

Studies on pathophysiological significance
of intraislet ghrelin using transgenic
animal model.

(遺伝子改変動物を用いた膵島由来
グレリンの病態生理学的意義の検討)

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Transgenic overexpression of intra-islet ghrelin does not affect insulin secretion or glucose

metabolism *in vivo*

Running title: Transgenic overexpression of intra-islet ghrelin

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Abstract

While ghrelin is primarily produced in the stomach, but a small amount of ghrelin is also produced in pancreatic islets. Although exogenous administration of ghrelin suppresses insulin secretion *in vitro* or *in vivo*, the role of intra islet ghrelin in the regulation of insulin secretion *in vivo* remains unclear. To understand the physiological role of intra-islet ghrelin in insulin secretion and glucose metabolism, we developed a transgenic (Tg) mouse model, rat insulin II promoter ghrelin- internal ribosomal entry site –ghrelin O-acyl transferase (RIP-GG) Tg mice, in which mouse ghrelin cDNA and ghrelin O-acyltransferase are overexpressed under the control of the rat insulin II promoter.

Although pancreatic desacyl ghrelin levels were elevated in RIP-GG Tg mice, pancreatic ghrelin levels were not altered in animals on standard diet. When Tg mice were fed a medium chain triglyceride rich diet (MCTD), however, pancreatic ghrelin levels were elevated to approximately 16 times that seen in control animals. It seems likely that the gastric ghrelin cells possess specific machinery to provide the octanoyl acid necessary for ghrelin acylation, but that this machinery is absent from pancreatic β cells. Despite the overexpression of ghrelin, plasma ghrelin levels in the portal veins of RIP-GG Tg mice were unchanged from control levels. Glucose tolerance, insulin secretion and islet architecture in RIP-GG Tg mice were not significantly different even when the mice were fed a MCTD. These results indicate that

34 intra-islet ghrelin does not play a major role in the regulation of insulin secretion *in vivo*.

35 Key words: ghrelin, pancreas, insulin

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Introduction

38 Ghrelin is a 28-amino acid peptide hormone with a unique modification of acylation at
39 the third serine residue, first described by Kojima *et al.* in 1999 (17). The acyl-modification of
40 ghrelin is mediated by the recently discovered enzyme ghrelin O-acyl transferase (29), and the
41 modification is essential for ghrelin binding to its cognate receptor (12). Ghrelin is primarily
42 produced in the stomach, but small amounts of ghrelin are also produced in pancreatic islets (1,
43 5, 8, 10, 12, 26, 27). Controversy remains about which type of islet cell produces ghrelin (5, 20,
44 26, 27). Date *et al.* reported that ghrelin is present in α cells in humans and rats (5), while
45 Volante *et al.* reported that ghrelin is produced by β cells in humans (26). In contrast, Wierup *et*
46 *al.* and Prado *et al.* reported that ghrelin-expressing cells comprise a new islet cell type distinct
47 from α , β , δ and PP cells in human, rat, and mouse islets (20, 27, 28).

48 Exogenous ghrelin suppresses insulin secretion from pancreatic β cells *in vitro* (4, 9,
49 22) or *in vivo* (3, 22, 25). Although several studies have demonstrated contradictory results (1, 5,
50 11, 18, 24), data from genetically-engineered mice are consistent with this concept. Chronic
51 elevation of plasma ghrelin levels suppresses insulin secretion, inducing glucose intolerance in
52 transgenic mice (2, 13, 21), while ablation of ghrelin improves glucose tolerance by enhancing
53 insulin secretion in diet-induced obesity (7) or ob/ob mouse models (23). Although *in vitro*
54 studies demonstrate that intra-islet ghrelin can suppress insulin secretion from isolated islets (6),

55 the physiological role of intra-islet ghrelin on the regulation of insulin secretion *in vivo* is
56 unclear. As only minimal amounts of ghrelin are produced by the pancreas in comparison to that
57 made by the stomach (15), the effect of stomach-derived ghrelin may overpower the effects of
58 intra-islet ghrelin *in vivo*.

59 In this study, we developed a transgenic mouse model, in which the ghrelin and
60 ghrelin O-acyltransferase (GOAT) genes are overexpressed by pancreatic β cells under the
61 control of the rat insulin II promoter (RIP) to ascertain the physiological role of intra-islet
62 ghrelin on insulin secretion and glucose metabolism *in vivo*.

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Materials and Methods

66 **Generation of RIP-ghrelin-GOAT Transgenic Mice**

67 We designed a fusion gene comprised of RIP, mouse ghrelin cDNA, internal
68 ribosomal entry site (IRES), and mouse GOAT cDNA coding sequences. The purified
69 fragment (10 µg/ml) was microinjected into the pronuclei of fertilized C57/B6J mouse
70 (SLC, Shizuoka, Japan) eggs. Viable eggs were transferred into the oviducts of
71 pseudopregnant female ICR mice (SLC) using standard techniques. Transgenic founder
72 mice were identified by Southern blot analyses of tail DNA using a mouse ghrelin cDNA
73 fragment as a probe. For experimentation, we utilized heterozygous transgenic mice.
74 Animals were maintained on a 12-h light/12-h dark cycle and fed with a standard diet
75 (SD; CE-2, 352 kcal/100g, Japan CLEA, Tokyo, Japan) or an MCTD containing 45%
76 Dermol M5 (C8:60%, C10:40%; Research Diet Inc., New Brunswick, NJ) as indicated.
77 All experimental procedures were approved by the Kyoto University Graduate School of
78 Medicine Committee on Animal Research.

79 **Measurement of Plasma and Tissue Ghrelin Concentrations**

80 Blood was drawn from the proximal end of the portal vein under ether
81 anesthesia, transferred immediately to chilled siliconized glass tubes containing
82 Na₂EDTA (1mg/ml) and aprotinin (1000 KIU/ml), and centrifuged at 4°C. Hydrogen

83 chloride was added to the samples at a final concentration of 0.1 N immediately after
84 separation of plasma. Plasma was immediately frozen and stored at -80°C until assay.
85 Plasma ghrelin concentration was determined by AIA-600 II (Tosoh, Tokyo, Japan).

86 To measure tissue ghrelin concentrations, pancreata or stomachs were isolated
87 from mice, then boiled for 5 min in the 10-fold v/w of water. Acetic acid was added to
88 each solution to adjust the final concentration to 1 M before tissues homogenization. We
89 determine the tissue ghrelin concentration in supernatants obtained after
90 centrifugation by radioimmunoassay (RIA) using anti-ghrelin [13-28] (C-RIA) and
91 anti-ghrelin [1-11] (N-RIA) antisera as described previously (12, 15).

92 **Real-time Quantitative RT-PCR**

93 Total RNA was extracted from pancreata using an RNeasy Protect mini kit
94 (QIAGEN, Hilden, Germany). Reverse transcription (RT) was performed using a
95 high-capacity cDNA reverse transcription kit (Applied Biosystems, Foster City, CA). Real-time
96 quantitative PCR was performed on an ABI PRISM 7500 Sequence Detection System
97 (Applied Biosystems) using the following primers and TaqMan probes were used: mouse
98 ghrelin (sense, 5'-GCATGCTCGGATGGACATG-3'; antisense,
99 5'-TGGTGGCTTCTTGGATTCCT-3'; TaqMan probe,
100 5'-AGCCCAGAGCACCAGAAAGCCCA-3'); mouse insulin (sense,

101 5'-CAGCTATAATCAGAGACCATCAGCAA-3'; antisense,
102 5'-GGGTAGGAAGTGCACCAACAG-3'; TaqMan probe, 5'-CAGGTCATTGTTTCAAC-3');
103 GOAT (sense, 5'-AGGGACTCTAGGAAGGACAG-3'; antisense,
104 5'-CCCATCTGAAAGAAGAAGGT-3', with Power SybrGreen). Data were normalized to
105 the content of 18 S rRNA in each sample.

106 **Glucose Tolerance Tests**

107 For glucose tolerance testing, the *ad libitum*-fed mice were intraperitoneally
108 injected with 1.5 g/kg glucose. Blood was sampled from the tail veins before and 30, 60,
109 90, and 120 min after the injection. Blood glucose levels were determined by the glucose
110 oxidase method using a Glutest sensor (Sanwa Kagaku, Kyoto, Japan).

111 **Insulin Release**

112 *Ad libitum*-fed mice were injected with 3.0 g/kg glucose intravenously. Plasma was
113 sampled from a retroorbital vein before and 2 or 30min after injections into heparin-coated tubes.
114 Insulin concentrations were measured by a high-range speedy mouse insulin kit (Morinaga,
115 Yokohama, Japan).

116 **Immunohistochemistry**

117 Formalin-fixed, paraffin-embedded tissue sections were immunostained using the
118 avidin-biotin peroxidase complex method (Vectastain "ABC" Elite Kit, Vector Laboratories,
119 Burlingame, CA, USA) as described previously (14). Serial sections of a 5- μ m thickness were

120 incubated with anti-C-terminal ghrelin (1:1000) (17), and anti-N-terminal ghrelin (1:2000) (17),
121 anti-glucagon (1:500), anti-insulin (1:500), anti-somatostatin (1:500), and anti-pancreatic
122 polypeptide (PP, 1:500, DAKO, Glostrup, Denmark) antisera.

123 **Statistical Analysis**

124 All values were expressed as the means $\pm$ S.E. The statistical significance of the
125 differences in mean values was assessed by ANOVA with a post-hoc test (Turkey's test) or
126 Student's t-test as appropriate. Differences with $P < 0.05$ were considered significant. Statistical
127 analyses were performed using Statcel2 (OMS, Saitama, Japan).

