Exogenously administered somatostatin (SST) inhibits secretion of insulin and glucagon. Furthermore, it is hypothesized that islet SST regulates glucagon secretion by a local action. A number of studies utilizing SST antibodies have been performed to test this hypothesis, and their results have been conflicting. Five subtypes of SST receptor (SSTR1–5) mediate the effect of SST on target cells. In rodents, SST inhibits the release of glucagon, but not that of insulin, via SSTR2. A novel SSTR2-selective antagonist, DC-41-33, was synthesized recently. We have investigated the effects of this antagonist on arginine-stimulated glucagon and insulin release in batch incubations of isolated rat islets, perfused isolated rat islets, and isolated perfused rat pancreas. In batch incubations at 3.3 mmol/l glucose, DC-41-33 increased glucagon release in a dose-dependent manner. At the maximum dose tested (2 μmol/l), DC-41-33 enhanced the glucagon response by 4.3- to 5-fold. Similarly, this compound increased arginine-induced glucagon release in perfused islets at 3.3 mmol/l glucose (2.8-fold) and perfused pancreas at 3.3 and 5.5 mmol/l glucose (2.5- and 2.3-fold, respectively). In the two latter experimental systems, DC-41-33 had no significant effect on insulin release. In conclusion, our results strongly support the hypothesis that islet SST inhibits glucagon secretion via a local action. Diabetes 52:1176–1181, 2003

It is well established that exogenously administered somatostatin (SST) inhibits the release of insulin (1,2) and glucagon (3,4) from the endocrine pancreas. In addition, it has been hypothesized that SST released from islet D-cells regulates the secretion of insulin and glucagon by a local “paracrine” action (5,6). This hypothesis was supported by experiments demonstrating that immunoneutralization of endogenous SST in batch incubations of isolated pancreatic islets enhances glucagon and insulin secretion (7,8). However, the results of these studies do not necessarily depict physiological events, since released hormones accumulate in the medium and islet interstitium during the 30- to 90-min incubation period, reaching concentrations that most probably exceed those that are physiologically relevant. Additionally, isolated islets retain neither their normal interstitial structure nor their microcirculation. Further support for the involvement of local effects of SST came from an in vivo study in dogs, in which low and medium doses of a nonimmunoreactive SST analog suppressed the release of endogenous SST and markedly enhanced glucagon release, while insulin release was enhanced moderately (9). The possibility remains, however, that this analog had systemic effects that influenced hormone release.

For the reasons stated above, studies with isolated perfused pancreas are of special relevance when considering paracrine interactions between islet cells. In the perfused isolated canine pancreas, exogenous SST inhibited arginine-stimulated insulin and glucagon secretion at concentrations as low as 20% of those measured in venous effluent (10). The authors interpreted this finding as indicating that islet SST receptors (SSTRs) are not in contact with high local concentrations of endogenous SST. The integrity of this separation determines the sensitivity of islet cells to circulating SST. The study thus argued against a local regulatory role for SST in the islet (11). This conclusion is supported by a series of immunoneutralization studies in isolated perfused pancrea of rat, dog, and humans, in which anterograde perfusion with polyclonal SST antibodies did not significantly affect either insulin or glucagon secretion (12–16). In contrast, Brunicardi and colleagues (17,18) reported that neutralization of intra-islet SST with monoclonal antibodies enhances both glucagon and insulin secretion from isolated perfused human pancreas.

Five subtypes of SSTRs (SSTR1–5) mediate the effect of SST on target cells (19,20). Previous studies in rats have indicated that SST inhibits glucagon and insulin release via SSTR2 and SSTR5, respectively (21–24). The recent development of a specific SSTR2 antagonist, DC-41-33, also known as PRL-2903 (25), gave us the unique possibility to explore whether islet SST regulates glucagon release locally. For this purpose, we first characterized the effects of DC-41-33 on glucagon and insulin release in batch incubations of isolated rat islets and then applied DC-41-33 to perfused isolated rat islets and isolated perfused rat pancreata.
Isolation of pancreatic islets, batch incubation, and perifusion studies. Islets were isolated by digestion with collagenase (Hoffmann-La Roche, Basel, Switzerland) and cultured for 20–22 h in RPMI-1640 medium supplemented with 11 mmol/l glucose and 10% (vol/vol) FCS. For both batch incubation and perifusion studies, the islets were first preincubated for 35 min in Krebs-Ringer bicarbonate buffer (KRBB) containing 3.3 mmol/l glucose and 2 g/l bovine plasma albumin (Sigma, St. Louis, MO). Batches of ten islets were then incubated for 1 h in 350 μl KRBB-albumin-glucose. As a stimulus for hormone release, 20 mmol/l arginine was used. DC-41-33 and/or SST (SST-14; Sigma, St. Louis, MO) were added to incubations with arginine. After each incubation, 100-μl aliquots of incubation medium were stored at −20°C for subsequent radioimmunoassay of insulin (26) and glucagon (27).

