Vildagliptin Enhances Islet Responsiveness to Both Hyper- and Hypoglycemia in Patients with Type 2 Diabetes

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Context: Dipeptidyl peptidase-4 inhibitors act by increasing plasma levels of glucagon-like peptide-1 and suppressing excessive glucagon secretion in patients with type 2 diabetes. However, their effects on the glucagon response to hypoglycemia are not established.

Objective: The aim of the study was to assess effects of the dipeptidyl peptidase-4 inhibitor vildagliptin on α-cell response to hyper- and hypoglycemia.

Design: We conducted a single-center, randomized, double-blind, placebo-controlled, two-period crossover study of 28-d treatment, with a 4-wk between-period washout.

Patients: We studied drug-naive patients with type 2 diabetes and baseline glycosylated hemoglobin of 7.5% or less.

Intervention: Participants received vildagliptin (100 mg/d) or placebo as outpatients.

Primary Outcome Measure(s): We measured the following: 1) change in plasma glucagon levels during hypoglycemic (2.5 mM glucose) clamp; and 2) incremental (Δ) glucagon area under the concentration-time curve from time 0 to 60 min ($AUC_{0-60min}$) during standard meal test. Before the study, it was hypothesized that vildagliptin would suppress glucagon secretion during meal tests and enhance the glucagon response to hypoglycemia.

Results: The mean change in glucagon during hypoglycemic clamp was 46.7 $\pm$ 6.9 ng/liter with vildagliptin treatment and 33.9 $\pm$ 6.7 ng/liter with placebo; the between-treatment difference was 12.8 $\pm$ 7.0 ng/liter ($P = 0.039$), representing a 38% increase with vildagliptin. In contrast, the mean glucagon $\Delta AUC_{0-60min}$ during meal test with vildagliptin was 512 $\pm$ 163 ng/liter $\cdot$ min *vs.* 861 $\pm$ 130 ng/liter $\cdot$ min with placebo; the between-treatment difference was -349 ± 158 ng/liter $\cdot$ min ($P = 0.019$), representing a 41% decrease with vildagliptin.

Conclusions: Vildagliptin enhances α-cell responsiveness to both the suppressive effects of hyperglycemia and the stimulatory effects of hypoglycemia. These effects likely contribute to the efficacy of vildagliptin to improve glycemic control as well as to its low hypoglycemic potential. **(*J Clin Endocrinol Metab* 94: 1236–1243, 2009)**

Vildagliptin is a potent and selective dipeptidyl peptidase-4 (DPP-4) inhibitor that improves glycemic control in patients with type 2 diabetes mellitus (T2DM) when given as monotherapy (1–3) or in combination with metformin (4), thiazolidinediones (5, 6), sulfonylureas (7), or insulin (8). By inhibiting DPP-4, vildagliptin increases plasma levels of the intact, active form of glucagon-like peptide-1 (GLP-1) and gastric inhibitory polypeptide (8–13). The glucose-dependent insulinotropic ef-

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Abbreviations: AE, Adverse event; AUC, area under the curve; ΔAUC, incremental AUC; BMI, body mass index; DPP-4, dipeptidyl peptidase-4; FPG, fasting plasma glucose; GLP-1, glucagon-like peptide-1; HbA_{1c}, glycosylated hemoglobin; ISR, insulin secretory rate; OAD, oral antidiabetic drug; PP, pancreatic polypeptide; T2DM, type 2 diabetes mellitus.

fects of both GLP-1 and gastric inhibitory polypeptide, as well as the glucagonostatic effect of GLP-1, are thought to underlie the therapeutic efficacy of vildagliptin (5, 6, 8–13).

The relative contributions of improvements in α- and β-cell function are debatable. However, the correlation between the suppression of the glucagon response to meal ingestion and the improved glucose tolerance after treatment with vildagliptin (9), and the observation that vildagliptin significantly reduced glycosylated hemoglobin (HbA_{1c}) in patients with T2DM treated with high-dose (>80 U/d) insulin monotherapy (8) clearly indicate that the contribution of glucagon suppression is not negligible. Because of the critical role that glucagon plays in the prevention or correction of hypoglycemia (14), it was possible that suppressing glucagon secretion with vildagliptin would predispose insulin-treated patients to hypoglycemia. However, hypoglycemia was less frequent and less severe when vildagliptin was given as an add-on to insulin (*vs.* placebo added to insulin), suggesting that vildagliptin may exert a protective effect against severe hypoglycemia (8). Accordingly, we hypothesized that vildagliptin would increase the glucagon response to hypoglycemia while suppressing glucagon during hyperglycemia in patients with T2DM. To test this hypothesis, the present study was performed with drug-naive patients with T2DM and mild hyperglycemia ($HbA_{1c} \leq 7.5\%$). After 28-d treatment with vildagliptin (100 mg/d) or placebo, standard breakfast meal tests were performed, followed by stepped glucose clamps (7.5, 5.0, and 2.5 mmol/liter glucose).