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Results

131 **Generation of RIP-ghrelin-IRES-GOAT transgenic mice.**

132 After injecting the RIP-ghrelin-IRES-GOAT transgene into 286 eggs, we obtained
133 three lines (3-4, 9-3 and 11-5) confirmed to be insulin II promoter-ghrelin-IRES-GOAT
134 transgenic (RIP-GG Tg) mice. For further analyses, we selected the 9-3 line, which had the
135 highest expression of ghrelin and GOAT mRNA in the pancreas (data not shown). The
136 expression levels of pancreatic ghrelin mRNA in 9-3 line of RIP-GG Tg mice were
137 approximately 20-fold higher than those seen in controls (Figure 1B), while GOAT mRNA
138 levels were approximately 80-fold higher than those in controls (Figure 1C). There was also
139 increment in ghrelin and GOAT mRNA levels in the hypothalamus of RIP-GG Tg mice (non vs.
140 Tg; ghrelin; 1.0 ± 0.28 vs. 25.6 ± 5.6 , GOAT; 1.0 ± 0.26 vs. 5735.5 ± 1189.1 , arbitrary unit, n=8,
141 $P < 0.01$).

142 **Pancreatic and plasma ghrelin levels in RIP-GG Tg mice**

143 Total ghrelin levels measured by C-RIA were significantly elevated in the pancreata of
144 RIP-GG Tg mice on a SD or MCTD (Figure 2A). The ghrelin levels measured by N-RIA,
145 however, were elevated only when RIP-GG Tg mice were fed an MCTD (Figure 2B). Although
146 ghrelin levels 16-fold higher than those seen in control littermates were observed in the
147 pancreata of RIP-GG Tg mice fed MCTD, these absolute levels were low in comparison to

148 those isolated from stomach (Figure 1D, E). Further, the ratio of ghrelin to total ghrelin in the
149 pancreas of RIP-GG Tg mice was significantly low on SD, which was elevated on MCTD
150 (Figure 1C). Still, the level was significantly low in comparison to that of the stomach (Figure
151 1F).

152 Immunohistochemistry showed that the ghrelin-like immunoreactivities were
153 increased in the core of the islet of RIP-GG Tg mice on MCTD (Figure 3), indicating that
154 increased tissue levels of pancreatic ghrelin was originated from β cells.

155 We measured plasma ghrelin levels in the portal veins of RIP-GG Tg mice fed MCTD
156 to determine if this level of ghrelin overexpression in islets could affect plasma ghrelin levels.
157 No significant changes were observed either in ghrelin and desacyl ghrelin levels in the portal
158 veins of RIP-GG Tg mice (Figure 4A, B), indicating that ghrelin overexpression from the
159 transgene in islets produces minimal effect on plasma ghrelin levels.

160 **Glucose metabolism and insulin secretion in RIP-GG Tg mice**

161 No significant changes in blood glucose levels were seen by intraperitoneal glucose
162 tolerance tests between 10 week-old RIP-GG Tg mice and controls on MCTD (Figure 5A).
163 Plasma insulin levels before and after a glucose load were not significantly altered in
164 15-week-old RIP-GG Tg mice on MCTD (Figure 5B). There were also no significant changes in
165 blood glucose and plasma insulin levels after glucose load in old mice (around 84-weeks old) or

166 in female mice (Figure 5C, D, E, F).

167 **Islet Architecture**

168 There were no obvious abnormalities in intra-islet cytoarchitecture or in the cell
169 numbers of insulin-, glucagon-, somatostatin-, and PP-producing cells in the islets of RIP-GG
170 Tg mice on MCTD (Figure 6A–D). Staining intensities for these four islet hormones within
171 islets of RIP-GG Tg mice did not differ from those of nontransgenic littermates.

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Discussion

175 In previous studies, we developed transgenic mice in which mouse ghrelin cDNA is
176 overexpressed in pancreatic β cells under the control of the rat insulin II promoter to identify the
177 effect of ghrelin on pancreatic islets (15). These Tg mice, however, displayed elevated
178 expression of desacyl ghrelin only within the pancreas. At that time, the mechanism by which
179 ghrelin received an n-octanoyl modification was unknown. Recently, Yang *et al.* identified
180 ghrelin O-acyltransferase as the enzyme mediating this modification (29). In this study, we
181 developed a transgenic mouse in which ghrelin produced in the pancreas might be both
182 overexpressed and modified, with the overexpression of both mouse ghrelin and GOAT cDNA
183 in pancreatic β cells under the control of the rat insulin II promoter.

184 To our surprise, while pancreatic desacyl ghrelin levels were elevated in RIP-GG Tg
185 mice, pancreatic levels of (active, modified) ghrelin were unchanged on a SD. Ghrelin levels
186 were only elevated when mice were fed MCTD. Similar results were reported by Kirchner *et al*
187 (16), who created a transgenic mouse in which ghrelin and GOAT cDNA were overexpressed in
188 the liver under the control of the APOE promoter. These mice demonstrated elevated plasma
189 ghrelin levels only when mice were fed a medium-chain fatty acids rich-diet. Considering that
190 gastric ghrelin-producing cells can produce ghrelin regardless of diet, even in a fasting state, it
191 is likely that these gastric cells possess a specific machinery to generate the octanoyl acid

192 necessary for acylation, which is lacking from pancreatic β cells or hepatocytes.

193 In previous studies, we demonstrated that the chronic elevation of plasma ghrelin
194 levels at approximately 10-fold higher than the normal range suppresses insulin secretion and
195 induces glucose intolerance in mice (13). In this study, RIP-GG Tg mice, which produce
196 16-fold higher ghrelin levels from the pancreas as normal mice, exhibited normal glucose
197 tolerance and insulin secretion. The pancreatic ghrelin levels in RIP-GG Tg mice, while
198 elevated, were still considerably lower than the gastric ghrelin level. We tried to compare the
199 ghrelin levels in pancreatic vein with those in artery as Dezaki *et al.* conducted using rats (7), it
200 was difficult to determine the ghrelin levels in pancreatic vein of mice due to the small body
201 size. We measured ghrelin levels in portal vein instead, which were not elevated in RIP-GG Tg
202 mice. We cannot determine the exact concentration of ghrelin in the microenvironment
203 surrounding β cells, but these levels still seem to be overpowered by the circulating ghrelin
204 produced by the stomach. While it is possible that additional overproducing of ghrelin in islets
205 could eventually suppress insulin secretion, further enhancement of ghrelin expression by islets
206 would not be in the realm of physiological relevance. *In vitro*, intra-islet ghrelin may suppress
207 insulin secretion in a paracrine (or autocrine) manner where the effect of circulating ghrelin is
208 eliminated (6). This study, however, indicates that intra-islet ghrelin does not play a major role
209 in controlling insulin secretion *in vivo*, where high levels of circulating ghrelin are generated

210 by the stomach.

211 One drawback of this study is that elevated pancreatic ghrelin levels in RIP-GG Tg
212 mice could not be obtained without feeding mice MCTD. The MCTD consists of
213 medium-chain fatty acids (C6-C10) that can enter mitochondria without the carnitine shuttle.
214 Medium-chain triglycerides generally have favorable effects on obesity or diabetes (19),
215 suppressing fat accumulation and improving insulin sensitivity. We cannot exclude the
216 possibility that MCTD may have interfered with the effects of ghrelin within islets. In addition,
217 ghrelin and GOAT mRNA levels were increased not only in the islet but also in the
218 hypothalamus of RIP-GG Tg mice. There is a possibility that the over-expressed ghrelin in the
219 hypothalamus may have influenced on the effects of overexpressed ghrelin in the islet.

220 In summary, we have developed RIP-GG Tg mice, in which intra-islet ghrelin levels
221 were elevated to approximately 16 times control levels when mice were fed MCTD. The
222 glucose tolerance and insulin secretion of RIP-GG Tg mice were unchanged, indicating that
223 intra-islet ghrelin does not play a major role in regulating insulin secretion *in vivo*.

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Disclosures

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All authors have nothing to declare.

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Figure Legends

Figure 1. Constructs of RIP-GG Tg mice and the expression levels of ghrelin and GOAT mRNA in the pancreas.

A. We designed a fusion gene containing rat insulin II promoter (RIP), mouse ghrelin cDNA, IRES and mouse GOAT cDNA. B, C. The resultant expression levels of ghrelin (B) and GOAT (C) mRNA in the pancreata of RIP-GG Tg mice. non: nontransgenic littermate, Tg: RIP-GG Tg mice, n=7–11, **: P<0.01 in comparison to nontransgenic littermates

Figure 2. Pancreatic and gastric ghrelin levels in RIP-GG Tg mice on STD or MCTD.

A, B. Pancreatic ghrelin levels in RIP-GG Tg mice (black bar) and nontransgenic controls (open bar) measured by C-RIA (A) and N-RIA (B). Although total ghrelin levels measured by C-RIA were elevated in RIP-GG Tg mice on both a standard diet (SD) and a medium-chain triglyceride-rich diet (MCTD), ghrelin levels measured by N-RIA were only elevated when RIP-GG Tg mice were fed MCTD. E, F Gastric ghrelin levels of RIP-GG Tg mice (black bar) and nontransgenic controls (open bar) measured by C-RIA (E) or N-RIA (F) were significantly higher than pancreatic levels, regardless of diet. C, G. The ratio of C-RIA/N-RIA. **: P<0.01, *: P<0.05 in comparison to controls, ###: P<0.01 in comparison to SD, n=5–7

Figure 3. Immunohistochemical analysis of the expression of ghrelin in the islet of RIP-GG Tg mice.

361 Ghrelin-like immunoreactivities were increased in the core of the islet of RIP-GG Tg mice on
362 MCTD.

363 **Figure 4. Portal ghrelin levels of RIP-GG Tg mice.**

364 A, B. Portal ghrelin (A) and desacyl ghrelin (B) levels in male RIP-GG Tg mice (black bar) and
365 nontransgenic littermates (open bar) fed MCTD. n=7–8,

366 **Figure 5. Glucose metabolism in GP-Tag Tg mice.**

367 A, C, E. Glucose tolerance tests in 10-week-old male (A), 11-week-old female (C) or
368 83-week-old male (E) RIP-GG Tg mice on MCTD (■) and nontransgenic littermates (◆).
369 n=7–10

370 B, D, F. Serum insulin levels at baseline and at 2 min or 30 min after intravenous glucose
371 injection in 15-week-old male (B), 10-week-old female (D) or 84-week-old male (F) RIP-GG
372 Tg mice fed MCTD (black bars) and in nontransgenic littermates (open bars). n = 5–10.

