Upregulation of β-cell genes and improved function in rodent islets following chronic glucokinase activation

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Abstract

Glucokinase (GK) plays a critical role in controlling blood glucose; GK activators have been shown to stimulate insulin secretion acutely both in vitro and in vivo. Sustained stimulation of insulin secretion could potentially lead to β-cell exhaustion; this study examines the effect of chronic GK activation on β-cells. Gene expression and insulin secretion were measured in rodent islets treated in vitro with GKA71 for 72 h. Key β-cell gene expression was measured in rat, mouse and global GK heterozygous knockout mouse islets (gkd½½). Insulin secretion, after chronic exposure to GKA71, was measured in perifused rat islets. GKA71 acutely increased insulin secretion in rat islets in a glucose-dependent manner. Chronic culture of mouse islets with GKA71 in 5 mmol/l glucose significantly increased the expression of insulin, IAPP, GLUT2, PDX1 and PC1 and decreased the expression of C/EBPβ compared with 5 mmol/l glucose alone. Similar increases were shown for insulin, GLUT2, IAPP and PC1 in chronically treated rat islets. Insulin mRNA was also increased in GKA71-treated gkd½½ islets. No changes in GK mRNA were observed. Glucose-stimulated insulin secretion was improved in perifused rat islets following chronic treatment with GKA71. This was associated with a greater insulin content and GK protein level. Chronic treatment of rodent islets with GKA71 showed an upregulation of key β-cell genes including insulin and an increase in insulin content and GK protein compared with glucose alone.

Journal of Molecular Endocrinology (2011) 47, 59–67

Introduction

Glucokinase (GK) exists as two isoforms that have independent tissue-specific promoters. In the pancreatic β-cell, GK acts as a glucose sensor and contributes to the regulation of glucose-stimulated insulin secretion (GSIS). The pancreatic isoform of GK is also found in glucose-sensing cells in the anterior pituitary gland, hypothalamus and entero-endocrine K- and L-cells (Schuit et al. 2001). The liver isoform is specific to hepatocytes, where it is the rate-limiting enzyme for glucose utilisation and glycogen synthesis (Matschinsky 1990, Schuit et al. 2001).

Naturally occurring mutations in man support the importance of GK in the regulation of glucose homeostasis. Loss of both GK alleles results in permanent neonatal diabetes, whereas heterozygous inactivating mutations of GK lead to maturity-onset diabetes of the young (MODY2; Hattersley et al. 1992). Conversely, rare activating mutations of GK result in hyperinsulinaemic hypoglycaemia (Glaser et al. 1998, Christesen et al. 2002, Gloyn et al. 2003, Cuesta-Munoz et al. 2004).

Isoform-specific, tissue-specific and global GK knockout (gkd½½) mice have been extensively phenotyped and provide further evidence for the role of GK in glucose sensing and disposal. The pancreatic GK isoform is an absolute requirement for survival, as gkd½½ (either global or β-cell specific) is lethal, whereas global or β-cell-specific heterozygous (gkd½½) deletion causes only modest hyperglycaemia (Bali et al. 1995, Grupe et al. 1995, Terauchi et al. 1995). Deletion of liver GK leads to mild hyperglycaemia but decreases glucose utilisation and glycogen synthesis (Postic et al. 1999).

The pivotal role of GK in controlling blood glucose has made it attractive as a potential drug target for the treatment of type 2 diabetes. A number of small molecule GK activators (GKAs) have been described. These agents have effects on hepatic glucose metabolism and insulin secretion, both in vitro and in normal and diabetic animal models (Grimsby et al. 2003, Brocklehurst et al. 2004, Kamata et al. 2004, Efano et al. 2005, Coope et al. 2006, Futamura et al. 2006, Matschinsky et al. 2006, Johnson et al. 2007, Coghlan & Leighton 2008).

Several studies have demonstrated that GKAs increase GSIS from β-cells (Coghlan & Leighton 2008), but the consequences of long-term direct action of GKAs on the islet have only recently begun to be investigated. Of potential concern is that sustained stimulation of insulin secretion, without a concomitant increase in insulin biosynthesis, could lead to β-cell exhaustion.

