Renal extraction and acute effects of glucagon-like peptide-1 on central and renal hemodynamics in healthy men

Ali Asmar,1 Lene Simonsen,1 Meena Asmar,1 Sten Madshad,2 Jens J. Holst,3,4 Erik Frandsen,5 Cedric Moro,6 Thomas Jonassen,4 and Jens Bülow1,4

1Department of Clinical Physiology and Nuclear Medicine, Bispebjerg University Hospital, Copenhagen, Denmark; 2Department of Endocrinology, Hvidovre University Hospital, Copenhagen, Denmark; 3NFF Center for Basic Metabolic Research, University of Copenhagen, Copenhagen, Denmark; 4Department of Biomedical Sciences, University of Copenhagen, Copenhagen, Denmark; 5Department of Diagnostics, Clinical Physiology and Nuclear Medicine, Glostrup University Hospital, Copenhagen, Denmark; and 6Institut National de la Santé et de la Recherche Médicale, UMR 1048, Institute of Metabolic and Cardiovascular Diseases, Paul Sabatier University, Toulouse, France

Submitted 19 September 2014; accepted in final form 3 February 2015

Asmar A, Simonsen L, Asmar M, Madshad S, Holst JJ, Frandsen E, Moro C, Jonassen T, Bülow J. Renal extraction and acute effects of glucagon-like peptide-1 on central and renal hemodynamics in healthy men. Am J Physiol Endocrinol Metab 308: E641–E649, 2015. First published February 10, 2015; doi:10.1152/ajpendo.00429.2014.—The present experiments were performed to elucidate the acute effects of intravenous infusion of glucagon-like peptide (GLP)-1 on central and renal hemodynamics in healthy men. Seven healthy middle-aged men were examined on two different occasions in random order. During a 3-h infusion of either GLP-1 (1.5 pmol·kg⁻¹·min⁻¹) or saline, cardiac output was estimated noninvasively, and intravenous blood pressure and heart rate were measured continuously. Renal plasma flow, glomerular filtration rate, and uptake/release of hormones and ions were measured by Fick’s Principle after catheterization of a renal vein. Subjects remained supine during the experiments. During GLP-1 infusion, both systolic blood pressure and arterial pulse pressure increased by 5 ± 1 mmHg (P = 0.015 and P = 0.002, respectively). Heart rate increased by 5 ± 1 beats/min (P = 0.005), and cardiac output increased by 18% (P = 0.016). Renal plasma flow and glomerular filtration rate as well as the clearance of Na⁺ and Li⁺ were not affected by GLP-1. However, plasma renin activity decreased (P = 0.037), whereas plasma levels of atrial natriuretic peptide were unaffected. Renal extraction of intact GLP-1 was 43% (P < 0.001), whereas 60% of the primary metabolite GLP-1 9–36amide was extracted (P = 0.017). In humans, an acute intravenous administration of GLP-1 leads to increased cardiac output due to a simultaneous increase in stroke volume and heart rate, whereas no effect on renal hemodynamics could be demonstrated despite significant extraction of both the intact hormone and its primary metabolite.

Glucagon-like peptide-1; blood pressure; heart rate; cardiac output; renal plasma flow

GLUCAGON-LIKE PEPTIDE (GLP)-1 is a 30-amino acid peptide hormone primarily synthesized by enteroendocrine L cells distributed in the small and large intestines and secreted in a nutrient-dependent manner. GLP-1 stimulates insulin secretion and inhibits glucagon secretion and gastric emptying, resulting in reduced postprandial glycaemia (14). The GLP-1 receptor is a G protein-coupled receptor and a member of the glucagon receptor family (18). The GLP-1 receptor was originally identified in islet β-cells in the pancreas, but it is also widely expressed in extrapancreatic tissues in humans (17, 25, 33).

GLP-1 receptor agonists have been approved for the treatment of hyperglycemia in subjects with diabetes, and, in addition, they may have significant cardiovascular effects (6, 28). However, results regarding the effects on arterial blood pressure are conflicting (2, 9, 11, 20–22, 29, 31). The reasons for the apparent discrepancies are not clear, although differences between species, doses applied, and durations of treatment may contribute.