373 **Figure 6. Islet morphology in RIP-G G Tg mice.**

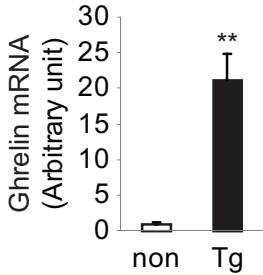
374 The pancreatic sections from RIP-GG Tg (Tg) mice and nontransgenic littermates (non) were
375 stained with anti-insulin (A), anti-glucagon (B), anti-somatostatin (C), or anti-PP (D) antibodies.
376 Representative images are presented.

377

A.



B.



C.

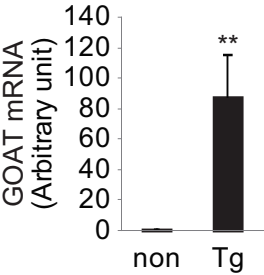


Figure 1

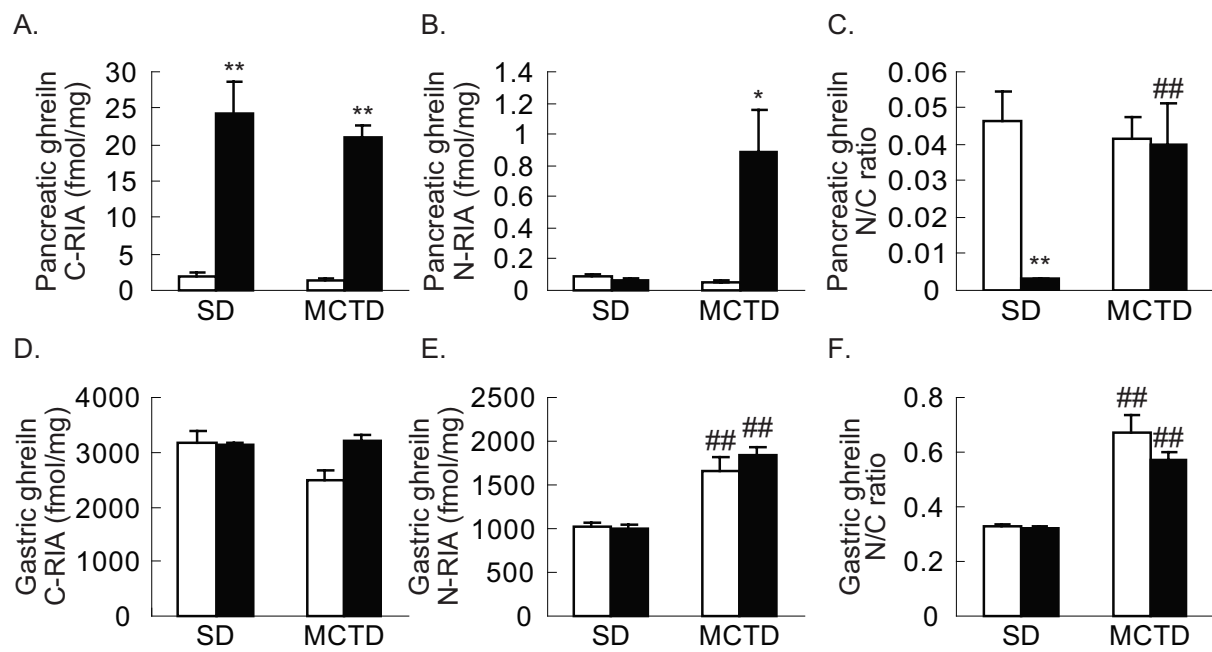


Figure 2

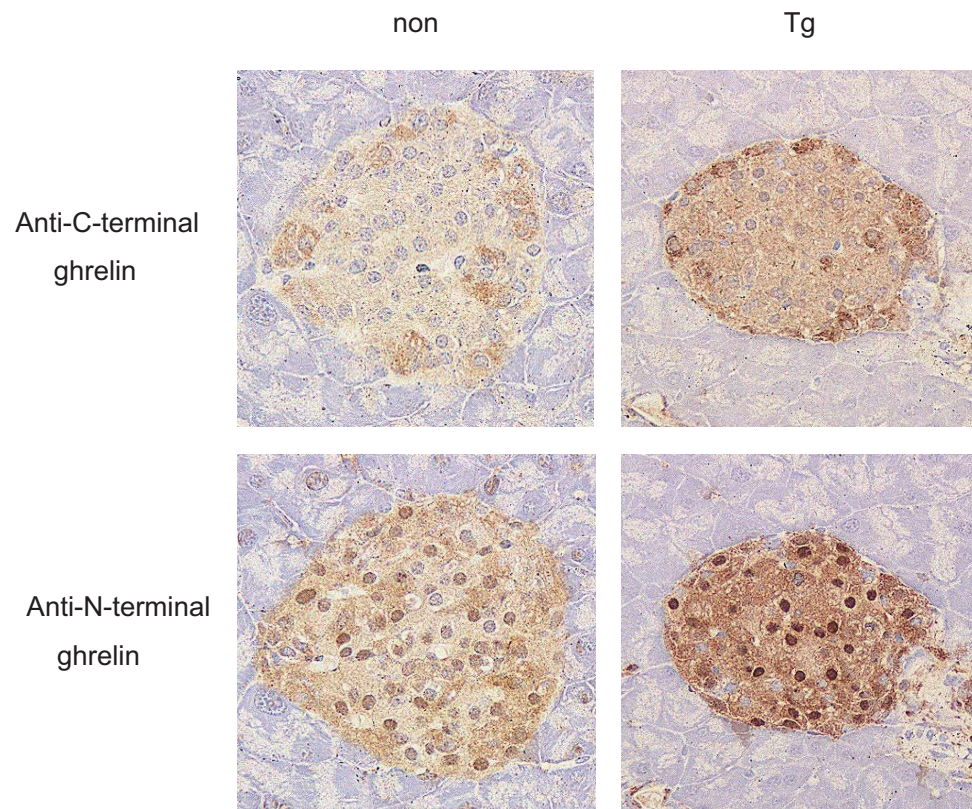


Figure 3

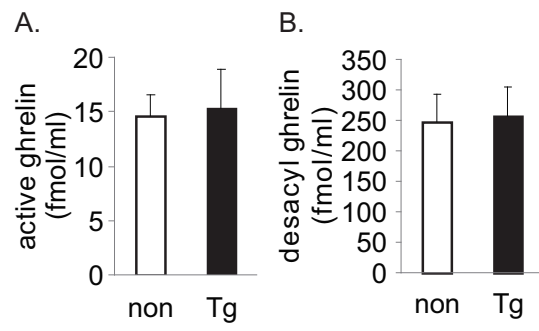


Figure 4

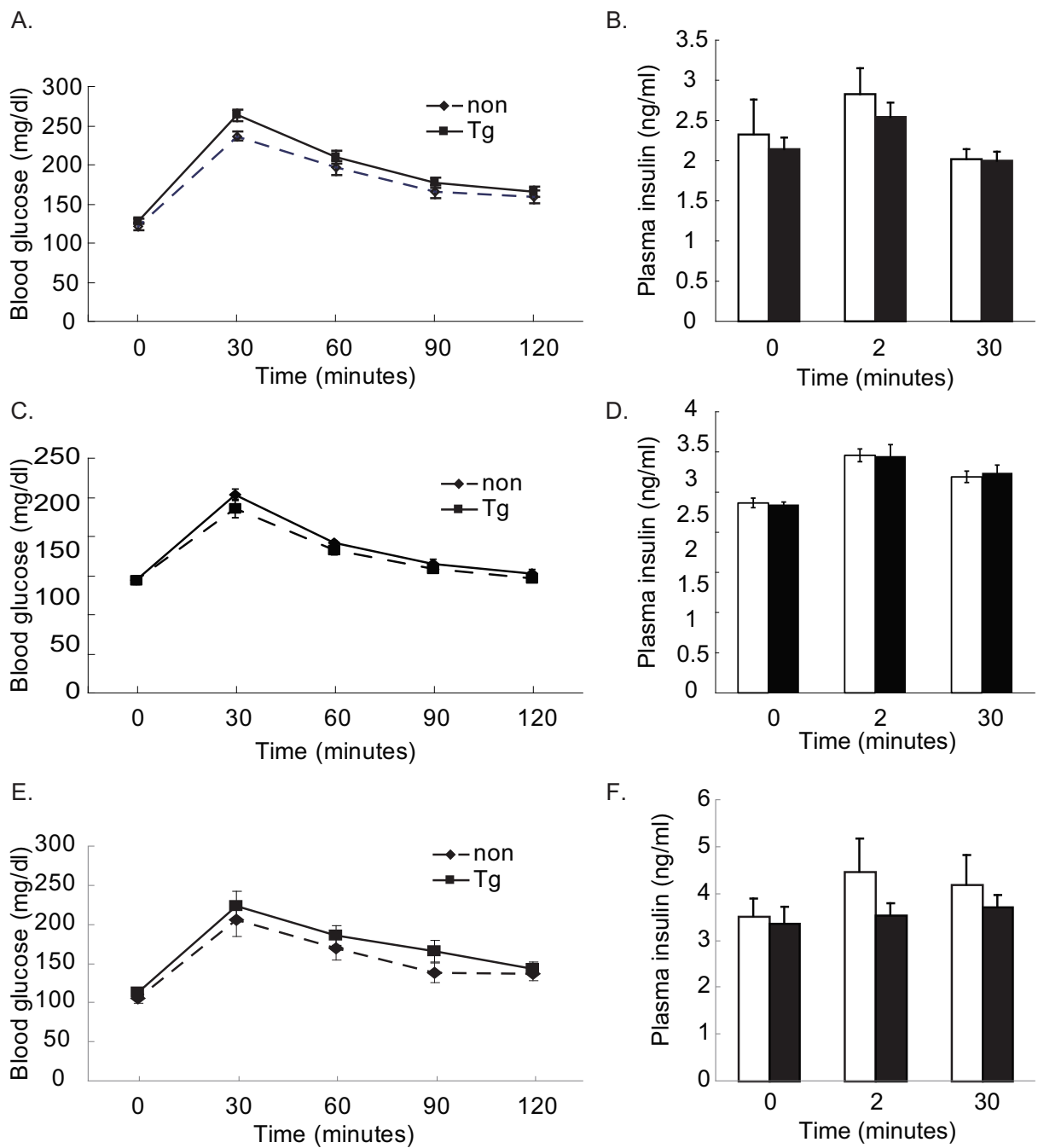


Figure 5

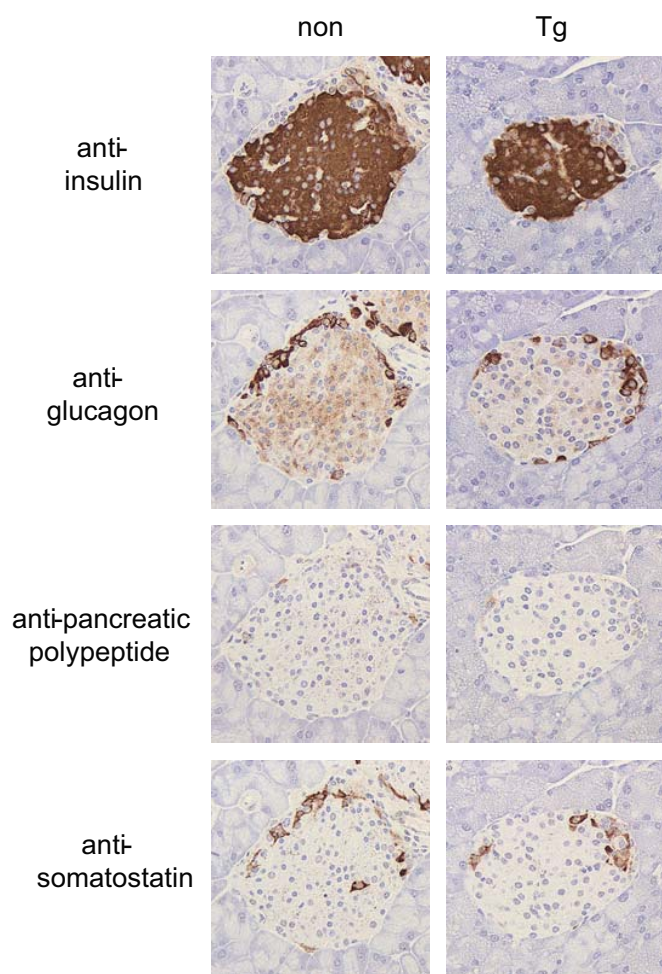


Figure 6

**Overexpression of intra-islet ghrelin enhances β -cell proliferation after
streptozotocin-induced β -cell injury in mice**

Running head: Ghrelin enhances β -cell proliferation

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Abstract

Previously, we reported that exogenous administration of ghrelin ameliorates glucose metabolism in a neonate streptozotocin (STZ)-induced diabetic rat model through enhancement of β -cell proliferation. However, it was not clear whether the observed β -cell proliferation was a direct or indirect effect (*e.g.*, via orexigenic or growth hormone-stimulated pathways) of ghrelin activity. Here, we aim to investigate whether ghrelin directly impacts β -cell proliferation after STZ-induced injury in mice.

Seven-week-old male rat insulin II promoter-ghrelin internal ribosomal sequence ghrelin O-acyltransferase transgenic (RIP-GG Tg) mice, which have elevated pancreatic ghrelin levels, but only minor changes in plasma ghrelin levels, when fed a medium-chain triglyceride-rich diet, were treated with STZ. Then, serum insulin, pancreatic insulin mRNA expression, and islet histology were evaluated.

We found that the serum insulin levels, but not blood glucose levels, of RIP-GG Tg mice were significantly ameliorated 14 days post-STZ treatment. Pancreatic insulin mRNA expression was significantly elevated in RIP-GG Tg mice, and β -cell numbers in islets were increased. Furthermore, the number of phospho-histone H3⁺ or Ki67⁺ proliferating β cells was significantly elevated in RIP-GG Tg mice, while the apoptotic indices within the islets, as determined by the TUNEL assay, were not changed.

33 These results indicated that ghrelin can directly stimulate β -cell proliferation *in vivo* after
34 β -cell injury even without its orexigenic or GH-stimulating activities.

35

36 Key words: ghrelin, beta cell, diabetes, streptozotocin

37

38

Introduction

39 Decreased insulin secretion is one of the major features of diabetes. Insulin is
40 produced in pancreatic islets by β cells, whose numbers are reduced or eliminated during the
41 pathology of the disease. Autoimmune-mediated destruction of β cells causes type I diabetes,
42 and a decrease in β -cell mass is also noted in patients with type II diabetes (5). Accordingly, a
43 substantial effort has been made towards preventing or reversing β -cell degradation. One
44 approach has been to find hormones or growth factors that impact proliferation or survival
45 after β -cell injury. Several hormones, including growth hormone (22), prolactin (11) and
46 GLP-1(11), have been suggested to stimulate β -cell proliferation in cell lines or animal models.
47 Although these hormones have not yet been tested in the clinic, this approach may lead to the
48 development of a new class of anti-diabetic drugs.

49 Ghrelin is a 28 amino acid stomach-derived peptide hormone bearing a unique acyl
50 modification on the third Ser residue, which is essential for binding to its receptor (18). We
51 previously reported that exogenous ghrelin administration prevents the development of diabetes
52 at the adult stage of a rat neonate streptozotocin (STZ) model (13). In that study, we observed
