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## **Neuropeptide 26RFa (QRFP) is a key regulator of glucose homeostasis and its activity is markedly altered in obese/hyperglycemic mice**

Gaëtan Prévost, Arnaud Arabo, Marie-Anne Le Sollicec, Justine Bons, Marie Picot, Julie Maucotel, Hind Berrahmoune, Mouna El Mehdi, Saloua Cherifi, Alexandre Benani, et al.

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4  
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25  
26 **Running head:** the neuropeptide 26RFa and chronic hyperglycemia

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34

35 **ABSTRACT**

36 Recent studies have shown that the hypothalamic neuropeptide 26RFa regulates glucose  
37 homeostasis by acting as an incretin, and increasing insulin sensitivity. In this study, we  
38 further characterized the role of the 26RFa/GPR103 peptidergic system in the global  
39 regulation of glucose homeostasis using a 26RFa receptor antagonist, and also assessed  
40 whether a dysfunction of the 26RFa/GPR103 system occurs in obese hyperglycemic mice.  
41 Firstly, we demonstrate that administration of the GPR103 antagonist reduces the global  
42 glucose-induced incretin effect and insulin sensitivity whereas, conversely, administration of  
43 exogenous 26RFa attenuates glucose-induced hyperglycemia. Using a mouse model of high-  
44 fat diet-induced obesity and hyperglycemia, we found a loss of the anti-hyperglycemic effect  
45 and insulinotropic activity of 26RFa, accompanied with a marked reduction of its insulin-  
46 sensitive effect. Interestingly, this resistance to 26RFa is associated with a down-regulation of  
47 the 26RFa receptor in the pancreatic islets, and insulin target tissues. Finally, we observed that  
48 the production and release kinetics of 26RFa after an oral glucose challenge is profoundly  
49 altered in the high-fat mice. Altogether, the present findings support the view that 26RFa is a  
50 key regulator of glucose homeostasis whose activity is markedly altered under  
51 obese/hyperglycemic conditions.

52

53 **Key words:** 26RFa; incretin; glucose homeostasis; diabetes; obesity

54

## 55 INTRODUCTION

56

57 The neuropeptide 26RFa, also referred to as QRFP (for pyroglutamylated RFamide  
58 peptide), is the latest member of the RFamide peptide family discovered (5,9,16). 26RFa and  
59 its N-extended form 43RFa were identified as the cognate ligands of the human orphan G-  
60 protein-coupled receptor, GPR103 (6,9,16,30). This peptidergic system is abundantly  
61 expressed in the hypothalamus and is involved in the control of feeding behaviour (3,4,5,30).  
62 Indeed, 26RFa (or 43RFa) stimulates food intake (5,20,21,30), and the neuropeptide exerts its  
63 orexigenic activity via a modulation of the NPY/POMC network in the arcuate nucleus (20).  
64 These observations have been recently confirmed by data obtained from 26RFa-deficient mice  
65 showing that the knockout (KO) mice are lean and hypophagic, and that, under a high-fat  
66 (HF) diet, the 26RFa KO mice show a lower weight gain than the wild-type animals (22). In  
67 line with this, a more sustained orexigenic activity of 26RFa/43RFa has been reported in wild  
68 type mice submitted to a HF diet (21,27). Moreover, the expression of prepro26RFa mRNA is  
69 up-regulated in the hypothalamus of genetically obese *ob/ob* and *db/db* mice, and rodents  
70 submitted to a HF diet (27,30). Altogether, these findings support the notion that 26RFa could  
71 play a role in the development and maintenance of the obese status (7).

72 Accumulating evidence over the last decade supports the role of neuropeptides controlling  
73 feeding behavior such as neuropeptide Y (NPY), orexins, ghrelin, corticotropin-releasing  
74 factor (CRF) or apelin, in the peripheral regulation of glucose homeostasis (14,15,23,32,33).  
75 This has led to the new concept that hypothalamic neuropeptides may serve as a link between  
76 energy and glucose homeostasis, and therefore, they represent potential therapeutic targets for  
77 the treatment of diabetes and obesity (28,29). In this context, the potential role of 26RFa in  
78 the control of glucose homeostasis was investigated. It was found that 26RFa/43RFa and  
79 GPR103 are expressed in pancreatic islets, as well as in various insulin-secreting cell lines

80 (11,26), and that 26RFa and 43RFa prevent cell death and apoptosis of  $\beta$  cell lines and  
81 isolated human pancreatic islets (11). It has been shown that 26RFa is abundantly expressed  
82 by the gut and that i.p. administration of the neuropeptide attenuates glucose-induced  
83 hyperglycemia by increasing plasma insulin via a direct insulinotropic effect on the pancreatic  
84  $\beta$  cells, and also by increasing insulin sensitivity (26). Furthermore, it was reported that an  
85 oral glucose challenge induces a massive secretion of 26RFa by the gut into the blood,  
86 strongly suggesting that this neuropeptide plays an important role in the regulation of  
87 glycemia by acting as an incretin (26).

88 The incretin effect is known to be markedly reduced in diabetic patients (18), although  
89 most studies have reported that levels of GLP-1 and gastric inhibitory polypeptide (GIP) in  
90 response to oral glucose were similar in diabetic and non-diabetic subjects (8,13,18). This  
91 incretin defect is notably characterized by a decreased, albeit partially preserved,  
92 insulinotropic potency of GLP-1 and an almost complete loss of insulin secretion to GIP (18).  
93 In this context, the objective of the present study was twofold: (1) to further characterize the  
94 role of 26RFa/GPR103 peptidergic system in the global regulation of glucose homeostasis  
95 (via an oral glucose tolerance test) using a 26RFa receptor antagonist (namely 25e) (10); and  
96 (2) to determine whether a dysfunction of the 26RFa/GPR103 system occurs in  
97 obese/hyperglycemic conditions.

98

99 **MATERIAL AND METHODS**

100

101 *Animals.* Male C57Bl/6 mice (Janvier laboratory, Le Genest-Saint-Isle, France), weighing  
102 22–25 g, were housed at 5 animals per cage, with free access to standard diet (U.A.R.,  
103 Villemoisson-sur-Orge, France) and tap water. They were kept in a ventilated room at a  
104 temperature of 22±1°C under a 12-h light/12-h dark cycle (light on between 7 h and 19 h). All  
105 the experiments were carried out between 09.00 h and 18.00 h in testing rooms adjacent to the  
106 animal rooms. Animal manipulations were performed according to the European Community  
107 Council Directive of November 24<sup>th</sup> 1986 (86:609: EEC), and were conducted by authorized  
108 investigators.

109 *High-fat (HF) model.* Mice were submitted to a dietary challenge at two months of age by  
110 using a standard chow (U8200G10R; energy density: 2 830 kcal/kg; Scientific Animal Food  
111 & Engineering (SAFE), Augy, France) or a HF diet (U8978; energy density: 5 283 kcal/kg;  
112 SAFE). Experiments were performed after three months of dietary challenge. Our Institutional  
113 Animal Use and Care Committee (CENOMAX, Agreement of the Ministry of Research n°54)  
114 approved the experimental procedures (Agreement n°: #11752).

115 *Peptides and chemicals.* Mouse 26RFa (ASGPLGTLAEELSSYSRRKGGFSFRF-NH<sub>2</sub>)  
116 was synthesized (0.1 mmol scale) by the solid phase methodology on a Rink amide 4-  
117 methylbenzhydrylamine resin (Biochem, Meudon, France) by using a 433A Applied  
118 Biosystems peptide synthesizer and the standard fluorenylmethoxycarbonyl (Fmoc)  
119 procedure. The synthetic peptide was purified by reversed-phase HPLC on a 2.2 × 25-cm  
120 Vydac 218TP1022 C<sub>18</sub> column (Alltech, Templemars, France) by using a linear gradient (10-  
121 50% over 50 min) of acetonitrile/trifluoroacetic acid (99.9 : 0.1 ; v/v) at a flow rate of 10  
122 mL/min. Analytical HPLC, performed on a Vydac 218TP54 C<sub>18</sub> column (0.46 × 25-cm),  
123 showed that the purity of the peptides was greater than 99%. The identity of the synthetic

124 peptide was confirmed by mass spectrometry on a JEOL model AX-500 mass spectrometer.  
125 The GPR103 antagonist 25e was synthesized as previously described (10). Insulin and  
126 exenatide were purchased from Eli Lilly (Neuilly-sur-Seine, France).