Human studies have reported a natriuretic effect of native GLP-1, possibly due to reduced Na⁺ reabsorption in the proximal tubule (12, 29). However, in a recent study (25) validating a new, monoclonal GLP-1 receptor antibody, GLP-1 receptors could not be identified in the proximal tubule, whereas they were expressed in renin-secreting cells of the juxtaglomerular apparatus.

It has not yet been clarified whether GLP-1 influences central and renal hemodynamics in men. The present study was designed with the purpose of investigating native GLP-1’s central and renal hemodynamic effects.

METHODS

Subjects. Seven male subjects of Caucasian origin (age: 47 ± 2 yr, height: 1.78 ± 0.01 m, and weight: 76.0 ± 2.4 kg) participated in the present study, which involved two experiments performed in random order separated by ∼4 wk. All subjects were healthy and none took medication at the time of the study (Table 1). Consent to participate was obtained after subjects had read a description of the experimental protocol, which was approved by the Scientific Ethics Committee of the Capital Region of Copenhagen (H-2-2012-139).

Protocol. All subjects consumed a controlled diet for 4 days before testing (16% protein, 55% carbohydrate, and 29% fat). The energy content was 2,822 kcal/day. The basal NaCl content of the diet, as measured at Eurofins Stein’s Laboratory in Denmark, was 55–75 mmol/day. This was supplemented with additional 2 mmol NaCl/kg body wt⁻¹·day⁻¹. To assess the compliance of the subjects with the dietary regimen, 24-h urine collections were performed on the last day, and electrolyte concentrations were analyzed. Water intake was ad libitum, and strenuous excess physical activity was not allowed. Subjects were given 600 mg Li⁺ orally at 09:00 PM the day before each experiment. Under Na⁺-standardized conditions as in the present study, it is generally accepted that the renal clearance and renal extraction of Li⁺ are in accord with fractional Na⁺ and thereby fluid reabsorption in proximal tubules.

Subjects fasted for 12 h before the beginning of the experiment (Fig. 1). After emptying the bladder, confirmed by ultrasound, the subject remained supine throughout the experiment. A forearm vein was catheterized with a 18-gauge catheter (BD Venflon: 1.2-mm outer...
steady state using 51Cr-labeled EDTA (51Cr-EDTA). Urine was collected over 5 min before and after a determination of 51Cr activity. Measurements obtained during intervals of ~5 min before and after blood sampling were used for analyses. Mean heart rate range was calculated by subtracting the maximum heart rate during inspiration from the minimum heart rate during expiration for each cycle of breathing followed by a determination of the mean of these differences.

Blood and urine analyses. Samples of blood were drawn simultaneously from the radial artery and renal vein every 20 min from time 0 to 60 min and then every 60 min throughout the experiments. All arterial and venous blood samples were analyzed for GLP-1, glucose, Na+, K+, H+, Li+, hematocrit, O2 saturation, and 51Cr activity. Insulin and C-peptide levels in plasma were measured using a commercial enzyme immunoassay kit (Insulin Human ELISA EIA-2935 and C-peptide ELISA EIA-1293, AH Diagnostics, Aarhus, Denmark).

Plasma electrolyte concentrations, glucose, hematocrit, and O2 saturation were measured by an automated benchtop blood analyzer system (ABL 700 series, Radiometer Medical Aps, Brønshøj, Denmark).

Table 1. Subject characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>7</td>
</tr>
<tr>
<td>Age, yr</td>
<td>47 ± 2</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.78 ± 0.01</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>76 ± 0.24</td>
</tr>
<tr>
<td>Fasting blood glucose mmol/l</td>
<td>5.5 ± 0.2</td>
</tr>
<tr>
<td>Fasting insulin pmol/l</td>
<td>41.5 ± 7.5</td>
</tr>
<tr>
<td>Fasting C-peptide ng/ml</td>
<td>2.8 ± 0.4</td>
</tr>
</tbody>
</table>

Data are presented as means ± SE.