Patients and Methods

Study design

This was a single-center, double-blind, randomized, placebo-controlled, crossover study of 28-d treatment with vildagliptin (100 mg/d) with a 4-wk between-treatment washout period. Each patient attended one screening visit (wk −4), during which inclusion/exclusion criteria were assessed. Eligible patients were randomized at visit 2 (d 1) and expected to complete two treatment periods, receiving a different blinded study medication during each period (vildagliptin 100 mg/d and placebo, in random order). At the baseline (d 1) visit of each treatment period, HbA_{1c}, fasting plasma glucose (FPG), and baseline safety assessments were made, and study medication was dispensed for 4 wk of outpatient treatment.

The test procedure (see *Study assessments*) was performed after an overnight fast, on d 28 of the first treatment period. Study medication was then discontinued, and a 4-wk washout period occurred before the alternative treatment period. The test procedure was repeated on d 28 of the second treatment period.

Study population

The study enrolled male and female patients (females of child-bearing potential were required to use a medically approved birth control method) aged 18 or older; with a body mass index (BMI) between 22 and 35 kg/m^2, inclusive; and with HbA_{1c} no greater than 7.5%. Enrollment required patients to have been diagnosed with T2DM at least 6 wk before visit 1, to have received no oral antidiabetic drug (OAD) for at least 12 wk before study entry, and to have never received an OAD for more than 3 consecutive months at any time in the past. These patients were considered to be representative of a drug-naive population with mild hyperglycemia.

Patients were excluded if they had a history of type 1 or secondary forms of diabetes, acute metabolic diabetic complications, or evidence of significant diabetic complications. A history of significant cardiac arrhythmia, congestive heart failure (New York Heart Association class III or IV), or liver disease (*i.e.* cirrhosis, chronic active hepatitis) also precluded participation, as did any significant laboratory abnormalities.

Study assessments

The test procedure (performed after overnight fast, following placement of a cannula in an antecubital vein) began with a standard breakfast meal test comprising 180 ml orange juice; two slices (60 g) bread; 30 g jam or preserves; 15 g butter or margarine; 120 ml whole milk (or equivalent amount of cheese plus 120 ml water); and decaffeinated coffee or tea, supplying 500 kcal (60% carbohydrate, 30% fat, 10% protein). This was followed by a three-step hyperinsulinemic clamp (glucose, 7.5, 5.0, and 2.5 mmol/liter; 45 min per step). A baseline blood sample was taken (time, −20 min); then study medication was given 15 min before the meal was provided (time, 0 min). A premeal blood sample was obtained (time, −5 min), and the meal was consumed in 10 min. During the meal test, samples for determination of glucose, glucagon, insulin, and C-peptide were obtained at times −20, −5, 15, 30, 45, 60, 90, 115, and 120 min (with time 120 min serving as baseline for the hyperglycemic step of the clamp). Samples for measurement of intact (active) GLP-1 were obtained at times −20, 30, 60, and 90 min. No further samples were obtained due to limitations on the volume of blood withdrawn.

For the stepped clamp, patients received a primed, continuous infusion of insulin (600 pmol/m^2/min, 0–4 min; 500 pmol/m^2/min, 4–7 min; 400 pmol/m^2/min, 7–10 min; and 300 pmol/m^2/min thereafter), with glucose infused at a variable rate to achieve three glycemic plateaus: 1) hyperglycemic step of 45 min at 7.5 mmol/liter glucose (times, 120 to 165 min); 2) euglycemic step of 45 min at 5.0 mmol/liter glucose (times, 165 to 210 min); and 3) hypoglycemic step of 45 min at 2.5 mmol/liter glucose (times, 210 to 255 min). After the hypoglycemic step, the insulin infusion was discontinued; glucose was infused if necessary, so that all subjects "began" recovery with a plasma glucose level of 3.2 mmol/liter; subsequently, plasma glucose levels were allowed to recover.