127 *Blood glucose and insulin measurements in mice.* For i.p. glucose tolerance test and  
128 glucose-stimulated insulin secretion assay, mice were fasted for 16 h with free access to water  
129 and then injected i.p. with glucose (1.5 g/kg) and 26RFa (500 µg/kg) or PBS solution. For  
130 measurements of basal glycemia, mice were fed ad libitum and injected i.p. with 26RFa (500  
131 µg/kg) or PBS solution. Blood plasma glucose concentrations were measured from tail vein  
132 samplings at various times using an AccuChek Performa glucometer (Roche Diagnostic,  
133 Saint-Egreve, France). Plasma insulin concentrations were determined using an AlphaLISA  
134 insulin detection kit (ref AL204c, Perkin Elmer, Courtabeuf, France). For insulin tolerance  
135 test, mice were fasted for 6 h and injected i.p. with 0.75 units/kg body weight of human  
136 insulin (Eli Lilly, Neuilly-sur-Seine, France) and 26RFa (500 µg/kg) or the GPR103  
137 antagonist 25e (5 mg/kg), or PBS. For oral glucose tolerance test, mice were fasted for 16 h  
138 before the test with free access to water and injected i.p. with the GPR103 antagonist 25e (5  
139 mg/kg) or PBS 30 min before a 2 g/kg oral glucose load. For the experiments with 26RFa, the  
140 peptide (500 µg/kg) was injected (i.p.) just before the glucose load. Blood plasma glucose  
141 and insulin concentrations were measured from tail vein samplings at various times and  
142 plasma samples for 26RFa concentration measurements were obtained from decapitation just  
143 before or 30 and 120 min after the glucose challenge, and then assayed for 26RFa.

144 *Insulin secretion by the EndoC-βH1 cells.* Human β cells (EndoC-βH1), a kind gift from  
145 Dr R. Scharfmann (INSERM U1016, Institut Cochin, Paris, France), were grown in DMEM  
146 containing 2.8 mM glucose and supplemented with 2% heat-inactivated fetal bovine serum, 2-  
147 mercaptoethanol (50 µM), nicotinamide (10 mM), selenite sodium (6.7 ng/ml), transferrin (5.5  
148 µg/ml), penicillin (100 mg/l) and streptomycin (100 mg/l), in a humidified atmosphere of 5%

149 CO<sub>2</sub>, 95% air at 37° C. Concurrently, some wells containing the EndoC-βH1 cells were  
150 incubated in the same medium containing a solution of palmitate (10 mM, P9767-5G, Sigma  
151 Aldrich) for four days. Before the experiments, the culture medium was removed and EndoC-  
152 βH1 cells (4.3x10<sup>5</sup> cells/well) were preincubated in a Krebs-Ringer bicarbonate buffer  
153 containing 0.2% BSA and 2.8 mM glucose (low glucose, LG) for 1 h at 37° C (period P1) to  
154 evaluate basal insulin secretion. The culture medium was then removed and replaced by the  
155 same culture medium (LG) or a culture medium with 16.5 mM of glucose (high glucose, HG)  
156 added or not with 26RFa (10<sup>-6</sup> M) and the GLP-1 analogue exenatide (5 10<sup>-7</sup> M) for 1 h  
157 (period P2). Insulin secreted in the culture medium was measured using a commercial ELISA  
158 kit (Mercodia Insulin ELISA, Uppsala, Sweden) and was expressed as the ratio between  
159 secretion during the P2 period/secretion during the P1 period.

160 *Immunohistochemical procedure.* Deparaffinized sections (15-μm thick) of duodenum and  
161 pancreas of control or HF mice were used for immunohistochemistry. Tissue sections were  
162 incubated for 1 h at room temperature with rabbit polyclonal antibodies against 26RFa (3)  
163 diluted 1:400 or GPR103 (#NLS1922; Novus Biologicals, Littleton, CO) diluted 1:100. The  
164 sections were incubated with a streptavidin-biotin-peroxydase complex (Dako Corporation,  
165 Carpinteria, CA), and the enzymatic activity was revealed with diaminobenzidine. Some  
166 slices were then counterstained with hematoxylin. Observations were made under a Nikon E  
167 600 light microscope.

168 *Quantitative PCR.* Total RNA from the skeletal muscle, adipose tissue, liver and  
169 duodenum of HF and control mice, and from EndoC-βH1 cells was isolated as previously  
170 described (25). Relative expression of the 26RFa, GPR103, GLP-1 receptor, GLUT-1 and  
171 GLUT-2 genes was quantified by real-time PCR with appropriate primers (Table 1). GAPDH  
172 or cyclophilin A were used as internal controls for normalization. PCR was carried out using  
173 Gene Expression Master Mix 2X assay (Applied Biosystems, Courtaboeuf, France) in an ABI



174 Prism 7900 HT Fast Real-time PCR System (Applied Biosystems). The purity of the PCR  
175 products was assessed by dissociation curves. The amount of target cDNA was calculated by  
176 the comparative threshold (Ct) method and expressed by means of the  $2^{-\Delta\Delta C_t}$  method.

177 *26RFa radioimmunoassay.* Quantification of 26RFa in plasma and tissue samples was  
178 carried out using a specific radioimmunoassay (RIA) set up in the laboratory that has been  
179 previously described in detail (3). For the RIA procedure, each plasma sample was diluted  
180 (1:1) in a solution of water/TFA (99.9:0.1; v/v). The duodenum fragments were immersed for  
181 15 min in boiling 0.5 M acetic acid, homogenized at 4°C using a glass potter homogenizer  
182 and centrifuged (6,000 g, 4°C, 30 min). Diluted plasma and supernatant fluid of tissue extracts  
183 were pumped at a flow rate of 1.5 ml/min through one Sep-Pak C<sub>18</sub> cartridge. Bound material  
184 was eluted with acetonitrile/water/TFA (50:49.9:0.1; v/v/v) and acetonitrile was evaporated  
185 under reduced pressure. Finally, the dried extracts were resuspended in PBS 0.1 M and  
186 assayed for 26RFa.

187 *Statistical analysis.* Statistical analysis was performed with Statistica (5<sup>th</sup> version). A  
188 student *t*-test or ANOVA for repeated measures were used for comparisons between two  
189 groups. A post-hoc comparison using Tukey HSD was applied according to ANOVA results.  
190 Statistical significance was set up at  $p < 0.05$ .

191

192

193 **RESULTS**

194

195 *Consequence of blocking 26RFa action on glucose and insulin tolerance in control mice.*

196 Administration of the 26RFa receptor antagonist, 25e, 30 min before an oral glucose tolerance  
197 test resulted in a significant increase of the glycemia between 30 and 60 min after the oral  
198 glucose challenge (Fig. 1A), as assessed by the calculation of the areas under the curve (Fig.  
199 1A insert). Plasma insulin concentrations tended to be slightly higher in animals that received  
200 the GPR103 antagonist, but without reaching the statistical significance (Fig. 1B).

201 Administration of 25e during an insulin tolerance test significantly reduced insulin  
202 sensitivity from 15 to 90 min after the i.p. injection of insulin ( $p < 0.05$ - $p < 0.001$ ) (Fig. 1C) as  
203 assessed with a statistical difference of the areas under the curve of  $p = 0.07$  between 25e-  
204 treated mice and animals that did not receive the GPR103 antagonist (Fig. 1C insert).

205 *Effect of a 26RFa injection on blood glucose and plasma insulin levels following an oral*  
206 *glucose challenge.*

207 We completed the experiments using the 26RFa receptor antagonist, by performing oral  
208 glucose tolerance tests with administration of exogenous 26RFa. In these experiments, the  
209 hyperglycemic effect induced by the glucose challenge was significantly reduced by the i.p.  
210 injection of 26RFa (Fig. 1D), but without any significant alteration of plasma insulin levels  
211 (Fig. 1E).

212 *Effect of 26RFa on basal glycemia, glucose-induced hyperglycemia and insulin tolerance.*

213 The high-fat (HF) diet challenge induced a significant ( $p < 0.001$ ) weight gain right from the  
214 first month of treatment (Fig. 2A). After three months, the HF mice exhibited a weight of  
215  $43.00 \pm 0.65$  g, whereas mice fed a standard chow weighted  $27.00 \pm 0.85$  g (Fig. 2A).  
216 Similarly, plasma glucose was significantly increased ( $p < 0.01$ ) after one month of HF diet  
217 (Fig. 2B). After 3 months, the HF mice exhibited a fasting glycemia of  $2.11 \pm 0.06$  g/l,

218 whereas that of the mice fed a standard chow at the same time was  $1.16 \pm 0.05$  g/l ( $p < 0.001$ ;  
219 Fig. 2B).

220 The impact of 26RFa was investigated on basal glycemia in mice fed a standard chow and  
221 in HF mice. As illustrated in figure 2C, D, i.p. administration of 26RFa did not affect  
222 significantly basal plasma glucose levels during the 90-min period of the test in the two diet  
223 conditions. By contrast, an IPGTT performed in the two groups of mice revealed that 26RFa  
224 significantly attenuated ( $p < 0.05$ ) the hyperglycemia induced by an i.p. glucose challenge in  
225 mice fed a standard chow during the first 30 min of test, whereas this anti-hyperglycemic  
226 effect of the neuropeptide was totally abolished in HF mice (Fig. 2E, F). I.p. injection of  
227 26RFa also significantly potentiated ( $p < 0.05$ ) insulin-induced hypoglycemia during the 90  
228 min following the insulin challenge in mice fed a standard chow as illustrated by the  
229 quantification of the areas under the curves (Fig. 3A, C). By contrast, the beneficial effect of  
230 26RFa on insulin sensitivity was strongly attenuated in HF mice (Fig. 3B, C). Quantification  
231 of GPR103 mRNA in insulin target tissues revealed a significant decrease ( $p < 0.05$ ) in the  
232 expression of the 26RFa receptor in the muscle and the adipose tissue of HF mice (Fig. 3D).  
233 No expression of GPR103 was detected in the liver of the two groups of animals (Fig. 3D).

