28).

RESEARCH DESIGN AND METHODS

Solutions and drugs. The medium used for the preparation of islet cells was a bicarbonate-buffered solution that contained (in mmol/l): 120 NaCl, 4.8 KCl, 2.5 $CaCl_2$, 1.2 $MgCl_2$, 24 $NaHCO_3$, 5 HEPES, and 10 mmol/l glucose (pH adjusted to 7.40 with NaOH). The Ca^{2+}-free medium used to disrupt the islets into single cells had the following composition (in mmol/l): 138 NaCl, 5.6 KCl, 1.2 $MgCl_2$, 5 HEPES, and 1 mmol/l EGTA (pH adjusted to 7.40 with NaOH). All solutions used for tissue preparation were gassed with O_2:CO_2 (94:6%) and supplemented with 1 mg/ml BSA (fraction V; Roche Molecular Biochemicals; Mannheim, Germany).

For electrophysiological measurements of I_{KATP}, the standard extracellular solution contained (in mmol/l): 120 NaCl, 4.8 KCl, 2.5 $CaCl_2$, 1.2 $MgCl_2$, 24 $NaHCO_3$, 5 HEPES (pH adjusted to 7.40 with NaOH), and various concentrations of glucose as indicated. When a Ca^{2+}-free solution was needed, $CaCl_2$ was substituted by $MgCl_2$, and 2 mmol/l EGTA was added. These solutions were gassed with O_2:CO_2 (94:6%). The pipette solution contained (in mmol/l): 70 K_2SO_4, 10 NaCl, 10 KCl, 3.7 $MgCl_2$, and 5 HEPES (pH adjusted to 7.1 with KOH). The electrical contact was established by adding a pore-forming antibiotic, amphotericin B or nystatin, to the pipette solution. Amphotericin (stock solution of 60 mg/ml in DMSO) was used at a final concentration of 300 μg/ml. Nystatin (stock solution of 10 mg/ml in DMSO) was used at a final concentration of 200 μg/ml. The tip of the pipette was filled with antibiotic-free solution, and the pipette was then back-filled with the amphotericin- or nystatin-containing solution. The voltage clamp was considered satisfactory when the series conductance was >35–40 nS.

Thapsigargin was obtained from Sigma (St. Louis, MO) or from Alomone Labs (Jerusalem, Israel), diazoxide from Schering-Plough Avondale (Rathdrum, Ireland), and nimodipine from Bayer (Wuppertal, Germany). Unless otherwise stated, all other chemicals were from Sigma.

Preparation of cells. The pancreases were taken from Naval Medical Research Institute mice killed by cervical dislocation. Pancreatic islets were isolated aseptically by collagenase digestion followed by hand selection. To obtain single cells, the islets were first incubated for 5 min in a Ca^{2+}-free medium. After a brief centrifugation, this solution was replaced by culture medium, and the islets were disrupted by gentle pipetting through a siliconized glass pipette. The cells were plated on 22 mm–diameter glass coverslips and maintained for 1–4 days in RPMI 1640 tissue culture medium containing 10 mmol/l glucose, 10% heat-inactivated FCS, 100 IU/ml penicillin, and 100 μg/ml streptomycin.

Electrophysiological recordings. Two criteria were used to identify β-cells. The capacitance of mouse α-, δ-, and β-cells averages 4.4, 5, and 7.4 pF, respectively (29). Therefore, only large cells with a capacitance >5 pF were chosen for the present study. For 150 randomly chosen cells, the average capacitance was 7.6 ± 0.2 pF. After verification of the capacitance, a depolarizing protocol was applied to identify the properties of the voltage-dependent Na^+ current, which is known to be inactivated at resting potential in β-cells but not in α- and δ-cells (30). Thus, cells in which a Na^+ current could be activated by a small depolarizing pulse from a prolonged holding potential of −70 mV were discarded. By contrast, cells that displayed a Na^+ current only after a hyperpolarizing pulse to −140 mV were considered to be β-cells (30,31) and were used for the experiments.

Patch-clamp measurements were carried out using the perforated whole-cell mode of the patch-clamp technique at 33–35°C, using an EPC-9 patch-clamp amplifier (Heka Electronics, Lambrecht/Pfalz, Germany) and the software Pulsefit, or an Axopatch 200 B patch-clamp amplifier (Axon Instruments, Foster City, CA) and the software pClamp 8. Patch pipettes were pulled from borosilicate glass capillaries (World Precision Instruments, Hertfordshire, U.K.) to give a resistance of 4–5 MΩ.

I_{KATP} was monitored by 100 ms–duration pulses of ±20 mV from a holding potential of −70 mV (Figs. 1–4) or pulses of −20 mV from a holding potential of −60 mV (Figs. 5 and 6). In the latter protocol, −60 mV was chosen because it corresponds best to the interburst potential in spontaneously oscillating cells within an islet, whereas the depolarizing pulses were omitted to avoid activation of voltage-dependent Ca^{2+} channels. To prevent the capacitive transient due to electrical charge of the pipette, which might complicate I_{KATP} measurements, each change in voltage was preceded by 100-ms ramps (except for in Fig. 1*D*). Two protocols of depolarization were used: either a single 30-s pulse to 0 mV (Figs. 2 and 3) or a train of depolarizations mimicking the oscillations of the membrane potential induced by 10 mmol/l glucose in whole islets. These trains consisted in the succession of 18-s hyperpolarizing phases, during which I_{KATP} was measured (pulses of −20 mV from a holding potential of −60 mV), and 6-s depolarizing phases. During these depolarizing phases, action potentials were mimicked by 50-ms pulses from −40 to 0 mV; their frequency was 10 Hz at the beginning of the pulse and decreased progressively to 5 Hz at the end of the pulse (Figs. 5 and 6).

$[Ca^{2+}]_c$ measurements. Islet cells were loaded with 1 μmol/l fura-2/AM (Molecular Probes, Eugene, OR) for 45 min at 37°C in a bicarbonate-buffered solution containing 10 mmol/l glucose. The glass coverslips onto which the loaded cells were attached constituted the bottom of a temperature-controlled perifusion chamber (Intracell, Royston, Herts, U.K.) mounted on the stage of an inverted microscope. The Ca^{2+} probe within the cells was excited at 340 and 380 nm, and the fluorescence emitted at 510 nm was captured at 20 Hz by a photometric-based system (PTI, Lawrenceville, NJ). $[Ca^{2+}]_c$ was calculated by comparing the ratio of the 510-nm signals successively acquired at 340 and 380 nm with a calibration curve based on the equation of Grynkiewicz et al. (32) and established by filling the chamber with an intracellular-type solution containing 10 μmol/l fura-2 free acid, and either 10 mmol/l free Ca^{2+} or <1 nmol/l free Ca^{2+}. A K_d for the fura-2-Ca^{2+} complex of 224 nmol/l was used.