The effect of glucose on the regulation of insulin production has been studied extensively, by direct
measurement of insulin biosynthesis and by measuring gene expression. Prolonged culture of isolated rodent islets in high glucose leads to increased insulin biosynthesis and increased insulin mRNA levels (Brunstedt & Chan 1982, Docherty & Clark 1994, Leibiger et al. 2000, Khaldi et al. 2004). Data generated with GKAs provide support for these molecules acting in a ‘glucose-like’ manner on insulin secretion; we hypothesised that GKAs would also mimic the effect of elevated glucose concentration on insulin biosynthesis. We describe the use of a potent GKA, GKA71, to determine the effect of concentration on insulin biosynthesis. We describe the use of a potent GKA, GKA71, to determine the effect of sustained GK activation on the expression of key β-cell genes, including insulin, in isolated rat and mouse islets.

Materials and methods

Materials

The novel GK activator GKA71 was dissolved in dimethylsulphoxide (DMSO) prior to dilution to the final concentration in the required medium.

Experimental animals and islet isolation

Animals used in these studies were supplied by AstraZeneca Biological Animal Breeding Unit and were kept under standard laboratory conditions with free access to food and water. Male C57Bl/6J mice were 8–10 weeks of age (230–260 g) and male Hannover Wistar rats 8–9 weeks of age (220–260 g). Male global heterozygous GK knockout (gkdel/wt) and wild-type (gkw/wt) mice were used between 10 and 16 weeks of age; these animals were generated as described previously (Gorman et al. 2008). All procedures were carried out in accordance with the Animals (Scientific Procedures) Act 1986. Animals were rendered insentient by inhalation of a 5:1 mixture of CO2:O2 and killed by cervical dislocation with the Animals (Scientific Procedures) Act 2008). All procedures were carried out in accordance with the Animals (Scientific Procedures) Act 1986.

Animals used in these studies were supplied by Astra-Zeneca Biological Animal Breeding Unit and were kept under standard laboratory conditions with free access to food and water. Male C57Bl/6J mice were 8–10 weeks of age (220–240 g) and male Hannover Wistar rats 8–9 weeks of age (230–260 g). Male global heterozygous GK knockout (gkdel/wt) and wild-type (gkw/wt) mice were used between 10 and 16 weeks of age; these animals were generated as described previously (Gorman et al. 2008). All procedures were carried out in accordance with the Animals (Scientific Procedures) Act 1986.

Recombinant GK assays

Human, rat and mouse β-cell GK were cloned from cDNA using PCR. Each was expressed in Escherichia coli with an NH2-terminal 6His tag and purified using Ni-NTA chromatography. Recombinant proteins were >95% pure as assessed by SDS/PAGE analysis (Brocklehurst et al. 2004). GK was assayed at its So.5 glucose concentration as described previously (Brocklehurst et al. 2004).

Acute insulin secretion assay

Rat islets were allowed to recover overnight in RPMI medium supplemented with 10% (v/v) FCS, penicillin/streptomycin/glutamine (100 units/ml, 0·1 mg/ml and 2 mmol/l respectively, Invitrogen) and 11 mmol/l glucose. Insulin secretion was assessed according to the method described previously (Johnson et al. 2007); 30 min pre-incubation was followed by 2-h treatment. Insulin concentration was determined by homogeneous time-resolved fluorescence assay (HTRF assay, CisBio, Bognols/Cèze, France) according to the manufacturer’s high-range protocol (0–100 ng/ml).

Chronic treatment of islets

Islets were cultured in RPMI medium supplemented as above. Islets were incubated 20 islets/well in 6-well plates at 37 °C in a 5% CO2 humidified incubator.

Prior to chronic treatment, islets were allowed to recover overnight in medium containing the appropriate glucose concentration. Islets from C57Bl/6J mice and from rats were divided between media containing 5 or 25 mmol/l glucose. For experiments with gkw/wt and gkdel/wt islets, islets from animals of the same genotype were pooled and then divided between 8 and 25 mmol/l glucose.

Following the overnight incubation, islets were hand-picked into medium at the same glucose concentration containing either 1% (v/v) DMSO (control) or 10 μmol/l GKA71 in 1% DMSO. Islets were treated for 72 h and were hand-picked into fresh treatment medium daily.

