

# Improved Glycemic Control With No Weight Increase in Patients With Type 2 Diabetes After Once-Daily Treatment With the Long-Acting Glucagon-Like Peptide 1 Analog Liraglutide (NN2211)

A 12-week, double-blind, randomized, controlled trial

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**CONCLUSIONS** — A once-daily dose of liraglutide provides efficacious glycemic control and is not associated with weight gain. Adverse events with the drug are mild and transient, and the risk of hypoglycemia is negligible.

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**OBJECTIVE** — Liraglutide is a long-acting glucagon-like peptide 1 analog designed for once daily injection. This study assessed the efficacy and safety of liraglutide after 12 weeks of treatment in type 2 diabetic patients.

**RESEARCH DESIGN AND METHODS** — A double-blind, randomized, parallel-group, placebo-controlled trial with an open-label comparator arm was conducted among 193 outpatients with type 2 diabetes. The mean age was 56.6 years and the mean HbA<sub>1c</sub> was 7.6% across the treatment groups. Patients were randomly assigned to one of five fixed-dosage groups of liraglutide (0.045, 0.225, 0.45, 0.60, or 0.75 mg), placebo, or open-label sulfonylurea (glimepiride, 1–4 mg). The primary end point was HbA<sub>1c</sub> after 12 weeks; secondary end points were fasting serum glucose, fasting C-peptide, fasting glucagon, fasting insulin,  $\beta$ -cell function, body weight, adverse events, and hypoglycemic episodes.

**RESULTS** — A total of 190 patients were included in the intention-to-treat (ITT) analysis. HbA<sub>1c</sub> decreased in all but the lowest liraglutide dosage group. In the 0.75-mg liraglutide group, HbA<sub>1c</sub> decreased by 0.75 percentage points ( $P < 0.0001$ ) and fasting glucose decreased by 1.8 mmol/l ( $P = 0.0003$ ) compared with placebo. Improvement in glycemic control was evident after 1 week. Body weight decreased by 1.2 kg in the 0.45-mg liraglutide group ( $P = 0.0184$ ) compared with placebo. The proinsulin-to-insulin ratio decreased in the 0.75-mg liraglutide group ( $-0.18$ ;  $P = 0.0244$ ) compared with placebo. Patients treated with glimepiride had decreased HbA<sub>1c</sub> and fasting glucose, but slightly increased body weight. No safety issues were raised for liraglutide; observed adverse events were mild and transient.

Type 2 diabetes is characterized by insulin resistance and defective  $\beta$ -cell function and is associated with hyperglucagonemia, increased hepatic glucose production, and obesity (1). In addition, patients with type 2 diabetes experience a subnormal secretion of the incretin hormone glucagon-like peptide 1 (GLP-1) during meals (2,3). Sulfonylureas, although efficient in stimulating insulin secretion and lowering blood glucose, pose the disadvantages of weight gain and risk of hypoglycemia (4). Studies have demonstrated that GLP-1 stimulates insulin secretion, inhibits glucagon secretion in a glucose-dependent manner, and delays gastric emptying (2,5–7). In addition, several studies have shown GLP-1 to have an appetite-reducing effect (8–10), and one study has demonstrated weight loss after treatment with GLP-1 (11). These mechanisms make this hormone an attractive candidate for the treatment of type 2 diabetes. However, native GLP-1 has a very short half-life (1 min) (12), being rapidly metabolized by the enzyme dipeptidyl peptidase IV (13). It has been shown that GLP-1 must be present continuously in the blood stream to exert its actions (14).

Liraglutide is a long-acting, acylated GLP-1 analog, acting as a full agonist toward the GLP-1 receptor (15). Studies in animals and humans have demonstrated promising blood glucose-lowering ef-

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**Abbreviations:** GLP-1, glucagon-like peptide 1; HOMA, homeostasis model assessment; ITT, intention to treat; OHA, oral hypoglycemic agent.

A table elsewhere in this issue shows conventional and Système International (SI) units and conversion factors for many substances.

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fects as well as a favorable safety profile. The half-life of liraglutide is  $\sim 12$  h in both healthy subjects and type 2 diabetic patients after single and multiple dosing (16–18). The dosing regimen is a once daily injection. This trial investigated the efficacy and safety of liraglutide after 12 weeks of treatment in type 2 diabetic patients.

## RESEARCH DESIGN AND METHODS

This trial was a 12-week, multicenter, double-blind, randomized, parallel-group, dosage-response trial in six treatment arms. In addition, an open-label sulfonylurea (glimepiride) arm was included as a reference group. Patients were instructed to maintain their diet, exercise program, and daily routines during the course of the trial. After a 4-week wash-out period during which current oral hypoglycemic agent (OHA) treatment was discontinued, patients were equally randomized to double-blind treatment of one of six arms (one of five dosages of liraglutide or placebo) or to the open-label reference group (glimepiride). The trial was conducted between December 2000 and October 2001 in Scandinavia and the U.K. The trial was conducted in accordance with the Helsinki Declaration (19), and the protocol was approved by each institution's independent ethics committee. The trial was explained to all patients, and their written informed consent was obtained before any trial-related procedures were initiated.