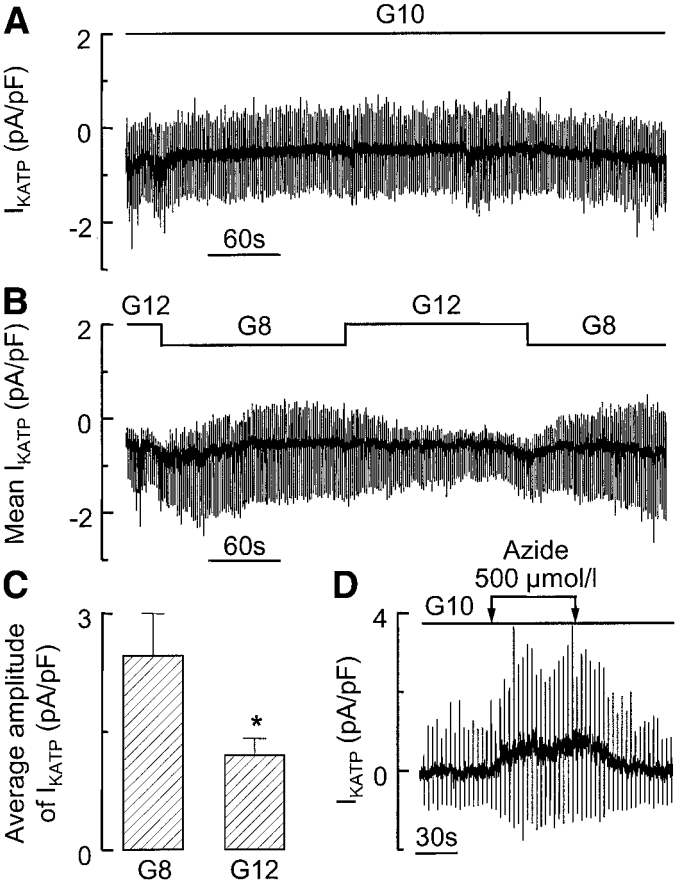

FIG. 1. Lack of oscillations of I_{KATP} at stable $[Ca^{2+}]_c$ and glucose concentrations in single mouse β-cells. I_{KATP} was monitored by pulses of ±20 mV from a holding potential of −70 mV using the perforated mode of the patch-clamp technique. *A–C*: The amplitude of I_{KATP} is reflected by the size of the vertical bars around the continuous thick line representing the holding current at −70 mV. The glucose concentration (G) was either 10 mmol/l throughout (*A*) or was alternated between 8 and 12 mmol/l (*B*). *C*: The average amplitude of I_{KATP} in the presence of G8 and G12 was measured during the last 12 test pulses at each glucose concentration in the experiments illustrated in *B*. *P < 0.05 vs. G8 by unpaired t test. *D*: Azide was added when indicated. Traces *A* and *D* are representative of results obtained in five cells. Trace *B* is the mean of results obtained in four cells.

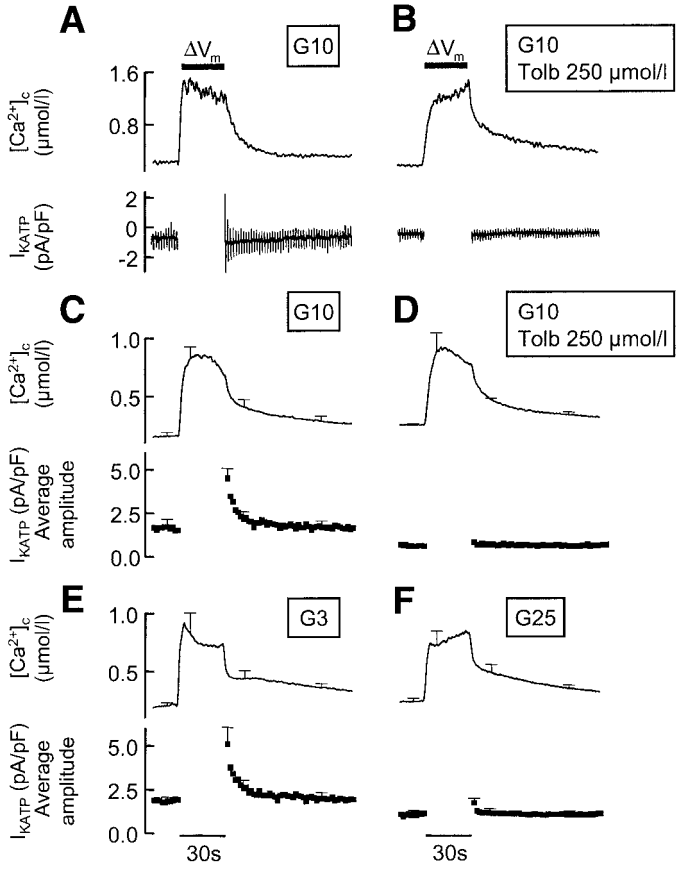

FIG. 2. Effects of a 30-s depolarization on $[Ca^{2+}]_c$ and I_{KATP} measured simultaneously in single mouse β-cells. Single β-cells loaded with fura-2 were perifused with a medium containing 3 (*E*), 10 (*A* and *C*), or 25 (*F*) mmol/l glucose (G) alone or 10 mmol/l glucose + 250 μmol/l tolbutamide (Tolb) (*B* and *D*). They were submitted to a 30-s depolarizing step from −70 to 0 mV (ΔV_m) during the period shown by the thick horizontal bar. I_{KATP} could not be monitored during the depolarization. *A* and *B* show representative traces. *C–F* show mean traces ± SE. Series *E* ($n = 6$) and *F* ($n = 7$) were performed with cells from the same cultures but different from those of series *C* ($n = 7$) and *D* ($n = 5$).

Presentation of results. The experiments are illustrated by traces that are means or representative traces of results obtained with the indicated number of cells from at least three different cultures. The statistical significance of differences between means was assessed by paired or unpaired Student's *t* test as appropriate. Differences were considered significant at $P < 0.05$.

RESULTS

Measurements of I_{KATP} at stable and low $[Ca^{2+}]_c$. To search for the existence of intrinsic Ca^{2+}-independent metabolic oscillations, I_{KATP} was measured in single metabolically intact β-cells hyperpolarized at −70 mV (Fig. 1). The cells were continuously perifused with a glucose concentration (10 mmol/l) that produces spontaneous $[Ca^{2+}]_c$ oscillations in unclamped β-cells (33). In the present experiments, $[Ca^{2+}]_c$ was low because of the hyperpolarization and not affected by the 20-mV hyperpolarizing and depolarizing pulses used to monitor I_{KATP} (see the beginning of the recording in Fig. 2*A*). I_{KATP} was small (1.6 ± 0.3 pA/pF, $n = 10$), corresponding to 3.4 ± 0.6% of the cell total I_{KATP} estimated by the combined application of diazoxide and azide to open K^+-ATP channels maximally (34). This result suggests that >95% of K^+-ATP channels were already closed at 10 mmol/l glucose, as previously reported (35).

During constant stimulation by 10 mmol/l glucose, no oscillations of I_{KATP} could be detected over a period of ~8 min (Fig. 1*A*), which is approximately twice as long as the period of the spontaneous oscillations of $[Ca^{2+}]_c$ induced by the sugar in single β-cells (33). In contrast, I_{KATP} fluctuations were detected when cell metabolism was changed by alternating the glucose concentration of the perifusion medium between 12 and 8 mmol/l (Fig. 1*B*). Average I_{KATP} was two times larger in the presence of 8 mmol/l glucose than in the presence of 12 mmol/l glucose (Fig. 1*C*). Moreover, decreasing the ATP-to-ADP ratio with a low concentration of azide (36), a mitochondrial poison, reversibly increased I_{KATP} (Fig. 1*D*). Therefore, the absence of apparent oscillations of I_{KATP} at stable glucose and $[Ca^{2+}]_c$ suggests that no intrinsic metabolic oscillations, independent from changes in $[Ca^{2+}]_c$, exist in β-cells.

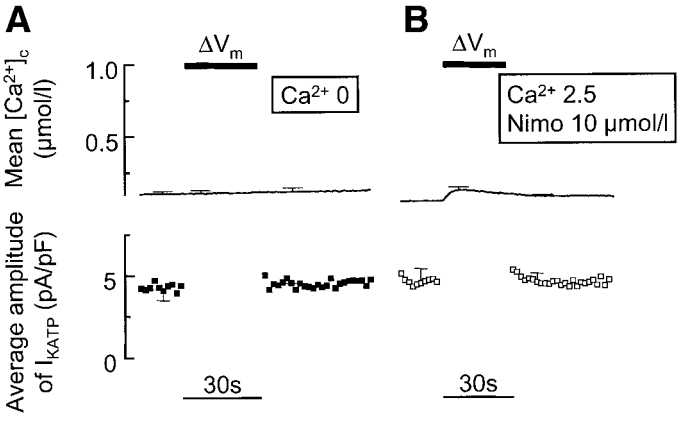

FIG. 3. Effects of a 30-s depolarization on $[Ca^{2+}]_c$ and I_{KATP} measured simultaneously in single mouse β-cells when Ca^{2+} influx was prevented. Single β-cells loaded with Fura-2 were perifused with a Ca^{2+}-free medium (*A*) or a Ca^{2+}-containing medium supplemented with 10 μmol/l nimodipine (Nimo) (*B*). They were submitted to a 30-s depolarization to 0 mV (ΔV_m), as in Fig. 2. The glucose concentration of the medium was 10 mmol/l throughout. The traces are means ± SE of results obtained in three (*A*) and four (*B*) cells.