RNA isolation and reverse transcription

Following chronic culture, RNA was prepared from pooled samples of 30 (rat) or 40 (mouse) islets (see figure legends for individual experiment replicate numbers). RNA isolation and gene expression analysis were carried out as described previously (Gorman et al. 2008).

Gene expression analysis

Quantitative PCR of single genes was performed by Taqman analysis in 384-well plate assays using ABI Prism 7900HT sequence detection system (Applied Biosystems, Carlsbad, CA, USA). Taqman analysis of mouse samples was carried out using primer and probe sets designed using Primer Express software (TaqMan primer and probe sequences are shown in Supplementary Table 1, see section on supplementary data given at the end of this article). ‘Assay on demand’ primer/probe mixes (Applied Biosystems) were used for analysis of rat samples: insulin (Rn01774648), GLUT2 (Rn00563565), hypoxanthine phosphoribosyltransferase (HPRT) (Rn01527838), cyclophilin (Rn00690933), β-glucuronidase (Rn00566655), IAPP (Rn00561411),
PDX1 (Rn00755591), GK (Rn00561265), PC1 (Rn0056266) and CEBPβ (Rn00824655). Samples from the C57Bl/6j chronic islet experiment were used to perform Taqman low-density arrays (TLDA), which were carried out as described previously (Gorman et al. 2008).

For both quantitative PCR and TLDA analysis, a number of housekeeper genes were used. For quantitative PCR analysis, the housekeeper genes were HPRT, cyclophilin and β-glucuronidase. For TLDA analysis, the included housekeeper genes were HPRT, 18S and β-tubulin. No qualitative differences were observed when the genes of interest were expressed relative to the different housekeepers; therefore, all data shown are normalised to HPRT expression.

Perifusion studies

Perifusion experiments were performed using a Brandel SF-12 Superfusion apparatus (Brandel, Gaithersburg, MD, USA). Following chronic culture, islets were loaded into perifusion chambers (50 islets/chamber in 200 µl medium), enclosed with polyethylene filters. Islets were perifused in HEPES-balanced Krebs-Ringer phosphate buffer (KRH), prepared as described previously (Johnson et al. 2007), at a flow rate 1 ml/min. During an initial stabilisation period (perifusion 30 min; 3 mmol/l glucose), no samples were collected. Islets were then perifused to obtain a GSIS profile: 30 min with 3 mmol/l glucose; 25 min with 15 mmol/l glucose; 17.5 min with 3 mmol/l glucose and 6 min with 40 mmol/l KCl, during which time samples were collected for analysis of insulin secretion. Insulin was determined using an HTRF kit, prepared according to the normal range protocol (0–10 ng/ml).

Total insulin measurement

Following chronic culture, three islets in 10 µl medium were transferred to individual wells of 96-well plates containing 115 µl KRH. Then, 115 µl 2% (v/v) Triton X-100 were added to each well, and the plates were frozen at −20°C to completely lyse the islets. For determination of insulin content, samples were thawed, centrifuged (700 g, 2 min) and diluted as appropriate, prior to analysis using the high-range HTRF assay.

Western blotting

Following chronic culture, 500–900 islets from each treatment group were lysed in 50 µl lysis buffer: 20 mmol/l Tris–HCl (pH 7.5), 150 mmol/l NaCl, 2 mmol/l EDTA, 1% (v/v) Triton X-100, with 1 mini-protease inhibitor tablet (Roche)/10 ml. Lysed sample (32.5 µl) was transferred to a tube containing 12.5 µl 4× loading buffer (Invitrogen) and 5 µl 10× denaturing buffer (Invitrogen). Samples were heated at 95°C for 5 min before storing at −20°C. Residual lysed sample was used for protein analysis via a DC protein assay (Bio-Rad).

Protein (50 µg/sample) was resolved by electrophoresis on 10% (v/v) Bis–Tris NuPage gels (Invitrogen), using 3-(N-morpholino)propanesulfonic acid buffer. The iBlot system (Invitrogen) was used for transfer onto nitrocellulose. After blocking overnight at 4°C in 5% (w/v) BSA/0.05% (w/v) polysorbate 20 in Tris-buffered saline, a 2 h room temperature incubation was carried out with rabbit polyclonal antibody raised against full-length human pancreatic GK (used at 1:5000 dilution). Incubation with secondary antibody, HRP-linked donkey anti-rabbit (GE Healthcare, Buckinghamshire, UK), 1:5000 dilution, was for 1 h at room temperature, followed by detection with an enhanced chemiluminescence system (Chemiglow West, Cell Biosciences, Santa Clara, CA, USA). The blot was imaged on a Chemi-imager (Alpha Innotech), and densitometry was performed using software installed on the machine.