Eligible patients were men and women age  $\geq 30$  years who had a type 2 diabetes diagnosis (according to American Diabetes Association criteria) (20), had BMI  $\leq 40$  kg/m<sup>2</sup>, were being treated with diet or an OHA, and had an HbA<sub>1c</sub>  $\leq 9.5\%$  (OHA) or 7.5–10.0% (diet). For patient safety, an upper limit for HbA<sub>1c</sub> was defined as a 4-week wash-out period and a placebo arm was included in the trial. Patients were excluded if any of the following were present: liver or renal disease, heart failure (New York Heart Association class III and IV) (21), unstable angina pectoris, myocardial infarction within the previous 12 months, concomitant treatment with thiazolidinediones or other investigational drugs, or other significant conditions likely to affect a patient's diabetes and/or ability to complete the trial. Women who were pregnant, breast-feeding, or not using an adequate method of contraception were also ex-

cluded. At randomization, fasting blood glucose had to be 6–13 mmol/l. Patients were withdrawn from the trial if fasting plasma glucose was  $>15$  mmol/l.

In total, 311 patients were screened and 193 patients were randomized to a treatment group (Table 1). The reasons for failing screening were not meeting any inclusion criteria or meeting any exclusion criteria ( $n = 86$ ), not meeting randomization criteria ( $n = 7$ ), withdrawn consent ( $n = 6$ ), and other ( $n = 19$ ). The majority of patients ( $n = 158$ ) were being treated with OHA(s) and the remaining 35 patients were being treated with diet only. Most patients were on monotherapy with either metformin (65 patients) or sulfonylureas (55 patients); 22 patients received a combination of metformin and sulfonylureas, 14 patients received repaglinide, and 2 patients received acarbose treatment. In all, 190 patients were exposed to the experimental protocol; 3 patients withdrew consent before receiving randomized treatment.

Patients were recruited from the participating investigators' outpatient clinics or by local advertisements. Each patient was seen on seven occasions: screening; baseline; after 1, 4, 8, and 12 weeks of treatment; and follow-up. Current treatment with oral antidiabetic medication was discontinued at screening. Patients were supplied with a blood glucose meter (One Touch Profile Glucometer) and instructed in its use. Fasting blood glucose was measured every morning. HbA<sub>1c</sub>, fasting serum glucose, insulin, C-peptide, and glucagon were measured every 4 weeks. Fasting serum glucose was also measured after the first week of treatment. Proinsulin was assessed in a subset of patients ( $n = 74$ , equally distributed among the groups). Fasting samples were obtained before administration of the trial drug. Safety parameters (adverse events, hypoglycemic episodes, weight, standard hematology and biochemistry profile, vital signs, and electrocardiogram) were assessed at each visit. Liraglutide antibodies were measured before and after treatment.

The trial was double blind for the five dosage levels of liraglutide and placebo, and open label for glimepiride. The blindness was kept until database release.

Liraglutide and placebo (Novo Nordisk A/S, Bagsvaerd, Denmark) were administered as a once-daily injection (subcutaneously) in the morning before

breakfast. The five dosages of liraglutide administered were 0.045, 0.225, 0.45, 0.60, and 0.75 mg. These dosages were chosen based on observations from previous trials (16–18). In one of those trials, a single dose of 10  $\mu$ g/kg (corresponding to  $\sim 0.80$  mg) showed significant effects on glycemia, but 2 of 11 patients reported nausea (18). Further, once-daily dosing for 7 days showed a 40% increase in C<sub>max</sub> in the steady state (17). Therefore, to avoid causing unacceptable side effects, the highest dosage included in this trial was 0.75 mg, corresponding to 7.5  $\mu$ g/kg (equivalent to 10.5  $\mu$ g/kg in steady state) for a person weighing 100 kg. The lowest dosage of 0.045 mg was considered too low to have any significant effect on glycemic control. Glimepiride (Amaryl; Aventis Pharma, Frankfurt, Germany) was supplied as 1- and 2-mg tablets for oral use, with the dosage adjusted according to glycemic control during the first 4 weeks, with the aim to achieve a fasting plasma glucose level  $<7$  mmol/l. The mean glimepiride dosage during the trial was 2.7 mg. Compliance was assessed by drug accountability and plasma concentration measurements.

## Analytic methods

HbA<sub>1c</sub> was analyzed with a Unimate HbA<sub>1c</sub> assay (Roche Diagnostics; normal range 4.5–5.7%). Liraglutide antibodies were determined by a radioimmunoassay developed by the Department of Immunochimistry at Novo Nordisk A/S. The serum concentrations of insulin, C-peptide, and proinsulin were analyzed by enzyme-linked immunosorbent assay methods. Plasma glucagon was analyzed by MDS Pharma Services (Wangen, Switzerland) using a radioimmunoassay (Linco Research, St. Charles, MO). Standard laboratory analyses were performed by a central laboratory (Novo Medical Medi-Lab, Clinical Trials Lab, Copenhagen, Denmark, if not otherwise stated).

## Statistical analysis

Pretrial calculation showed that a two-sided test of the highest dosage versus the placebo group required 30 patients per group to detect a difference in mean HbA<sub>1c</sub> of at least 1% unit with 5% significance and 95% power.

The primary end point HbA<sub>1c</sub>, as well as secondary end points (fasting serum glucose, fasting C-peptide, glucagon, insulin, homeostasis model assessment