Influence of a depolarization-induced $[Ca^{2+}]_c$ rise on I_{KATP}. The alternative hypothesis, suggesting that metabolic oscillations in β-cells are driven by $[Ca^{2+}]_c$ oscillations, was tested by measuring the effect of an imposed increase in $[Ca^{2+}]_c$ on I_{KATP}. In this series, $[Ca^{2+}]_c$ and I_{KATP} were measured simultaneously in the same single β-cells perifused with 10 mmol/l glucose and submitted to a 30-s depolarizing pulse to 0 mV from a holding potential of −70 mV (Fig. 2*A* and *C*). In β-cells held hyperpolarized at −70 mV, $[Ca^{2+}]_c$ was low and stable, and I_{KATP} was small. Depolarizing the cells to 0 mV rapidly increased $[Ca^{2+}]_c$, which slowly returned to basal levels upon repolarization to −70 mV. I_{KATP} was 276 ± 70% larger just after compared with before the depolarizing pulse. This increase was transient, with I_{KATP} decreasing with time to similar values as those before the depolarizing pulse. To ascertain that the increased current observed after the depolarizing pulse corresponds well to I_{KATP}, the same experiment was repeated in the presence of 250 μmol/l tolbutamide, a potent blocker of K^+-ATP channels (Fig. 2*B* and *D*). As expected, tolbutamide reduced I_{KATP} in the presence of 10 mmol/l glucose (compare the beginning of Fig. 2*C* and *D*). This inhibition amounted to 63% (0.60 ± 0.01 pA/pF, $n = 5$, vs. 1.62 ± 0.03 pA/pF, $n = 7$, in the presence and absence of tolbutamide, respectively; $P <$

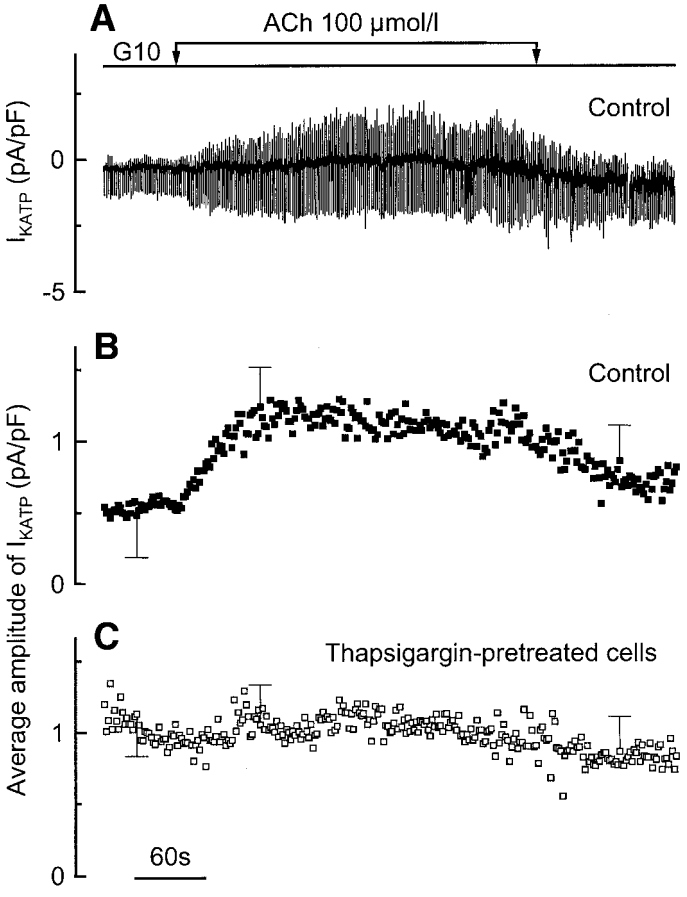

FIG. 4. Effects of ACh on I_{KATP} in single mouse β-cells. Single cells were perifused with a medium containing 10 mmol/l glucose (G) throughout, and 100 µmol/l ACh was added when indicated. *C*: Cells were pretreated for 1 h with 1 µmol/l thapsigargin. Trace *A* is representative, and traces *B* and *C* are means ± SE of results obtained in four single cells.

0.001). In contrast, tolbutamide did not affect the rise in $[Ca^{2+}]_c$ produced by the depolarizing pulse to 0 mV. However, the increase in current observed after the depolarizing pulse was abolished (compare Fig. 2*C* and *D*).

If the current activated by the depolarizing pulse is I_{KATP}, one could anticipate that it will be decreased by high glucose. This finding was tested by applying a 30-s depolarizing pulse to cells perifused with 3 or 25 mmol/l glucose (Fig. 2*E* and *F*). As expected, I_{KATP} measured before the depolarization to 0 mV was reduced by 45% in the presence of the high concentration of glucose (1.86 ± 0.02 pA/pF in G3, $n = 6$, vs. 1.03 ± 0.02 pA/pF in G25, $n = 7$, respectively; $P < 0.001$). Importantly, the increase in current observed after the 30-s depolarization to 0 mV was threefold smaller in 25 mmol/l glucose than in 3 mmol/l glucose (1.70 ± 0.26 pA/pF in G25, $n = 7$, vs. 5.10 ± 0.94 pA/pF, $n = 6$, in G3; $P < 0.01$), although the rise in $[Ca^{2+}]_c$ was similar at both glucose concentrations. The time for I_{KATP} to return to basal levels was also much reduced in the presence of 25 mmol/l glucose. Altogether, these experiments demonstrate that the increased current observed after the pulse in control cells does correspond to I_{KATP} and that the negative feedback effect of $[Ca^{2+}]_c$ on I_{KATP} can be modulated by glucose.

To ascertain that the increase in I_{KATP} is the consequence of the rise in $[Ca^{2+}]_c$ produced by the depolarizing pulse, the same protocol was repeated under conditions where Ca^{2+} influx was prevented. In the absence of external Ca^{2+}, $[Ca^{2+}]_c$ did not increase upon depolarization, and I_{KATP} was of similar amplitude before and after the pulse (Fig. 3*A*). In the presence of 2.5 mmol/l Ca^{2+} and 10 µmol/l nimodipine, an L-type Ca^{2+} channel blocker, the depolarizing pulse to 0 mV, increased $[Ca^{2+}]_c$ only marginally (Fig. 3*B*). This small elevation may be attributed to the activity of the Na^+/Ca^{2+} exchanger working in reverse mode at 0 mV or to an incomplete blockade of L-type Ca^{2+} channels. However, it was too small to affect I_{KATP} (Fig. 3*B*).

If a rise in $[Ca^{2+}]_c$ is really the cause of the increase in I_{KATP}, mobilization of intracellular Ca^{2+} should produce a similar effect as that of Ca^{2+} influx. Application of 100 µmol/l acetylcholine (ACh), a potent Ins(1,4,5)P_3 (IP_3)-producing agent, to hyperpolarized β-cells reversibly augmented I_{KATP} (Fig. 4*A* and *B*). To ascertain whether this effect resulted from a rise in $[Ca^{2+}]_c$, the same protocol was repeated after treatment of the cell with thapsigargin, a potent and specific inhibitor of the sarco-endoplasmic reticulum Ca^{2+}-ATPase. Thapsigargin depletes the endoplasmic reticulum of Ca^{2+} in β-cells (37) without impairing the production of IP_3 in response to phospholipase C–linked agonists. Addition of ACh to thapsigargin-pretreated cells did not affect I_{KATP} (Fig. 4*C*). Altogether, these experiments demonstrate that the rise in $[Ca^{2+}]_c$ is the mechanism that increases I_{KATP}.