diameter, length: 45 mm, Becton Dickinson Infusion Therapy, Helsingborg, Sweden) for infusions. The right femoral vein was catheterized by the Seldinger technique using a 6-F introducer (Avanti: 2.21-mm outer diameter, length: 110 mm, Cordis, Bridgewater, NJ). A 6 F catheter (Check-Flo Performer: 0.97-mm outer diameter, length: 750 mm, Cook Medical, Bloomington, IN) was advanced into the right or left renal vein under fluoroscopic control. The same vein was catheterized in both experiments. The position of the catheter tip in the renal vein was checked and confirmed throughout the experiments by measurements of O2 saturation. A radial artery was catheterized with a 20-gauge catheter (BD Arterial Cannula: 1.1-mm outer diameter, length: 45 mm, Becton Dickinson Medical, Franklin Lakes, NJ) for blood sampling and for continuous monitoring of arterial blood pressure. Blood was collected simultaneously from the radial artery and renal vein throughout the experiments as described below. Renal plasma flow and glomerular filtration rate were measured via Fick’s principle using 51Cr-labeled EDTA (51Cr-EDTA) as an indicator (GE Healthcare, Brøndby, Denmark). An intravenous bolus injection (2 MBq) in 10 ml of 0.9% NaCl was administered followed by a constant intravenous infusion (1.6 MBq/h for 6 h) in 0.9% NaCl (30 ml/h). Steady-state arterial concentrations were obtained after ~2 h.

Blood pressure and heart rate were monitored invasively (ADInstruments, Oxford, UK) as well as noninvasively (Finapres, Finapres Medical Systems, Amsterdam, The Netherlands). In addition, a three-lead ECG was applied at the chest throughout the experiments. Measurements obtained during intervals of ~5 min before and after blood sampling were used for analyses. After at least 2 h of infusion of 51Cr-EDTA, two baseline blood samples were drawn following commencement of a 3-h infusion of either GLP-1 (7–36, 1.5 pmol·kg−1·min−1) or saline (0.9% NaCl) corresponding to a total volume of 60 ml and a NaCl amount of ~35 mmol NaCl in each experiment. Solutions were prepared freshly by the physician in charge and were indistinguishable in appearance and given blinded to the subjects. During the experiments, bladder emptying was performed if necessary with the subjects remaining in the supine position. At the end of the 3-h infusion, subjects were instructed to perform deep breathing for 1 min with a frequency of 6 breaths/min to measure heart rate variability. This was repeated three times. Experiments continued for an additional 2 h, after which a final bladder emptying was requested; the emptying was verified by ultrasound. The total amount of urine voided during each experiment was mixed and quantified.

Materials. Synthetic human GLP-1 (7–36) was obtained from Bachem (Bubendorf, Switzerland), and 51Cr-EDTA was obtained from GE Healthcare.

Cardiac output and heart rate variability. Estimated cardiac output was recorded continuously and noninvasively using Finapres (15). The estimation of cardiac output via pulse contour analysis is an indirect method based on the development of the pulsatile unloading of the finger arterial walls using an inflatable finger cuff with a built-in photoelectric plethysmograph. The software, using a nonlinear three-element mathematical model consisting of aortic characteristic impedance, arterial compliance, and systemic vascular resistance, generated an aortic pulse waveform from the finger arterial pressure wave. Measurements obtained during intervals of ~5 min before and after blood sampling were used for analyses. Mean heart rate range was used to assess heart rate variability with respiratory cycles measured from a series of successive deep breaths at a rate of 6 breaths/min. Mean heart rate range was calculated by subtracting the maximum heart rate during inspiration from the minimum heart rate during expiration for each cycle of breathing followed by a determination of the mean of these differences.

Blood and urine analyses. Samples of blood were drawn simultaneously from the radial artery and renal vein every 20 min from time 0 to 60 min and then every 60 min throughout the experiments. All arterial and venous blood samples were analyzed for GLP-1, glucose, Na+, K+, H+, Li+, hematocrit, O2 saturation, and 51Cr activity. Insulin and C-peptide levels in plasma were measured using a commercial enzyme immunoassay kit (Insulin Human ELISA EIA-2935 and C-peptide ELISA EIA-1293, AH Diagnostics, Aarhus, Denmark).

Plasma electrolyte concentrations, glucose, hematocrit, and O2 saturation were measured by an automated benchtop blood analyzer system (ABL 700 series, Radiometer Medical Aps, Brønshøj, Denmark).