In addition to frequent samples for real-time glucose measurements used to adjust the glucose infusion rate [performed by the glucose dehydrogenase technique with a HemoCue device (HemoCueAB, Ängelholm, Sweden)], during the stepped clamps, samples for determination of glucose were obtained every 5 min from time 120 to 255 min, then at 10-min intervals until time 315 min. Samples for measurement of insulin, glucagon, and C-peptide were obtained at times 120, 135, 150, 165, 180, 195, 210, 225, 240, 255, 270, and 285 min. Additionally, during the hypoglycemic step, samples for measurement of epinephrine, norepinephrine, cortisol, and pancreatic polypeptide (PP) were obtained at times 210, 225, 240, 255, and 285 min.

HbA_{1c} and FPG were measured on d 1 and d 28 of both treatment periods. Vital signs and body weight were measured, and safety laboratory assessments were made at every study visit.

Assays

All assessments of samples obtained during the test procedure, except GLP-1, catecholamines, and cortisol, were made at Lund University. Plasma glucose was measured with the glucose oxidase method. Glucagon concentrations were analyzed with double-antibody RIA using guinea pig antihuman glucagon antibodies specific for pancreatic glucagon. Insulin concentrations were analyzed with double-antibody RIA technique using guinea pig antihuman insulin antibodies. PP was determined with double-antibody RIA using rabbit antihuman PP antibodies (all materials were from Linco Research Inc., St. Charles, MO). Norepinephrine and epinephrine concentrations were determined by HPLC. Cortisol was determined with the Beckman Coulter Access Immunoassay System (Fullerton, CA). These analyses were performed by the Department of Clinical Chemistry, University Hospital, Malmö.

GLP-1 was measured at Wuxi PharmaTech Co. (Shanghai, China) by ELISA with an N-terminally directed antiserum, thus detecting only intact, biologically active GLP-1. HbA_{1c}, FPG, and safety laboratory assessments were made by Covance (Geneva, Switzerland). Assays were

performed according to standardized and validated procedures and good laboratory practice.

Data analysis

The insulin secretory rate (ISR) was estimated by deconvolution of C-peptide levels. From samples obtained during the standard meal test, the total and incremental areas under the curve (AUC and ΔAUC) for the times 0 to 60 min, 0 to 90 min, and 0 to 120 min were calculated by the trapezoidal method for all analytes. Insulin secretion corrected for glucose (ISR/G = ISR AUC ÷ glucose AUC) was used as an index of β-cell function. During the hypoglycemic clamp step, the change from baseline (time, 210 min) to endpoint (time, 255 min) was calculated for all analytes. During the euglycemic and hypoglycemic clamp steps, insulin sensitivity was estimated by the glucose infusion rate divided by the mean plasma insulin level.

Between-treatment differences in each of the aforementioned variables were made with paired *t* tests in the completers population. Because the "direction" of change in each parameter was predicted (hypothesized) before study inception, one-sided tests were performed with a 0.05 significance level.

Ethics and good clinical practice

The protocol was approved by the ethics committee of Lund University, Sweden, and all subjects gave written informed consent before entering the study. The study was conducted using good clinical practice and in accordance with the Declaration of Helsinki.

Results

Patients studied

Thirty-two patients were screened, 30 were randomized (15 to each treatment sequence), and 25 patients comprised the completers population, defined as all randomized patients who received at least one dose of study drug and had a valid assessment of the primary variable at the end of each treatment period. Of the 30 randomized patients, two had no valid primary efficacy assessment during the double-blind treatment period, two had only one valid primary efficacy assessment during the double-blind treatment period, and one had hyperglucagonemia (premeal glucagon levels >200 ng/liter during both treatment periods); thus, these five subjects were excluded from the completers population. Table 1 summarizes the demographic and baseline characteristics of the completers population.

Patients were all Caucasian and predominantly male, with a mean age, BMI, disease duration, and baseline HbA_{1c} of approximately 66 yr, 28 kg/m^2, 6 yr, and 6.3%, respectively. Patients randomized to treatment sequence A (vildagliptin, then placebo) had somewhat higher baseline levels of HbA_{1c} and FPG and somewhat longer disease duration than did patients randomized to treatment sequence B (placebo, then vildagliptin). However, these modest differences should be of no significance because every patient received both treatments, and there was a 4-wk washout period between treatments.