Effect of imposed $[Ca^{2+}]_c$ oscillations on I_{KATP}. Because 30-s depolarizations to 0 mV might be stronger than spontaneous depolarizations, single cells were depolarized by a voltage clamp protocol mimicking the spontaneous electrical activity in islets. Cycles of 6 s depolarization and 18 s hyperpolarization were chosen to reproduce the durations of the depolarization and repolarization phases elicited by 10 mmol/l glucose (38). During depolarization, the cell was submitted to short depolarizing pulses resembling the burst of action potential of the slow waves (see RESEARCH DESIGN AND METHODS). The left part of Fig. 5 shows spontaneous oscillations of $[Ca^{2+}]_c$ induced by 10 mmol/l glucose in a single β-cell. The right part shows $[Ca^{2+}]_c$ oscillations imposed by the voltage clamp protocol in the same cell, ~5 min after establishment of the seal. The imposed $[Ca^{2+}]_c$ oscillations were similar to those occurring spontaneously in that cell. The average peak of $[Ca^{2+}]_c$ oscillations in several cells was not different during spontaneous oscillations (1,053 ± 91 nmol/l, $n = 23$) or during oscillations imposed by the pulse protocol (802 ± 132 nmol/l, $n = 12$) or 30-s depolarizations to 0 mV (823 ± 103 nmol/l, $n = 7$). Imposed $[Ca^{2+}]_c$ oscillations are thus within the physiological range.

The same pulse protocol as that used in Fig. 5 was then applied to measure the influence of $[Ca^{2+}]_c$ oscillations on I_{KATP} (Fig. 6). The cells were initially perifused with 6 mmol/l glucose, a subthreshold concentration at which the islets are electrically silent (1). Increasing glucose from 6 to 10 mmol/l decreased I_{KATP} from 1.57 to 0.89 pA/pF ($n = 8$). This difference in current is probably larger than that occurring in a cell that would not be voltage-clamped and in which the decrease in I_{KATP} produced by the acceleration of ATP production in response to the elevation of the glucose concentration is normally counterbalanced by the

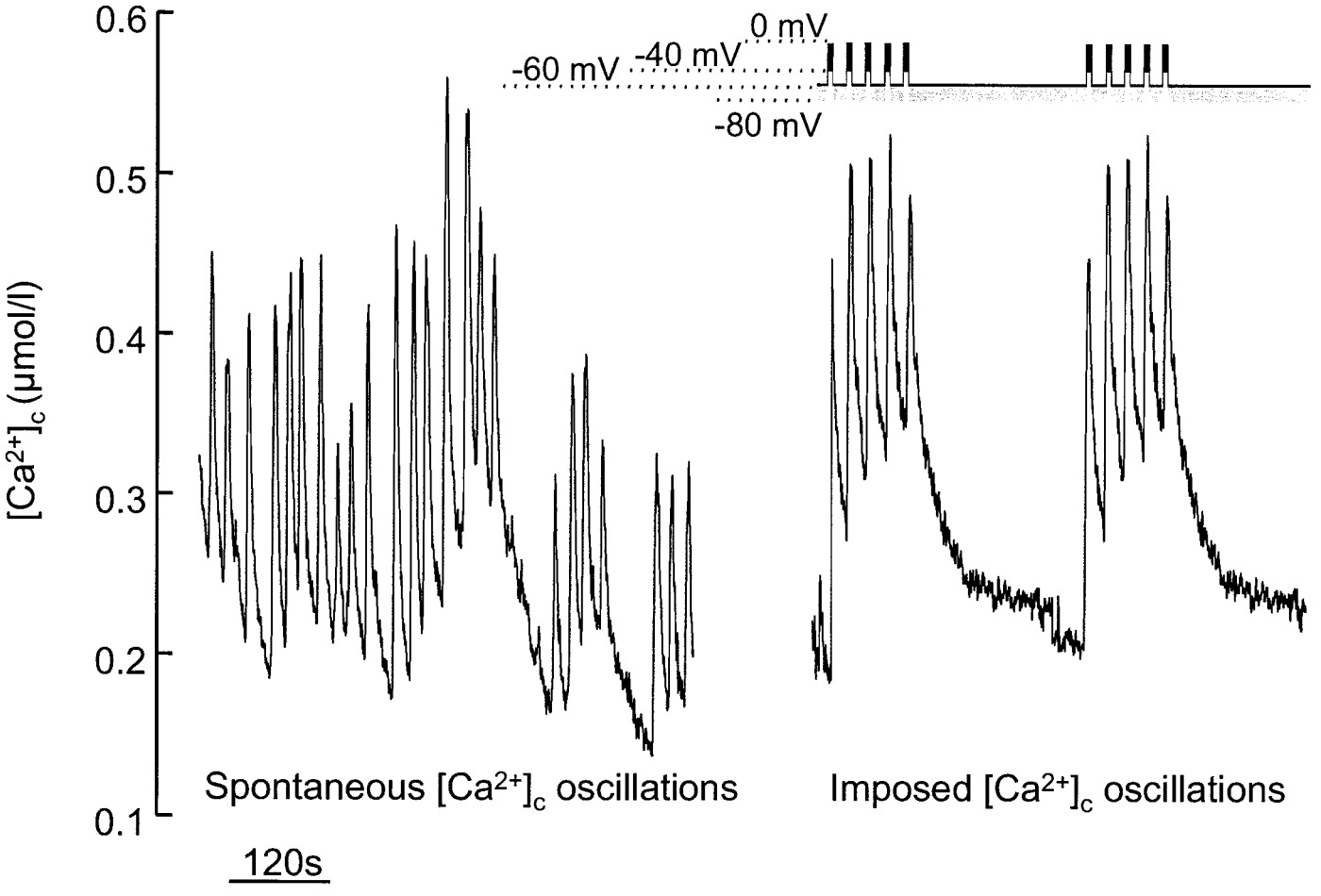

FIG. 5. Spontaneous and voltage clamp–imposed $[Ca^{2+}]_c$ oscillations in the same single β-cell. A single cell loaded with Fura-2 was perifused with a medium containing 10 mmol/l glucose throughout. Spontaneous $[Ca^{2+}]_c$ oscillations were recorded before the establishment of the seal (left panel). Approximately 5 min after establishment of the seal, the cell was submitted to two series of trains of depolarizing pulses designed to mimic the slow waves of the membrane potential induced by 10 mmol/l glucose in whole islets (see RESEARCH DESIGN AND METHODS) and illustrated on the top of the figure (right panel). The shaded areas represent the −20 mV hyperpolarizing pulses that were applied from the holding potential of −60 mV. This trace is an example of results obtained in six cells that displayed spontaneous $[Ca^{2+}]_c$ oscillations with different frequencies.

increase in I_{KATP} due to the concomitant rise in $[Ca^{2+}]_c$. In cells voltage-clamped between −60 and −80 mV (Fig. 6), I_{KATP} is only influenced by the change in glucose metabolism but not by the rise in $[Ca^{2+}]_c$ that is prevented by the hyperpolarization. Application of trains of depolarization repetitively increased I_{KATP} (Fig. 6). The average increase was such that the current after each train was similar (1.68 ± 0.09 pA/pF) to that measured in the presence of 6 mmol/l glucose. This increase in I_{KATP} might thus be sufficient to repolarize the membrane below the threshold potential for activation of voltage-dependent Ca^{2+} channels. The changes in current induced by the rise of the glucose concentration and by the pulse protocol were all prevented by 250 μmol/l tolbutamide, demonstrating that they really correspond to variations in I_{KATP} (n = 5, not shown).