Fig. 1. Glucagon-like peptide-1 (GLP-1; 1.5 pmol·kg−1·min−1) or saline (0.9% NaCl) intraarterial blood pressure and heart rate were measured continuously throughout the experiments. Cardiac output was monitored continuously throughout the experiments using Finapres. Renal plasma flow and glomerular filtration rate were measured via Fick’s principle during steady state using 51Cr-labeled EDTA (51Cr-EDTA). Urine was collected over ~420 min, and the total amount of urine voided during each experiment was mixed and quantified. Blood samples show time points of blood sampling during experiments.

GLP-1 (1.5 pmol kg−1·min−1) or saline (0.9 %NaCl)

Blood pressure, heart rate, and cardiac output

51Cr EDTA (1.6 MBq hour−1)

Urine collection (at voluntary voiding)

Blood samples

-120 -60 0 60 120 180 240 300

Time (min)
Plasma Li\(^+\) concentrations were measured by atomic absorption spectrophotometry (model 2380, Perkin-Elmer, Norwalk, CT).

Plasma and urine were analyzed for gamma radiation activity on a WIZARD\(^{\text{TM}}\) 1480 automatic gamma counter (Perkin-Elmer, Waltham, MA).

Plasma epinephrine and norepinephrine concentrations were measured by radioimmunoassay using a commercial kit (2-CAT RIA, Labor Diagnostika Nord, Nordhorn, Germany).

Plasma renin concentrations were determined using Liaison Direct Renin measurements (DiaSorin, Saluggia, Italy).

Plasma levels of proANP were measured by radioimmunoassay using antiserum and proANP(1–30) calibrator from Peninsula Laboratories. The tracer was prepared by in-house iodination and HPLC purification. Plasma samples were diluted 11-fold with radioimmunoassay buffer before assay.

Plasma levels of ANP were measured by enzyme immunoassay using a commercial kit (RayBio Human ANP Enzyme, RayBiotech, Norcross, GA).

Urine electrolytes and urine Li\(^+\) were measured by atomic spectrophotometry (model 2380, Perkin-Elmer).

Urine creatinine was measured by an enzymatic method (Cobas 8000 System, Indianapolis, IN).

Urine pH was measured by a XC161 Combination pH electrode (Radiometer Medical Aps).

Plasma Li\(^+\) was measured by atomic spectrophotometry (model 2380, Perkin-Elmer, Norwalk, CT). Results are presented as means ± SE. The area under the curve (AUC) was calculated using the trapezoidal rule, and a t-test for paired data was used to compare changes in the AUC during GLP-1 infusion with changes in the AUC during saline infusion. P values of <0.05 were considered statistically significant.

**RESULTS**

**Standardized NaCl intake.** On the last day of the 4-day period with standardized NaCl intake before GLP-1 or saline infusion, 24-h urine volumes (2,469 ± 337 and 2,498 ± 559 ml/24 h, P = 0.961), renal Na\(^+\) excretions (215 ± 30 and 209 ± 12 mmol/24 h, P = 0.842), and renal Li\(^+\) excretions (6.4 ± 1.9 and 6.4 ± 0.6 mmol/24 h, P = 0.977) were similar.

**Renal extraction of GLP-1.** Arterial and renal venous plasma concentrations of total GLP-1, intact GLP-1, and GLP-1 metabolite (GLP-1 9-36amide) are shown in Fig. 2. During saline infusion, arterial and renal venous plasma concentrations of total GLP-1 remained constant throughout the experiments (6.1 ± 0.5 and 5.0 ± 0.3 pmol/L; Fig. 2A). During GLP-1 infusion, arterial and venous plasma concentrations of total GLP-1 increased significantly (128.4 ± 36.6 and 64.5 ± 5.0 pmol/L), and steady state was obtained within 40 min (Fig. 2A). Analysis of the contributions of intact GLP-1 7-36amide and the metabolite demonstrated that both moieties were extracted (P < 0.001 and P = 0.012, respectively), with the fraction for the metabolite being slightly higher than that of intact GLP-1 (60% vs. 43%; Fig. 2, B and C). During saline infusion, a statistically significant renal extraction of GLP-1 could not be demonstrated.

**Effects of GLP-1 on arterial blood glucose and plasma insulin.** During GLP-1 infusion, arterial plasma insulin levels increased transiently with a maximum at 20 min (P = 0.027; Fig. 3, A–C) and blood glucose levels were transiently reduced (P = 0.004; Fig. 3, D and E) with a nadir of 4.34 ± 0.14 mmol/L at 40 min and a range of 3.89–5.70 mmol/L within the first 60 min (Fig. 3D). None of the subjects developed symptoms of hypoglycemia.