234 *Consequence of blocking 26RFa action on glucose and insulin tolerance in HF mice.*  
235 Administration of the GPR103 antagonist 25e during an oral glucose tolerance test in HF  
236 mice had no significant effect on plasma glucose and insulin levels (Fig. 4A, B) in contrast to  
237 what was observed in mice fed a standard chow (Fig. 1A, B). i.p. injection of 25e had no  
238 significant impact on insulin sensitivity during an insulin tolerance test in HF mice (Fig. 4C)  
239 in contrast to the insulin-resistant effect of the GPR103 antagonist observed in mice fed a  
240 standard chow (Fig. 1C). In addition, administration of 26RFa had no effect on the  
241 hyperglycemia induced by the oral glucose load (Fig. 4D) nor on plasma insulin levels (Fig.  
242 4E).

243 *Effect of 26RFa on insulin production.* The effect of 26RFa on insulin production was  
244 investigated *in vivo* and *in vitro*. An acute glucose-stimulated insulin secretion test showed  
245 that injection of 26RFa significantly stimulated glucose-induced insulin production in mice  
246 fed a standard chow ( $p<0.05$ ; Fig. 5A), whereas this insulinotropic effect of the neuropeptide  
247 was totally abolished in HF mice (Fig. 5B). Concurrently, the impact of 26RFa on insulin  
248 secretion by pancreatic  $\beta$  cells was examined using the human insulin-secreting cell line,  
249 EndoC- $\beta$ H1, that were treated with palmitate to mimic conditions of lipotoxicity. As  
250 illustrated in figure 5C, addition of 26RFa in the culture medium significantly stimulated  
251 insulin secretion by untreated EndoC- $\beta$ H1 cells incubated in LG ( $p<0.05$ ) or HG ( $p<0.01$ )  
252 conditions. The GLP-1 analogue, exenatide, used as a positive control, also significantly  
253 stimulated insulin secretion ( $p<0.01$ ) by the untreated EndoC- $\beta$ H1 cells (Fig. 5C).  
254 Conversely, when the cells were treated for 96 h with palmitate, the insulinotropic effect of  
255 26RFa was totally abolished whatever the glucose concentration in the culture medium (Fig.  
256 5D). By contrast, exenatide still significantly stimulated insulin secretion by palmitate-treated  
257 cells ( $p<0.01$ , Fig. 5D). Comparison of insulin secretion between native and palmitate-treated  
258 EndoC- $\beta$ H1 cells revealed that, in non-stimulated conditions, basal insulin release was not  
259 affected in palmitate-treated cells (Fig. 5E). By contrast, under stimulatory conditions (26RFa  
260 or exenatide), insulin secretion was dramatically altered in palmitate-treated cells as compared  
261 to native cells (Fig. 5E). Finally, expression of GLUT-1, GLUT-2, the GLP-1 receptor and  
262 GPR103 was evaluated in native and palmitate-treated EndoC- $\beta$ H1 cells (Fig. 5F). GLUT-1  
263 and the GLP-1 receptor mRNA levels were not altered by the lipotoxic treatment of the cells  
264 (Fig. 5F). By contrast, expression of GLUT-2 was significantly decreased ( $p<0.05$ ) in  
265 palmitate-treated cells and that of GPR103 was also lowered ( $p=0.06$ ; Fig. 5F). Consistent  
266 with this latter observation, immunohistochemical observation of pancreas of mice fed a

267 standard chow and HF mice revealed a decrease in the intensity of the GPR103 labeling in the  
268 pancreatic islets of HF mice (Fig. 5G, H).

269 *Effect of the high fat diet on gut 26RFa production.* We first investigated the expression  
270 and distribution of 26RFa in the duodenum of HF mice and mice fed a standard chow using a  
271 Q-PCR approach combined with immunohistochemistry (Fig. 6A, B). The expression of  
272 26RFa was significantly lowered ( $p<0.01$ ) in the duodenum of HF mice as compared to mice  
273 fed a standard chow (Fig. 6A). In agreement with this finding, the immunohistochemistry  
274 revealed an important decrease in the number of enterocytes immunostained with the 26RFa  
275 antibody in the duodenum of HF mice (Fig. 6B).

276 The impact of a 2 g/kg oral glucose load on plasma glucose, insulin and 26RFa, and on  
277 26RFa content in the duodenum was investigated in HF mice and mice fed a standard chow  
278 (Fig. 6C-G). In mice fed a standard chow, the oral glucose challenge induced an important  
279 increase of the glycemia at 30 min, followed by a decrease at 120 min (Fig. 6C). The HF mice  
280 exhibited a similar glycemic profile although plasma glucose levels were significantly higher  
281 all along the test ( $p<0.05-0.01$ ; Fig. 6C). Measurement of plasma insulin during the OGTT  
282 indicated that insulinemia was always higher in HF mice as compared to mice fed a standard  
283 chow, as assessed by the point by point statistical analysis ( $p<0.05-0.001$ ) and the  
284 measurement of the area under the curve ( $p<0.01$ ) (Fig. 6D). Plasma 26RFa profile in mice  
285 fed a standard chow was very similar to that observed for glycemia and insulinemia, with an  
286 increase of plasma 26RFa levels observed at 30 min followed by a decrease at 120 min (Fig.  
287 6E). In HF mice, plasma 26RFa concentration was similar to that of mice fed a standard chow  
288 during the first 30 min of the test, but the obese/hyperglycemic mice exhibited a dramatic rise  
289 in plasma 26RFa levels at 120 min ( $p<0.05$ ) that was not observed in mice fed a standard  
290 chow (Fig. 6E), as underlined by the significant difference of the areas under the curves (Fig.  
291 6F). Quantification of 26RFa content in the duodenum showed a significant decrease ( $p<0.01$ )

292 of the neuropeptide production in HF mice under basal condition (at T0) (Fig. 6G). During the  
293 oral glucose tolerance test, 26RFa content in the duodenum exhibited a profile closely related  
294 to that of plasma 26RFa in the two groups of mice with, in particular, a highly significant rise  
295 of duodenal 26RFa production ( $p < 0.001$ ) 120 min after the oral glucose challenge in HF mice  
296 (Fig. 6G).  
297

298 **DISCUSSION**

299

300 In the first part of the present study, we took advantage of the first disclosed GPR103  
301 antagonist (10) that can be used as an *in vivo* tool to decipher the role of 26RFa in glucose  
302 homeostasis. We have previously demonstrated that 26RFa could be considered as a novel  
303 incretin (26). This conclusion was based on experiments carried out by our team showing that  
304 26RFa is secreted by the gut in response to an oral glucose load, and that the neuropeptide  
305 stimulates insulin secretion from pancreatic  $\beta$  cells, leading to an anti-hyperglycemic effect  
306 (26). However, without a specific antagonist molecule, it is difficult to isolate the proper role  
307 of 26RFa on the glycemic status from the well-known effects of the other incretins such as  
308 GLP-1 and GIP during an oral glucose challenge, which is recognized as the gold standard  
309 test to assess the effects of incretin hormones. Here, we further characterized the role of  
310 26RFa in the global regulation of glucose homeostasis using a GPR103 antagonist with  
311 DMPK properties suitable for *in vivo* experiments, namely 25e (10). In our set of experiments,  
312 administration of 25e induced a robust hyperglycemic effect during an oral glucose load in  
313 mice fed a standard chow. We also found that administration of the 26RFa receptor antagonist  
314 significantly reduces insulin sensitivity, confirming that one mechanism of action of the  
315 26RFa/GPR103 system to control glucose homeostasis is to increase insulin sensitivity in  
316 addition to its incretin activity (26). There was a tendency for 25e to increase plasma insulin  
317 levels during a glucose challenge. We hypothesize that this may reflect the occurrence of a  
318 compensatory mechanism to counteract the insulin-resistant effect of the GPR103 antagonist.  
319 However, this increase of insulin secretion is not sufficient to maintain normoglycemia,  
320 suggesting that blockade of 26RFa action also alter the insulin secreting capacity of the  
321 pancreatic islets. Conversely, we show that exogenous administration of 26RFa during an oral  
322 glucose load significantly reduces the hyperglycemia without any significant alteration of the

323 plasma insulin levels. In this experiment, it is important to note that, in fact, we have analyzed  
324 the effects of both exogenous and endogenous 26RFa. Thus, it seems that exogenous  
325 administration of 26RFa could potentiate the antihyperglycemic effect already induced by  
326 endogenous 26RFa production. We may speculate that the decrease of the glycemia induced  
327 by exogenous 26RFa is rather linked to an alteration of the insulin sensitivity than insulin  
328 secretion since no modification of plasma insulin levels was observed. Together, these  
329 findings confirm our previous data (26) and support the view that the 26RFa/GPR103 system  
330 plays a crucial role to sustain normoglycemia in stimulatory conditions.