53 increased numbers of phospho-histone H3⁺/insulin⁺ cells in the islets of ghrelin-treated rats,
54 suggesting that ghrelin had enhanced β -cell proliferation. However, it was not clear whether that
55 was a direct or indirect effect of ghrelin treatment. Because ghrelin strongly stimulates GH

56 secretion (18, 27) and food intake (20, 25), we could not rule out the possibilities that elevated
57 GH or nutritional status may have affected β -cell proliferation (6).

58 Here, we directly examined the effects of ghrelin on β cells after STZ treatment by
59 using a recently developed rat insulin II promoter-ghrelin internal ribosomal sequence ghrelin
60 O-acyl transferase (GOAT) transgenic (RIP-GG Tg) mice, in which ghrelin and GOAT genes
61 are overexpressed in pancreatic β cells under the control of the rat insulin II promoter (2). As
62 compared to control mice, RIP-GG Tg mice display a ~16-fold increase in pancreatic ghrelin
63 concentrations, but no change in plasma ghrelin levels, when fed a medium-chain triglyceride
64 rich diet (MCTD) (2). The aim of this study was to determine whether ghrelin directly
65 stimulated the proliferation of β cells after STZ-induced injury.

66

67 **Materials and Methods**

68 **RIP-GG Tg Mice**

69 RIP-GG Tg mice were generated as reported previously (2). In this study, we used
70 male heterozygous transgenic mice along with their nontransgenic littermates as controls.
71 Animals were maintained on a 12-h light/12-h dark cycle and fed with a standard diet (SD;
72 CE-2, 352 kcal/100g; Japan CLEA, Tokyo, Japan) or an MCTD containing 45% Dermol M5
73 (C8:60%, C10:40%; Research Diet Inc., New Brunswick, NJ) as indicated. RIP-GG Tg mice
74 show elevated pancreatic ghrelin only when they were on MCTD presumably due to the lack of
75 machinery providing octanoyl acid for acylation in β cells (2). RIP-GG Tg mice have normal
76 glucose tolerance and insulin secretion in the absence of STZ (2). All experimental procedures
77 were approved by the Kyoto University Graduate School of Medicine Committee on Animal
78 Research.

79 **STZ treatment**

80 Seven-week-old male mice were randomly assigned to vehicle or STZ groups. STZ
81 (100 mg/kg body weight in 100 mM citrate buffer, pH 4.5; Sigma-Aldrich, St. Louis, MO) or
82 vehicle alone was injected after overnight fasting.

83 Blood glucose levels were determined by the glucose oxidase method using a Glutest
84 sensor (Sanwa Kagaku, Kyoto, Japan) and serum insulin levels were determined using an

85 Ultrasensitive Plus Mouse Insulin kit or a High-Range Speedy Mouse Insulin kit (Morinaga,
86 Yokohama, Japan).

87 **Real-time Quantitative RT-PCR**

88 Total RNA was extracted from pancreata using an RNeasy Protect mini kit (QIAGEN,
89 Hilden, Germany). Reverse transcription (RT) was performed using a high-capacity cDNA
90 reverse transcription kit (Applied Biosystems, Foster City, CA). Real-time quantitative PCR was
91 performed on an ABI PRISM 7500 Sequence Detection System (Applied Biosystems) using the
92 following primers and TaqMan probes: mouse ghrelin, sense,
93 5'-GCATGCTCGGATGGACATG-3', antisense, 5'-TGGTGGCTTCTTGGATTCCT-3';
94 TaqMan probe, 5'-AGCCCAGAGCACCAGAAAGCCCA-3'; mouse insulin 1, sense,
95 5'-CAGCTATAATCAGAGACCATCAGCAA-3', antisense,
96 5'-GGGTAGGAAGTGCACCAACAG-3'; TaqMan probe, 5'-CAGGTCATTGTTTCAAC-3';
97 mouse Pdx1, sense, 5'-CAAAGCTCACGCGTGGAA-3', antisense,
98 5'-TGTAGGCAGTACGGGTCCTCTT-3'; TaqMan probe, 5'-AGGAGGTGCTTACAC-3';
99 mouse GHS-R, sense, 5'-CTGCTCACCGTGATGGTATG-3', antisense,
100 5'-CAGCAGAGGATGAAAGCAAA-3', with Power SybrGreen. Data were normalized to the
101 18 S rRNA content in each sample.

102 **Pancreatic insulin concentration**

103 To measure of pancreatic insulin concentration, pancreata were obtained from the mice
104 under the ether anesthesia and homogenized in acid-ethanol. The supernatants were used for
105 assay after centrifugation.