Data handling and statistical analysis

Acute insulin secretion induced by GKA71 was compared with the control insulin secretion at each glucose concentration by Student’s t-test. For statistical analysis of the gene expression data, each gene of interest was normalised to the housekeeper gene HPRT and statistical evaluation was carried out on log-transformed data. For each stimulatory phase of the perifusion profile, insulin secretion after treatment with GKA71 or high glucose was compared with 5 mmol/l glucose-treated islets using Student’s t-tests. Two-sided unequal variance Student’s t-tests were used throughout.

Results

GKA71 is a potent activator of human pancreatic GK and acutely stimulates insulin secretion from rat islets

In isolated enzyme assays, GKA71 activated recombinant human pancreatic GK with EC50 112 nmol/l (n=8, 95% confidence interval (CI) 70–170 nmol/l). GKA71 also activated the rat and mouse pancreatic GK isoforms: EC50 88 nmol/l (n=3, 95% CI 86–91 nmol/l) and 411 nmol/l (n=3, 95% CI 350–490 nmol/l) respectively.

The acute effect of GKA71 on GSIS from isolated rat islets is shown in Fig. 1. GKA71 increased insulin secretion at 3, 5, 8 and 10 mmol/l glucose; although at 10 mmol/l, the increase was not significantly different from control.
increased; whereas treatment with GKA71 on islets from compromised, we explored the effect of chronic also maintain islet function where GK activity is cally significant (for full gene list, seeGorman summarises the data for those genes in which changes the same samples using TLDA analysis. Table 1 was observed, consistent with the individual gene (2008)). A marked increase in insulin gene expression incubation in 5 mmol/l glucose.

The level of insulin mRNA in islets from a twofold (8 mmol/l glucose, chronic culture with GKA71 induced the expression of other key β-cell genes was explored in these samples; however, no significant changes were observed (data not shown). Chronic exposure to 25 mmol/l glucose also significantly increased, ~80-fold, the level of insulin mRNA compared with incubation in 5 mmol/l glucose.

The expression of other β-cell genes was explored in the same samples using TLDA analysis. Table 1 summarises the data for those genes in which changes were observed, either greater than twofold or statistically significant (for full gene list, see Gorman et al. (2008)). A marked increase in insulin gene expression was observed, consistent with the individual gene Taqman. IAPP, PDX1, PC1 and GLUT2 also significantly increased, whereas CEBPβ expression decreased by 80%.

To investigate whether sustained GK activation will also maintain islet function where GK activity is compromised, we explored the effect of chronic treatment with GKA71 on islets from gkwt/wt mice. Results obtained from the wild-type (gkwt/wt) and heterozygous knockout (gkd/wt) mouse islets are summarised in Fig. 3; these data were generated by single-gene Taqman analysis. In gkwt/wt islets, cultured in 8 mmol/l glucose, chronic culture with GKA71 induced a twofold (P<0.05) increase in insulin mRNA (Fig. 3A). The level of insulin mRNA in islets from gkd/wt mice cultured in 8 mmol/l glucose was markedly lower than that in wild-type islets; however, chronic culture with GKA71 induced a 30-fold (P<0.001) increase to a level that was undistinguishable from the level attained by GKA71 stimulation of islets from gkwt/wt mice. These changes in insulin mRNA induced by GKA71 were similar in both genotypes to those elicited by 25 mmol/l glucose.

Expression of GK did not significantly change in the presence of GKA71 or 25 mmol/l glucose in islets from gkwt/wt or gkd/wt mice (Fig. 3B). GK mRNA levels were lower in gkd/wt islets compared with gkwt/wt islets in basal 8 mmol/l glucose, but in the presence of GKA71 or 25 mmol/l glucose, there was no significant difference in GK mRNA between genotypes.