Standard meal tests

Figure 1 depicts the time courses of glucose, GLP-1, glucagon, and ISR during the standard meal test that was performed immediately before the stepped glucose clamp. It may be appreciated that relative to placebo, vildagliptin treatment was associated with lower FPG and postprandial glucose levels and fasting and postprandial glucagon levels, with greatly enhanced fasting and postprandial plasma levels of intact GLP-1, but essentially no effect on absolute ISR.

Table 2 summarizes the integrated responses to the standard meal. Vildagliptin significantly increased the GLP-1 response and significantly decreased the glucagon response to meals, whether expressed as total secretion or the incremental response, integrated over the first hour of sampling or the entire postmeal sampling period. Similarly, postprandial glucose levels were significantly decreased during vildagliptin treatment.

The incremental ISR was significantly increased when integrated over the first 60 min, but the absolute ISR was unaffected if the total AUC was considered, regardless of the time interval used, and the incremental insulin response integrated over the 2-h postmeal period showed only a slight trend toward an increase with vildagliptin *vs.* placebo administration. In contrast, insulin secretion relative to glucose was significantly increased, whether integrated over the first 60 min or the entire 2-h postmeal sampling period, and whether the total responses or the incremental responses were considered. Again, the percentage

TABLE 1. Demographic and baseline characteristics of the completers population

	Sequence A (vildagliptin 100 mg qd/ placebo)	Sequence B (placebo/vildagliptin 100 mg qd)	All
n	14	11	25
Age (yr)	66.6 ± 6.4	64.1 ± 3.7	65.5 ± 5.4
Age category			
<65 yr	5 (35.7)	6 (54.5)	11 (44.0)
≥65 yr	9 (64.3)	5 (45.5)	14 (56.0)
Males	13 (92.9)	9 (81.8)	22 (88.0)
Caucasian	14 (100.0)	11 (100.0)	25 (100.0)
BMI (kg/m^2)	28.1 ± 2.7	27.6 ± 3.5	27.9 ± 3.0
HbA_{1c} (%)	6.4 ± 0.6	6.2 ± 0.6	6.3 ± 0.6
Median (min, max)	6.6 (5.3, 7.1)	6.2 (5.3, 7.3)	6.25 (5.6, 9.3)
FPG (mmol/liter)	7.7 ± 1.2	7.2 ± 0.7	7.5 ± 1.0
Median (min, max)	8.0 (5.6, 9.3)	7.3 (5.9, 8.4)	7.35 (5.6, 9.3)
Disease duration (yr)	6.7 ± 7.9	4.2 ± 4.0	5.6 ± 6.5

Data are expressed as mean ± SD or number (percent). Min, Minimum; max, maximum.

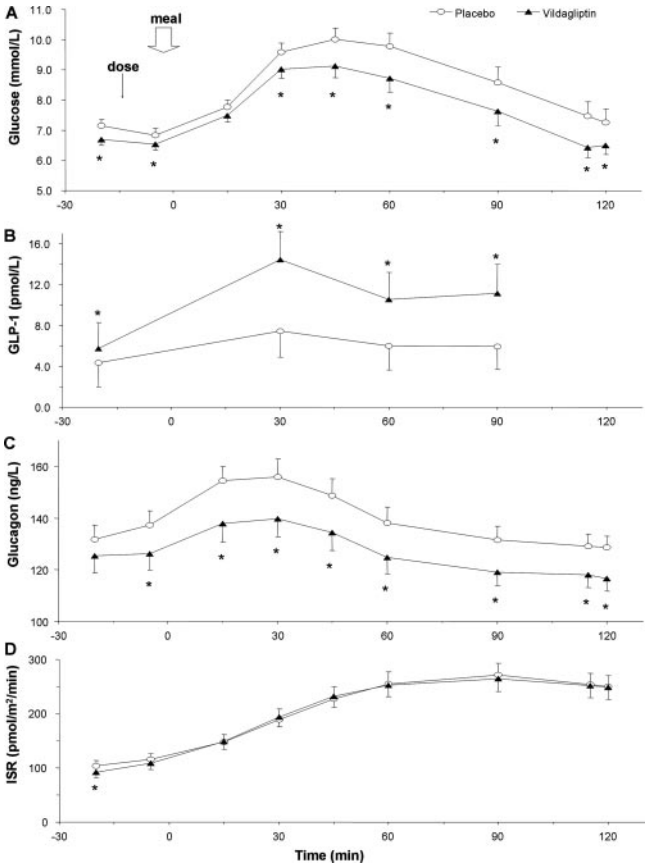

FIG. 1. Plasma glucose (A), GLP-1 (B), glucagon (C), and ISR (D) during standard breakfast meal tests performed on d 28 of treatment with vildagliptin (*closed triangles*) or placebo (*open circles*). Mean ± SE, n = 25 per treatment. *, $P <$ 0.05 or better *vs.* placebo.

changes in the incremental AUCs were greater than the percentage changes in the total AUCs.