Table 1—Patient disposition and characteristics

	Placebo	Liraglutide					Glimepiride	Total
		0.045 mg	0.225 mg	0.45 mg	0.60 mg	0.75 mg		
Patient disposition								
Screened	—	—	—	—	—	—	—	311
Screening failures	—	—	—	—	—	—	—	118
Nonfulfillment of any inclusion/exclusion criteria	—	—	—	—	—	—	—	86
Not meeting randomization criterion	—	—	—	—	—	—	—	7
Withdrew consent	—	—	—	—	—	—	—	6
Other	—	—	—	—	—	—	—	19
Randomized	29	26	25	27	30	29	27	193
Exposed	29	26	24	27	30	28	26	190
Withdrawals	5	3	3	7	2	2	0	22
Adverse events	0	0	1	0	1	1	0	3
Ineffective therapy	3	2	1	4	1	1	0	12
Other	2	1	1	3	0	0	0	7
Completed	24	23	21	20	28	26	26	168
Included in ITT population	29	26	24	27	30	28	26	190
Baseline characteristics								
Age (years)	57 ± 9.4	53 ± 9.0	58 ± 7.5	57 ± 11.3	57 ± 7.7	58 ± 9.7	57 ± 9.2	
Sex								
Male	20	22	15	18	20	16	16	
Female	9	4	9	9	10	12	10	
BMI (kg/m <sup>2</sup> )	30.3 ± 4.2	30.2 ± 5.4	32.0 ± 5.3	30.1 ± 5.0	30.4 ± 4.8	31.9 ± 4.3	30.2 ± 4.6	
Previous diabetes treatment								
Diet	4	2	11	2	4	4	7	
OHA	25	24	13	25	26	24	19	
Duration of diabetes (years)	3.4 ± 2.9	4.1 ± 3.7	4.4 ± 4.0	4.5 ± 4.6	4.6 ± 4.6	6.1 ± 7.9	3.8 ± 3.4	
HbA <sub>1c</sub> (%)	7.4 ± 1.2	7.4 ± 0.8	7.9 ± 0.8	7.7 ± 1.0	7.4 ± 1.2	7.4 ± 0.9	7.8 ± 0.9	
Fructosamine (mmol/l)	335 ± 72.5	344 ± 77.9	358 ± 57.7	374 ± 104.9	352 ± 74.2	344 ± 73.7	364 ± 69.5	
Fasting serum glucose (mmol/l)	9.7 ± 2.9	10.2 ± 2.2	10.9 ± 3.6	11.2 ± 2.8	10.8 ± 2.8	9.9 ± 2.3	10.6 ± 2.4	
C-peptide (mmol/l)	1.1 ± 0.4	1.0 ± 0.5	1.0 ± 0.5	1.1 ± 0.5	1.1 ± 0.6	1.0 ± 0.4	0.9 ± 0.5	
Insulin (mmol/l)	84.7 ± 43.6	74.1 ± 40.1	81.2 ± 73.0	73.8 ± 51.0	72.5 ± 55.3	71.5 ± 42.0	64.1 ± 40.4	
Glucagon (mmol/l)	110 ± 37.7	111 ± 47.6	131 ± 140.0	110 ± 33.0	99 ± 31.1	91 ± 23.4	101 ± 23.6	
Proinsulin-to-insulin ratio	0.23 ± 0.15	0.23 ± 0.16	0.26 ± 0.17	0.30 ± 0.20	0.21 ± 0.11	0.25 ± 0.15	0.28 ± 0.19	
β-Cell function (%)	44.06 ± 26.3	34.65 ± 23.1	31.83 ± 22.6	31.95 ± 31.7	34.40 ± 37.3	33.75 ± 21.7	26.78 ± 18.2	

Data are means ± SD. Demographics were obtained at visit 1 (screening) and diabetes characteristics at visit 2 (baseline). Of the 193 patients randomized, 3 were never exposed. Preferred terms for adverse event withdrawals include sinusitis and fever (0.225 mg), aggressive reaction (0.60 mg), and abnormal hepatic function (0.75 mg). Pro-insulin was measured only in a subset of patients ( $n = 74$ ).

[HOMA], proinsulin-to-insulin ratio, and weight) were analyzed in a mixed-effects model with treatment, visit, and center as fixed effects and patient as the random effect. The interaction term, baseline HbA<sub>1c</sub> by visit, was included in the model as a covariate. Adjusted end point levels at 12-week follow-up were calculated for each treatment group by means of this model.

The HOMA(S) (β-cell function) was determined as  $\beta\text{-cell function (\%)} = 20 \times \text{insulin}/(\text{glucose} - 3.5)$ . HOMA(R) (insulin resistance) was determined as  $\text{resistance} = \text{insulin}/(22.5e^{-\ln[\text{glucose}]})$  (22).

All analyses were performed for the

intention-to-treat (ITT) population (i.e., all patients who received at least one dose of a trial drug). Statistical analyses were performed using SAS software (version 8; SAS Institute, Cary, NC).

## RESULTS

### Enrollment

The 193 patients randomized in this trial were evenly distributed across treatment groups (Table 1). Baseline clinical characteristics of the 190 patients exposed to the experimental protocol are given in Table 1. No apparent differences were seen

among the treatment groups with regard to baseline characteristics.

### Effect on glycemic control

After 12 weeks of treatment, HbA<sub>1c</sub> was decreased in all groups except the lowest liraglutide dosage group (Fig. 1A). Treatment with the two highest dosages reduced HbA<sub>1c</sub> significantly more than placebo (Table 2). At these dosage levels, the effect of liraglutide was comparable with that of glimepiride with respect to effect on HbA<sub>1c</sub>. The effect of liraglutide increased with duration of treatment. The largest decreases in HbA<sub>1c</sub> levels were observed at the end of the 12-week treat-

ment period for the highest dosages (Fig. 1B), and it seemed that HbA<sub>1c</sub> levels were still decreasing at the end of the treatment period at these dosages. We observed that 59% of patients completing the trial in the two highest liraglutide dosage groups achieved HbA<sub>1c</sub> ≤7% after 12 weeks.