Chronic activation of GK by GKA71 increases the expression of insulin and changes the expression of other key β-cell genes in rat islets

In order to obtain islets in sufficient quantity, subsequent experiments were carried out in rat islets. Initial experiments were carried out to confirm that the above findings could be reproduced in rat islets.

Following culture in the presence of GKA71 for 72 h, mRNA levels of key β-cell genes were determined using Taqman. Insulin expression increased 2.7-fold (Fig. 4A, P<0.001). GLUT2 (2.3-fold, P<0.001; Fig. 4B), PC1 (2.5-fold, P<0.001; Fig. 4C) and IAPP (2.2-fold, P<0.001; Fig. 4D) also increased; changes were qualitatively similar to those induced by 25 mmol/l glucose. A small but non-significant increase was observed for both PDX1 and GK and there was a significant decrease in expression of CEBPβ (data not shown).

GSIS in rat islets is increased after chronic activation of GK by GKA71

Following chronic culture, rat islets were perifused with sub-stimulatory (3 mmol/l) and stimulatory (15 mmol/l) glucose; the perifusion profile is shown in Fig. 5A. Following the 30-min pre-perifusion phase, all treatment groups had the same basal insulin secretion, indicating that no residual compound remained in the islets. Islets cultured in 5 mmol/l glucose exhibited no measurable GSIS response when stimulated with 15 mmol/l glucose; however, islets

**Figure 1** GKA71 (1 μmol/l) acutely stimulates insulin secretion from rat islets in a glucose-dependent manner. Control islets (black bars) and islets treated with 1 μmol/l GKA71 (striped bars). Values are mean±s.e.m., n=6, each of three islets. **P<0.01, ***P<0.001 versus the respective control in the absence of GKA71. Data are representative of four separate experiments.

**Figure 2** Chronic treatment of C57Bl/6J mouse islets with GKA71 (10 μmol/l) increases insulin mRNA levels. mRNA levels determined by single-gene Taqman analysis (mean±s.e.m. of triplicate samples, each of 40 islets). **P<0.01 versus 5 mmol/l glucose alone.
cultured in the presence of GKA71 exhibit clear first- and second-phase insulin secretion and have a profile very similar to that of the islets cultured in 25 mmol/l glucose. The effects of GKA71 on first- and second-phase insulin secretion were quantified by calculating the area under curve (AUC) for each phase. The first-phase (30–39 min) response was 65-fold (P<0.001) greater in islets previously cultured in the presence of GKA71 compared with those cultured in 5 mmol/l glucose alone and not significantly different from islets cultured in 25 mmol/l glucose. AUC for the second-phase response (40–76.5 min) was 585-fold (P<0.001) greater after culture with GKA71 and also similar to islets cultured in 25 mmol/l glucose. These data are shown in Fig. 5B and C.

The response to perifusion with 40 mmol/l KCl was determined from the AUC (76.5–81 min). Insulin release was fourfold (P<0.006) greater in islets cultured in the presence of GKA71 compared with those cultured in 5 mmol/l glucose alone and similar to that in islets previously cultured in 25 mmol/l glucose (Fig. 5D).

**Total insulin content in rat islets is increased after chronic activation of GK by GKA71**

We hypothesised that the greater KCl response in islets treated with GKA71 resulted from elevated total insulin content in those islets. Chronically treated islets were lysed and the total insulin content was measured (Fig. 6). The insulin content was 2.4-fold higher in islets cultured in the presence of GKA71 than in those cultured in 5 mmol/l glucose alone. Again, the results for GKA71 were similar to those for islets cultured in 25 mmol/l glucose.

**GK protein is increased in rat and mouse islets with chronic activation of GK by GKA71**

Although GK mRNA levels were not changed by chronic culture with either GKA71 or with 25 mmol/l glucose, GK is known to be regulated at the protein level, rather than at the gene level. Therefore, western blotting was performed to quantify GK protein in chronically treated islet samples. In isolated rat islets, chronic culture with GKA71 resulted in increased GK protein; this change was again consistent with that observed for islets cultured in 25 mmol/l glucose (Fig. 7A and B). Similar findings were observed in islets taken from gkt/wt and gkdel/wt mice (Fig. 7C and D).