Effect of injection of a hyperpolarizing current equivalent to the Ca^{2+}-induced increase in I_{KATP} on the β-cell membrane potential. We next verified whether the Ca^{2+}-induced increase in I_{KATP} is sufficient to repolarize the plasma membrane to the resting potential. This increase (ΔI_{KATP}) was calculated by averaging the difference in I_{KATP} after and before the last four trains of depolarizing pulses ($\Delta I_{KATP1-4}$ in Fig. 6). It amounted to 0.59 ± 0.06 pA/pF. A current of similar amplitude, adjusted for cell size (0.59 multiplied by the capacitance of the tested cell), was then injected into β-cells studied in the current-clamp mode and stimulated by 10 mmol/l glucose. Figure 7*A* shows the electrical activity induced by glucose in one of these cells. Injection of a hyperpolarizing current corresponding to the average ΔI_{KATP} (−5 pA in this cell) suppressed the electrical activity and repolarized the plasma membrane to the resting level. Removal of this current was accompanied by the immediate resumption of action potentials. In other experiments (Fig. 7*B*), the hyperpolarizing current was increased stepwise by increments corresponding to one-sixth of the average ΔI_{KATP}. As shown in Fig. 7*B*, 50% of average ΔI_{KATP} was sufficient to repolarize the cell below the threshold for activation of voltage-dependent Ca^{2+} channels. This result strongly suggests that the Ca^{2+}-induced rise in I_{KATP} might control the oscillations of the membrane potential.

DISCUSSION

Oscillations of the membrane potential are one of the major characteristics of the pancreatic β-cell response to glucose. They underlie the periodic influx of Ca^{2+} that

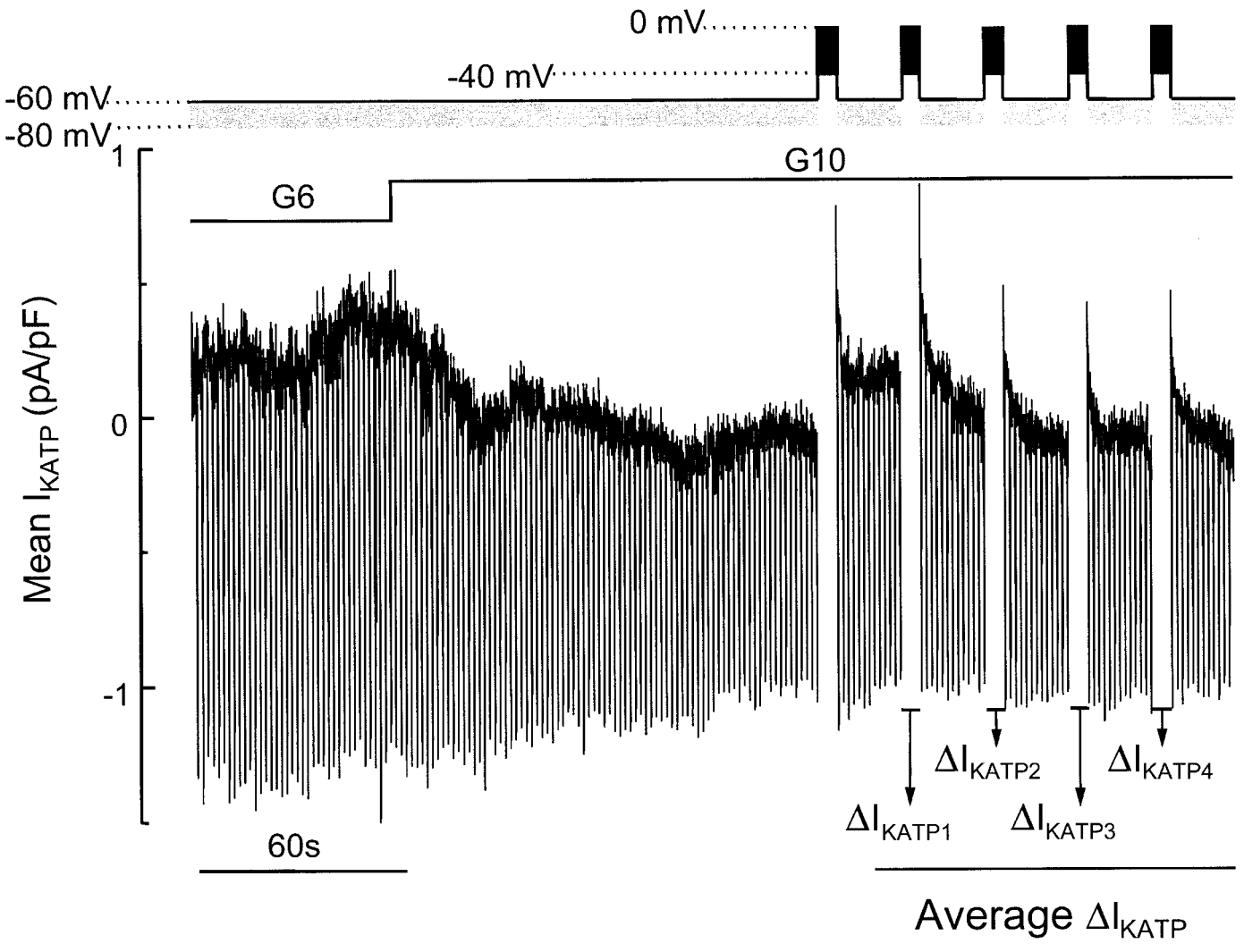

FIG. 6. Increase of I_{KATP} by imposed $[Ca^{2+}]_c$ oscillations mimicking spontaneous $[Ca^{2+}]_c$ oscillations induced by glucose. Single β-cells were initially perifused with a medium containing 6 mmol/l glucose (G6). After 1 min of recording I_{KATP}, the glucose concentration was increased to 10 mmol/l (G10). Two minutes later, the cell was submitted to the same pulse protocol as that used in Fig. 5 and designed to mimic spontaneous $[Ca^{2+}]_c$ oscillations induced by 10 mmol/l glucose. The mean difference in I_{KATP} before and after the depolarizing pulses (average ΔI_{KATP}) was calculated by averaging the increase in I_{KATP} occurring after each of the last four trains of depolarizations ($\Delta I_{KATP1-4}$). This trace is the mean of results obtained in eight single cells.

triggers oscillations of insulin secretion. Understanding their fine control is thus of utmost importance. The present study demonstrates that $[Ca^{2+}]_c$ oscillations in pancreatic β-cells rhythmically increase I_{KATP} and provide direct support to the proposal (20) that such an effect constitutes a feedback control of the oscillations of membrane potential.

Intrinsic metabolic oscillations do not drive membrane potential oscillations. It has been suggested that intrinsic Ca^{2+}-independent metabolic oscillations exist in β-cells (24) and that they lead to cycles of K^+-ATP channel activity (23). To verify this hypothesis, single metabolically intact β-cells were hyperpolarized to keep $[Ca^{2+}]_c$ at basal and stable levels, and I_{KATP} was continuously monitored during perifusion with a stimulatory glucose concentration. In no cell did we find I_{KATP} oscillations under these conditions. This suggests that either no intrinsic metabolic oscillations exist, or they are unable to modulate K^+-ATP channel activity and membrane potential because of their nature or small amplitude (smaller than those imposed by 4 mmol/l glucose changes). Experiments monitoring O_2 consumption (39), glucose consumption (27), and the fluorescence of reduced pyridine nucleotides [NAD(P)H) in single islets (6)] have also concluded to the absence of Ca^{2+}-independent metabolic oscillations in β-cells.