As was seen with HbA<sub>1c</sub>, fasting serum glucose levels decreased in most treatment groups during the trial, with the decreases being statistically significant for the 0.225-, 0.60-, and 0.75-mg liraglutide dosage groups compared with placebo (Table 2). In accordance with the observations for HbA<sub>1c</sub>, the effect of the highest dosages of liraglutide was comparable with that of glimepiride with respect to fasting serum glucose (Fig. 1C). In the liraglutide groups, maximal effect on fasting serum glucose was evident after the first week of treatment (Fig. 1D).

### Effect on body weight

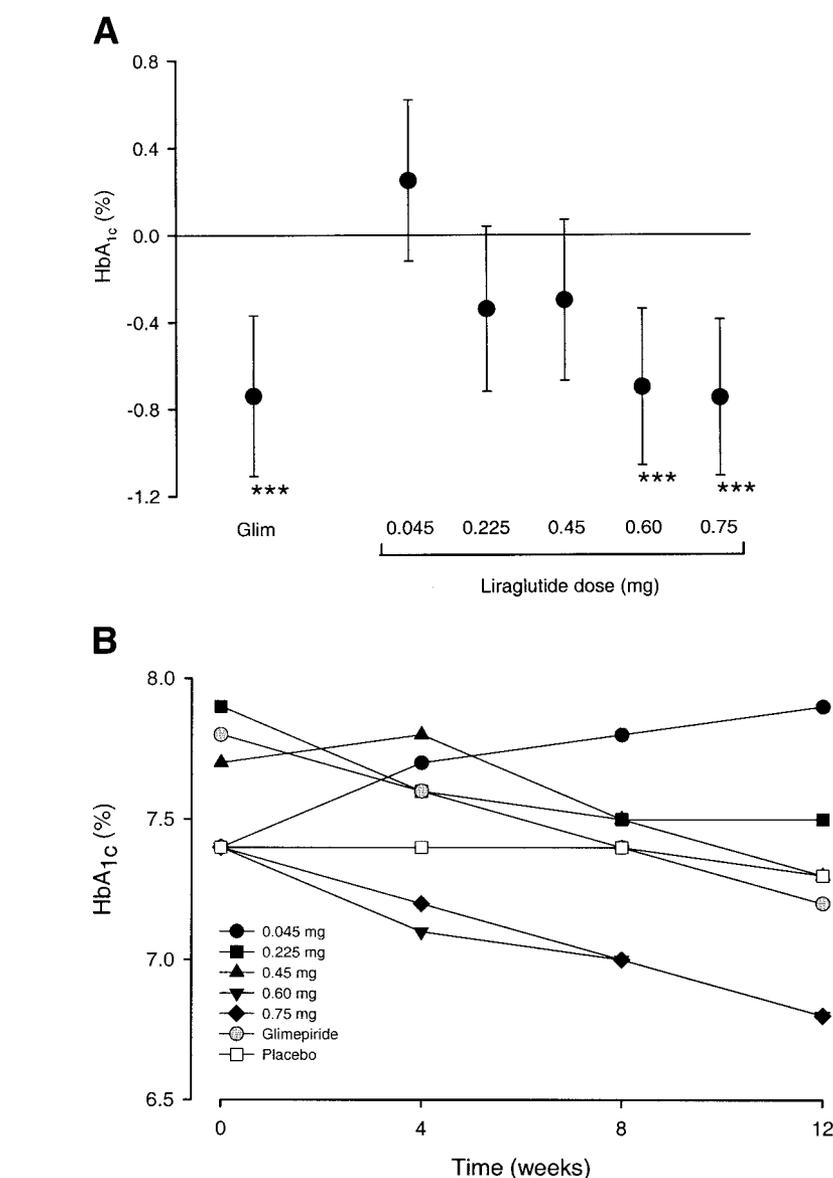
Treatment with liraglutide did not increase body weight (Fig. 2). Furthermore, for the 0.45-mg liraglutide dosage group (Table 2), a statistically significant decrease, compared with placebo, was observed.

### Effect on islet cell function

HOMA (22) was used to assess β-cell function and insulin resistance after 12 weeks of liraglutide treatment. Mean β-cell function (derived from fasting insulin and glucose) was significantly higher in the 0.75-mg liraglutide group after 12 weeks than in the placebo group (Table 2). The effect obtained with the highest liraglutide dosage was similar to that observed with glimepiride. For insulin resistance, no differences were seen among the three treatments (liraglutide, glimepiride, and placebo; data not shown). Further, the proinsulin-to-insulin ratio decrease was statistically significantly after treatment with 0.75 mg liraglutide compared with placebo (Table 2). No change in the proinsulin-to-insulin ratio was demonstrated after treatment with glimepiride. There were no statistically significant differences between the liraglutide groups and the placebo group for fasting insulin, C-peptide, and glucagon (Table 2).

### Safety evaluation

Of the 135 patients exposed to liraglutide, 1 (in the 0.60-mg group) experienced minor hypoglycemia (defined in the study



**Figure 1**—Glycemic control. Mean difference in HbA<sub>1c</sub> compared with placebo (95% CI) after 12 weeks of treatment (A), mean HbA<sub>1c</sub> (%) during the 12-week treatment period (B), mean difference in fasting serum glucose compared with placebo (95% CI) after 12 weeks of treatment (C), and mean fasting serum glucose (mmol/l) during the 12-week treatment period in the ITT population (D). A and C: \*P < 0.05, \*\*P < 0.01, \*\*\*P < 0.001 vs. placebo. Glim, glimepiride. B and D: ●, 0.045 mg liraglutide; ■, 0.225 mg liraglutide; ▲, 0.45 mg liraglutide; ▼, 0.60 mg liraglutide; ◆, 0.75 mg liraglutide; [gray circles], glimepiride; □, placebo.

protocol as blood glucose <2.8 mmol/l) and 7 reported symptoms of hypoglycemia only. These incidences seemed lower than in the glimepiride group (n = 26), where four patients experienced minor hypoglycemia and five patients reported symptoms of hypoglycemia.