106 **Immunohistochemistry**

107 Formalin-fixed, paraffin-embedded tissue sections were immunostained using the
108 avidin–biotin peroxidase complex method (Vectastain ABC Elite Kit; Vector Laboratories,
109 Burlingame, CA, USA) as described previously (14). Serial sections (5 μ m) were incubated
110 with anti-insulin antibody (1:500; DAKO, Glostrup, Denmark). Counter staining was performed
111 with Myer's hematoxylin.

112 Quantitative evaluations of insulin⁺ areas were performed using WinROOF (Mitani,
113 Fukui, Japan). For each pancreas, insulin⁺ areas and islets were evaluated using five sections
114 spaced more than 40 μ m apart. The number of insulin⁺ cells within an islet was counted in five
115 sections spaced more than 40 μ m apart. The relative volume of insulin⁺ cells was determined by
116 calculating the ratio between the area occupied by insulin⁺ cells and the area encompassed by
117 islet cells.

118 **β -cell proliferation**

119 To detect β -cell proliferation, pancreatic tissue sections were double-stained to detect
120 both phospho-histone H3 (Ser10) or Ki67 and insulin. First, the immunoreactivity of the
121 anti-phospho-histone H3 (Ser10) antibody (1:50; Cell Signaling Technology, Beverly, MA) or

122 anti-Ki67 antibody (1:25; BD Pharmingen, Franklin Lakes, NJ) was detected using a Vectastain
123 ABC Elite Kit with a DAB (DAKO) substrate. Then, the sections were incubated with
124 anti-insulin antibody (1:500, DAKO), which was visualized with VECTOR VIP (Vector
125 Laboratories). Quantitation of β -cell proliferation was performed by counting phospho-histone
126 H3⁺ or Ki67⁺/insulin⁺ cells using five sections spaced more than 40 μ m apart. The relative
127 number of phospho-histone H3⁺ or Ki67⁺ cells was determined by calculating the ratio between
128 the numbers of phospho-histone H3⁺ or Ki67⁺ cells and insulin⁺ cells.

129 **Apoptosis**

130 Apoptotic cells were detected using the terminal deoxynucleotidyl
131 transferase-mediated dUTP nick-end labeling (TUNEL) assay (ApoMark apoptosis detection
132 Kit; Exalphi Biologicals, Maynard, MA). Quantitation of apoptotic cells was performed by
133 counting TUNEL⁺ cells within islets using five sections spaced more than 40 μ m apart. The
134 number of TUNEL⁺ cells was presented as the number of TUNEL⁺ cells/area of necrotic β cells.

135 To detect apoptotic cells with DNA not yet fragmented, pancreatic tissue sections were
136 stained with anti-cleaved caspase-3 (Asp175) antibody (1:300; Cell Signaling Technology,
137 Beverly, MA). Quantitation of apoptotic cells was performed by counting cleaved caspase-3⁺
138 cells within islets using five sections spaced more than 40 μ m apart. The number of cleaved
139 caspase-3⁺ cells was presented as the number of cleaved caspase-3⁺ cells/area of necrotic
140 β cells.

141 **Statistical Analyses**

142 All values were expressed as the mean $\pm$ S.E. The statistical significance of differences
143 in mean values was assessed by the Student's *t*-test. Differences where $p < 0.05$ were considered
144 significant. Statistical analyses were performed using Statcel2 (OMS, Saitama, Japan).

145

146

147

Results

148 **Glucose metabolism and insulin secretion in RIP-GG Tg mice treated with STZ**

149 When RIP-GG Tg mice and their nontransgenic littermates were fed a diet of MCTD
150 and treated with STZ, blood glucose levels were significantly elevated in both groups at 7 and
151 14 days post-treatment as compared to those in vehicle-treated mice (Figure 1A), and body
152 weights were significantly decreased in both groups at 7 and 14 days post-treatment as
153 compared to those in vehicle-treated mice (Figure 1B). At 14 days post-treatment, serum insulin
154 levels were significantly decreased in STZ-treated mice, and when compared between
155 genotypes, the insulin levels, but not blood glucose levels, were significantly higher in RIP-GG
156 Tg mice than those in nontransgenic littermates (Figure 1D), although only the tendency was
157 observed at 7 days post-treatment (Figure 1C).

158 **Insulin mRNA expression and β -cell numbers in RIP-GG Tg mice treated with STZ**

159 The pancreatic insulin 1 and PDX-1 mRNA levels were not changed in RIP-GG Tg
160 mice 7 days after STZ treatment, but were significantly elevated in RIP-GG Tg mice 14 days
161 after STZ treatment with increased tendency in pancreatic insulin contents (Figure 2A, B, E).
162 Pancreatic ghrelin mRNA levels were increased by ~70-fold in RIP-GG Tg mice as compared to
163 their nontransgenic littermates (Figure 2C). The pancreatic GHS-R mRNA levels were not
164 changed with STZ treatment and not different between the genotype (Figure 2D). We assessed β

165 cell numbers in the islets of RIP-GG Tg mice 7 days and 14 days after STZ treatment. (Figure
166 3A-F). In accord with the insulin mRNA levels, the ratio of insulin⁺ cell area per islet was
167 significantly higher in RIP-GG Tg mice than in their nontransgenic littermates 14 days after
168 STZ treatment (Figure 3D, E), although the restoration of β cell area was limited, considering
169 the fact that the β cell area in vehicle-treated RIP-GG Tg mouse was $83.7 \pm 0.67\%$ and their
170 nontransgenic littermates was $82.9 \pm 0.74\%$ (Figure 3G). And the difference was not observed
171 without STZ treatment (β cell areas on day 0: RIP-GG Tg vs. non: $88.9 \pm 0.71\%$ vs.
172 $87.6 \pm 0.99\%$, $P=0.29$) as reported previously (2). The number of insulin⁺ cells per islet was
173 also significantly higher in RIP-GG Tg mice as compared to vehicle-treated control animals 14
174 days after STZ treatment (Figure 3F). These differences were not observed 7 days after STZ
175 treatment (Figure 3A-C).

176 **Phospho-histone H3⁺/insulin⁺ cells and Ki67⁺/insulin⁺ cells in RIP-GG Tg mice treated**
177 **with STZ**

178 To determine whether the increased number of insulin⁺ cells in the islets of RIP-GG
179 Tg mice was due to increased β -cell proliferation, we assessed phospho-histone H3 and Ki67
180 expression, which indicate proliferating cells, in the islets of RIP-GG Tg mice 7 days and 14
181 days after STZ treatment. The ratio of phospho-histone H3⁺/insulin⁺ cells or Ki67⁺/insulin⁺ cells
182 to insulin⁺ cells were not changed in RIP-GG Tg mice 7 days after STZ treatment (Figure 4A-D),

183 but were significantly higher in the islets of RIP-GG Tg mice 14 days after STZ treatment
184 (Figure 4E-H), indicating that β -cell proliferation had increased in these animals at 14 days post
185 treatment.

186 **Short-term effects of STZ-treatment: residual β -cell numbers and apoptotic index in islets**
187 **of RIP-GG Tg mice**

188 Finally, we attempted to elucidate whether overexpressed ghrelin had direct protective
189 effects on β cells against STZ treatment. Since we could not detect any TUNEL positive cells or
190 cleaved caspase-3 positive cells in the islets 14 days after STZ treatment (data not shown), we
191 examined residual β cells and the apoptotic index in islets of RIP-GG Tg mice soon after STZ
192 administration. One day post-administration of the drug, cell nuclei in the islet core were
193 diminished, however strong immunoreactivity for insulin was still broadly observed, probably
194 due to leakage of insulin from damaged β cells (Figure 5A). This artifact made it difficult to
195 accurately determine the number of residual β cells. As an alternative, we assessed insulin
196 mRNA levels in the pancreas of RIP-GG Tg mice before and 1 day post-treatment. The
197 pancreatic insulin mRNA levels were significantly decreased in both groups 1 day
198 post-treatment, and there was no difference in insulin mRNA levels between the genotypes,
199 indicating that β -cell destruction by STZ was not affected by overexpressed ghrelin (Figure 5B).
200 In addition, to determine whether the apoptotic cells were increased, we assessed TUNEL and

201 cleaved caspase-3 expression, in islets from RIP-GG Tg mice. The ratio of TUNEL⁺ cell or
202 cleaved caspase-3⁺ cell number per islets area was not significantly different from that of their
203 nontransgenic littermates (Figure 5C-F).
204

205

Discussion

206 In this study, we found that the overexpression of intra-islet ghrelin ameliorated
207 insulin secretion in an STZ-induced diabetic mouse model by stimulating the proliferation of β
208 cells in the islets. This finding is in accord with our previous reports that exogenous ghrelin
209 administration stimulates β -cell proliferation in STZ-treated neonate rats (13). In the previous
210 study, it was not clear whether the stimulatory effects of ghrelin on β cells were direct or
211 indirect. We hypothesized that indirect mechanisms could be mediated through ghrelin's
212 GH-stimulating and/or orexigenic properties. Here, by using RIP-GG Tg mice, in which
213 intra-islet ghrelin levels are elevated without major changes in plasma ghrelin levels (2), we
214 clearly demonstrated that ghrelin directly stimulated β -cell proliferation *in vivo* after STZ
215 treatment.

216 Although serum insulin levels were elevated in STZ-treated RIP-GG Tg mice, glucose
217 levels were not improved to the degree observed in ghrelin-treated neonate STZ rats (13). The
218 relatively weak effect observed in this study may have been due to the differences in age and
219 species as compared to the previous study. In rats, β -cell numbers continue to increase after
220 birth, and reach a steady-state level at weaning (10). Accordingly, in the neonate STZ-treated rat
221 model, β -cell numbers recover to some degree even without any therapeutic treatment and
222 elevated glucose levels temporally return to normal for several weeks after STZ administration

223 (30). Here, we used adult mice with limited capacity for β -cell proliferation (10). Since RIP-GG
224 Tg mice must be fed with MCTD in order to increase islet ghrelin levels, we could not study the
225 mice before weaning. The age-related differences in β -cell proliferative capacities may explain
226 the disparities in the intensity of ghrelin activity between the current study and the previous
227 report. Another possibility is that the differences reflect species-specific variations. β -cell
228 sensitivity to STZ is known to be different among species (31). For example, rats are more
229 sensitive than mice to the effects of the drug (31). This difference in STZ sensitivity may have
230 affected the results of these studies. Age and species differences aside, we cannot completely
231 rule out the possibility that exogenously administered ghrelin may have exhibited both direct
232 and indirect effects on β cells in the neonate rat STZ model.