I_{KATP} oscillations driven by $[Ca^{2+}]_c$ oscillations. When $[Ca^{2+}]_c$ was increased by stimulating Ca^{2+} influx or mobilizing Ca^{2+} from intracellular Ca^{2+} stores, I_{KATP} increased. There is no doubt that this increase resulted from the $[Ca^{2+}]_c$ rise because I_{KATP} did not change when Ca^{2+} influx was prevented by omission of external Ca^{2+} and blockade of voltage-dependent Ca^{2+} channels or when Ca^{2+} mobilization was prevented by pretreatment with thapsigargin. It is also clear that the current increased by the rise in $[Ca^{2+}]_c$ is I_{KATP} because it was attenuated by a rise in ambient glucose concentration and completely inhibited by tolbutamide, a blocker of K^+-ATP channels. K^+ channels sensitive to sulfonylureas but distinct from K^+-ATP channels have been described in some systems (40,41), but not in β-cells. It is likely that the current that

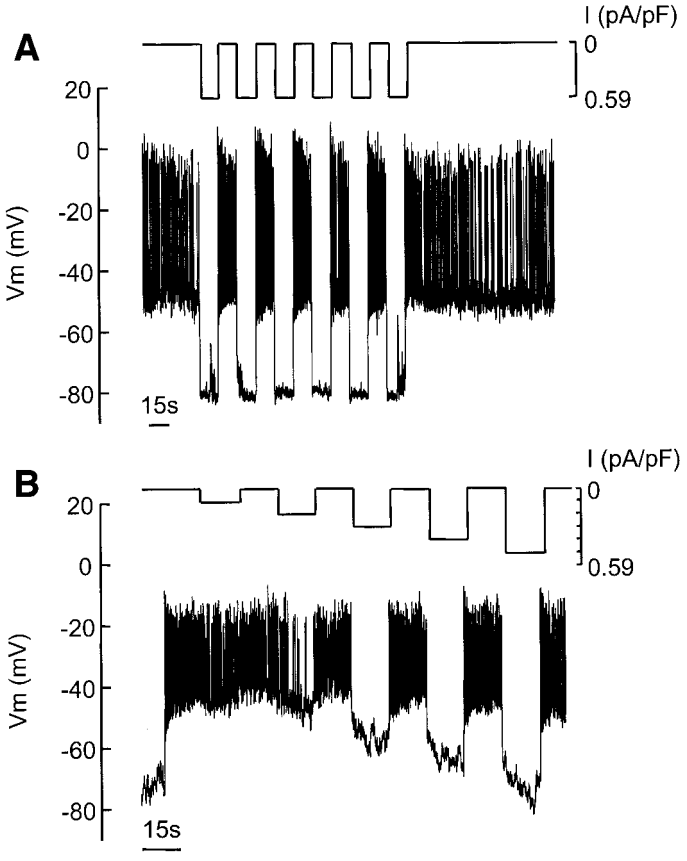

FIG. 7. Effect of injection of a hyperpolarizing current on the β-cell membrane potential. The membrane potential of single β-cells was monitored in the current-clamp mode of the patch-clamp technique. The glucose concentration of the medium was 10 mmol/l throughout. No current (0) was injected into the cells except when indicated by the downward deflections of the upper traces above each panel. The value of 0.59 pA/pF was calculated from the experiments illustrated in Fig. 6. In *A*, the full current (−0.59 × 8.5 pF = −5 pA in this cell) was repetitively injected. In *B*, the current was increased by steps of one-sixth of the total current. When no current was injected, the cell in *A* was continuously depolarized during the recording, whereas the cell in *B* showed a spontaneous depolarization (seen at the beginning of the recording). The traces are representative of results obtained in five (*A*) and four (*B*) single cells.

we studied here is similar to the voltage-independent Ca^{2+}-activated K^+ current previously described in β-cells (14). This current, which was originally thought to not involve K^+-ATP channels (14), was recently found to be largely sensitive to tolbutamide by the same authors (42).

Mechanisms by which a rise in $[Ca^{2+}]_c$ increases I_{KATP}. A rise in $[Ca^{2+}]_c$ could increase I_{KATP} by different mechanisms, including a direct action of Ca^{2+} on K^+-ATP channels, an indirect action through Ca^{2+}-sensitive regulators of the channels, and an indirect action through changes in cell metabolism. A direct effect of Ca^{2+} on K^+-ATP channels has been reported in inside-out patches of membranes of normal β-cells or tumoral insulin-secreting RINm5F cells in which application of Ca^{2+} inhibited K^+-ATP channels (millimolar range of Ca^{2+}) (43) and attenuated the ADP-induced channel activation (micromolar range of Ca^{2+}) (44). Ca^{2+} increased the ability of ATP to block K^+-ATP channels or inactivated these channels in inside-out patches of skeletal muscle (45) and ventricular (46) membranes. However, all these effects are opposite to the Ca^{2+}-induced increase in I_{KATP} observed in the present study. Others did not find any direct effect of Ca^{2+} on K^+-ATP channels in β-cells (9). It is worth noting that the K^+-ATP channels of β-cells and muscle cells have different subunit compositions (SUR1 and Kir6.2 for β-cells and SUR2 and Kir6.2 for muscle cells) (47), which might confer different sensitivities to Ca^{2+}.

Several Ca^{2+}-dependent processes influencing K^+-ATP channels have been described in pancreatic β-cells or muscle cells. They involve cytoskeletal proteins (44), the Ca^{2+}-dependent protein phosphatase type 2B (48), or other proteins (49). Activation of phospholipase C by Ca^{2+}, with subsequent hydrolysis of phosphatidylinositol 4,5-bisphosphate (PIP_2), is unlikely to be involved for two reasons. First, acceleration of PIP_2 breakdown would be expected to decrease I_{KATP} (44), which is opposite to the effect of a rise in $[Ca^{2+}]_c$ observed in the present study. Second, ACh, a potent Ca^{2+}-independent activator of phospholipase C, was without effect on β-cell I_{KATP} when Ca^{2+} mobilization was prevented by thapsigargin pretreatment.

Metabolic oscillations might be driven by $[Ca^{2+}]_c$ oscillations. Indeed, each rise in $[Ca^{2+}]_c$ could stimulate ATP production (50) and increase the ATP-to-ADP ratio by activating mitochondrial dehydrogenases (51,52). Oscillations of oxygen consumption driven by $[Ca^{2+}]_c$ oscillations have recently been reported in islets (27). Our data do not exclude this possibility. Alternatively, each rise in $[Ca^{2+}]_c$ could decrease the ATP-to-ADP ratio. This hypothesis is supported by direct measurements of adenine nucleotide levels within mouse islets (25) or of ATP concentration in INS-1 cells expressing luciferase (53). These studies demonstrated that, at a fixed glucose concentration, the ATP-to-ADP ratio and the ATP concentration decreased when $[Ca^{2+}]_c$ was raised by high K^+. By demonstrating that a rise in $[Ca^{2+}]_c$ increases I_{KATP}, the present study supports this proposal. The drop in the ATP-to-ADP ratio could either result from inhibition of ATP production (26,54) or stimulation of ATP consumption (25,53).

Physiological implications for the control of membrane potential oscillation. In glucose-stimulated β-cells, I_{KATP} was found to be larger during the interburst intervals than during the depolarizing phases (22). These fluctuations were tentatively ascribed to metabolic oscillations, but no mechanistic explanation was provided. The present study strongly suggests that the rise in $[Ca^{2+}]_c$ might be the feedback mechanism controlling I_{KATP} and hence the oscillations of the membrane potential. Thus, during a voltage clamp protocol mimicking the repetitive changes in electrical activity induced by 10 mmol/l glucose in islets, each imposed $[Ca^{2+}]_c$ oscillation evoked a transient increase in I_{KATP}. This increase had a similar amplitude to that of the difference in I_{KATP} measured at substimulating (6 mmol/l) and stimulating (10 mmol/l) glucose concentrations. Theoretically, this current should be able to repolarize the membrane to a potential more negative than that of the activation threshold of voltage-dependent Ca^{2+} channels. This finding was amply supported by current-clamp experiments. Injection of current corresponding to 50% of the Ca^{2+}-induced I_{KATP} increase was sufficient to repolarize the β-cell membrane in the presence of 10 mmol/l glucose. Because the voltage-

dependent Ca^{2+} current is larger in β-cells within intact islets than in isolated single cells (29), it is possible that the amplitude of the Ca^{2+}-induced increase in I_{KATP} in whole islets exceeds our estimate. We have no explanation why, in a previous report, no oscillations of I_{KATP} were detected in single β-cells displaying membrane potential oscillations (55). The reported experimental procedures were indeed similar to those used in the present study.