The number of patients with adverse events (based on spontaneous adverse event reporting) was comparable across the liraglutide groups and the placebo

group (60% [81 of 135] vs. 55% [16 of 29] of patients, respectively) and was lower in the open-label reference group (35% [9 of 26] of patients). For gastrointestinal events, the incidence seemed to increase with increasing doses of liraglutide; nausea was reported by 1–2 patients in each of the lowest dose groups and by 5 of 28 patients in the highest dose group (in total, reported by 10 of 135 patients exposed to liraglutide) compared

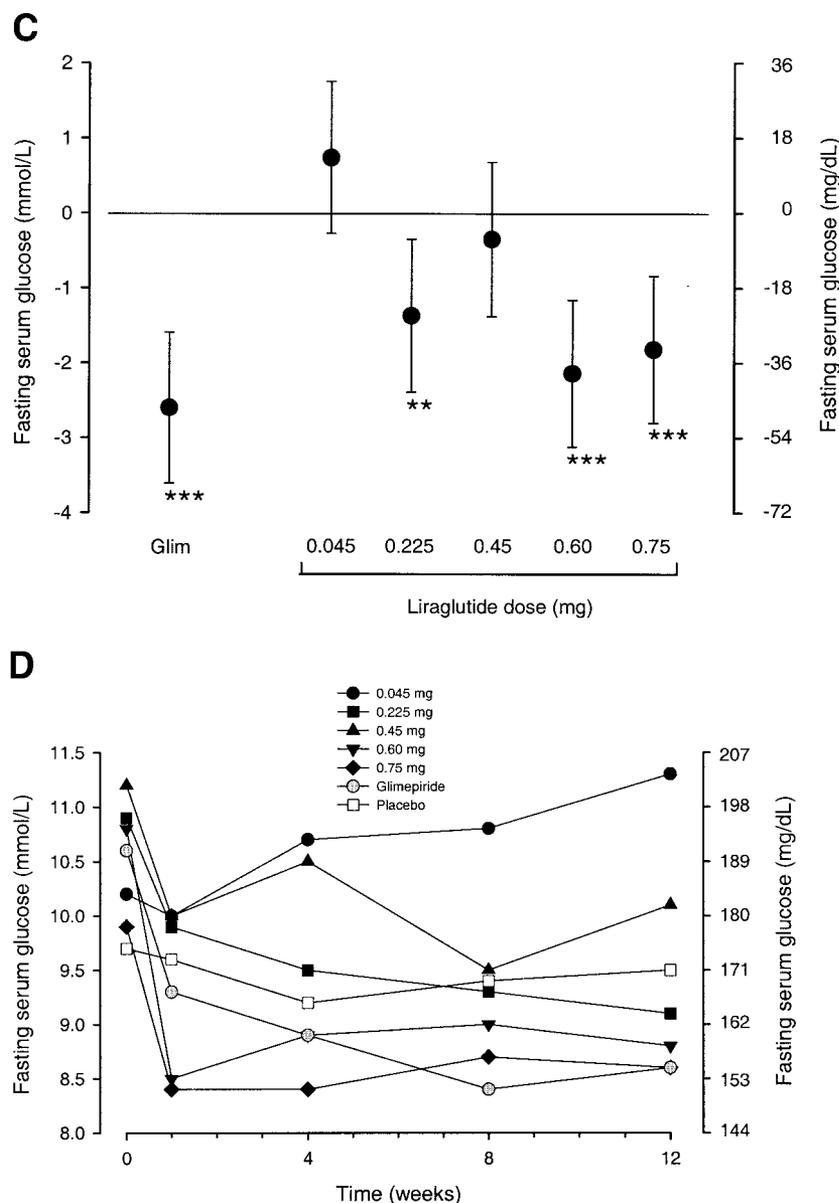


Figure 1—Continued

with 1 of 29 patients in the placebo group. Other gastrointestinal events included diarrhea (5 of 135 liraglutide-treated patients), vomiting (3 of 135 patients), and constipation (3 of 135 patients). None of these events were reported in the placebo or glimepiride groups, with the exception of one patient experiencing vomiting in the glimepiride group. Approximately two-thirds of the gastrointestinal events reported during treatment with liraglutide were resolved within 1–3 days. None of the patients withdrew due to gastrointestinal events (Table 1). Overall, the most frequent adverse events were headache and nausea, which were also the events most often assessed as related to the trial product. Generally, adverse events were mild or moderate and completely resolved. Only 1 of the 135 patients exposed to liraglutide experienced two mild injection site reactions, described as an “urticarial reaction at injection place.” No antibody formation against liraglutide could be detected in this trial.

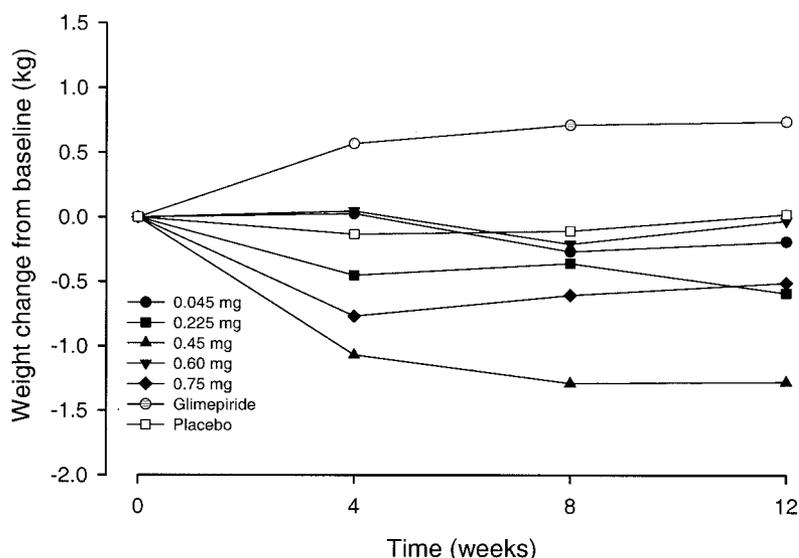
No safety issues with regard to vital signs, electrocardiogram, or laboratory analysis were raised by this trial.