**Effects of GLP-1 on vasoactive hormones.** Plasma epinephrine concentrations tended to increase transiently with a maximum at 60 min concomitantly with a reduction in plasma glucose concentrations during GLP-1 infusion but remained unchanged during saline infusion (Fig. 4, A and B). Plasma norepineph-
Effects of GLP-1 on the heart. Heart rate and systolic blood pressure increased within 60 min (P < 0.001 and P < 0.001, respectively; Fig. 5, A–C and G–I). Plasma proANP and ANP concentrations remained constant in both experiments (Fig. 4, G–J).

Effects of GLP-1 on central and renal hemodynamics. Effects of GLP-1 on blood pressure, heart rate, and cardiac output are shown in Fig. 5.

During GLP-1 infusion, systolic blood pressure and arterial pulse pressure increased within 60 min (P = 0.011 and P < 0.001, respectively; Fig. 5, B and H), and both pressures remained increased throughout GLP-1 infusion with a mean increase of 5 ± 1 mmHg (P = 0.015 and 0.002, respectively; Fig. 5, A–C and G–I). Diastolic blood pressure remained unchanged in both experiments (Fig. 5, D–F). Heart rate increased within 60 min (P = 0.039; Fig. 5K) and remained elevated throughout GLP-1 infusion with a mean increase of 5 ± 1 beats/min (P = 0.005; Fig. 5, J–L). Mean heart rate range (heart rate variability) was measured in the end of the infusion period and was similar during GLP-1 and saline infusion (33 ± 6 and 33 ± 9 beats/min, P = 0.888). Cardiac output increased within 60 min (P = 0.038; Fig. 5N) by 18% (P = 0.016; Fig. 5, M–O).

Effects of GLP-1 on renal hemodynamics are shown in Fig. 6. Renal plasma flow and glomerular filtration rate, as measured continuously by 51Cr-EDTA infusion and arterial and renal venous concentrations, were unaffected by GLP-1 infusion (Fig. 6, A–D).

Average renal electrolyte clearances and urinary secretion rates. In the present study, differences in arteriovenous plasma concentrations of Na⁺, K⁺, H⁺, and Li⁺ could not be demonstrated (data not shown). Furthermore, using samples from urine collected throughout each experiment (446 ± 18 and 465 ± 13 pg/ml), renal electrolyte excretions as well as clearances were not statistically different (Table 2).

DISCUSSION

The major finding in the present study is a sustained increase in cardiac output during an intravenous GLP-1 infusion. This was due to a simultaneous increase in stroke volume and heart rate. Despite GLP-1 being extracted by the kidneys, it was not possible to demonstrate any significant effect on renal plasma flow and glomerular filtration rate. Furthermore, plasma renin activity decreased during GLP-1 infusion, whereas it was not possible to demonstrate an effect on ANP levels.

Plasma levels of GLP-1 in the present study were in the slightly supraphysiological range (5, 7).

To our knowledge, this is the first human study investigating the acute effects of GLP-1 on blood pressure invasively. Systolic blood pressure increased significantly during GLP-1 infusion, whereas diastolic blood pressure remained unchanged, indicating an increase in stroke volume, which, along with a significant increase in heart rate, led to an increase in cardiac output. The mechanisms behind the increase in arterial pulse pressure remain unclear. Since the GLP-1 receptor probably may be exclusively localized in the sinoatrial node (25), a direct GLP-1 receptor-mediated positive inotropic effect, generating a subsequent increase in stroke volume, seems unlikely.

During the transient decrease in plasma glucose, a transient and statistically nonsignificant increase in plasma epinephrine concentrations was seen. Thus, the sustained positive chronotropic effect was probably not due to the hypoglycemic activation of the sympathetic nervous system. Furthermore, the transient increase in plasma insulin concentrations subsided within 1 h. An insulin-mediated activation of the sympathetic nervous system is therefore unlikely. Therefore, the increase in