After culture and preincubation, 100 islets were added to each of two perfusion chambers by passing between inert polystyrene beads (Bio-Gel 200-400 mesh; Bio-Rad Laboratories, Richmond, CA). This perfusion system has been previously described (28). As a basal perfusion medium, we used the KRBB-albumin-glucose as described above, with the flow rate of 0.4 ml/2 min. The perfusion protocol was started by a 30-min equilibration period with basal medium, followed by a 20-min stimulation period, and finally by a 10-min reperfusion with the basal medium. Arginine at a concentration of 20 mmol/l was used as the stimulus for hormone release. Samples were collected at 2-min intervals, ice-chilled immediately, frozen, and kept at −20°C until analysis (described above).

Perfusion of isolated rat pancreas. Each animal was anesthetized with an intraperitoneal injection of sodium thiopental (100 mg/kg body wt). The pancreata were dissected away from adjacent tissues, as described previously (29). An open, nonrecycling perfusion system was used to administer perfusion medium via a cannula inserted in the abdominal aorta. The perfused pancreas was mounted on the cannula within the perfusion chamber. The temperature in the chamber was maintained at 37°C. Samples of the perfusate emerging from the portal vein were collected at 1-min intervals. The basal perfusion medium consisted of KRBB (in mmol/l: 115 NaCl, 4.7 KCl, 2.6 CaCl2, 1.2 KH2PO4, 1.2 MgSO4, and 20 NaHCO3) supplemented with 3.3 or 5.5 mmol/l glucose and 20 g/l BSA. In one series of experiments, the buffer was supplemented with only 20% of the standard calcium content (Fig. 6). The medium was continuously gassed with a mixture of 95% O2:5% CO2. Pancreata were first perfused with this basal medium for a 20-min equilibration period. During the following 10 min, either 1 μmol/l DC-41-33 or 10 nmol/l SST-14 (Sigma) were added to the perfusion medium, except for control experiments. Arginine (20 mmol/l) was then added for a 20-min stimulation period. Finally, basal medium only was perfused for the last 10 min of the protocol. The flow rate was maintained at 3 ml/min, and variations from 2.8 to 3.2 ml/min were allowed. The hormone release from isolated islets in batch incubation, 100-μl aliquots of incubation medium were stored at −20°C until subsequent radioimmunoassay of insulin (26) and glucagon (27).

RESULTS

Hormone release from isolated islets in batch incubations. In batch incubations of isolated islets at 3.3 mmol/l glucose, DC-41-33 was added at concentrations of 10–200 nmol/l (Fig. 1). This antagonist had a slight but significant stimulatory effect on the insulin response to 20 nmol/l arginine only at concentrations of 100 nmol/l (0.19 ± 0.01 vs. 0.23 ± 0.01 pmol·islet−1·h−1, P < 0.05). At a concentration of ≥100 nmol/l, DC-41-33 markedly stimulated the glucagon response to arginine (26.1 ± 2.9 vs. 76.5 ± 5.8 pg·islet−1·h−1, P < 0.001), and this increase was dose dependent. The two highest doses tested, 1 and 2 μmol/l DC-41-33, enhanced glucagon release by 3.8- and 4.3-fold, respectively.

SST (10–1,000 nmol/l) had no significant effect on the insulin response in batch-incubated islets (Fig. 2 and Table 1) at 20 mmol/l arginine. However, the addition of 2 μmol/l DC-41-33 enhanced the arginine-stimulated insulin response (P < 0.001) in the absence or presence of exogenous SST in the medium. In these experiments, inhibition
GLUCAGON RELEASE AND ISLET SOMATOSTATIN

Table of the effect of DC-41-33 on hormonal responses in the presence of SST, in batch-incubated islets

<table>
<thead>
<tr>
<th>SST (nmol/l)</th>
<th>DC-41-33 (µmol/l)</th>
<th>Insulin (pmol/µl)</th>
<th>Glucagon (pg/µl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.17 ± 0.01</td>
<td>30.8 ± 6.2</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>0.22 ± 0.02*</td>
<td>158.7 ± 11.9*</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0.15 ± 0.01</td>
<td>11.0 ± 1.1</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>0.24 ± 0.02*</td>
<td>138.7 ± 11.7*</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0.14 ± 0.01</td>
<td>13.4 ± 2.5</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>0.20 ± 0.02*</td>
<td>68.1 ± 9.4*</td>
</tr>
<tr>
<td>1,000</td>
<td>0</td>
<td>0.12 ± 0.01</td>
<td>13.3 ± 1.9</td>
</tr>
<tr>
<td>1,000</td>
<td>2</td>
<td>0.17 ± 0.03*</td>
<td>25.2 ± 5.1†</td>
</tr>
</tbody>
</table>

Data were obtained from the batch incubations shown in Fig. 2 and are presented as means ± SE of three experiments (three to five observations per experiment). *P < 0.001 vs. without DC-41-33; †P < 0.001 vs. 0 nmol/l SST + DC-41-33.