Hyperinsulinemic stepped glucose clamps

Figure 2 depicts plasma glucose and glucagon levels and the ISR during the hyperinsulinemic stepped glucose clamps initiated immediately after the standard meal tests on d 28 of both treatment periods. It can be seen that, although plasma glucose levels were significantly lower in the vildagliptin treatment period during the hyperglycemic step, plasma glucose levels were well matched during the euglycemic and hypoglycemic steps, and plasma glucose levels recovered in less than 1 h in both treatment periods. Plasma glucagon levels were suppressed during the hyperglycemic step in the vildagliptin treatment period, despite significantly lower plasma glucose levels, and remained suppressed during the euglycemic step. However, during the hypoglycemic clamp step, plasma glucagon levels increased from a significantly lower level at time 210 min, to a level slightly higher and not significantly different at the end of the hypoglycemic clamp (time, 255 min) during vildagliptin treatment when compared with placebo administration. Thus, as reported in Table 3, the increase in glucagon during hypoglycemia with vildagliptin (change = 46.7 ± 6.9 ng/liter) was significantly greater than the increase during hypoglycemia with placebo (change = 33.9 ± 6.7 ng/liter; $P = 0.039$ *vs.* vildagliptin).

The ISR was significantly higher during vildagliptin treatment from times 165 to 255 min of the stepped clamp (*i.e.* during euglycemia and hypoglycemia) (Fig. 2). However, during hypoglycemia with vildagliptin treatment, ISR decreased from 151.5 to 81.9 pmol/m^2/min (change = −69.6 ± 6.6 pmol/m^2/min), whereas with placebo during hypoglycemia, ISR decreased from 134.0 to 71.7 pmol/m^2/min (change = −62.3 ± 6.9 pmol/m^2/min; $P = 0.011$ *vs.* vildagliptin; Table 3). Additionally, insulin sensitivity as quantified by the glucose infusion rate/mean insulin level was significantly greater during the euglycemic step with vildagliptin (0.73 ± 0.46 mg · liter/pmol · min) than with placebo (0.62 ± 0.46 mg · liter/pmol · min; $P = 0.011$). Insulin sensitivity was unchanged during the hypoglycemic clamp step (data not shown).

Table 3 summarizes the changes from time 210 to time 255 min in plasma glucagon, ISR, and plasma epinephrine, norepinephrine, cortisol, and PP (*i.e.* the pancreatic, sympathoadrenal, and parasympathetic nervous system responses to hypoglycemia). The increase in plasma glucagon during hypoglycemia was significantly greater, and the suppression of insulin secretion was significantly more pronounced during vildagliptin than placebo administration. The between-treatment differences in the hypoglycemia-induced changes in glucagon and insulin secretion represent a 38% increase in the α-cell response (*i.e.* increase in glucagon) and a 12% increase in the β-cell response (*i.e.* suppression of ISR) with vildagliptin relative to placebo. Although the sympathoadrenal responses (epinephrine, norepinephrine, and cortisol) to hypoglycemia did not differ between treatment periods, there was a strong trend toward enhanced PP release during hypoglycemia with vildagliptin *vs.* placebo (between-treatment difference = 51.6 ± 31.5 pmol/liter; $P = 0.057$).

Glycemic control

Four-week treatment with vildagliptin also improved glycemic control, despite low baseline levels of HbA_{1c} (~6.3%). In patients receiving placebo, FPG increased (Δ = 0.3 ± 0.1 mmol/liter), whereas FPG decreased in patients receiving vildagliptin (Δ = −0.5 ± 0.1 mmol/liter; $P < 0.001$ *vs.* placebo). Similarly, HbA_{1c} increased slightly in patients receiving placebo (Δ = 0.1 ± 0.1%) and decreased in those receiving vildagliptin (Δ = −0.2 ± 0.1%; $P = 0.002$ *vs.* placebo).