Fig. 3. Effects of GLP-1 or saline infusion on arterial plasma concentrations of insulin (A–C) and glucose (D–F). A and D: time courses of the concentrations during (0–180 min) and 60 min after (180–240 min) the infusion. B, C, E, and F: integrated effects during the infusion from 0 to 60 min (B and E) and 0 to 180 min (C and F). Data are presented as means ± SE. AUC, area under the curve.
Fig. 4. Effects of GLP-1 or saline infusion on arterial plasma concentrations of epinephrine (A and B), norepinephrine (C and D), renin (E and F), proatrial natriuretic peptide (proANP; G and H), and ANP (I and J). A, C, E, G, and I: time courses of concentrations during the infusion from 0 to 180 min. B, D, F, H, and J: integrated effects during the infusion from 0 to 180 min. Data are presented as means ± SE.
GLP-1 AND HEMODYNAMICS IN HEALTHY MEN

Fig. 5. Effects of GLP-1 or saline infusion on intra-arterial blood pressure (A–I), heart rate [in beats/min (bpm); J–L], and cardiac output (M–O). A, D, G, J, and M: time courses of measurements during the infusion from 0 to 180 min. B, C, E, F, H, I, K, L, N, and O: integrated effect during the infusion from 0 to 60 min (B, E, H, K, and N) and 0 to 180 min (C, F, I, L, and O). Data are presented as means ± SE.
heart rate could be due to a direct GLP-1 receptor-mediated mechanism located in the sinoatrial node (25). However, since GLP-1 powerfully inhibits central nervous parasympathetic outflow in humans, another possibility is that the effects of GLP-1 involve inhibition of vagal activity, which would also result in an increased heart rate (34, 35). However, it was not possible to demonstrate changes in heart rate variability in the present experiments.

Since cardiac output increased to a larger extent than mean arterial pressure during GLP-1 infusion, and since renal hemodynamics were not affected by GLP-1 infusion, this suggests that the increase in cardiac output is compensatory to vasodilation in other vascular beds, e.g., in the splanchnic tissues, skeletal muscles, and/or adipose tissue. However, this hypothesis needs to be studied in additional experiments.

A novel finding in the present study is that GLP-1 is extracted in the human kidneys, comparable to the renal extraction of GLP-1 in pigs (27). Clearly, the extraction exceeds what can be explained by glomerular filtration. In this context, it is of interest that the GLP-1 receptor has also been localized to the renal afferent arterioles, and binding to these could be involved in the additional extraction (25). However, the metabolite, which is a weak antagonist of the receptor but may importantly influence blood vessels (1), was extracted at an even higher rate, suggesting that additional mechanisms might be involved. Despite this extraction, we were not able to measure any change in Na⁺, K⁺, H⁺, or Li⁺ clearance or excretion rate during GLP-1 infusion, in agreement with a constant renal plasma flow and glomerular filtration rate. Nevertheless, plasma renin activity decreased during GLP-1 infusion. It can be argued that there may be a slight underestimation of GFR by 10% using ⁵¹Cr-EDTA in the present study. This is due to a small amount (12.15 ± 0.59%) of ⁵¹Cr-EDTA that is plasma protein bound, and, consequently, this may affect their ultrafiltration (8, 13). However, in the present experimental setup, arterial ⁵¹Cr-EDTA levels were constant during the experiments, implying that also the protein-bound fraction of ⁵¹Cr-EDTA must have been constant.

In contrast to the present study, Gutzwiller et al. (12) found that a 3-h GLP-1 infusion dose dependently increased renal Na⁺ excretion and decreased glomerular filtration rate, as measured as the renal clearance of creatinine. Due to a simultaneous decrease in renal H⁺ excretion, the authors suggested that GLP-1 has a direct effect on Na⁺/H⁺ exchange at proximal tubular cells. Decreased Na⁺ reabsorption at a segment proximal to the macula densa would increase NaCl delivery to the macula densa and initiate a decrease in the glomerular filtration rate through tubuloglomerular feedback (24). GLP-1

Table 2. Effects of GLP-1 or saline on renal electrolyte excretions and clearances