233 Ghrelin is reported to stimulate the proliferation of several cell lines, including the
234 pancreatic cancer cell line PANC1 (9), the somatotroph cell line GH3 (21), the prostate cancer
235 cell line PC3 (15) and osteoblasts (19). Conversely, the peptide has been observed to inhibit the
236 growth of tumors and tumor-derived cell lines including human breast carcinoma (6), and fetal
237 thyroid and thyroid follicular tumors (28). Thus, our results are in accord with previous reports
238 that ghrelin can stimulate cell proliferation. Given that β -cell proliferation is not increased at a
239 basal state in RIP-GG Tg mice (2), the proliferative effects of ghrelin on β cells seem to be
240 limited. β -cell proliferation is enhanced in STZ- (30) or alloxan-treated rodents (29), in a

241 partially pancreatectomized rat (4), and in a ductally ligated hamster (23). However, the
242 mechanisms underlying the stimulation of β -cell proliferation in these injury models have not
243 yet been completely elucidated. Ghrelin may synergize with these injury-derived proliferative
244 effects on β cells. Further studies will be needed to clarify the precise mechanisms by which
245 ghrelin stimulates β -cell proliferation.

246 Several lines of evidence suggest that ghrelin can exhibit anti-apoptotic effects on a
247 variety of cell types (1, 7, 12, 16, 17). With respect to β cells, Granata *et al.* reported that ghrelin
248 prevented apoptosis in the β -cell lines HIT-T15 and INS-1E, as well as in human islets (12). By
249 contrast, in this study, we could not detect differences in the apoptotic index of the islets
250 between RIP-GG Tg and control mice. The discrepancy between the previous results and this
251 study may be due to differences in experimental conditions. For example, Granata *et al.* used
252 β -cell lines and isolated islets *in vitro*, and induced apoptosis by serum starvation or the addition
253 of interferons (12), while we used an *in vivo* STZ-induced diabetic mouse model. Furthermore,
254 it has been reported that low doses of STZ induce β -cell apoptosis, whereas high doses cause
255 β -cell necrosis (24). In this study, we used 100 mg/kg, which is a relatively high dose. Therefore,
256 although we detected very few apoptotic cells in RIP-GG Tg islets, based upon these results we
257 cannot determine whether ghrelin directly protected β cells from apoptosis.

258 The results of this study indicate that introduction of ghrelin and GOAT to β cell may

259 have beneficial effects on diabetes in the sense that it may increase β cell mass. On the other
260 hand, previous reports indicate that exogenous ghrelin administration suppresses insulin
261 secretion and elevates blood glucose level and that inhibition of ghrelin or GOAT ameliorates
262 glucose tolerance in mice by enhancing insulin secretion (3, 26, 32). Considering that RIP-GG
263 Tg mice has normal glucose tolerance and insulin secretion, the level of ghrelin needed to
264 stimulate β cell proliferation after STZ-induced β cell injury seems to be lower than the level to
265 suppress insulin secretion. It would be necessary to keep in mind the deleterious side of
266 ghrelin's effect on β cell when therapeutic application of ghrelin on β cell injury is considered.

267 One drawback of this study is that ghrelin may be produced in the tissues other than
268 the β cell such as hypothalamus as is the case in the RIP-Cre mice (8), which may have affected
269 β cell proliferation. Actually, the mRNA levels of ghrelin and GOAT was elevated in the
270 hypothalamus of RIP-GG Tg mice (2). However, when we examined the expression of the
271 peptide by immunohistochemistry, we found no apparent differences of the ghrelin-like
272 immunoreactivities in the hypothalamus between Tg mice and controls (data not
273 shown). Further, there were no differences in body weights between two groups.
274 Therefore, we doubt that physiologically meaningful levels of ghrelin were produced in
275 the hypothalamus of RIP-GG Tg mice. Nonetheless, we cannot completely eliminate the
276 possibility that the leakage expression of ghrelin in other tissues may have also affected

277 the β cell proliferation indirectly.

278 In conclusion, we found that serum insulin levels, β -cell numbers and β -cell
279 proliferation were significantly elevated in RIP-GG Tg mice after STZ treatment. These results
280 indicated that ghrelin can directly stimulate β -cell proliferation *in vivo* after β -cell injury even
281 without its orexigenic or GH-stimulating activities.

282

283

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284

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288

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289

Disclosures

290

All authors have nothing to declare.

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Figure Legends

Figure 1. Serum insulin levels are increased in STZ-treated RIP-GG Tg mice as compared to control animals

A, B. Blood glucose levels (A) and body weight (B) in RIP-GG Tg mice (Tg) and their nontransgenic littermates (non-Tg) treated with STZ or vehicle alone. $n = 8-10$. **, ###. $p < 0.01$ in comparison to vehicle alone. C, D. Serum insulin levels in RIP-GG Tg mice and their nontransgenic littermates treated with STZ or vehicle 7 days post treatment (C) or 14 days post treatment (D). $n = 8-10$. * $p < 0.05$.

Figure 2. Pancreatic insulin and PDX-1 mRNA levels are increased in STZ-treated RIP-GG Tg mice as compared to controls.

A, B, C, D. Pancreatic insulin1 (A), PDX-1 (B), ghrelin (C), GHS-R (D) mRNA levels in RIP-GG Tg mice (Tg) and their nontransgenic littermates (non-Tg) 0, 7, 14 days post-STZ treatment. $n=7-10$. At day14, pancreatic insulin 1, PDX-1, and ghrelin mRNA levels were significantly higher in RIP-GG Tg mice (Tg) as compared to their nontransgenic littermates (non-Tg). ** $p < 0.01$. E. Pancreatic insulin concentration in RIP-GG mice (Tg) and their nontransgenic littermates (non-Tg) 14 days post-STZ treatment. $n=7$.

Figure 3. Compared to control animals, RIP-GG Tg mice have more insulin⁺ islet cells after STZ treatment.

422 The area occupied by insulin⁺ cells and the absolute number of these cells in islets 14 days
423 post-STZ treatment were significantly higher in RIP-GG Tg mice as compared to their
424 nontransgenic littermates. A, D. Representative images of tissue sections from RIP-GG Tg (Tg)
425 and nontransgenic (non-Tg) islets 7 days post-STZ treatment (A) and 14 days post-STZ
426 treatment (D) reacted with an anti-insulin antibody. B, E. Ratio of the area occupied by insulin⁺
427 cells to the area of the entire islet 7 days post-STZ treatment (B) and 14 days post-STZ
428 treatment (E). C, F. The number of insulin⁺ cells in islets of RIP-GG Tg mice 7 days post-STZ
429 treatment (C) and 14 days post-STZ treatment (F). n = 7–8. ***p* < 0.01. G. Representative
430 images of tissue sections from RIP-GG Tg (Tg) and nontransgenic (non-Tg) islets 14 days
431 post-vehicle treatment. H. Ratio of the area occupied by insulin⁺ cells to the area of the entire
432 islet 14 days post-vehicle treatment. n = 7.

433 **Figure 4. Phospho-histone H3⁺ cells are more abundant in islets of RIP-GG Tg mice as**
434 **compared to controls.**

435 A, C. Representative images of islet tissue sections from RIP-GG Tg mice (Tg) and their
436 nontransgenic littermates (non-Tg) 7 days post-STZ treatment. Sections were immunostained
437 with an anti-phospho-histone H3 antibody (A) or an anti-Ki67 antibody (C) (brown, arrow) and
438 an anti-insulin antibody (purple). B, D. Ratio of phospho-histone H3⁺ cells (B) or Ki67⁺ cells
439 (D) to insulin⁺ cells in islets of RIP-GG Tg mice (Tg) and their nontransgenic littermates

440 (non-Tg) 7 days post-STZ treatment. n = 5. E, G. Representative images of islet tissue sections
441 from RIP-GG Tg mice (Tg) and their nontransgenic littermates (non-Tg) 14 days post-STZ
442 treatment. Sections were immunostained with an anti-phospho-histone H3 antibody (E) or an
443 anti-Ki67 antibody (G) (brown, arrow) and an anti-insulin antibody (purple). F, H. Ratio of
444 phospho-histone H3⁺ cells (F) or Ki67⁺ cells (H) to insulin⁺ cells in islets of RIP-GG Tg mice
445 (Tg) and their nontransgenic littermates (non-Tg) 14 days post-STZ treatment. n = 7-8. ***p* <
446 0.01.

447 **Figure 5. No differences were observed between the residual β -cell populations and the**
448 **apoptotic indices in islets of STZ-treated RIP-GG Tg and control mice.**

449 A. Representative images of islet tissue sections from RIP-GG Tg mice (Tg) and their
450 nontransgenic littermates (non-Tg). One day post-STZ treatment, sections were stained with an
451 anti-insulin antibody (brown). B. Pancreatic insulin 1 mRNA levels observed in RIP-GG Tg
452 mice and their nontransgenic littermates before or one day post-STZ treatment. n = 11–12. **,
453 *##*. *p* < 0.01 in comparison to before. C, E. Representative images of tissue sections from
454 RIP-GG Tg (Tg) and nontransgenic (non-Tg) islets one day post-STZ treatment reacted with
455 TUNEL reagents (C) or an anti-cleaved caspase-3 antibody (E). D, F. The number of TUNEL⁺
456 cells (D) or cleaved caspase-3⁺ cells (F) in islet cores did not differ between RIP-GG Tg mice
457 and controls (non-Tg). n = 5.