**CONCLUSIONS** — This trial was the first to demonstrate a sustained improvement in glycemic control after long-term treatment with the GLP-1 analog liraglutide, administered once daily. After 12 weeks of treatment with 0.60 or 0.75 mg liraglutide, both HbA<sub>1c</sub> and fasting serum glucose levels were significantly lower than with placebo. Glycemic control was maintained throughout the treatment period and was as effective at the highest liraglutide dosages as that provided by the open-label reference therapy glimepiride

Table 2—Repeated measures analysis after 12 weeks, comparison with placebo in ITT population

	Liraglutide (mg)						Glimepiride
	0.045	0.225	0.45	0.60	0.75		
n	26	24	27	30	28	26	
HbA <sub>1c</sub> (%)	0.25 (0.1905)	-0.34 (0.0877)	-0.30 (0.1131)	-0.70 (0.0002)	-0.75 (<0.0001)	-0.74 (0.0001)	
Fasting serum glucose (mmol/l)	0.74 (0.1499)	-1.37 (0.0090)	-0.35 (0.4976)	-2.14 (<0.0001)	-1.82 (0.0003)	-2.60 (<0.0001)	
Weight (kg)	-0.03 (0.9602)	-0.74 (0.1544)	-1.20 (0.0184)	0.27 (0.5838)	-0.39 (0.4391)	0.94 (0.0622)	
Proinsulin-to-insulin ratio	-0.04 (0.6468)	-0.12 (0.1314)	-0.04 (0.6502)	-0.12 (0.1775)	-0.18 (0.0244)	-0.003 (0.9635)	
β-Cell function (%)	-6.07 (0.3546)	7.55 (0.2514)	8.55 (0.1978)	7.33 (0.2409)	23.56 (0.0002)	24.57 (0.0002)	
Fasting insulin (mmol/l)	-2.44 (0.8425)	-4.15 (0.7381)	-0.50 (0.9679)	-7.47 (0.5269)	8.57 (0.4708)	16.79 (0.1597)	
Fasting C-peptide (mmol/l)	-0.09 (0.4033)	-0.01 (0.9449)	0.05 (0.6374)	-0.08 (0.4308)	0.11 (0.2921)	0.08 (0.4636)	
Fasting glucagon (mmol/l)	12.74 (0.3619)	-15.84 (0.2710)	-6.77 (0.6277)	-7.68 (0.5625)	-9.33 (0.4980)	-7.21 (0.5970)	

P value given in parentheses.



**Figure 2**—Mean weight change from baseline (kg), ITT population. ●, 0.045 mg liraglutide; ■, 0.225 mg liraglutide; ▲, 0.45 mg liraglutide; ▼, 0.60 mg liraglutide; ◆, 0.75 mg liraglutide; [gray circles], glimepiride; □, placebo.

at an average dosage of 2.7 mg (a near-maximal dosage) (23), with trends toward less hypoglycemia and weight loss. At the highest dosage levels, there was a trend toward improved HbA<sub>1c</sub> with duration of treatment. This suggests that further improvements in HbA<sub>1c</sub> levels may be seen with extended (>12 weeks) treatment. More than half the patients in the two highest dosage liraglutide groups had HbA<sub>1c</sub> ≤ 7% after 12 weeks of treatment. Furthermore, treatment with liraglutide caused no weight increase, and, at the highest dosage, the difference with glimepiride was statistically significant. This observation was in accordance with findings that GLP-1 suppresses energy intake in humans (8).

The full dosage-response curve for liraglutide remains to be elucidated, and future trials will investigate higher dosages of drug, but the current trial confirmed the proposed once-daily dosing regimen for liraglutide.

The proinsulin-to-insulin ratio decreased during 12 weeks' treatment with liraglutide. This ratio is known to be elevated in type 2 diabetes and is considered an index of insulin secretory dysfunction (24,25). It is believed that the hyperproinsulinemia is caused by an increased demand placed on the  $\beta$ -cell by hyperglycemia and insulin resistance, which in turn leads to secretion of an increased amount of incompletely processed granules containing proinsulin. This is also

known as the "overworked  $\beta$ -cell" hypothesis (26). An alternative hypothesis is that the increased proinsulin concentration is related to an intrinsic  $\beta$ -cell defect in type 2 diabetes (24). In both cases, improvement of the proinsulin-to-insulin ratio, and thus of  $\beta$ -cell function, would be a desirable effect of a potential new treatment for type 2 diabetes.  $\beta$ -Cell function, as determined by HOMA analysis, was significantly improved at the highest liraglutide dosage compared with placebo. There was no effect on the  $\alpha$ -cells in the fasting state, in so far as the glucagon concentrations were unaltered.