**Discussion**

Although many groups have demonstrated the potential of GKAs to drive insulin secretion, no studies, to date, have investigated whether GKAs activate the appropriate pathways to ensure that β-cell exhaustion does not occur in response to prolonged treatment with a GKA. We designed a series of experiments to assess the effect of a high concentration of GKA71 (at least ten times greater than the EC50) on isolated islets following a 72-h treatment period. The primary end point for these investigations was the effect of GKA71 on insulin mRNA levels.

We demonstrate that islets chronically treated with a GKA have a greater level of insulin production than

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**Table 1** GKA71 influences the expression of key β-cell genes in mouse islets

<table>
<thead>
<tr>
<th>Gene</th>
<th>Direction of change</th>
<th>Fold change</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAPP</td>
<td>Increase</td>
<td>4-6</td>
<td>0-005</td>
</tr>
<tr>
<td>Insulin</td>
<td>Increase</td>
<td>15-9</td>
<td>0-001</td>
</tr>
<tr>
<td>PDX1</td>
<td>Increase</td>
<td>4-5</td>
<td>0-012</td>
</tr>
<tr>
<td>PC1</td>
<td>Increase</td>
<td>6-5</td>
<td>0-001</td>
</tr>
<tr>
<td>GLUT2</td>
<td>Increase</td>
<td>29-9</td>
<td>&lt;0-001</td>
</tr>
<tr>
<td>CEBPβ</td>
<td>Decrease</td>
<td>5-0</td>
<td>0-040</td>
</tr>
</tbody>
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**Figure 3** Effect of chronic treatment with GKA71 (10 μmol/l) on mRNA levels of insulin and GK in gkwt/wt and gkdel/wt mouse islets. Islets were cultured in 8 mmol/l glucose alone (black bars); 10 μmol/l GKA71 (striped bars) or 25 mmol/l glucose (grey bars). (A) Insulin mRNA. (B) GK mRNA. mRNA levels determined by single-gene Taqman analysis (mean ± s.e.m. of seven or eight samples, each with 40 islets). *P<0.05, ***P<0.001 versus 8 mmol/l glucose alone. #P<0.05 for the comparison of gkwt/wt with gkdel/wt.
insulin expression and production, and also on the expression of other key genes, to those induced by high glucose concentration. Therefore, these novel findings again demonstrate the "glucose-like" nature of GKAs, consistent with what is already known about the mechanism of action of these molecules (Leighton et al. 2005).

In preliminary experiments, GSIS of islets from C57Bl/6J mice, and of Wistar rats, was assessed following culture for 72 h. These experiments indicated that while rat islets retained a small GSIS response after 72 h in 5 mmol/l glucose, mouse islets required 8 mmol/l glucose to maintain a similar level of functionality. Therefore, all subsequent mouse islet chronic culture experiments were performed using 8 mmol/l glucose. The insulin mRNA response to GKA71 on C57Bl/6J mouse islets cultured in 5 mmol/l glucose was qualitatively similar to that in gkwt/wt islets cultured in 8 mmol/l glucose; however, islets cultured in the same glucose concentration in the absence of GKA. In these experiments, we used insulin mRNA as a measure of insulin biosynthesis rather than measuring insulin biosynthesis directly. However, as there was a corresponding increase in insulin content and functional response of the islets, it is reasonable to conclude that the increase in insulin mRNA induced by GKA71 is translated to an increase in insulin production. The effect on insulin mRNA has been demonstrated consistently in isolated islets from normal mouse and rat and islets from mice with heterozygous deletion of the GK gene. Having established that GKA increased insulin mRNA, we carried out experiments to explore the mechanisms for these changes. The TLDA analysis highlighted a subset of key β-cell genes that were induced following chronic treatment with GKA71. All these genes (insulin, GLUT2, IAPP and PDX1) are regulated by PDX1 (Watada et al. 1996, Campbell & Macfarlane 2002), suggesting that GKA71 influences the expression of these important proteins via PDX1. All these genes were upregulated in both mouse and rat islets. However, although PDX1 expression increased in normal mouse islets, this was not seen in rat islet studies. It is possible that the effects on gene expression are the result of a modulation of the activity of PDX1, rather than a change in expression. In addition to the regulatory effects of PDX1 on these key β-cell genes, MafA is known to be an important regulator of their expression (Aramata et al. 2005). We did attempt to measure MafA mRNA in disease model islets; however, the expression level was too low to be detected.