The negative feedback effect of $[Ca^{2+}]_c$ on I_{KATP} might be important for the control of oscillations of the β-cell membrane potential according to the following model. Acceleration of glucose metabolism in β-cells increases the ATP-to-ADP ratio, which closes K^+-ATP channels. This leads to depolarization of the plasma membrane and opening of voltage-dependent Ca^{2+} channels. Ca^{2+} influx then raises $[Ca^{2+}]_c$, which decreases the ATP-to-ADP ratio (25) and leads to reopening of K^+-ATP channels, partial repolarization of the plasma membrane, arrest of Ca^{2+} influx, and a drop in $[Ca^{2+}]_c$. The eventual restoration of a high ATP-to-ADP ratio then initiates a new cycle. Our observation that the negative feedback effect of $[Ca^{2+}]_c$ on I_{KATP} is largely attenuated by glucose can explain the lengthening of the depolarized phases and shortening of the repolarized intervals occurring when the glucose concentration is raised within the stimulatory range. Indeed, as the glucose concentration increases, the ATP-to-ADP ratio rises and closes more K^+-ATP channels. The depolarizing phase progressively becomes longer because a stronger feedback effect of Ca^{2+} on I_{KATP} is required to counteract the effects of increased metabolism on I_{KATP}. Continuous electrical activity occurs at glucose concentrations that reduce I_{KATP} to such an extent that it is no longer counteracted by the $[Ca^{2+}]_c$ rise unless the latter is increased by augmenting the extracellular Ca^{2+} concentration (20).

The central role of K^+-ATP channels in membrane potential oscillations suggested in our model are compatible with those in most studies on K^+-ATP channel-deficient mice. Thus, pancreatic β-cells from SUR1 or Kir 6.2 knockout mice display a continuous spike activity (56,57) and a sustained and stable elevation of $[Ca^{2+}]_c$ (56,58) at both nonstimulating and stimulating glucose concentrations. Only one abstract reported $[Ca^{2+}]_c$ oscillations in β-cells from SUR1 knockout mice, but it is not known whether these oscillations resulted from concomitant changes in membrane potential (59). In view of the important role played by K^+-ATP channels in the control of pancreatic β-cell membrane potential, further studies should now elucidate the interplay between $[Ca^{2+}]_c$ and ATP turnover.

ACKNOWLEDGMENTS

This work was supported by Grant 3.4552.98 from the Fonds de la Recherche Scientifique Médicale (Brussels), by Grants 1.5.212.00 and 1.5.121.00 from the Fonds National de la Recherche Scientifique (Brussels), by Grant ARC 00/05-260 from the General Direction of Scientific Research of the French Community of Belgium, and by the Interuniversity Poles of Attraction Program (P4/21), Federal Office for Scientific, Technical and Cultural Affairs of Belgium. P.G. is Maître de Recherches of the Fonds National de la Recherche Scientifique, Brussels.

REFERENCES

1. Henquin JC, Meissner HP: Significance of ionic fluxes and changes in membrane potential for stimulus-secretion coupling in pancreatic β-cells. *Experientia* 40:1043–1052, 1984
2. Atwater I, Carroll P, Li MX: Electrophysiology of the pancreatic β-cell. In *Insulin Secretion*. Draznin B, Melmed S, Leroith D, Eds. Liss A.R., New York, 1989, p. 49–68
3. Cook DL, Satin LS, Hopkins WF: Pancreatic β-cells are bursting, but how? *Trends Neurosci* 14:411–414, 1991
4. Gomis A, Sánchez-Andrés JV, Valdeolmillos M: Oscillatory patterns of electrical activity in mouse pancreatic islets of Langerhans recorded in vivo. *Plfügers Arch* 432:510–515, 1996
5. Santos RM, Rosario LM, Nadal A, Garcia-Sancho J, Soria B, Valdeolmillos M: Widespread synchronous $[Ca^{2+}]_i$ oscillations due to bursting electrical activity in single pancreatic islets. *Plfügers Arch* 418:417–422, 1991
6. Gilon P, Henquin JC: Influence of membrane potential changes on cytoplasmic Ca^{2+} concentration in an electrically excitable cell, the insulin-secreting pancreatic β-cell. *J Biol Chem* 267:20713–20720, 1992
7. Ashcroft FM, Rorsman P: Electrophysiology of the pancreatic β-cell. *Prog Biophys Mol Biol* 54:87–143, 1989
8. Detimary P, Jonas JC, Henquin JC: Possible links between glucose-induced changes in the energy state of pancreatic β-cells and insulin release: unmasking by decreasing a stable pool of adenine nucleotides in mouse islets. *J Clin Invest* 96:1738–1745, 1995
9. Cook DL, Hales CN: Intracellular ATP directly blocks K^+ channels in pancreatic β-cells. *Nature* 311:271–273, 1984
10. Rorsman P, Trube G: Glucose dependent K^+-channels in pancreatic β-cells are regulated by intracellular ATP. *Plfügers Arch* 405:305–309, 1985
11. Henquin JC: Opposite effects of intracellular Ca^{2+} and glucose on K^+ permeability of pancreatic islet cells. *Nature* 280:66–68, 1979
12. Atwater I, Dawson CM, Ribalet B, Rojas E: Potassium permeability activated by intracellular calcium ion concentration in the pancreatic β-cell. *J Physiol* 288:575–588, 1979
13. Ämmälä C, Larsson O, Berggren PO, Bokvist K, Juntti-Berggren L, Kindmark H, Rorsman P: Inositol trisphosphate-dependent periodic activation of a Ca^{2+}-activated K^+ conductance in glucose-stimulated pancreatic β-cells. *Nature* 353:849–852, 1991
14. Göpel SO, Kanno T, Barg S, Eliasson L, Galvanovskis J, Renström E, Rorsman P: Activation of Ca^{2+}-dependent K^+ channels contributes to rhythmic firing of action potentials in mouse pancreatic β-cells. *J Gen Physiol* 114:759–770, 1999
15. Kukuljan M, Goncalves AA, Atwater I: Charybdotoxin-sensitive K(Ca) channel is not involved in glucose-induced electrical activity in pancreatic β-cells. *J Membr Biol* 119:187–195, 1991
16. Keizer J, Smolen P: Bursting electrical activity in pancreatic β-cells caused by Ca^{2+}- and voltage-inactivated Ca^{2+} channels. *Proc Natl Acad Sci U S A* 88:3897–3901, 1991
17. Andreu E, Soria B, Sanchez-Andres JV: Oscillation of gap junction electrical coupling in the mouse pancreatic islets of Langerhans. *J Physiol (Lond)* 498:753–761, 1997
18. Dukes ID, Roe MW, Worley JF III, Philipson LH: Glucose-induced alterations in β-cell cytoplasmic Ca^{2+} involving the coupling of intracellular Ca^{2+} stores and plasma membrane ion channels. *Curr Opin Endocrinol Diabetes* 4:262–271, 1997
19. Gilon P, Arredouani A, Gailly P, Gromada J, Henquin JC: Uptake and release of Ca^{2+} by the endoplasmic reticulum contribute to the oscillations of the cytosolic Ca^{2+} concentration triggered by Ca^{2+} influx in the electrically excitable pancreatic β-cell. *J Biol Chem* 274:20197–20205, 1999
20. Henquin JC: Glucose-induced electrical activity in β-cells: feedback control of ATP-sensitive K^+ channels by Ca^{2+}. *Diabetes* 39:1457–1460, 1990
21. Ding WG, He LP, Omatsu-Kanbe M, Kitasato H: A possible role of the ATP-sensitive potassium ion channel in determining the duration of spike-bursts in mouse pancreatic β-cells. *Biochim Biophys Acta* 1279:219–226, 1996
22. Larsson O, Kindmark H, Bränström R, Fredholm B, Berggren PO: Oscillations in K_{ATP} channel activity promote oscillations in cytoplasmic free Ca^{2+} concentration in the pancreatic β-cell. *Proc Natl Acad Sci U S A* 93:5161–5165, 1996
23. Dryselius S, Lund P-E, Gylfe E, Hellman B: Variations in ATP-sensitive K^+ channel activity provide evidence for inherent metabolic oscillations in pancreatic β-cells. *Biochem Biophys Res Commun* 205:880–885, 1994
24. Tornheim K: Are metabolic oscillations responsible for normal oscillatory insulin secretion? *Diabetes* 46:1375–1380, 1997
25. Detimary P, Gilon P, Henquin JC: Interplay between cytoplasmic Ca^{2+} and the ATP/ADP ratio: a feedback control mechanism in mouse pancreatic islets. *Biochem J* 333:269–274, 1998