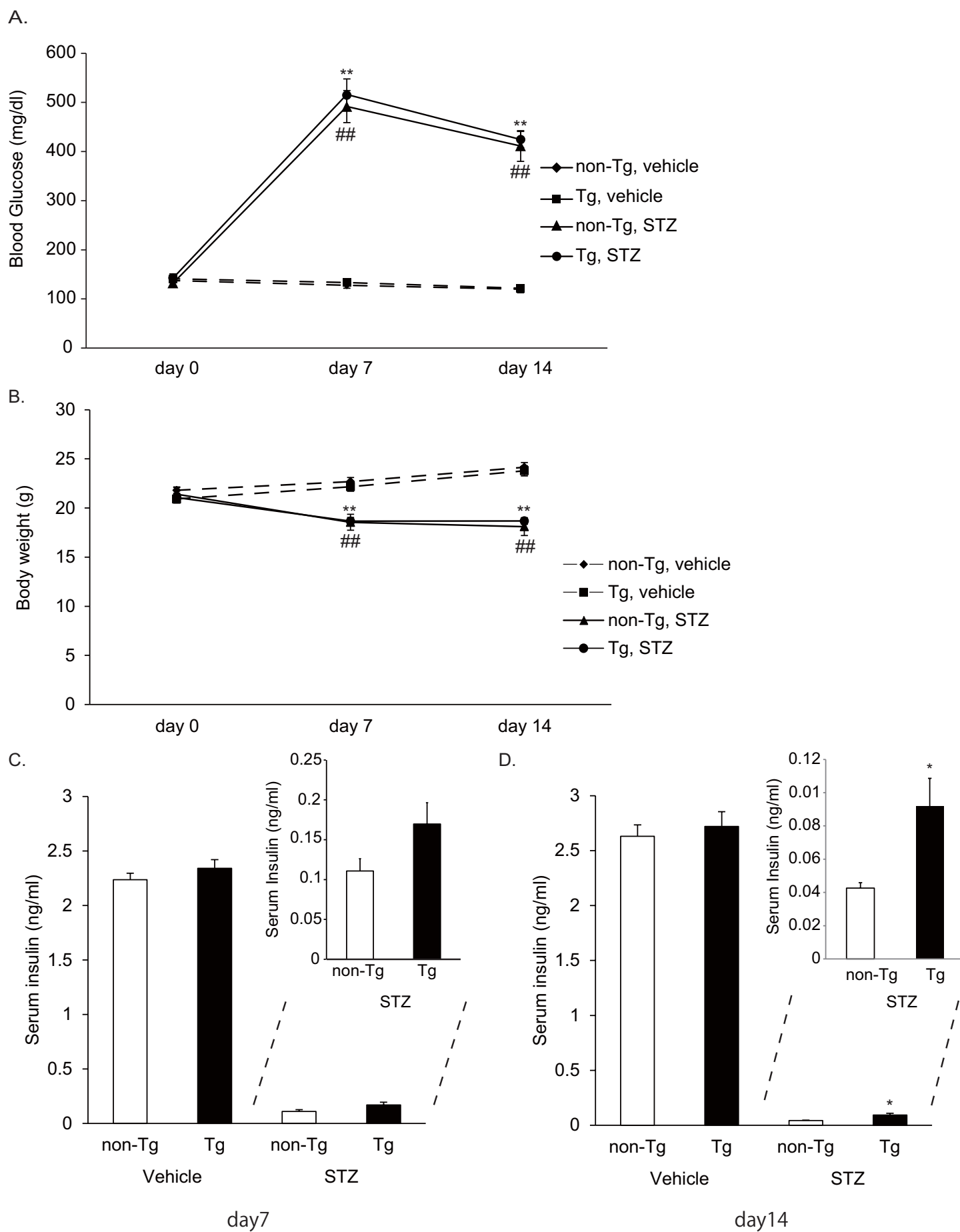


Figure 1

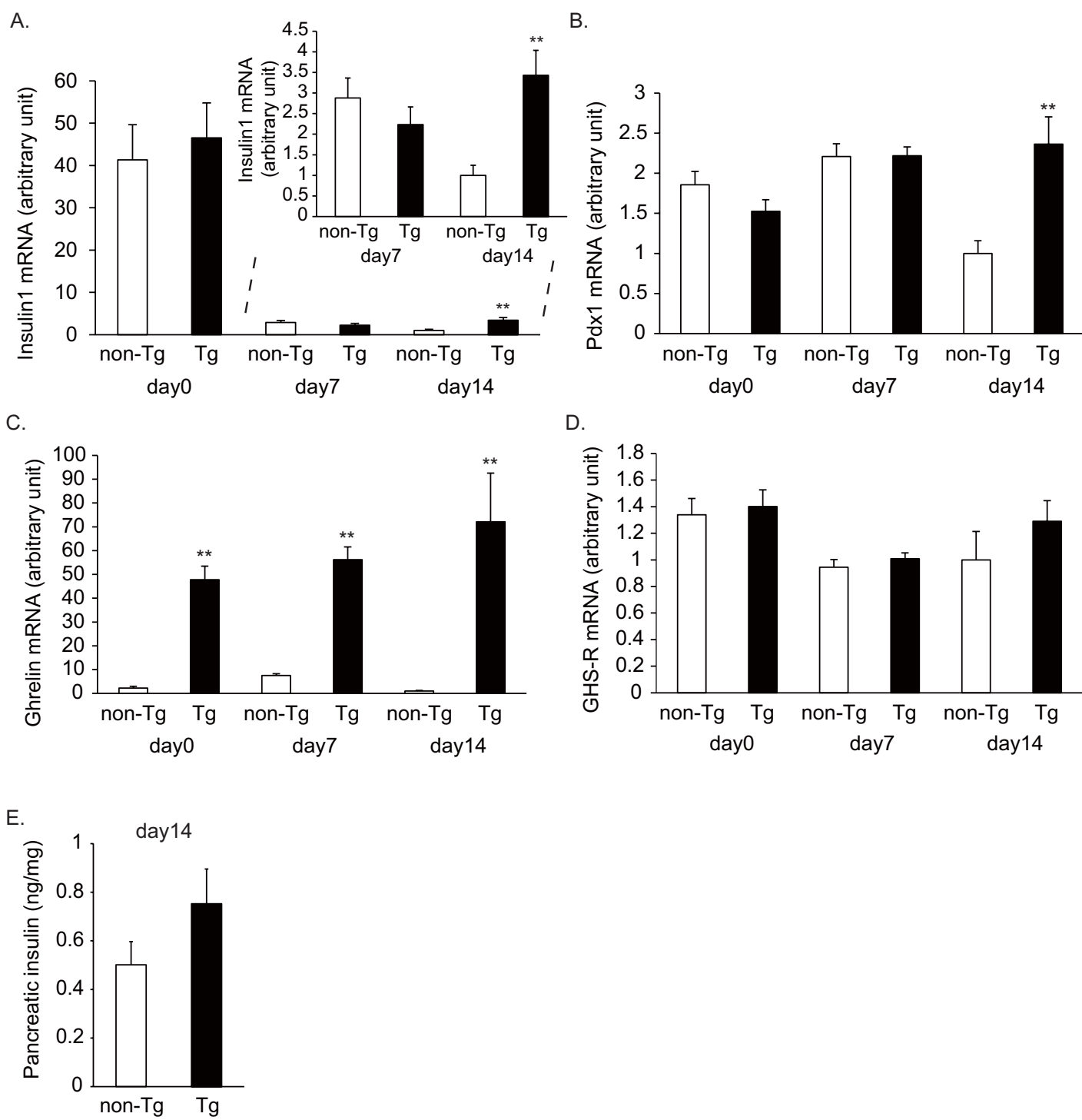
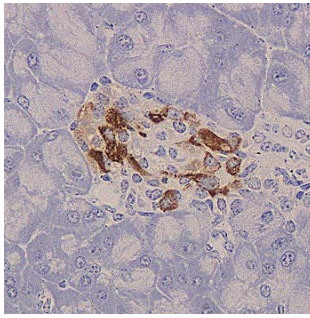
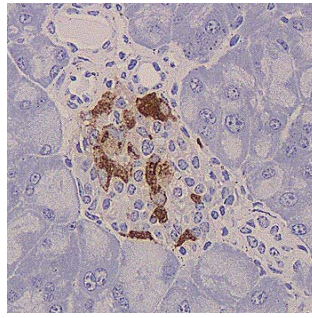


Figure 2

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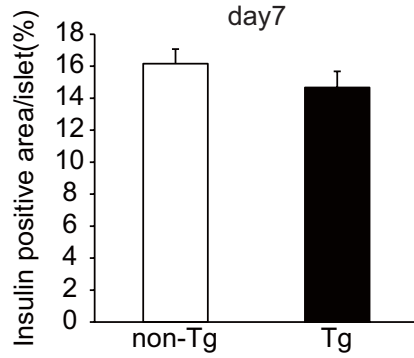


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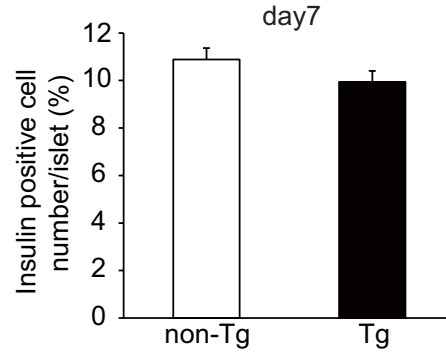


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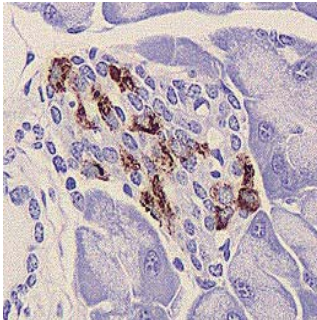
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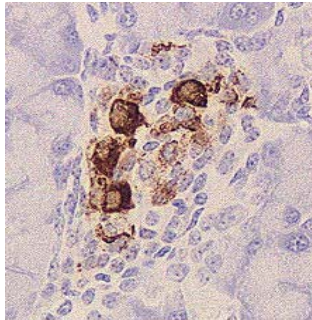
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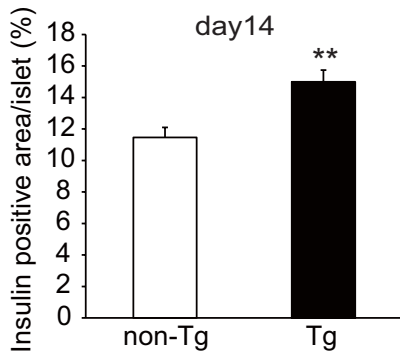