We have demonstrated that treatment with GKA71 in basal glucose concentration produces similar effects on insulin expression and production, and also on the expression of other key genes, to those induced by high glucose concentration. Therefore, these novel findings again demonstrate the "glucose-like" nature of GKAs, consistent with what is already known about the mechanism of action of these molecules (Leighton et al. 2005).

In preliminary experiments, GSIS of islets from C57Bl/6J mice, and of Wistar rats, was assessed following culture for 72 h. These experiments indicated that while rat islets retained a small GSIS response after 72 h in 5 mmol/l glucose, mouse islets required 8 mmol/l glucose to maintain a similar level of functionality. Therefore, all subsequent mouse islet chronic culture experiments were performed using 8 mmol/l glucose. The insulin mRNA response to GKA71 on C57Bl/6J mouse islets cultured in 5 mmol/l glucose was qualitatively similar to that in gkwt/wt islets cultured in 8 mmol/l glucose; however,
a larger fold stimulation was observed in 5 mmol/l glucose. This may result from lower basal insulin expression in the lower glucose concentration; however, the two conditions were not directly compared.

In addition to investigating the effect of GKA71 on the regulation of insulin biosynthesis, and expression of other key β-cell genes, these experiments were designed to study the effect of GKA71 on GK regulation. GK is known to be regulated post-translationally in the β-cell rather than at the expression level (Chen et al. 1994). It is clear from our results that there is no effect of chronic treatment with GKA71 on GK mRNA. However, using immunoblotting to study GK protein levels revealed that in rat islets, GK protein was elevated in islets treated with GKA71. Again, this is consistent with the increase induced by high glucose. Results obtained in rat islets were reproduced in both the wild-type and the heterozygous GK knockout mouse islets. Although we did not measure GK activity of islets, we would predict that chronic treatment with GKA would increase enzyme activity. This would be consistent with the effects of GKA5s measured in experiments assessing direct activation of the isolated GK enzyme, albeit in hepatocytes (Brocklehurst et al. 2004).

Exposure of islets to very high concentrations of glucose is eventually detrimental to function, manifested as abnormal insulin gene expression, insulin content and defective GSIS (Robertson et al. 2003). Elements of this β-cell glucotoxicity have been demonstrated in vivo in rodents (Leahy et al. 1986, Jonas et al. 1999, Laybutt et al. 2002). Furthermore, in vivo, chronic hyperglycaemia may also deplete β-cell mass (Pick et al. 1998). Therefore, it is a concern that sustained activation of GK via GKA may mimic the effects of chronic high glucose and contribute to glucotoxicity, via reduction of β-cell mass and by depleting the available pool of readily secretable insulin. However, GK may in fact be important to maintain both GSIS and β-cell mass: mice heterozygous for β-cell-specific deletion of GK fail to adequately expand β-cell mass on a high-fat diet (Terauchi et al. 2007) and have reduced GSIS (Aizawa et al. 1996, Gorman et al. 2008).

Recently, the effect of chronic GKA administration was evaluated in wild-type mice and mice with a β-cell-specific deletion of GK (Nakamura et al. 2009). In both genotypes, β-cell mass was unchanged after 20 weeks’ treatment, but it was less clear whether the potential for GKA to stimulate GSIS was retained. Relative insulin secretion increased in response to feeding, although this could potentially have resulted from improved insulin sensitivity. Although GSIS tended to be greater in islets from GKA-treated mice when evaluated ex vivo, this study did not investigate whether insulin biosynthesis had been maintained. Our own results clearly support the conclusion that chronic exposure to GKA71 results in islets with an increased GSIS response, and indeed provide evidence that insulin content and insulin secretory capacity are significantly improved. It should, however, be noted that in our studies, all end points are compared following 72 h of culture; therefore, our findings do not enable us to differentiate between action of GKA71 to prevent loss of function in low glucose culture and action to increase function during sustained treatment. Study of the kinetics of changes in insulin biosynthesis and GSIS induced by GKA would clarify this.