331 The second objective of the present study was to investigate whether an obese/chronic  
332 hyperglycemic status is associated with a dysfunction of the 26RFa/GPR103 system. For this  
333 purpose, we submitted mice to a HF diet for a period of three months. Measurement of weight  
334 and glycemia revealed that the HF mice were actually obese and intolerant to glucose. 26RFa  
335 did not affect basal plasma glucose levels neither in the HF mice nor in control animals. This  
336 observation is consistent with the incretin status of the neuropeptide previously reported (26).  
337 By contrast, we found that the anti-hyperglycemic effect of 26RFa observed during a glucose  
338 tolerance test in control mice was lost in HF mice. We previously showed that the anti-  
339 hyperglycemic effect of 26RFa was the result of both increased insulin sensitivity in target  
340 tissues and a direct stimulation of insulin production by the pancreatic  $\beta$  cells (26). Here, we  
341 show that during an insulin tolerance test, the beneficial effect of 26RFa on insulin sensitivity  
342 is significantly attenuated. This was probably due to the fact that the expression of GPR103  
343 mRNA was down-regulated in muscle and adipose tissues of HF mice compared to controls.  
344 In the *in vivo* experiments, we found that the stimulatory effect of 26RFa on insulin  
345 production was totally lost in the HF mice. We have previously shown that 26RFa exerts a  
346 direct insulinotropic effect on pancreatic  $\beta$  cells via activation of GPR103 (26). In this study,  
347 we used a human  $\beta$  pancreatic cell line that expresses GPR103 (i.e., EndoC- $\beta$ H1cells) to



348 further explore the direct effects of 26RFa on insulin secretion. We show that 26RFa robustly  
349 stimulates insulin release by these cells. Treatment of the EndoC- $\beta$ H1 cells with palmitate, that  
350 mimics conditions of lipotoxicity observed in diabetes, totally abolished the insulinotropic  
351 effect of 26RFa. By contrast, the GLP-1 analogue, exenatide, was still able to stimulate  
352 insulin release (albeit with a reduced potency) under the same lipotoxic conditions. This latter  
353 observation is in agreement with previous studies showing a reduction of GLP-1-induced  
354 insulin secretion under conditions of lipo and glucotoxicity induced by a HF diet (12).  
355 Finally, we show that the expression of the 26RFa receptor is lowered in the EndoC- $\beta$ H1 cells  
356 cultured in lipotoxic conditions as well as in the pancreatic islets of HF mice, suggesting that  
357 this decreased expression of GPR103 in  $\beta$ -cells is responsible, at least in part, for the loss of  
358 the insulinotropic effect of 26RFa in obese/hyperglycemic conditions. In accordance with  
359 these findings, a loss of GIP insulinotropic effect has also been reported in type 2 diabetes  
360 (13,19) and down-regulation of the GIP receptor has been proposed as one of the mechanisms  
361 underlying the lack of GIP activity in type 2 diabetic patients (1, 17, 24). Similarly, a down-  
362 regulation of the GLP-1 receptor has been described in pancreatic  $\beta$  cells under diabetic  
363 conditions that may underlie the reduced incretin effect of GLP-1 in diabetes (17). However,  
364 some studies suggest that the loss or altered incretin effect in type 2 diabetes is a consequence  
365 of the diabetic state and not a primary event and that the incretin defect is mainly a  
366 consequence of general  $\beta$  cell dysfunction (8, 13, 17, 18). Together, these observations  
367 support the idea that the altered insulinotropic activity of the incretins in diabetes is probably  
368 the result of a down-regulation of their receptor expression in  $\beta$ -cells associated with a  
369 dysfunction of insulin synthesis and production.

370 We have previously found that the enterocytes of the duodenum are the main source of  
371 peripheral 26RFa and that its release to the general circulation is increased after an oral  
372 glucose challenge (26). Here, we show that, after an overnight fasting, the expression and

373 production of 26RFa in the duodenum is significantly decreased in HF mice. This finding,  
374 together with the low expression of the 26RFa receptor in insulin target tissues in HF mice,  
375 suggests that the 26RFa/GPR103 peptidergic system is markedly altered under obese/chronic  
376 hyperglycemic condition. However, we concurrently show that, under stimulatory conditions  
377 (an oral glucose load), the duodenum of HF mice keeps its ability to produce and secrete large  
378 amounts of 26RFa in the general circulation and is even over-stimulated as compared to  
379 control mice. Indeed, in HF mice, plasma 26RFa levels still increase 2 h after the oral glucose  
380 load whereas, in mice fed a standard chow, they return to basal values as previously reported  
381 (26). Interestingly, this plasma 26RFa profile during the OGTT in HF animals follows that of  
382 duodenal 26RFa production suggesting that the duodenum is the main source of circulating  
383 26RFa. In addition, these high plasma 26RFa levels 2 h after glucose ingestion might reflect  
384 the occurrence of a mechanism of action involving 26RFa production by the gut, aiming at  
385 decreasing glycemia. In this context, it would be interesting to investigate whether insulin,  
386 whose plasma levels also remain high 2 h after the oral glucose challenge in HF mice, could  
387 regulate 26RFa production by the gut as the hormone has already been reported to be able to  
388 regulate glucose intestinal absorption, in addition to its peripheral effects (31). It is  
389 noteworthy that this discrepancy in the plasma 26RFa profile during an oral glucose tolerance  
390 test between normal and chronic hyperglycemic conditions is not found for GLP-1 and GIP  
391 (2) and thus seems to be a specificity of 26RFa that deserves further investigation.

392 Finally, we show that administration of the 26RFa receptor antagonist 25e or 26RFa in  
393 obese/hyperglycemic mice has no effect on the glycemic response during an oral glucose  
394 tolerance test or an insulin tolerance test, nor an insulin secretion during an acute glucose-  
395 stimulation insulin secretion test. This observation is in agreement with the blunted 26RFa  
396 response we have observed in HF mice and can be linked to the decreased expression of  
397 GPR103 in insulin target tissues and in  $\beta$  pancreatic cells of the HF mice.

398 In conclusion, we have confirmed, using a 26RFa receptor antagonist, that the  
399 neuropeptide 26RFa is a key regulator of glucose homeostasis by acting as an incretin and  
400 improving insulin tolerance. Our data also reveal a loss of the incretin and insulin-sensitive  
401 effect of 26RFa in obese/chronic hyperglycemic conditions that is associated with a down-  
402 regulation of its receptor. Together, these observations strongly suggest that dysfunction of  
403 the 26RFa/GPR103 system participate to the general reduced incretin effect and insulin  
404 intolerance observed in diabetes.

405

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407

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410

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419

## 420 **DISCLOSURES**

421

422 The authors declare that there is no conflict of interest that could be perceived as prejudicing  
423 the impartiality of the research reported.

424

#### 425 **AUTHOR CONTRIBUTIONS**

426

427 G.P. and N.C. contributed to the study design and interpretation and wrote the manuscript.  
428 MA. LS., J.B., A.A., M.P., J.M. and M.M. contributed to the in vivo experiments on mice.  
429 J.B., MP. H.B., M.C. and P.D. contributed to the in vitro experiments on cell lines. S.C. and  
430 M.P. contributed to the immunohistochemical experiments. J.B., M.P., V.B. and H.B.  
431 contributed to the PCR experiments. A. B. and E. N. performed the insulin assays. J. L. and  
432 A. N. produced 26RFa and 25e. H.L. and Y. A. revised and approved the final version of the  
433 manuscript. N.C. is the guarantor of this work and, as such, had full access to all the data in  
434 the study and takes responsibility for the integrity of the data and the accuracy of the data  
435 analysis.

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- 552
- 553

554 **LEGENDS TO FIGURES**

555

556 **Figure 1: Consequence of blocking 26RFa action on glucose and insulin tolerance in**  
557 **control mice. (A, B)** i.p. injection of the GPR103 antagonist 25e at a dose of 5 mg/kg  
558 significantly increases the blood glucose level during an oral glucose tolerance test (*A, insert*).  
559 During the same test, plasma insulin concentrations tend to be higher all along the test in  
560 animals that received the GPR103 antagonist (*B*), although statistical analysis does not reveal  
561 any significant difference between treated and non-treated animals (*B insert*). (*C*)  
562 Administration of 25e during an insulin tolerance test significantly reduces insulin sensitivity  
563 from 15 to 90 min after the i.p. injection of insulin. (*D, E*) i.p. administration of 26RFa (500  
564 µg/kg) reduces significantly the hyperglycemia induced by a 2-g/kg oral glucose challenge  
565 (*D*), but without affecting plasma insulin levels (*E*). (*Inserts*) Calculation of the areas under  
566 the curves. Data represent means ± SEM of 3 independent experiments (n=10-15/group). \*,  
567 p<0.05; \*\*, p<0.01; \*\*\* p<0.001 vs non-treated animals.