26. Krippeit-Drews P, Düfer M, Drews G: Parallel oscillations of intracellular calcium activity and mitochondrial membrane potential in mouse pancreatic β-cells. *Biochem Biophys Res Commun* 267:179–183, 2000
27. Jung SK, Kauri LM, Qian WJ, Kennedy RT: Correlated oscillations in glucose consumption, oxygen consumption, and intracellular free Ca^{2+} in single islets of Langerhans. *J Biol Chem* 275:6642–6650, 2000
28. Rolland JF, Henquin JC, Gilon P: Modulation of the K^+ATP current by Ca^{2+} may contribute to oscillations of the membrane potential in β-cells (Abstract). *Diabetologia* 43 (Suppl. 1):A116, 2000
29. Göpel SO, Kanno T, Barg S, Rorsman P: Patch-clamp characterisation of somatostatin-secreting δ-cells in intact mouse pancreatic islets. *J Physiol* 528:497–507, 2000
30. Göpel SO, Kanno T, Barg S, Galvanovskis J, Rorsman P: Voltage-gated and resting membrane currents recorded from β-cells in intact mouse pancreatic islets. *J Physiol (Lond)* 521:717–728, 1999
31. Plant TD: Na^+ currents in cultured mouse pancreatic β-cells. *Pflügers Arch* 411:429–435, 1988
32. Grynkiewicz G, Poenie M, Tsien RY: A new generation of Ca^{2+} indicators with greatly improved fluorescence properties. *J Biol Chem* 260:3440–3450, 1985
33. Jonkers FC, Henquin JC: Measurements of cytoplasmic Ca^{2+} in islet cell clusters show that glucose rapidly recruits β-cell and gradually increases the individual cell response. *Diabetes* 50:540–550, 2001
34. Garcia-Barrado MJ, Ravier MA, Rolland JF, Gilon P, Nenquin M, Henquin JC: Inhibition of protein synthesis sequentially impairs distinct steps of stimulus-secretion coupling in pancreatic β-cells. *Endocrinology* 142:299–307, 2001
35. Ashcroft FM, Ashcroft SJ, Harrison DE: Properties of single potassium channels modulated by glucose in rat pancreatic beta-cells. *J Physiol* 400:501–527, 1988
36. Detimary P, Gilon P, Nenquin M, Henquin JC: Two sites of glucose control of insulin release with distinct dependence on the energy state in pancreatic β-cells. *Biochem J* 297:455–461, 1994
37. Miura Y, Henquin JC, Gilon P: Emptying of intracellular Ca^{2+} stores stimulates Ca^{2+} entry in mouse pancreatic β-cells by both direct and indirect mechanisms. *J Physiol (Lond)* 503:387–398, 1997
38. Henquin JC: ATP-sensitive K^+ channels may control glucose-induced electrical activity in pancreatic β-cells. *Biochem Biophys Res Commun* 156:769–775, 1988
39. Jung SK, Aspinwall CA, Kennedy RT: Detection of multiple patterns of oscillatory oxygen consumption in single mouse islets of Langerhans. *Biochem Biophys Res Commun* 259:331–335, 1999
40. Seutin V, Shen KZ, North RA, Johnson SW: Sulfonylurea-sensitive potassium current evoked by sodium-loading in rat midbrain dopamine neurons. *Neuroscience* 71:709–719, 1996
41. Gomora JC, Enyeart JJ: Dual pharmacological properties of a cyclic AMP-sensitive potassium channel. *J Pharmacol Exp Ther* 290:266–275, 1999
42. Göpel SO, Kanno T, Rorsman P: Two components of activity-dependent transient K^+-current (I_{Kslow}) in mouse pancreatic β-cells (Abstract). *Diabetologia* 44 (Suppl. 1):A20, 2001
43. Findlay I: The effects of magnesium upon adenosine triphosphate-sensitive potassium channels in a rat insulin-secreting cell line. *J Physiol* 391:611–629, 1987
44. Koriyama N, Kakei M, Nakazaki M, Yaekura K, Ichinari K, Gong Q, Morimitsu S, Yada T, Tei C: PIP_2 and ATP cooperatively prevent cytosolic Ca^{2+}-induced modification of ATP-sensitive K^+ channels in rat pancreatic β-cells. *Diabetes* 49:1830–1839, 2000
45. Hehl S, Moser C, Weik R, Neumcke B: Internal Ca^{2+} ions inactivate and modify ATP-sensitive potassium channels in adult mouse skeletal muscle. *Biochim Biophys Acta* 1190:257–263, 1994
46. Findlay I: Calcium-dependent inactivation of the ATP-sensitive K^+ channel of rat ventricular myocytes. *Biochim Biophys Acta* 943:297–304, 1988
47. Bryan J, Aguilar-Bryan L: Sulfonylurea receptors: ABC transporters that regulate ATP-sensitive K^+ channels. *Biochim Biophys Acta* 1461:285–303, 1999
48. Wilson AJ, Jabr RI, Clapp LH: Calcium modulation of vascular smooth muscle ATP-sensitive K^+ channels: role of protein phosphatase-2B. *Circ Res* 87:1019–1025, 2000
49. Rorsman P, Trube G: Biophysics and physiology of ATP-regulated K^+ channels (K_{ATP}). In *Potassium Channels: Structure*, *Classification*, *Function and Therapeutic Potential*. Cook NS, Ed. Ellis Horwood series in Pharmaceutical Technology, Chinchester, U.K., 1990, p. 97–116
50. Kennedy HJ, Pouli AE, Ainscow EK, Jouaville LS, Rizzuto R, Rutter GA: Glucose generates sub-plasma membrane ATP microdomains in single islet β-cells: potential role for strategically located mitochondria. *J Biol Chem* 274:13281–13291, 1999
51. MacCormack JG, Longo EA, Corkey BE: Glucose-induced activation of pyruvate dehydrogenase in isolated rat pancreatic islets. *Biochem J* 267:527–530, 1990
52. MacDonald MJ, Brown LJ: Calcium activation of mitochondrial glycerol phosphate dehydrogenase restudied. *Arch Biochem Biophys* 326:79–84, 1996
53. Maechler P, Kennedy ED, Sebo E, Valeva A, Pozzan T, Wollheim CB: Secretagogues modulate the calcium concentration in the endoplasmic reticulum of insulin-secreting cells: studies in aequorin-expressing intact and permeabilized ins-1 cells. *J Biol Chem* 274:12583–12592, 1999
54. Magnus G, Keizer J: Model of β-cell mitochondrial calcium handling and electrical activity. I. Cytoplasmic variables. *Am J Physiol* 274:C1158–C1173, 1998
55. Smith PA, Ashcroft FM, Rorsman P: Simultaneous recordings of glucose dependent electrical activity and ATP-regulated K^+-currents in isolated mouse pancreatic β-cells. *FEBS Lett* 261:187–190, 1990
56. Miki T, Nagashima K, Tashiro F, Kotake K, Yoshitomi H, Tamamoto A, Gonoi T, Iwanaga T, Miyazaki J, Seino S: Defective insulin secretion and enhanced insulin action in K_{ATP} channel-deficient mice. *Proc Natl Acad Sci U S A* 95:10402–10406, 1998
57. Seghers V, Nakazaki M, DeMayo F, Aguilar-Bryan L, Bryan J: Sur1 knockout mice: a model for K_{ATP} channel-independent regulation of insulin secretion. *J Biol Chem* 275:9270–9277, 2000
58. Efanov AM, Hoy M, Branstrom R, Zaitsev SV, Magnuson MA, Efendic S, Gromada J, Berggren PO: The imidazoline RX871024 stimulates insulin secretion in pancreatic beta-cells from mice deficient in K_{ATP} channel function. *Biochem Biophys Res Commun* 284:918–922, 2001
59. Ämmälä C, Aguilar-Bryan L, Bryan J, Dukes ID: Glucose modulation of intracellular calcium, electrical activity and insulin secretion in Sur1 null islets (Abstract). *Diabetes* 50 (Suppl. 2):A350, 2001