The safety profile of liraglutide was favorable, with the expected very low risk of hypoglycemic episodes as anticipated with the glucose-dependent mode of action of native GLP-1 (27). Adverse events were isolated, with the most frequent being headache and nausea. Usually the events were transient and of mild or moderate severity and resolved without intervention. Although both nausea and vomiting were reported, neither of these was of a severity that caused the patient to withdraw. Most gastrointestinal events were transient (i.e., they resolved within 1–3 days). Side effects within the gastrointestinal system are known to occur after GLP-1 treatment and seem to be dosage related (14,28,29). These effects probably result from the inhibition of gastric emptying by GLP-1 (9,30–32). No formation of antibodies toward liraglutide was de-

tected after 12 weeks of treatment. The sensitivity of the assay has been found to be 30 ng/ml (data on file) using a monoclonal antibody. The liraglutide antibody assay is essentially similar to a previously published assay used to assess insulin and insulin aspart antibodies with a similar and acceptable sensitivity (33).

Another approach for investigating the potential of GLP-1 includes administering native GLP-1 by means of continuous infusion (11,14). Continuous intravenous infusion of GLP-1 for 1 week resulted in an instant decrease in blood glucose levels in patients in whom sulfonylurea therapy failed to be effective (14). A 6-week trial with GLP-1 administered as continuous subcutaneous infusion via an insulin pump demonstrated significant effects on fasting and 8-h plasma glucose and HbA<sub>1c</sub>, as well as an inhibition of gastric emptying and body weight loss (11). The latter trial was conducted in patients with poorly controlled HbA<sub>1c</sub> levels, indicating that the GLP-1 treatment concept may be applied to a wide range of glycemia in type 2 diabetes. Also, the peptide exenatide (synthetic exendin-4) has demonstrated effects similar to those of GLP-1 (34). In this 28-day study, adding exenatide to the existing treatment two or three times daily showed a significant effect in controlling patients' HbA<sub>1c</sub> levels, which were previously not satisfactorily controlled with diet and/or OHAs.

In conclusion, the long-acting GLP-1 analog liraglutide shows considerable promise as a once-daily therapy in type 2 diabetes for lowering blood glucose without weight gain or substantial risk of hypoglycemia.