568

569 **Figure 2: Effect of 26RFa on basal glycemia and glucose-induced hyperglycemia. (A, B)**  
570 A 3-month high fat diet induces a highly significant weight gain (*A*) and increase of glycemia  
571 (*B*) right from the first month of treatment as compared to mice fed a standard chow. (*C, D*)  
572 Effect of i.p. administration of 26RFa (500 µg/kg) on basal plasma glucose levels. 26RFa  
573 does not alter basal plasma glucose during the 90 min following its injection neither in mice  
574 fed a standard chow (*C*) nor in HF mice (*D*). (*E, F*) Effect of i.p. administration of 26RFa  
575 (500 µg/kg) during a glucose tolerance test. 26RFa significantly attenuates the hyperglycemia  
576 induced by the i.p. injection of glucose (1.5 g/kg) throughout the duration of the test in mice  
577 fed a standard chow (*E*). In HF mice, the anti-hyperglycemic effect of 26RFa during the  
578 glucose tolerance test is totally abolished (*F*). Calculation of the areas under the curves reveal

579 no significant difference between the PBS and the 26RFa groups whatever the type of diet  
580 given (*inserts*). Data represent means  $\pm$  SEM of 5 independent experiments (n=20/group). ns,  
581 non significant; \*, p<0.05; \*\*, p<0.01; \*\*\*, p<0.001 vs mice fed a standard chow.

582

583 **Figure 3: Effect of 26RFa on insulin tolerance.** (A-C) i.p. administration of 26RFa (500  
584  $\mu$ g/kg) during an insulin tolerance test significantly potentiates insulin-induced hypoglycemia  
585 during the 90 min following the insulin load (0.75 Units/kg) in mice fed a standard chow (A)  
586 as illustrated by the quantification of the areas under the curves (C) whereas, in HF mice, the  
587 beneficial effect of 26RFa on insulin sensitivity is strongly attenuated (B, C). Data represent  
588 means  $\pm$  SEM of 5 independent experiments (n=20/group). (D) Expression of GPR103  
589 mRNA was determined by quantitative polymerase chain reaction and adjusted to the signal  
590 intensity of GAPDH in the muscle, the adipose tissue and the liver. GPR103 mRNA levels are  
591 significantly lowered in the muscle and adipose tissue of HF mice as compared to those  
592 measured in mice fed a standard chow. No expression of GPR103 is detected in the liver of  
593 control or HF mice. Data represent means  $\pm$  SEM of 3 independent experiments (n=6-  
594 9/group). \*, p<0.05 vs mice fed a standard chow.

595

596 **Figure 4: Consequence of blocking 26RFa action on glucose and insulin tolerance in HF**  
597 **mice.** (A, B) Administration of the GPR103 antagonist 25e (5 mg/kg) during an oral glucose  
598 tolerance test in HF mice has no significant effect on plasma glucose (A) and insulin levels  
599 (C), as assessed by the calculation of the areas under the curves (*inserts*). (C) Similarly, i.p.  
600 injection of 25e does not alter insulin sensitivity during an insulin tolerance test in HF mice.  
601 (D, E) i.p. administration of 26RFa (500  $\mu$ g/kg) has no significant effect on the  
602 hyperglycemia induced by an oral glucose challenge in HF mice (2 g/kg) (D), nor on plasma

603 insulin levels (*E*). (**Inserts**) Calculation of the areas under the curves. Data represent means  $\pm$   
604 SEM of 3 independent experiments (n=10-12/group).

605

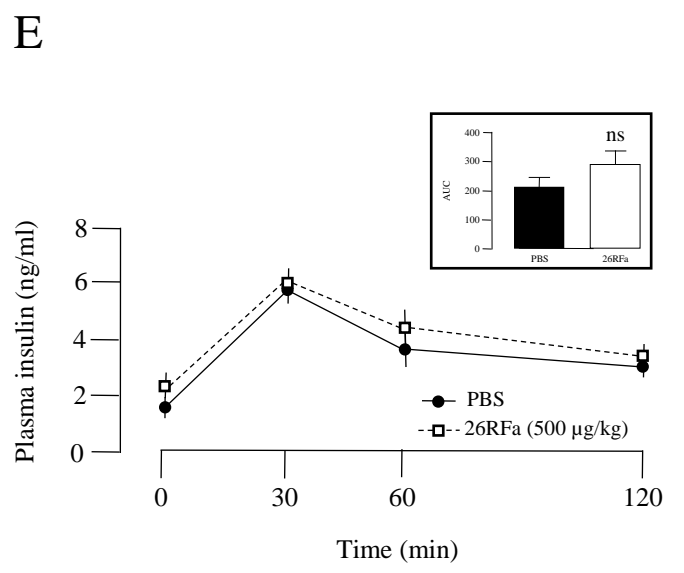
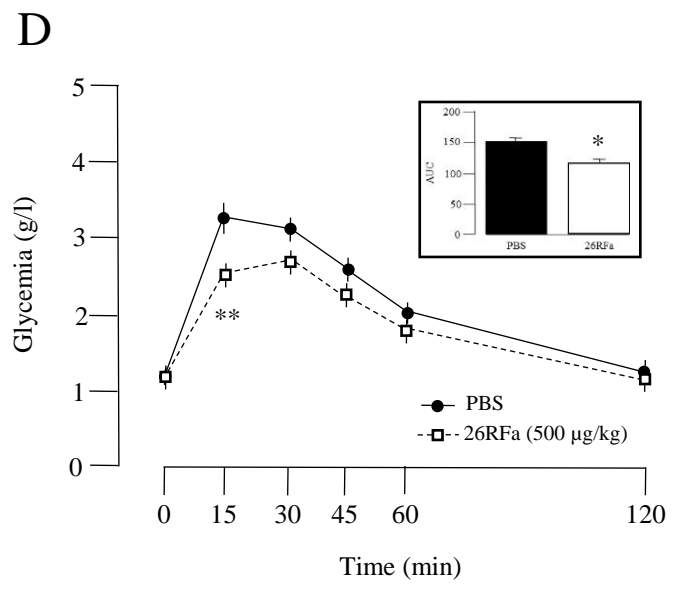
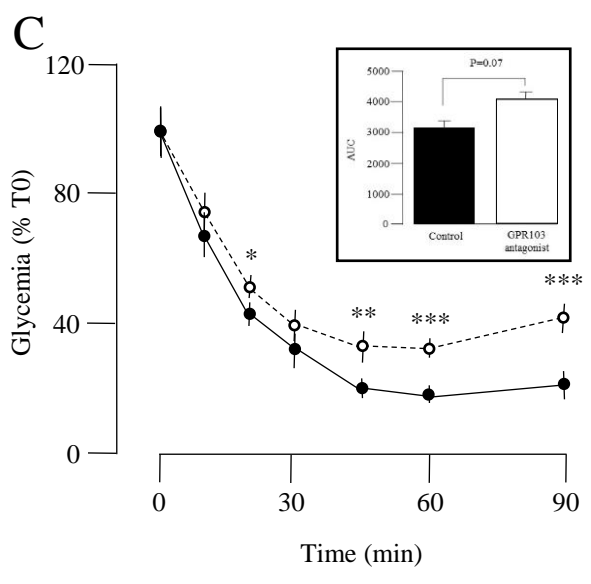
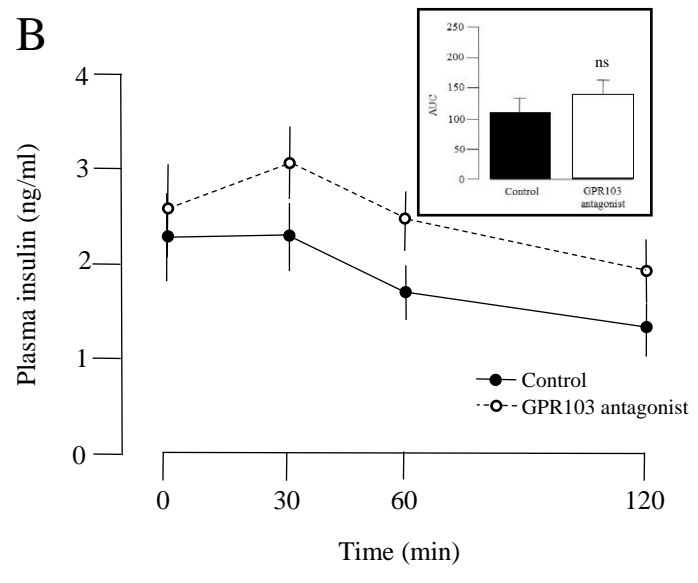
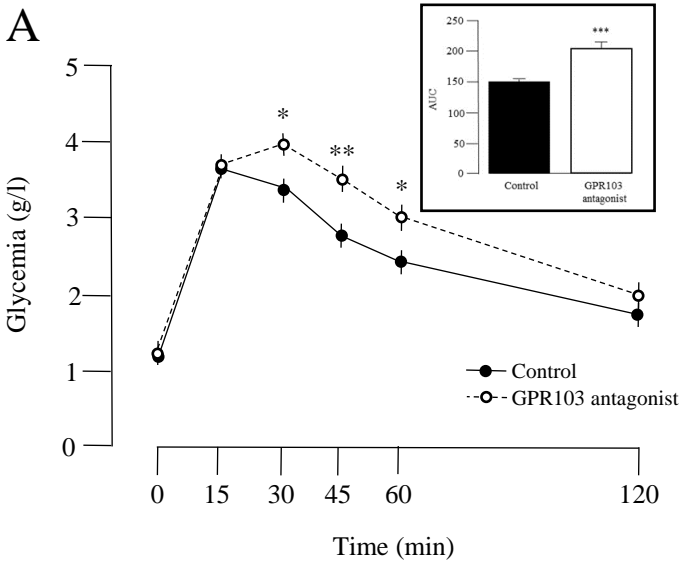
606 **Figure 5: Effect of 26RFa on insulin production.** (**A, B**) 26RFa (500  $\mu\text{g}/\text{kg}$ ) stimulates  
607 significantly glucose-induced insulin production during an acute glucose (1.5 g/kg)-stimulated  
608 insulin secretion test in mice fed a standard chow (*A*), whereas injection of the neuropeptide  
609 has no effect on plasma insulin in HF mice (*B*). Data represent means  $\pm$  SEM of 5  
610 independent experiments (n=20/group). (**C, D**) Effect of 26RFa ( $10^{-6}$  M) on insulin secretion  
611 by the human pancreatic  $\beta$  cell line EndoC- $\beta$ H1non treated or treated by palmitate for 96 h.  
612 26RFa significantly stimulates insulin secretion in untreated EndoC- $\beta$ H1 cells incubated in a  
613 low glucose (LG) or a high glucose (HG) medium (*C*). Conversely, when the cells are treated  
614 with palmitate, the insulinotropic effect of 26RFa is abolished whatever the glucose  
615 concentration in the culture medium (*D*). Data represent means  $\pm$  SEM of 4 independent  
616 experiments (n=10/condition). (**E**) Comparison of insulin secretion between native and  
617 palmitate-treated EndoC- $\beta$ H1 cells. In non-stimulatory conditions, insulin release is not  
618 affected in palmitate-treated cells as compared to native cells. By contrast, under stimulatory  
619 conditions (26RFa or exenatide), the secreting response of the cells is significantly altered by  
620 the palmitate treatment. Data represent means  $\pm$  SEM of 4 independent experiments  
621 (n=10/condition). (**F**) Expression of the glucose transporters GLUT-1 and GLUT-2, the GLP-  
622 1 receptor (GLP1R) and GPR103 mRNA was determined in native EndoC- $\beta$ H1 cells and in  
623 palmitate-treated EndoC- $\beta$ H1 cells by quantitative polymerase chain reaction and adjusted to  
624 the signal intensity of cyclophilin A. GLUT-1 and the GLP1R mRNA levels are not altered by  
625 the lipotoxic treatment of the cells whereas the expression of GLUT-2 and GPR103 is  
626 decreased in palmitate-treated cells. Data represent means  $\pm$  SEM of 3 independent  
627 experiments (n=6-9/group). \*,  $p<0.05$ ; \*\*,  $p<0.01$ . (**G, H**) Immunohistochemical labeling of