Safety and tolerability

The overall adverse event (AE) profiles during treatment with vildagliptin were similar to those during placebo administration. No specific AE was reported by more than three patients during either treatment period, and the only AE reported by three patients was nasopharyngitis, which occurred during both treatment periods (*i.e.* during placebo and during vildagliptin). No serious AE was experienced by any patient during vildagliptin treatment; during placebo administration, three patients experienced a serious AE: one case of appendicitis, one of infective arthritis, and one myocardial infarction. Discontinuations due to an AE were limited to one case of decreased appetite in a patient receiving vildagliptin and the myocardial infarction experienced by a patient receiving placebo. There were no hypoglycemic events or occurrences of asymptomatic low blood glucose reported during either treatment.

TABLE 2. Integrated responses to meals

	Placebo (n = 25)	Vildagliptin (n = 25)	*P* value[a]	% Change
GLP-1 (pmol/liter · min)				
Total AUC_{0-60}	379 ± 101	678 ± 159	0.012	+79
ΔAUC_{0-60}	119 ± 106	334 ± 37	0.036	+180
Total AUC_{0-90}	558 ± 155	1,003 ± 240	0.002	+80
ΔAUC_{0-90}	169 ± 108	488 ± 52	0.008	+89
Glucagon (ng/liter · min)				
Total AUC_{0-60}	8,930 ± 356	8,060 ± 403	0.007	−10
ΔAUC_{0-60}	861 ± 130	512 ± 163	0.019	−41
Total AUC_{0-120}	16,878 ± 650	15,244 ± 713	0.005	−9
ΔAUC_{0-120}	740 ± 242	148 ± 274	0.025	−80
Glucose (mmol/liter · min)				
Total AUC_{0-60}	535 ± 17	499 ± 17	0.001	−7
ΔAUC_{0-60}	125 ± 8	107 ± 8	0.007	−15
Total AUC_{0-120}	1,048 ± 93	952 ± 40	<0.0001	−9
ΔAUC_{0-120}	227 ± 22	168 ± 22	<0.0001	−26
ISR (pmol/m^2)				
Total AUC_{0-60}	11,258 ± 1,051	11,349 ± 1,028	0.418	+1
ΔAUC_{0-60}	4,295 ± 486	4,797 ± 384	0.043	+12
Total AUC_{0-120}	26,976 ± 2,282	26,846 ± 2,372	0.448	−1
ΔAUC_{0-120}	10,351 ± 1,143	13,908 ± 1,116	0.167	+7
ISR/G (β-cell function, pmol/m^2/mM)				
Total AUC_{0-60}	21.7 ± 2.2	23.4 ± 2.3	0.039	+8
ΔAUC_{0-60}	37.5 ± 4.7	54.5 ± 7.2	<0.0001	+45
Total AUC_{0-120}	2.7 ± 2.5	29.1 ± 2.7	0.037	+9
ΔAUC_{0-120}	75.7 ± 11.7	151.5 ± 42.5	0.037	+100

Data represent mean ± SE.

[a] By one-tailed paired *t* test (for absolute, not percentage change).

Discussion

Glucagon secretion is stimulated by hypoglycemia and suppressed by hyperglycemia; in healthy subjects, the glycemic threshold for stimulation of glucagon release is approximately 4 mmol/liter. Numerous factors in addition to glucose can influence glucagon secretion and potentially contribute to the pathophysiology of glucagon secretion that occurs in T2DM (15). For example, epinephrine, sympathetic and parasympathetic neurotransmitters, amino acids, and several gut hormones (*e.g.* cholecystokinin, gastrin-releasing peptide) stimulate glucagon secretion, whereas free fatty acids and ketones, gut hormones (*e.g.* GLP-1, secretin), as well as locally released insulin and pancreatic somatostatin inhibit glucagon secretion. Indeed, it has been suggested that locally released insulin mediates the suppressive effects of hyperglycemia on glucagon secretion (16).

Abnormalities of glucagon secretion occur in patients with impaired glucose tolerance and T2DM, and most abnormalities, if not all, may actually reflect an impairment of α-cell glucose sensing (*i.e.* an impaired ability of glucose to suppress glucagon secretion) (15, 17, 18).