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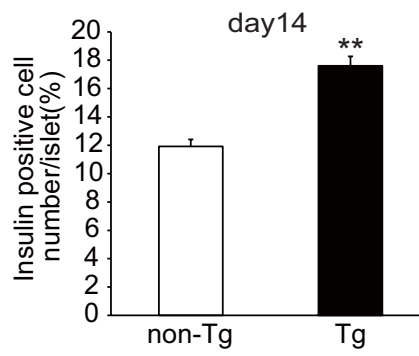


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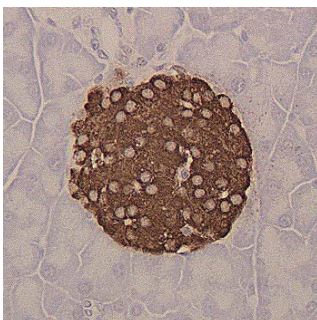
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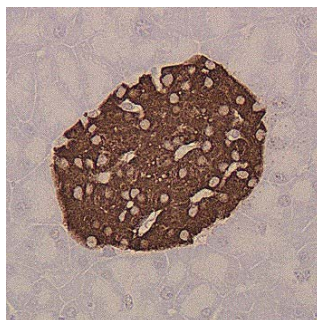
F.



G.



non-Tg



Tg

H.

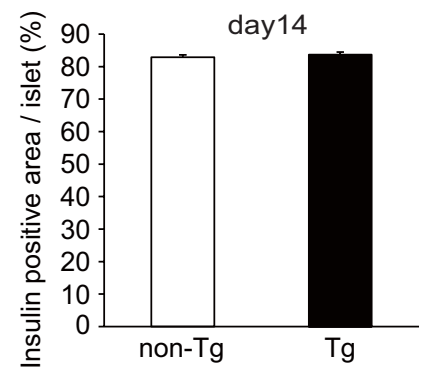


Figure 3

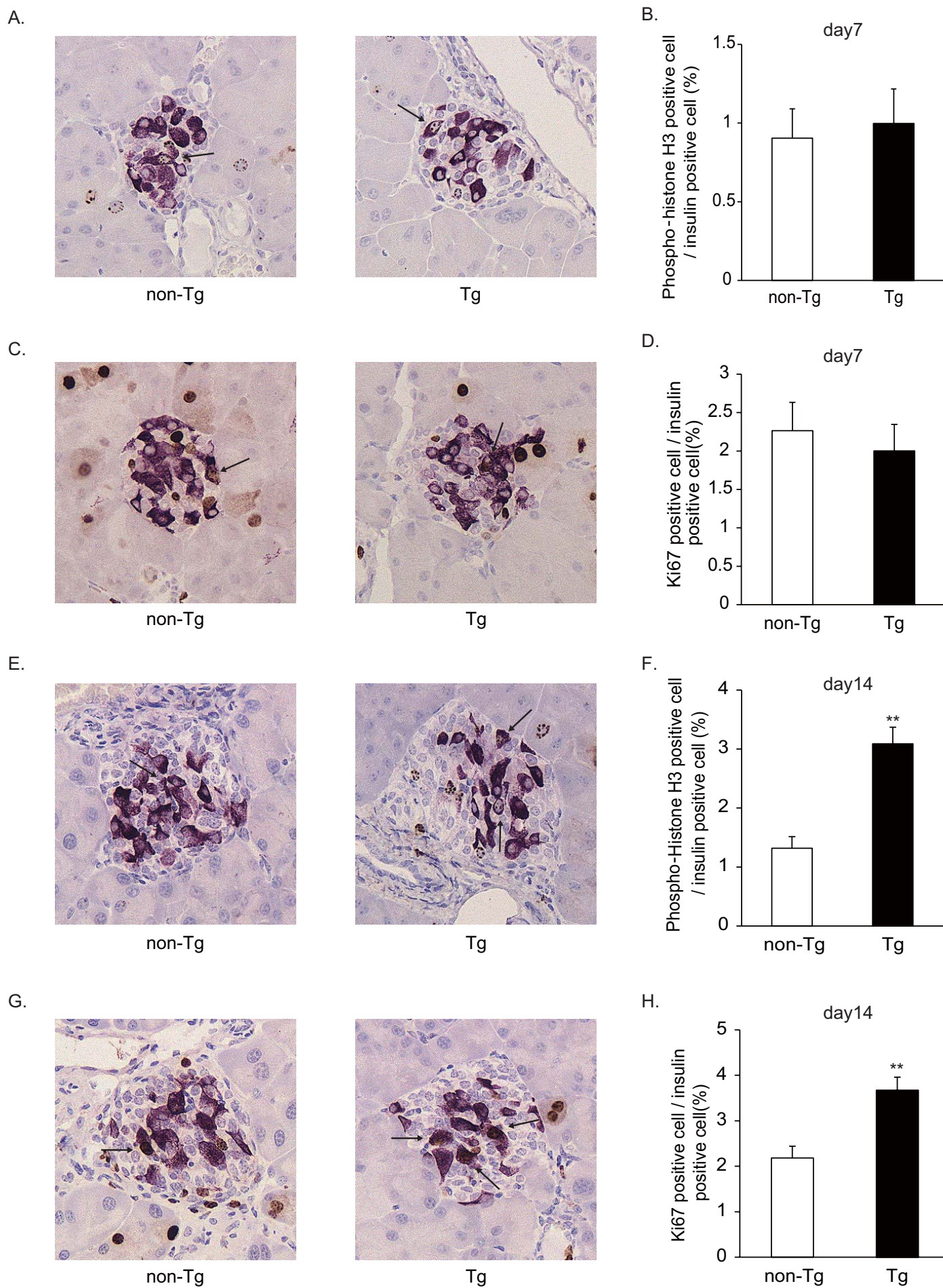


Figure 4

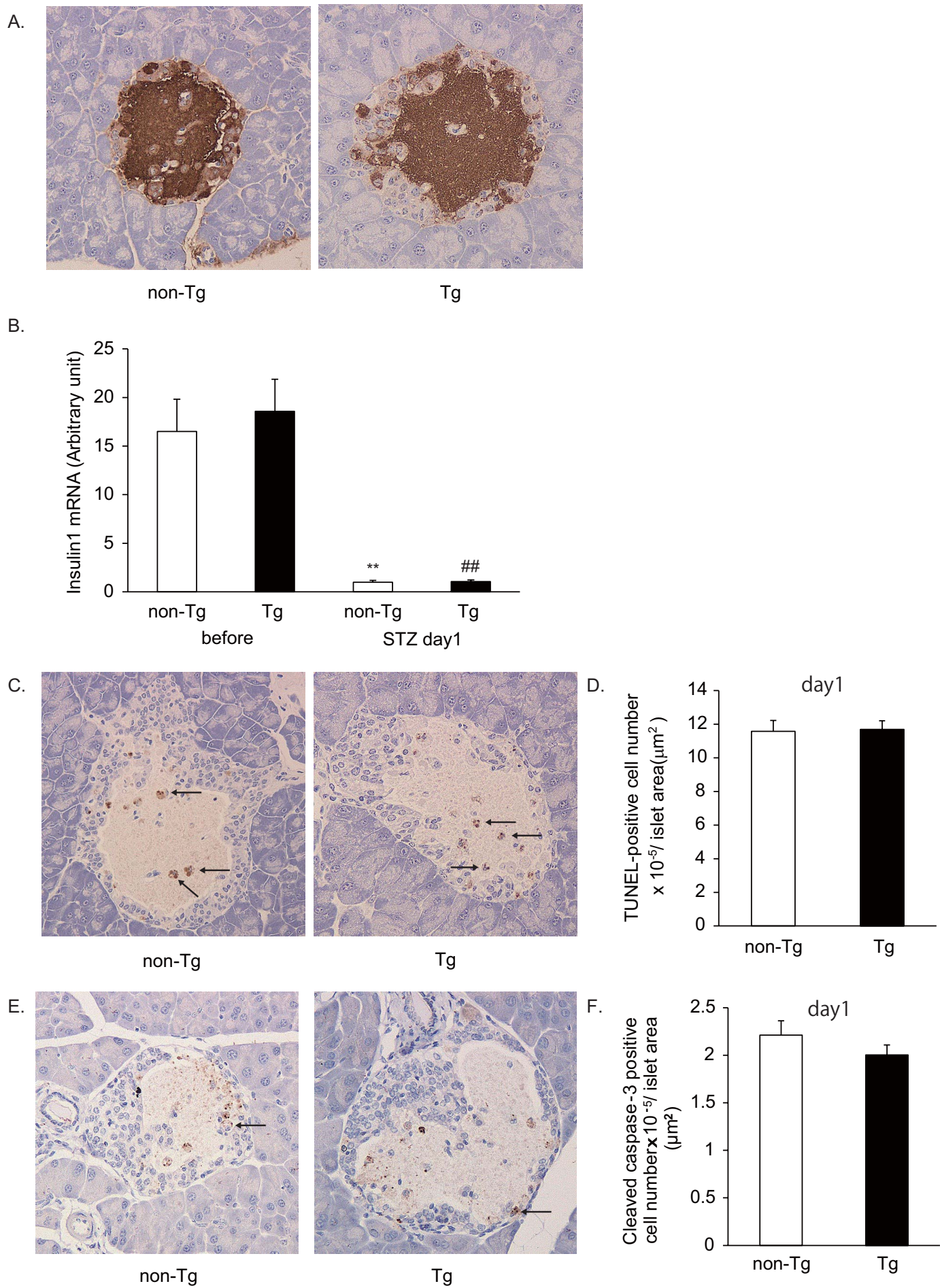


Figure 5