<table>
<thead>
<tr>
<th>Variable</th>
<th>GLP-1</th>
<th>Saline</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hematocrit, %</td>
<td>48 ± 1</td>
<td>49 ± 1</td>
<td>0.657</td>
</tr>
<tr>
<td>Urine volume, ml/420 min</td>
<td>496 ± 75</td>
<td>499 ± 73</td>
<td>0.996</td>
</tr>
<tr>
<td>Na⁺ excretion, mmol/420 min</td>
<td>84 ± 17</td>
<td>72 ± 7</td>
<td>0.494</td>
</tr>
<tr>
<td>Na⁺ clearance, ml/min</td>
<td>1.5 ± 0.2</td>
<td>1.3 ± 0.1</td>
<td>0.475</td>
</tr>
<tr>
<td>K⁺ excretion, mmol/420 min</td>
<td>32 ± 4</td>
<td>31 ± 3</td>
<td>0.766</td>
</tr>
<tr>
<td>K⁺ clearance, ml/min</td>
<td>20.3 ± 2.6</td>
<td>19.2 ± 2.0</td>
<td>0.716</td>
</tr>
<tr>
<td>H⁺ excretion, mmol/420 min</td>
<td>158 ± 46</td>
<td>301 ± 91</td>
<td>0.188</td>
</tr>
<tr>
<td>H⁺ clearance, ml/min</td>
<td>10.0 ± 2.9</td>
<td>18.8 ± 5.5</td>
<td>0.148</td>
</tr>
<tr>
<td>Li⁺ clearance, ml/min</td>
<td>25.1 ± 1.6</td>
<td>25.3 ± 1.4</td>
<td>0.628</td>
</tr>
<tr>
<td>Fractional extraction of Li⁺</td>
<td>0.22 ± 0.02</td>
<td>0.23 ± 0.02</td>
<td>0.671</td>
</tr>
<tr>
<td>Urine Na⁺-to-creatinine ratio</td>
<td>17 ± 2</td>
<td>28 ± 6</td>
<td>0.141</td>
</tr>
</tbody>
</table>

Data are presented as means ± SE. The total amount of urine voided during each experiment was mixed and quantified. Renal electrolyte excretions and clearances are based on samples from the mixed urine collected during each experiment.
receptors have been detected in porcine proximal tubular cells (26). However, it has not been possible to demonstrate the presence of GLP-1 receptors in proximal tubular cells in humans (17, 25). On the other hand, GLP-1 receptor expression in renin-secreting cells of the juxtaglomerular apparatus and in the afferent arteriole has been detected (25). In the present study, urine was collected ~2 h before and after the 3-h infusion, and subjects remained supine throughout the study. The mode of urine collection in the present study, beginning before the GLP-1 or saline infusion, did not allow any time resolution with respect to a possible natriuretic effect of GLP-1. Therefore, an initial natriuretic effect of GLP-1 cannot be excluded. However, with the sensitivity of the analytic method applied, it would have been possible to demonstrate an average natriuretic effect in humans of ~60%, as demonstrated by Gutzwiller et al. (12). Furthermore, based on this GLP-1-induced natriuresis (12), we would hypothetically expect a decrease in the arteriovenous plasma concentration of Na⁺ by ~1.3 mmol/l. In the present study, the coefficient of variation measure any exchange of plasma Na⁺ concentrations before the GLP-1 or saline infusion, did not allow any time resolution with respect to a possible natriuretic effect of GLP-1. Therefore, an initial natriuretic effect of GLP-1 cannot be excluded. However, with the sensitivity of the analytic method applied, it would have been possible to demonstrate an average natriuretic effect in humans of ~60%, as demonstrated by Gutzwiller et al. (12). Furthermore, based on this GLP-1-induced natriuresis (12), we would hypothetically expect a difference in the arteriovenous plasma concentration of Na⁺ by ~1.3 mmol/l. In the present study, the coefficient of variation of Na⁺ measurements in arterial and venous plasma was 0.004%, and the SE of the arteriovenous differences was calculated to be 0.21 mmol/L. Thus, despite a sufficient sensitivity of the analytic method applied, it was not possible to measure any exchange of plasma Na⁺ during GLP-1 or saline infusion. A study by Skov et al. (29), using an isotopic infusion technique coupled with urinary sampling, also showed an increase in renal Na⁺ clearance, compatible with the results of Gutzwiller et al. (12). Since the renal clearance of Li⁺ increased simultaneously, the authors suggested that the mechanism behind the possible GLP-1-mediated natriuresis is located to the proximal tubuli. On the other hand, glomerular filtration rate as well as renal plasma flow remained unchanged during GLP-1 infusion, similar to the present study. Nevertheless, the GLP-1-mediated natriuresis was not related to systemic hemodynamic effects, since blood pressure remained unchanged and heart rate only increased transiently, most likely related to a transient decrease in blood glucose levels. In the study of Skov et al., subjects changed to upright position every 20 min to urinate. Thus, high- and low-pressure baroreceptors were unloaded and thereby the renin-angiotensin-aldosterone system was activated. Despite the fact that blood samples and blood pressure measurements were separated by 10 min from voiding, it is likely that an interindividual variation in the activation of the renin-angiotensin-aldosterone system influenced the results of that study (10). This is supported by the finding that plasma renin concentrations remained unchanged during GLP-1 infusion, whereas only plasma ANG II concentrations surprisingly decreased. In the present study, we aimed at keeping the baroreceptors stimulated constantly by maintaining subjects in the supine position throughout the study. Furthermore, in studies by both Gutzwiller et al. (12) and Skov et al. (29), conditions (due to overhydration) were less physiological, and studies were not conducted under NaCl-standardized conditions before the experiments. The latter is particularly important in studies of acute renal effects potentially mediated by hormones (3). Natriuresis can be induced by pressure mechanisms and by volume mechanisms (4). In the study by Gutzwiller et al., subjects were given a 2.5% NaCl infusion for 120 min (0.03 ml-min⁻¹kg⁻¹), corresponding to a Na⁺ load of 9.9 g. Furthermore, in the study by Skov et al., subjects were given a 0.9% NaCl infusion for 450 min (750 ml/h), corresponding to a fluid volume of 5,625 ml and a Na⁺ load of ~50 g. In the present study, a total volume load of 240 ml (0.9% NaCl) was given during each experiment, corresponding to a Na⁺ load of ~2 g. Thus, a remarkable difference between the present experiments and the studies by Gutzwiller et al. and Skov et al. is that subjects in the latter studies were hydrated to a larger extent. This suggests that GLP-1 may contribute to natriuresis elicited via volume-regulating mechanisms, whereas it does not play a role in natriuresis elicited by pressure-regulating mechanisms (4). Thus, these natriuretic effects may be related to the supraphysiological volume and Na⁺ load in contrast to the present study. Nevertheless, from the present study, it cannot be excluded that GLP-1 may have a small natriuretic effect under normal physiological conditions; however, if so, it seems to be of minor biological importance.