628 pancreatic islets of control and HF mice with GPR103 antibodies. Representative  
629 photomicrographs of pancreatic islets showing a robust decrease in the intensity of the  
630 GPR103 labeling in the pancreatic islets of HF mice (*H*) as compared to the pancreatic islets  
631 of mice fed a standard chow (*G*). Scale bars: 50  $\mu$ m.

632

633 **Figure 6: Effect of the high fat diet on gut 26RFa production.** (*A, B*) Expression and  
634 distribution of 26RFa in the duodenum of control and HF mice. Expression of 26RFa mRNA  
635 in the duodenum was determined by quantitative polymerase chain reaction and adjusted to  
636 the signal intensity of GAPDH, and its distribution was determined by  
637 immunohistochemistry. The expression of 26RFa is significantly lower in the duodenum of  
638 HF mice as compared to mice fed a standard chow (*A*). In agreement with this finding, the  
639 immunohistochemistry reveals an important decrease in the number of enterocytes  
640 immunostained with the 26RFa antibody in the duodenum of HF mice in comparison to  
641 duodenal slices of mice fed a standard chow (*B*). Scale bars: 50  $\mu$ m. (*C-G*) Impact of a 2-g  
642 oral glucose load on plasma glucose, insulin and 26RFa, and on 26RFa content in the  
643 duodenum of HF mice and mice fed a standard chow. During an oral glucose challenge, the  
644 HF mice exhibit a similar glycemic profile to that of mice fed a standard show, although their  
645 plasma glucose levels are significantly higher all along the test (*C*). Measurement of plasma  
646 insulin during the same test reveals that insulinemia is always higher in HF mice as compared  
647 to mice fed a standard chow, as assessed by the point by point statistical analysis and the  
648 calculation of the areas under the curves (*D*). In HF mice, plasma 26RFa concentration is  
649 similar to that of mice fed a standard chow during the first 30 min of the test, but the  
650 obese/diabetic mice exhibit a dramatic rise in plasma 26RFa levels at 120 min that is not  
651 observed in mice fed a standard chow (*E*), as underlined by the significant difference of the  
652 areas under the curves (*F*). Quantification of 26RFa concentration in the duodenum reveals

653 lower duodenal 26RFa content in HF mice under basal condition (*G*). During the oral glucose  
654 tolerance test, 26RFa content in the duodenum exhibits a profile closely related to that of  
655 plasma 26RFa in mice fed a standard chow as well as in HF mice with, in particular, a  
656 significant rise of duodenal 26RFa production 30 and 120 min after the oral glucose challenge  
657 in obese/diabetic animals (*G*). Data represent means  $\pm$  SEM of 5 independent experiments  
658 (n=18-20/group). \*,  $p<0.05$ ; \*\*,  $p<0.01$ ; \*\*\*,  $p<0.001$  vs mice fed a standard chow. §,  
659  $p<0.05$ ; §§,  $p<0.01$  vs T0 min.



**Figure 1**  
Downloaded from www.physiology.org/journal/ajpendo at INRA Institut National de la Recherche Agronomique (138.102.192.062) on May 20, 2019.