A new class of OADs, the DPP-4 inhibitors, has been developed for the treatment of T2DM (19). The efficacy of DPP-4 inhibitors, such as vildagliptin, is attributable in part to a GLP-1-mediated glucagonostatic effect (10, 11, 20). However, if these agents suppressed glucagon secretion under all conditions, they could predispose patients to hypoglycemia; this, however, has not been observed. In fact, all clinical experience with DPP-4 inhibitors to date suggests that they have a low propensity to induce hypoglycemia. An earlier study in healthy volunteers suggested that short-term infusion of the incretin mimetic exenatide augmented the glucagon response to severe hypoglycemia (21), and another study found that vildagliptin added to high-dose insulin therapy in patients with T2DM actually decreased the incidence and severity of hypoglycemia (8). Consequently, we hypothesized that vildagliptin would enhance the ability of the α-cell to sense and respond appropriately to changes in plasma glucose concentrations.

To test this hypothesis, we examined the influence of 28-d treatment with vildagliptin (100 mg/d) on the glucagon response to both hyperglycemia and hypoglycemia in patients with T2DM and mild hyperglycemia (HbA_{1c} = 6.3%). As expected and shown previously (9–12), vildagliptin suppressed inappropriate glucagon secretion during meals. Furthermore, plasma glucagon levels remained suppressed not only during the hyperglycemic step, but also during the euglycemic step of the clamp. Thus, the enhanced response to hypoglycemia during vildagliptin treatment reflected solely the significantly lower initial levels (at time 210 min). Nonetheless, the present finding of an increase from a significantly lower level to a slightly higher glucagon level during the hypoglycemic step with vildagliptin *vs.* placebo clearly indicates that the α-cell response to hypoglycemia was not impaired. Indeed, the finding that the increment in plasma glucagon concentrations during hypoglycemia with vildagliptin was 38% higher than with placebo could be interpreted as an enhanced response. Because the duration of each glucose step was only 45 min and an apparent "steady-state" hypoglycemia was maintained for only 10 min, it remains to be determined whether a more sustained period of hypoglycemia would reveal a truly en-

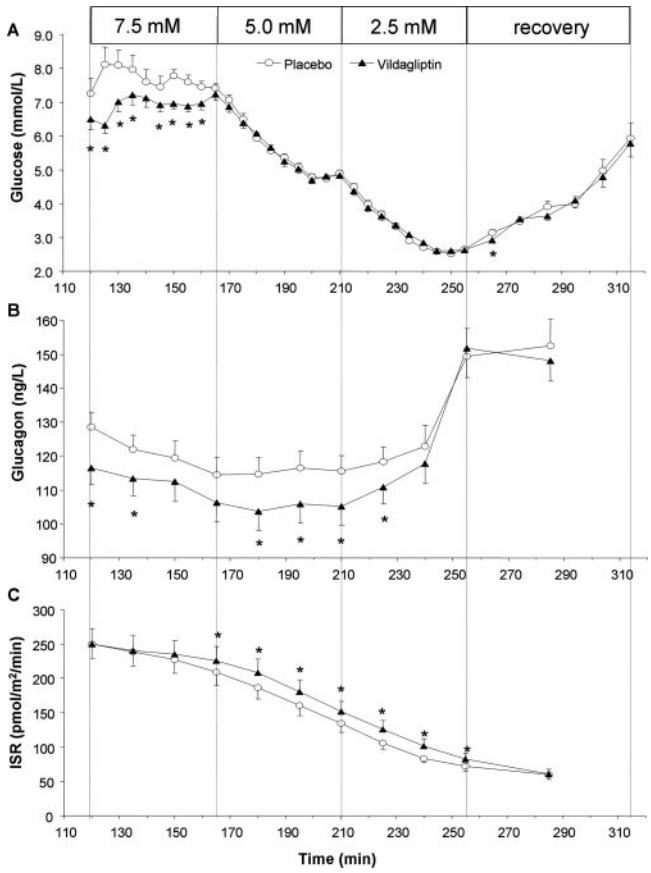

FIG. 2. Plasma glucose (A), glucagon (B), and ISR (C) during hyperinsulinemic, stepped glucose clamps performed on d 28 of treatment with vildagliptin (*closed triangles*) or placebo (*open circles*). Mean ± SE, n = 25 per treatment. *, $P <$ 0.05 or better *vs.* placebo.

hanced response with significantly higher glucagon levels with vildagliptin *vs.* placebo.