The effect of DC-41-33 on hormonal release in perfused pancreas

The effect of DC-41-33 (1 µmol/l) on insulin and glucagon release from isolated perfused rat islets at 3.3 mmol/l glucose. DC-41-33 had no effect on the insulin response to arginine, but enhanced arginine-induced glucagon release by 2.8-fold (area under the curve 3,219.5 ± 403.5 vs. 8,966.9 ± 1,485.7 pg, respectively, P < 0.01).

In the isolated perfused pancreas, 20 mmol/l arginine induced biphasic insulin and glucagon responses at 3.3 and 5.5 mmol/l glucose (Figs. 4 and 5, respectively). DC-41-33 (1 µmol/l) had no effect on insulin release at 3.3 mmol/l glucose (Fig. 4), but it enhanced the second phase of insulin response at 5.5 mmol/l glucose by 34.6% (Fig. 5). This effect was not significant (P = 0.4). The antagonist stimulated glucagon release by 2.5-fold at 3.3 mmol/l glucose and 2.3-fold at 5.5 mmol/l glucose (Table 2). The first phase of glucagon response was not significantly affected by DC-41-33 at either of these two glucose concentrations, while the second phase (4–20 min) was stimulated by 2.7-fold (P < 0.02) and 2.4-fold (P < 0.005) at 3.3 and 5.5 mmol/l glucose, respectively. However, the peak glucagon response at 3.3 mmol/l glucose, achieved at the second minute of arginine stimulation, was enhanced twofold by DC-41-33 (4,735.4 ± 826.8 vs. 9,750.2 ± 1,018.5 pg/min, controls vs. DC-41-33, respectively, P < 0.01) (Fig. 4).

To abolish the release of endogenous SST, we perfused pancreata with buffer supplemented with only 20% of the standard calcium content (30). In these experiments, at 3.3 mmol/l glucose, insulin and glucagon each responded to arginine in a biphasic manner, while DC-41-33 did not significantly affect these hormonal responses (Fig. 6). Addition of 10 nmol/l SST-14 to the perfusate completely abolished the release of insulin and glucagon, both in basal conditions and in the presence of arginine.

Discussion

SST is produced and secreted in various organ systems, such as the endocrine pancreas, gastrointestinal tract, and the brain, where it regulates endocrine and exocrine secretion, cell division, and neurotransmission (31). Of the two endogenous bioactive forms of SST (SST-14 and -28), SST-14 is the predominant form in pancreatic islets (31). Both forms of SST inhibit the secretion of glucagon and insulin, but SST-14 inhibits glucagon release more potently than that of insulin (16). SST exerts its effect on target cells via G-protein–coupled receptors, which are encoded for by five genes. Each of these genes expresses a single protein, except for SSTR2, which has two splice variants, SSTR2a and -b. These differ only in length and amino-acid sequence at the carboxy terminus (19,20,32). An immuno-histochemical study of human islets identified SSTR2 as the predominant subtype expressed in A-cells, and SSTR1 and SSTR5 as the predominant subtypes in B-cells (33). Similarly, such studies in rats localized SSTR2 to the A-cells and SSTR5 to the B-cells (21,22). Also, pharmacological studies in rats utilizing subtype-specific SST agonists demonstrated that SSTR2 mediates the action of SST on A-cells, while SSTR5 carries out this role in B-cells (23,24).

DC-41-33 is a highly specific SSTR2 antagonist (25). In CHO cells transfected with human SSTRs, this compound binds competitively to SSTR2 with a binding affinity (Kᵢ) of 26 ± 3.1 nmol/l and displays selectivity for human SSTR2 over SSTR5 by factor 20 (25). In primary cultures of rat pituitary cells, growth hormone release factor–stimulated
growth hormone release was inhibited by 1 nmol/l SST. This inhibition was potently reversed by DC-41-33, with a half-maximal inhibitory concentration of 2.5 nmol/l (25).

The use of DC-41-33 also allows a dissection of the acute effects of SST in events mediated by SSTR2, such as the inhibition of gastric acid secretion and certain hormonal responses. Hence, in vivo studies have demonstrated that DC-41-33 blocks intravenous SST-induced inhibition of pentagastrin-stimulated acid secretion in conscious rats (34) and reverses urethane-induced SST-mediated inhibition of gastric acid secretion (35).