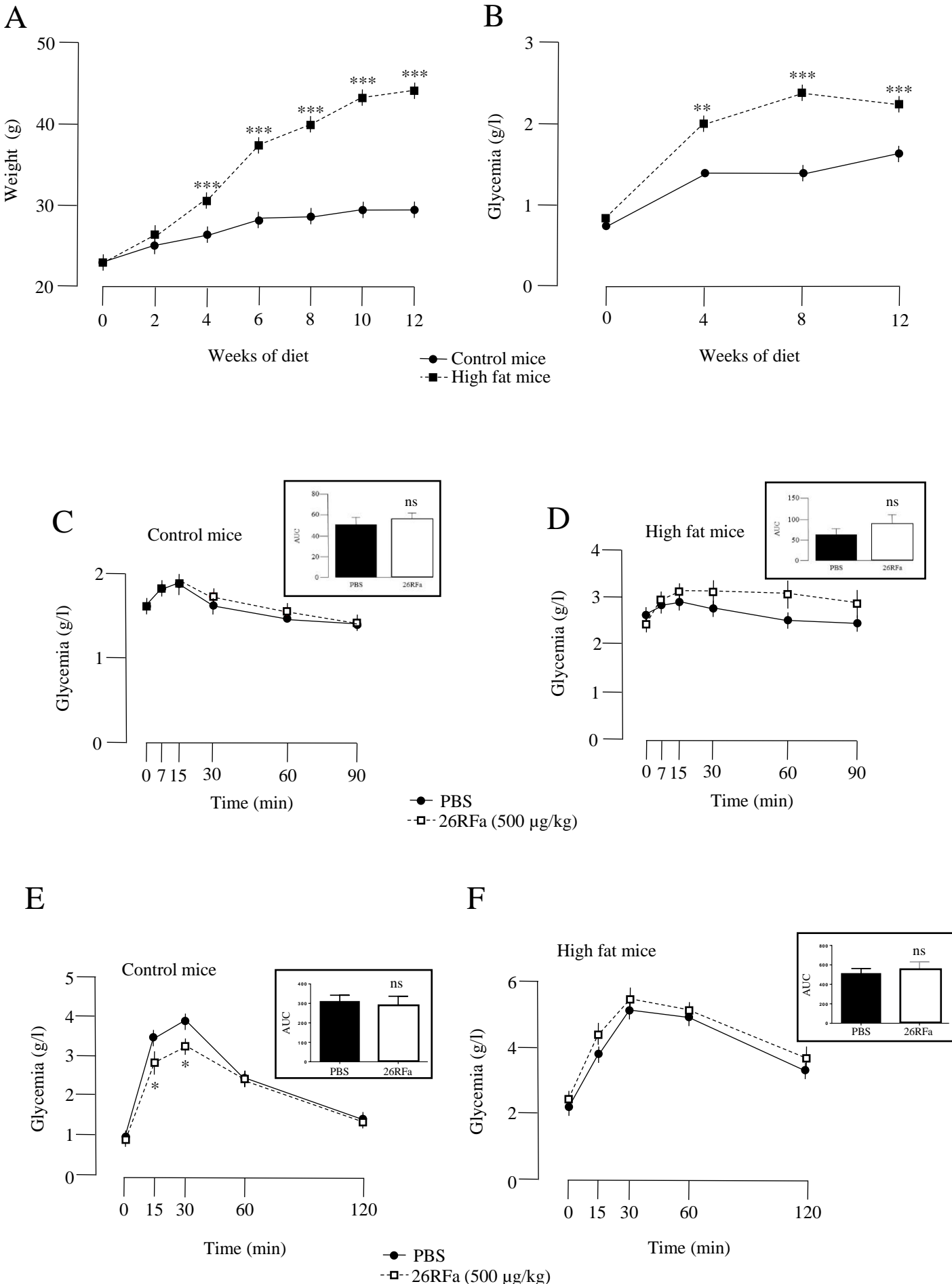


Figure 2



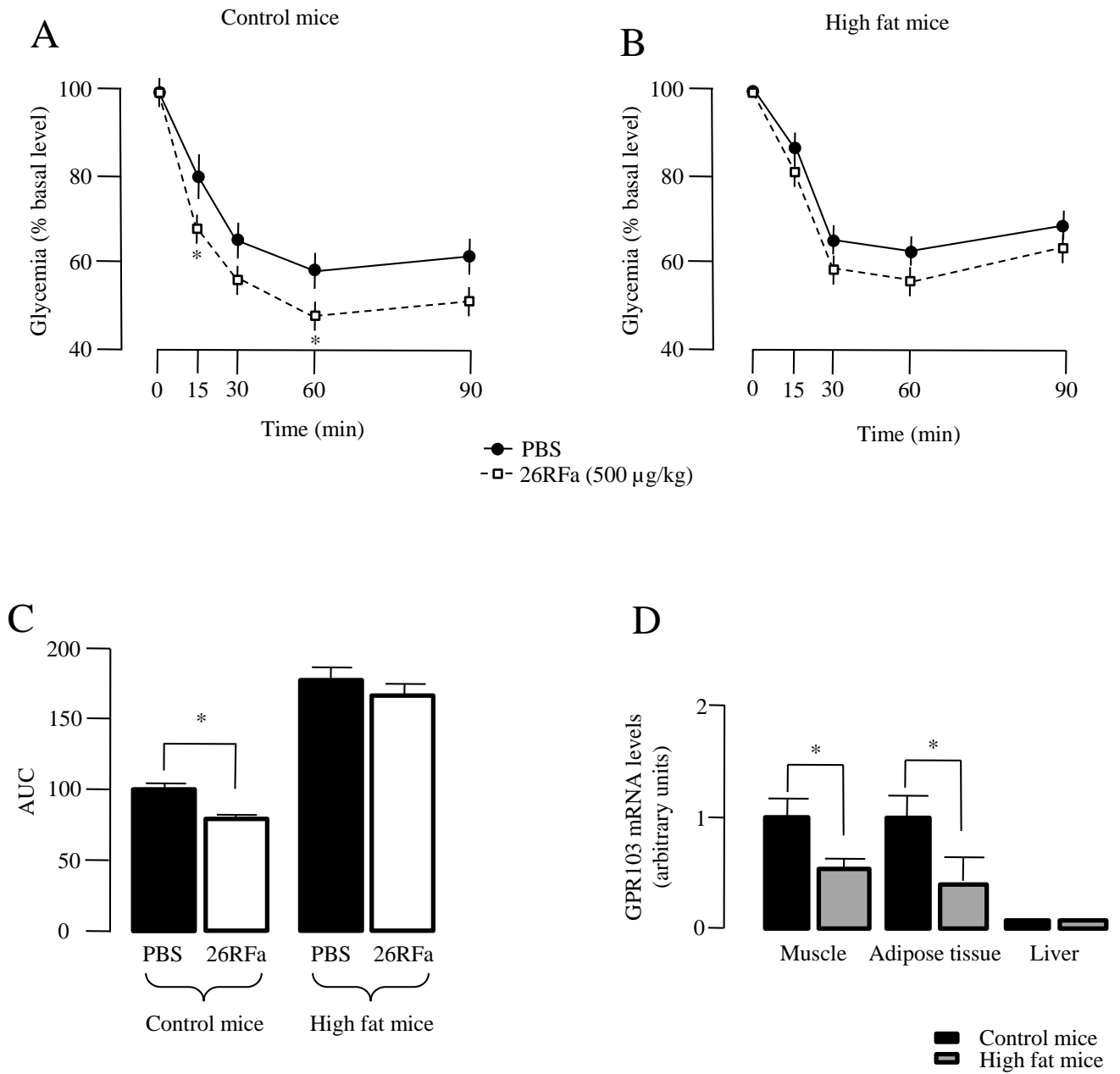
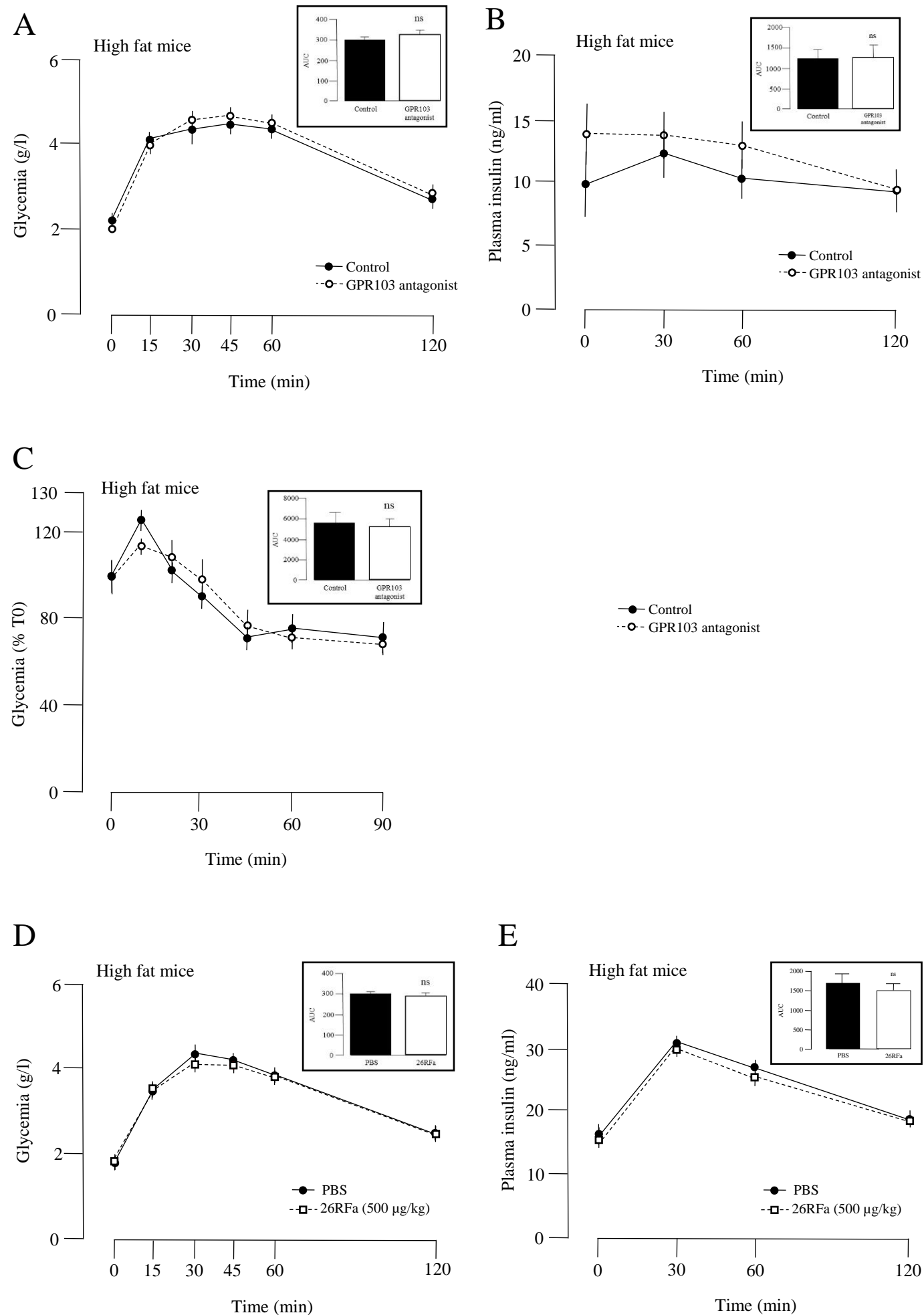


Figure 3 Downloaded from www.physiology.org/journal/ajpendo at INRA Institut National de la Recherche Agronomique (138.102.192.062) on May 20, 2019.