Several additional findings from this study may shed light on the mechanisms underlying the greater increase in glucagon with vildagliptin *vs.* placebo. During the hypoglycemic step of the clamp, the timing and degree of hypoglycemia were essentially identical during the two treatment periods, and the increases in epinephrine, norepinephrine, and cortisol also were unaffected by vildagliptin treatment. This suggests that, as intended, equivalent "stress" was induced by hypoglycemia during the two treatment periods. However, activation of the parasympathetic nervous system appears to have been augmented by vildagliptin treatment. Circulating PP levels are considered to be an index of parasympathetic nervous system activity (22), and, in the present study, the mean PP response to hypoglycemia increased by more than 80% during vildagliptin treatment; the trend approached, but did not achieve, statistical significance.

The strong trend toward an increase in the PP response to hypoglycemia with vildagliptin treatment suggests that increased vagal activity may mediate, or contribute to, the enhanced glucagon response. This would be consistent with the growing body of literature suggesting that many of the actions often ascribed to circulating GLP-1 may in fact be mediated by neuronal mechanisms (23–28).

The present study also found that the decrease of ISR during hypoglycemia was more pronounced with vildagliptin than with placebo, *i.e.* ISR decreased from a significantly higher level at time 210 min to an identical level at 285 min, with the change (reduction) in ISR during hypoglycemia being significantly greater with vildagliptin than with placebo. To our knowledge, this is the first demonstration that an agent presumably acting through GLP-1 receptor signaling enhances the effectiveness of low glucose levels to suppress insulin secretion. Although some would argue that this observation supports the concept that glucose control of glucagon secretion is mediated by local insulin levels (29–31), we have recently shown that vildagliptin suppresses postprandial glucagon levels in insulinopenic patients with type 1 diabetes (32). Thus, although enhanced suppression of insulin secretion may have contributed to the enhanced glucagon response to hypoglycemia seen with vildagliptin treatment, understanding the mechanisms underlying the effects on both insulin and glucagon secretion will require further study. Independent of the exact underlying mechanisms, the present study provides evidence that DPP-4 inhibition with vildagliptin improves (or restores) the ability of both α- and β-cells to sense and respond appropriately to changes in plasma glucose levels.

Vildagliptin (100 mg/d) was efficacious at decreasing FPG and HbA_{1c} as in all previous studies of more than 4-wk duration (1–3, 6–9, 33–36). In addition, as in previous trials, vildagliptin generally increased plasma levels of intact GLP-1, reduced prandial glucose and glucagon, and increased insulin secretion relative to glucose when these measures were made. These changes were judged to be independent of the patient's severity of disease or treatment duration (9–11, 13, 37–40).

In summary, the present study demonstrated that in patients with T2DM, the DPP-4 inhibitor vildagliptin improved the ability of both α- and β-cells to sense and respond appropriately to hypoglycemia. The concurrent strong trend toward an increased

TABLE 3. Pancreatic, sympathoadrenal, and parasympathetic responses (from time 210 min to time 255 min) to hypoglycemia

	Placebo (n = 25)	Vildagliptin (n = 25)	Difference	*P* value[b]
Glucagon (ng/liter)	33.9 ± 6.7	46.7 ± 6.9	12.8 ± 7.0	0.039
ISR (pmol/m²/min)	−62.3 ± 6.9	−69.6 ± 6.6	−7.3 ± 3.0	0.011
Epinephrine (nmol/liter)	2.12 ± 0.51	2.00 ± 0.42	−0.12 ± 0.29	0.684
Norepinephrine (nmol/liter)	0.99 ± 0.19	0.67 ± 0.30	−0.32 ± 0.30	0.305
Cortisol (nmol/liter)	76.6 ± 22.7	88.4 ± 24.3	11.9 ± 22.8	0.607
PP (pmol/liter)	63.2 ± 14.6	114.8 ± 29.3	51.6 ± 31.5	0.057

Data represent mean ± SE.

[a] By paired *t* test.

PP response to hypoglycemia suggests that vagal mechanisms may be involved. Improved islet glucose sensing/responsiveness likely underlies the low propensity of DPP-4 inhibitors to elicit hypoglycemia.

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This trial (NCT00390520) is registered with ClinicalTrials.gov.

Disclosure Summary: B.A. has consulted for Novartis A/S, GlaxoSmithKline, Merck, Sanofi Aventis, and Astra Zeneca and has received lecture fees from Novartis A/S and GlaxoSmithKline. A.S. is an employee of and holds stock in Novartis. S.D. is an employee of Novartis. B.E.D. has nothing to declare. P.M.N. declares having been a consultant for Novartis. M.P. has nothing to declare. J.E.F. is an employee of and holds stock in Novartis.

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