Although chronic administration of GKA did not change β-cell mass in the above study, sustained exposure of INS1 cells to GKA promoted β-cell replication and, in addition, one compound, GKA50, reduced apoptosis (Nakamura et al. 2009, Wei et al. 2009). Further evidence to support the lack of detrimental effect on β-cell mass comes from demonstration that a short (3 days) treatment in vivo, when glucose concentration was high, increased the rate of β-cell proliferation (Nakamura et al. 2009). Taken together, these two studies, with the current results, suggest that GKAs have the potential to at least prevent and at best reverse the three key elements of glucotoxicity;

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**Figure 6** Chronic treatment of rat islets with GKA71 (10 μmol/l) increases the total insulin content. Values are the mean ± S.E.M. of six samples, each of three islets. **P<0.01 versus 5 mmol/l glucose alone.

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**Figure 7** Chronic treatment of rodent islets with GKA71 (10 μmol/l) increases the amount of GK protein. Western blots were performed on cell lysates from rat islets (A: Immunoblot lane 1 = 5 mmol/l glucose, lane 2 = 25 mmol/l glucose and lane 3 = 5 mmol/l glucose plus 10 μmol/l GKA71; B: densitometry, 5 and 25 denote glucose concentration in mmol/l with 5 = GKA being 5 mmol/l glucose plus 10 μmol/l GKA71) or gk<sup>wt</sup> and gk<sup>del/</sup>del mouse islets (C: Immunoblot – lanes 1 and 4 = 8 mmol/l glucose, lanes 2 and 5 = 8 mmol/glucose plus 10 μmol/l GKA71 and lanes 3 and 6 = 25 mmol/l glucose – lanes 1–3 = gk<sup>wt</sup> lanes 4–6 = gk<sup>del/</sup>del; D: densitometry). Data are representative of n=2 experiments with each species.
impaired proliferation, increased apoptosis and impaired GSIS. Given the effectiveness of GKAs to decrease blood glucose, it may not be physiologically relevant to consider sustained effects at high glucose concentrations.

The mechanism of action of GKAs clearly distinguishes them from sulphonylureas. We have previously demonstrated the difference between GKA50 and tolbutamide on cytosolic Ca^{2+} rises in MIN6 cells and isolated rodent islets (Johnson et al. 2007). Although both agents induce insulin secretion, only the GKA does so in a glucose-dependent and ‘glucose-like’ manner. Administration of sulphonylureas results in eventual loss of insulin secretory capacity (Ball et al., 2004, Urban & Panten 2005), whereas in contrast, the experiments described in this study indicate that GKAs are able to stimulate the cellular mechanisms to increase insulin production, in addition to stimulating insulin secretion.

Type 2 diabetes in man results from failure of insulin secretion to compensate for the increased insulin demand that occurs as insulin resistance develops. Reduced insulin secretory capacity results from declining β-cell mass (Butler et al. 2005) and also reduced secretory capacity of individual β-cells (Ahren 2005). We have demonstrated that chronic GK activation improves or sustains insulin secretory capacity in vitro; studies in human islets and ultimately in diabetic patients are required to support this result. Taken together with the maintenance of β-cell mass, these results reinforce the attractive profile of GKAs as a therapy for type 2 diabetes.

Supplementary data

This is linked to the online version of the paper at http://dx.doi.org/10.1530/JME-10-0157.

Declaration of interest

All authors of this study were employees of AstraZeneca plc at the time the work was performed.

Funding

This research was solely funded by AstraZeneca plc.

Acknowledgements

We thank the Alderley Park breeding unit and biological services for provision of animals and harvesting of pancreas. We also thank the team who assisted with islet isolations; Anna Marley, Tracy Gorman, Claire Dunkley, Nicky James, Jackie Pierce and Linda Härndahl; and Alison Davies for her assistance with the Taqman analysis. We also thank Jonathan Bright and Elizabeth Mills for the statistical analysis, and Rachel Meyers for assistance with preparation of the manuscript. Finally, we thank Mark Dunne for his initial comments on these data and Brendan Leighton, Matthew Coghlan and Andrew Charles for their critical examination of this manuscript.

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Journal of Molecular Endocrinology (2011) 47, 59–67

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Received in final form 24 April 2011
Accepted 13 May 2011
Made available online as an Accepted Preprint 13 May 2011