In the present study, application of DC-41-33 in batch incubations of isolated rat islets induced a dose-dependent enhancement of arginine-stimulated glucagon release (Fig. 1). Furthermore, 2 μmol/l DC-41-33 antagonized the inhibitory action of 10 nmol/l SST on arginine-induced glucagon release. Since this concentration of SST is at least 5- to 50-fold higher than that estimated to be present in islet capillaries and interstitium (10,16), we assumed that 2 μmol/l DC-41-33 should abolish the effect of islet SST on glucagon release in our perfusion experiments (Fig. 3). The lower but nearly equipotent dose, 1 μmol/l, was used in perfused pancreas, because delivery of DC-41-33 was expected to be more efficient by islet microcirculation, which is preserved in this model (Figs. 4–6). Under these experimental conditions, DC-41-33 markedly increased the glucagon response to arginine in both isolated perfused islets and perfused rat pancreas. Since we have used a nonrecycling perfusion and perfusion system, these findings suggest that islet SST regulates glucagon release via a local action in rats. This may apply equally at both fasted and nonfasted conditions, since DC-41-33 enhanced the glucagon response of perfused pancreata to a similar degree at 3.3 and 5.5 mmol/l glucose (2.5- and 2.3-fold, respectively). We do not know whether the octapetide DC-41-33 is able to penetrate the capillary wall and pass into the islet interstitium in these experiments. Therefore,

FIG. 3. The effect of 2 μmol/l DC-41-33 on insulin and glucagon release induced by 20 mmol/l arginine in perifused isolated islets. Results are expressed as mean ± SE of four experiments.

FIG. 4. The effect of DC-41-33 (1 μmol/l) on insulin and glucagon release induced by 20 mmol/l arginine in isolated perfused pancreas at 3.3 mmol/l glucose. Results are expressed as mean ± SE. Controls: n = 6; DC-41-33: n = 4.

FIG. 5. The effect of DC-41-33 (1 μmol/l) on insulin and glucagon release induced by 20 mmol/l arginine in isolated perfused pancreas at 5.5 mmol/l glucose. Results are expressed as mean ± SE. Controls: n = 10; DC-41-33: n = 7.
it is not clear whether SST secreted from D-cells exerts its local effect on A-cells directly via the islet interstitium by paracrine action and/or via the islet microcirculatory system by a short-loop endocrine interaction. The hypothesis that islet SST regulates glucagon release via a local action is supported by the present findings that DC-41-33 failed to stimulate arginine-induced glucagon release in experiments with perfusion medium containing only 20% of the standard calcium content (Fig. 6). This procedure is known to blunt the endogenous SST response (30). Our findings are consistent with the results of a study using batch-incubated islets isolated from SSTR2-knockout mice, in which the glucagon response to arginine and potassium was enhanced twofold, while insulin release was unchanged (36). Furthermore, in a recent in vivo study, administration of another SSTR2-specific antagonist, BIM-23627, increased plasma glucagon levels in 10-day-old, freely moving rats (37).

In the experiments with perfused islets or isolated perfused pancreata at 3.3 mmol/l glucose, blockade of SSTR2 had no effect on insulin release. However, in perfused pancreata at 5.5 mmol/l glucose, DC-41-33 increased the second phase of insulin release by 34.6% (P = 0.4). Although this compound shows 20-fold higher affinity to SSTR2 (A-cells) than SSTR5 (B-cells) (25), it is possible that the antagonist enhanced glucagon as well as insulin release in experiments with higher basal glucose in the perfusate that facilitates SST release. Significant enhancements of insulin secretion occurred in most but not all of our batch incubations of isolated islets at 2 μmol/l DC-41-33. Currently, we have no obvious explanation for a synergistic insulinotropic effect of arginine and glucagon, accumulating in the medium during the 1-h incubation time.

In conclusion, our study demonstrates for the first time the local inhibitory effect of islet SST on arginine-stimulated glucagon release in intact rat islets in vitro. This inhibition is mediated by SSTR2. Further studies are needed to explore the physiological significance and mechanisms of this interaction in rats, as well as in other species.

ACKNOWLEDGMENTS

This work was supported by grants from the Swedish Medical Research Council (K2001-72X-00034-37C), Karolinska Institute, and the Novo-Nordisk Foundation Consortium.

The authors express their appreciation to Anita Nylén, Elvi Sandberg, and Yvonne Strömberg at the Department of Molecular Medicine, Karolinska Institute, for their skillful technical assistance. The authors thank Dr. Neil Portwood for careful reading of the manuscript and suggestions. For help with statistical analyses, the authors thank Agneta Hilding.

REFERENCES

17. Brunincardi FC, Kleinman R, Moldovan S, Nguyen TH, Watt PC, Walsh J,