It has been suggested that GLP-1 receptor stimulation in the atria induces ANP secretion in mice (16). To our knowledge, so far only one other human study (30) has investigated a possible GLP1-ANP axis. In that study, MR-proANP and not ANP itself was analyzed, because the analysis was carried out post hoc. ANP is stored in the form proANP(1–126) and cleaved from the propeptide upon secretion. Thus, proANP(1–98) and active peptide [ANP = proANP(99–126)] are secreted in equimolar amounts. Nevertheless, due to a longer half-life and better preservation in plasma, proANP is today used clinically as a surrogate for cardiac ANP secretion. Similar to the study by Skov et al. (29), GLP-1-infusion in our study did not affect proANP levels in plasma, and also plasma ANP levels remained constant, which seem to exclude a GLP1-ANP axis in humans.

In conclusion, the present study demonstrates significant acute hemodynamic effects of GLP-1 in healthy men under highly standardized conditions. These effects are not due to changes in renal perfusion, which was unaffected by GLP-1. Changes in renal function in healthy men could not be demonstrated, although a renal extraction of total GLP-1 by ~55% was found.

ACKNOWLEDGMENTS

The excellent technical support by technicians Bente Matthiessen (Bispebjerg University Hospital), M. A. Marqués (12MC Toulouse), Lilli Christensen (Glostrup University Hospital), and Lene Albæk and Sofie Pilgaard (Department of Biomedical Sciences, University of Copenhagen) is gratefully acknowledged.

GRANTS

This work was supported by The Danish Heart Foundation, The Board of Research of Bispebjerg University Hospital, The Arvid Nilssons Foundation, The Torben and Alice Frimodt Foundation, The Dagmar Marshalls Foundation, The Helen and Ejnar Bjørnsons Foundation, The Jens Anker Andersen Foundation, The Waagens Foundation 2012, The Else and Mogens Wedelborgs Fond, and The Snedkerkermst Sophus Jacobsen and hustru Astrid Jacobsens Foundation.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

REFERENCES