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## References

- DeFronzo RA: Pathogenesis of type 2 diabetes: metabolic and molecular implications for identifying diabetes genes. *Diabetes Rev* 5:177–269, 1997
- Toft-Nielsen MB, Madsbad S, Holst JJ: Continuous subcutaneous infusion of glucagon-like peptide 1 lowers plasma glucose and reduces appetite in type 2 diabetic patients. *Diabetes Care* 22:1137–1143, 1999
- Viltsboll T, Krarup T, Deacon CF, Madsbad S, Holst JJ: Reduced postprandial concentrations of intact biologically active glucagon-like peptide 1 in type 2 diabetic patients. *Diabetes* 50:609–613, 2001
- U.K. Prospective Diabetes Study (UKPDS) Group: Intensive blood-glucose control with sulphonylureas or insulin compared with conventional treatment and risk of complications in patients with type 2 diabetes (UKPDS 33). *Lancet* 352:837–853, 1998
- Nauck MA, Kleine N, Orskov C, Holst JJ, Willms B, Creutzfeldt W: Normalization of fasting hyperglycaemia by exogenous glucagon-like peptide 1 (7–36 amide) in type 2 (non-insulin-dependent) diabetic patients. *Diabetologia* 36:741–744, 1993
- Willms B, Werner J, Holst JJ, Orskov C, Creutzfeldt W, Nauck MA: Gastric emptying, glucose responses, and insulin secretion after a liquid test meal: effects of exogenous glucagon-like peptide-1 (GLP-1)-(7–36) amide in type 2 (noninsulin-dependent) diabetic patients. *J Clin Endocrinol Metab* 81:327–332, 1996
- Gutniak M, Orskov C, Holst JJ, Ahren B, Efendic S: Antidiabetogenic effect of glucagon-like peptide-1 (7–36)amide in normal subjects and patients with diabetes mellitus. *N Engl J Med* 326:1316–1322, 1992
- Flint A, Raben A, Astrup A, Holst JJ: Glucagon-like peptide 1 promotes satiety and suppresses energy intake in humans. *J Clin Invest* 101:515–520, 1998
- Gutzwiller JP, Drewe J, Goke B, Schmidt H, Rohrer B, Lareida J, Beglinger C: Glucagon-like peptide-1 promotes satiety and reduces food intake in patients with diabetes mellitus type 2. *Am J Physiol* 276:R1541–R1544, 1999
- Verdich C, Flint A, Gutzwiller JP, Naslund E, Beglinger C, Hellstrom PM, Long SJ, Morgan LM, Holst JJ, Astrup A: A meta-analysis of the effect of glucagon-like peptide-1 (7–36) amide on ad libitum energy intake in humans. *J Clin Endocrinol Metab* 86:4382–4389, 2001
- Zander M, Madsbad S, Madsen JL, Holst JJ: Effect of 6-week course of glucagon-like peptide 1 on glycaemic control, insulin sensitivity, and beta-cell function in type 2 diabetes: a parallel-group study. *Lancet* 359:824–830, 2002
- Deacon CF, Pridal L, Klarskov L, Olesen M, Holst JJ: Glucagon-like peptide 1 undergoes differential tissue-specific metabolism in the anesthetized pig. *Am J Physiol* 271:E458–E464, 1996
- Deacon CF, Johnsen AH, Holst JJ: Degradation of glucagon-like peptide-1 by human plasma in vitro yields an N-terminally truncated peptide that is a major endogenous metabolite in vivo. *J Clin Endocrinol Metab* 80:952–957, 1995
- Larsen J, Hylleberg B, Ng K, Damsbo P: Glucagon-like peptide-1 infusion must be maintained for 24 h/day to obtain acceptable glycemia in type 2 diabetic patients who are poorly controlled on sulphonylurea treatment. *Diabetes Care* 24:1416–1421, 2001
- Knudsen LB, Agero H, Bjenning C, Bregenholt S, Carr RD, Godfredsen C, Holst JJ, Huusfeldt PO, Larsen MO, Larsen PJ, Nielsen PF, Ribel U, Rolin B, Romer J, Sturis J, Wilken M, Kristensen P: GLP-1 analogs as novel compounds for the treatment of type 2 diabetes: selection of NN2211 for clinical development. *Drugs of the Future* 26:677–685, 2001
- Elbrond B, Jakobsen G, Larsen S, Agero H, Jensen LB, Rolan P, Sturis J, Hatorp V, Zdravkovic M: Pharmacokinetics, pharmacodynamics, safety, and tolerability of a single-dose of NN2211, a long-acting glucagon-like peptide 1 analog, in healthy male subjects. *Diabetes Care* 25:1398–1404, 2002
- Agero H, Jensen LB, Elbrond B, Rolan P, Zdravkovic M: The pharmacokinetics, pharmacodynamics, safety and tolerability of NN2211, a new long-acting GLP-1 analog, in healthy men. *Diabetologia* 45:195–202, 2002
- Juhl CB, Hollingdal M, Sturis J, Jakobsen G, Agero H, Veldhuis J, Porksen N, Schmitz O: Bedtime administration of NN2211, a long-acting GLP-1 analog, substantially reduces fasting and postprandial glycemia in type 2 diabetes. *Diabetes* 51:424–429, 2002
- World Medical Association Declaration of Helsinki: recommendations guiding physicians in biomedical research involving human subjects. *JAMA* 277:925–926, 1997
- American Diabetes Association: Guide to diagnosis and classification of diabetes mellitus and other categories of glucose intolerance (Position Statement). *Diabetes Care* 20 (Suppl. 1):S21, 1997
- Criteria Committee of the New York Heart Association: *Nomenclature and Criteria for Diagnosis of Diseases of the Heart and Great Vessels*. Boston, Little, Brown, 1994
- Matthews DR, Hosker JP, Rudenski AS, Naylor BA, Treacher DF, Turner RC: Homeostasis model assessment: insulin resistance and beta-cell function from fasting plasma glucose and insulin concentrations in man. *Diabetologia* 28:412–419, 1985
- Goldberg RB, Holvey SM, Schneider J: A dose-response study of glimepiride in patients with NIDDM who have previously received sulphonylurea agents: the Glimepiride Protocol #201 Study Group. *Diabetes Care* 19:849–856, 1996
- Porte D Jr, Kahn SE: Hyperproinsulinemia and amyloid in NIDDM: clues to etiology of islet  $\beta$ -cell dysfunction? *Diabetes* 38:1333–1336, 1989
- Clark A, Jones LC, de Koning E, Hansen BC, Matthews DR: Decreased insulin secretion in type 2 diabetes: a problem of cellular mass or function? *Diabetes* 50 (Suppl. 1):S169–S171, 2001
- Leahy JL: Impaired beta-cell function with chronic hyperglycemia: “overworked  $\beta$ -cell” hypothesis. *Diabetes Rev* 4:298–319, 1996
- Nauck MA, Heimesaat MM, Behle K, Holst JJ, Nauck MS, Ritzel R, Hufner M, Schmiegel WH: Effects of glucagon-like peptide 1 on counterregulatory hormone responses, cognitive functions, and insulin secretion during hyperinsulinemic, stepped hypoglycemic clamp experiments in healthy volunteers. *J Clin Endocrinol Metab* 87:1239–1246, 2002
- Ritzel R, Orskov C, Holst JJ, Nauck MA: Pharmacokinetic, insulinotropic, and glucagonostatic properties of GLP-1 [7–36 amide] after subcutaneous injection in healthy volunteers: dose-response-relationships. *Diabetologia* 38:720–725, 1995
- Nauck MA, Wollschlager D, Werner J, Holst JJ, Orskov C, Creutzfeldt W, Willms B: Effects of subcutaneous glucagon-like peptide 1 (GLP-1 [7–36 amide]) in patients with NIDDM. *Diabetologia* 39:1546–1553, 1996
- Layer P, Holst JJ, Grandt D, Goebell H: Ileal release of glucagon-like peptide-1 (GLP-1): association with inhibition of

- gastric acid secretion in humans. *Dig Dis Sci* 40:1074–1082, 1995
31. Naslund E, Barkeling B, King N, Gutniak M, Blundell JE, Holst JJ, Rossner S, Hellstrom PM: Energy intake and appetite are suppressed by glucagon-like peptide-1 (GLP-1) in obese men. *Int J Obes Relat Metab Disord* 23:304–311, 1999
  32. Naslund E, Gutniak M, Skogar S, Rossner S, Hellstrom PM: Glucagon-like peptide 1 increases the period of postprandial satiety and slows gastric emptying in obese men. *Am J Clin Nutr* 68:525–530, 1998
  33. Lindholm A, Jensen LB, Home PD, Raskin P, Boehm BO, Rastam J: Immune responses to insulin aspart and biphasic insulin aspart in people with type 1 and type 2 diabetes. *Diabetes Care* 25:876–882, 2002
  34. Fineman MS, Bicsak TA, Shen LZ, Taylor K, Gaines E, Varns A, Kim D, Baron AD: Effect on glycemic control of exenatide (synthetic exendin-4) additive to existing metformin and/or sulfonylurea treatment in patients with type 2 diabetes. *Diabetes Care* 26:2370–2377, 2003