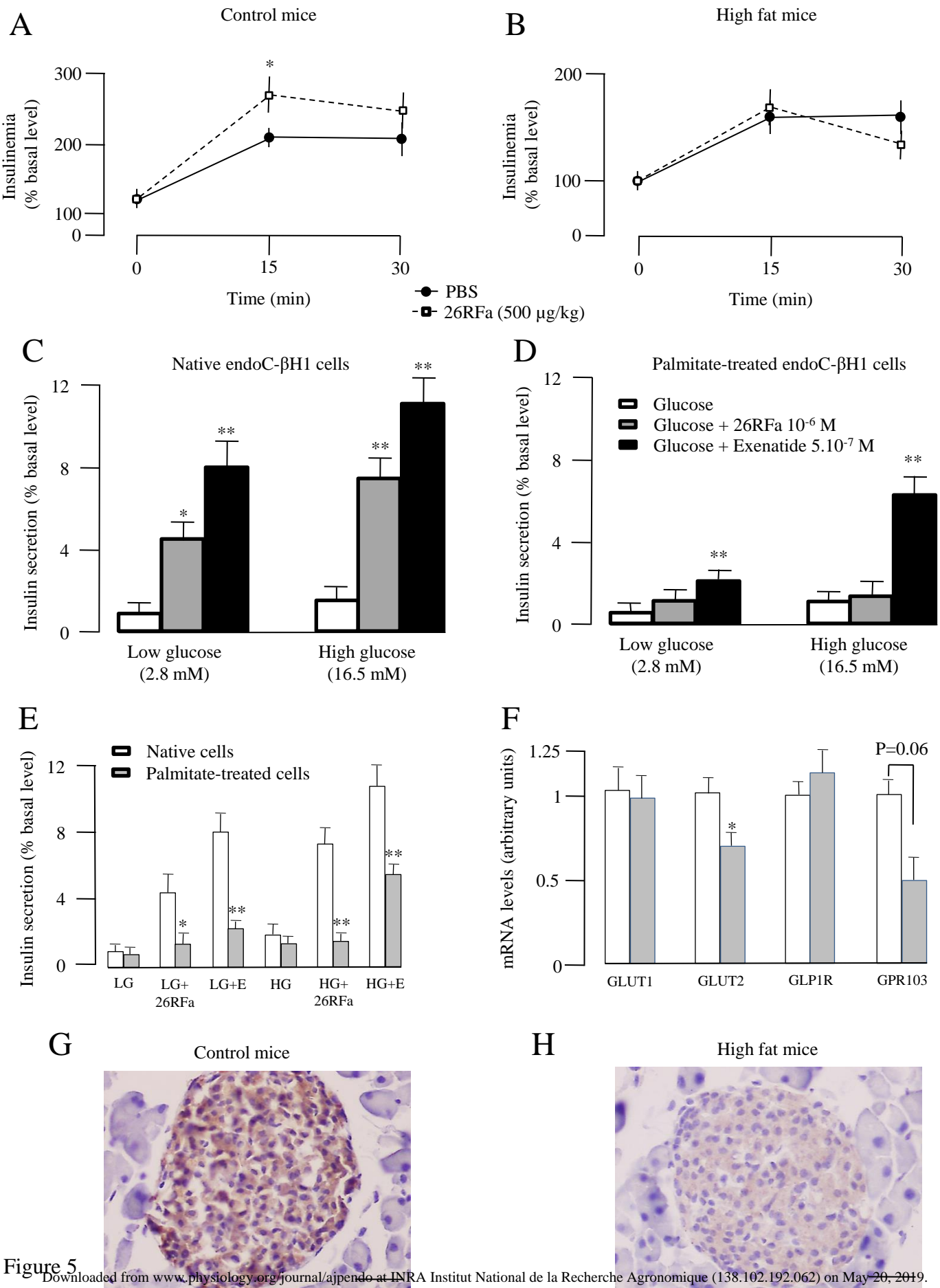


Figure 5 Downloaded from www.physiology.org/journal/ajpendo at INRA Institut National de la Recherche Agronomique (138.102.192.062) on May 20, 2019.

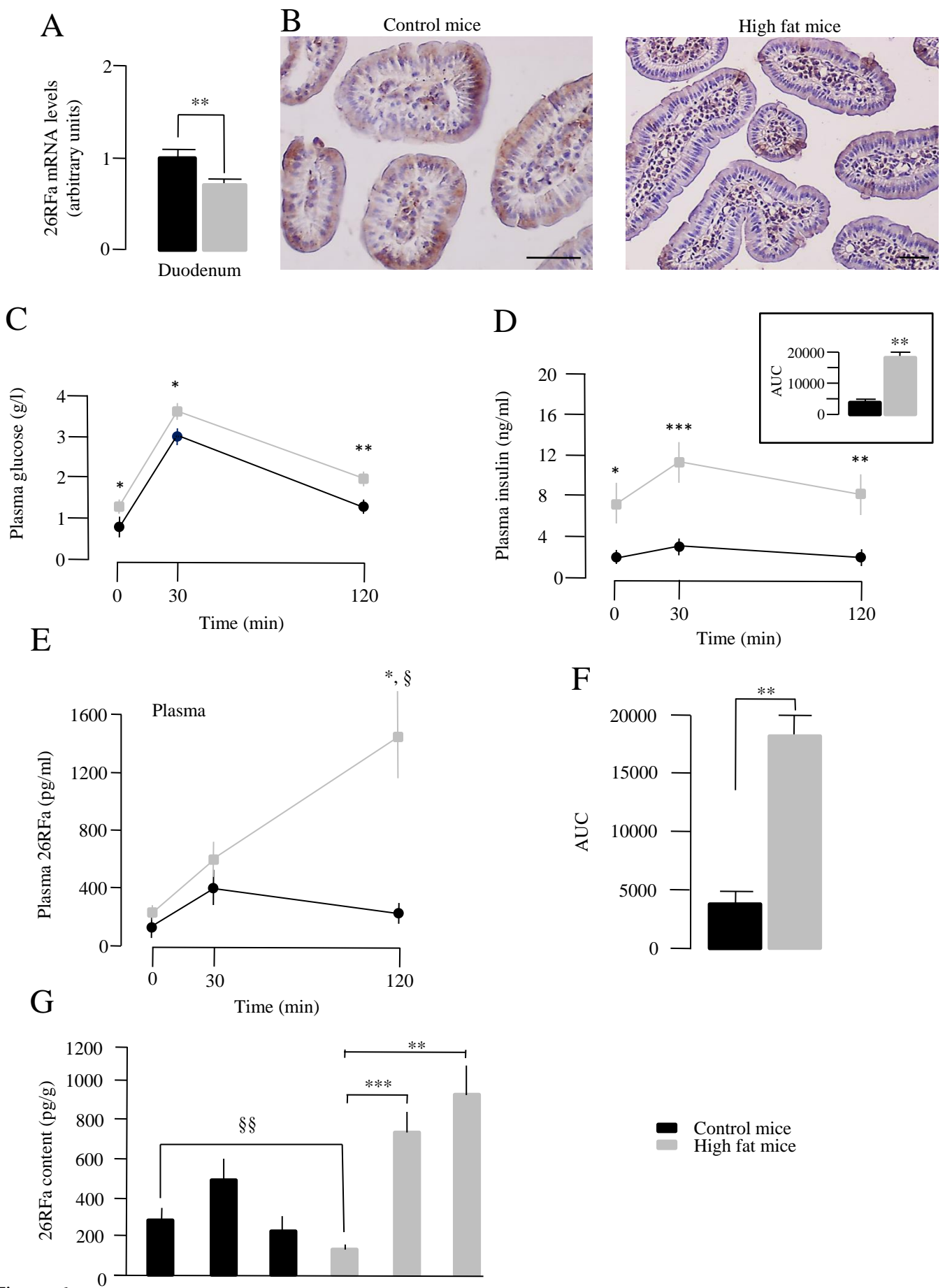


Figure 6 Downloaded from www.physiology.org/journal/ajpendo at INRA Institut National de la Recherche Agronomique (138.102.192.062) on May 20, 2019.

**Table 1 - Sequence of the primers used for the Q-PCR experiments**

	Forward primer	Reverse primer
Human GPR103	GAAAGGCACCAGGGACTTGT	CCAGACCACACCTAGCATTGT
Human GLP-1 rec	TGAGCATAGGCTGGGGTGTT	CAGCCGGATAATGAGCCAGT
Human Glut-1	TGGCATCAACGCTGTCTTCT	AGCCAATGGTGGCATAACA
Humain Glut-2	CTAGTCAGGTGCATGTGCCA	AGGGTCCCAGTGACCTTATCT
Mouse GPR103	GGACGAAGGGCACCATCTT	CGTCACGATGCTCCAGAACA
Mouse 26RFa	TCTGCCGTCCTTACCATCTCA	TCTCAGGACTGTCCCAAAGGAG
Mouse GAPDH	TCCGGACGCACCCTCAT	CGGTTGACCTCCAGGAAATC
Human cyclophilin A	ATGGCACTGGTGGCAAGTCC	TTGCCATTCCTGGACCCAAA