Cannabinoids Inhibit Insulin Receptor Signaling in Pancreatic β-Cells

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OBJECTIVE—Optimal glucose homeostasis requires exquisitely precise adaptation of the number of insulin-secreting β-cells in the islets of Langerhans. Insulin itself positively regulates β-cell proliferation in an autocrine manner through the insulin-receptor (IR) signaling pathway. It is now coming to light that cannabinoid 1 receptor (CB1R) agonism/antagonism influences insulin action in insulin-sensitive tissues. However, the cells on which the CB1Rs are expressed and their function in islets have not been firmly established. We undertook the current study to investigate if intraislet endogenous cannabinoids (ECs) regulate β-cell proliferation and if they influence insulin action.

RESEARCH DESIGN AND METHODS—We measured EC production in isolated human and mouse islets and β-cell line in response to glucose and KCl. We evaluated human and mouse islets, several β-cell lines, and CB1R-null (CB1R−/−) mice for the presence of a fully functioning EC system. We investigated if ECs influence β-cell physiology through regulating insulin action and demonstrated the therapeutic potential of manipulation of the EC system in diabetic (db/db) mice.

RESULTS—ECs are generated within β-cells, which also express CB1Rs that are fully functioning when activated by ligands. Genetic and pharmacologic blockade of CB1R results in enhanced IR signaling through the insulin receptor substrate 2-AKT pathway in β-cells and leads to increased β-cell proliferation and mass. CB1R antagonism in db/db mice results in reduced blood glucose and increased β-cell proliferation and mass, coupled with enhanced IR signaling in β-cells. Furthermore, CB1R activation impedes insulin-stimulated IR autophosphorylation on β-cells in a Gαi-dependent manner.

CONCLUSIONS—These findings provide direct evidence for a functional interaction between CB1R and IR signaling involved in the regulation of β-cell proliferation and will serve as a basis for developing new therapeutic interventions to enhance β-cell function and proliferation in diabetes.

Insulin is the prime mediator of glucose homeostasis. A paucity (as occurs in type 1 diabetes) or surplus (due to excessive exogenous insulin administration or insulin-secreting tumors) of insulin causes somatic damage by energy deprivation and neuroglucopenic brain damage. Therefore, the number of insulin-secreting β-cells is tightly regulated to maintain a very narrow blood glucose range. Intriguingly, insulin also has major effects on its own secretory cells. Exogenously infused insulin increases β-cell mass (1), and mice lacking β-cell insulin receptors (IRs) develop insulin-dependent diabetes because of insufficient β-cell proliferation and defective insulin secretion (2,3). IR activation on β-cells, in addition to being necessary for optimal function of the glucose-sensing machinery (3), causes phosphorylation of insulin receptor substrate 2 (IRS2), which then transduces the signal to the AKT-forkhead box protein O1 (FoxO1) cascade and increases β-cell proliferation (4).

The endogenous cannabinoids (ECs), 2-arachidonoylglycerol (2-AG), and anandamide (AEA), are lipid transmitters synthesized only on demand by Ca2+-dependent enzymes in the brain and the periphery (5,6). The biologic effects of ECs are mediated by two G protein-coupled receptors (CB1R and CB2R) that use the G-αi class of heterotrimeric proteins to regulate intracellular signaling pathways (5). ECs are key players of feeding behavior through the activation of the CB1Rs in the brain (5). Initial studies found that CB1Rs are expressed mainly in the brain and modulate food intake and energy balance. However, new evidence has accumulated that suggests that ECs also influence insulin action through peripheral CB1Rs in insulin-sensitive tissues, such as adipose tissue, liver, and muscle, and that these effects are independent of food intake or central CB1R activation (6). Indeed, AEA impairs insulin-stimulated AKT phosphorylation and decreases glucose uptake in skeletal muscle cells (7), and CB1R antagonism enhances insulin responsiveness of skeletal muscle (8). However, the mechanism by which CB1R regulates insulin action remains unknown.

Recent studies have extended this notion to the endocrine pancreas, where CB1Rs and EC metabolic enzymes were found in rodent and human islets (9–15). The cells on which CB1Rs are expressed have not been firmly established, however. Initial studies suggested that CB1Rs are densely located in α-cells and to a lesser degree in β-cells (10,11), another reported the absence of CB1R in β-cells (13), whereas still other reports point to the presence of CB1R in β-cells (9,12,14,15). The presence of CB2R in β-cells is also controversial. Studies reported the presence of CB2R in β-cells (9,11,15), whereas other studies pointed...
to the absence of CB2R in β-cells (10,12). Here, we tried to settle the controversy over the existence of the EC receptors in β-cells and provide a novel, fundamental, and potentially exploitable function for CB1Rs in insulin-mediated β-cell proliferation. We found that an intraislet EC system (ECS) indeed exists and serves as a negative feedback on insulin-mediated β-cell proliferation. We also demonstrate the therapeutic potential of manipulation of the ECS in a mouse model of type 2 diabetes.

RESEARCH DESIGN AND METHODS

Materials. Sources and dilutions of primary antibodies used in immunoblotting, immunoprecipitation, and immunostaining are listed in Supplementary Table 1. AEA, 2-AG, AEA-d8, 2-AG-d5, WIN55, 212-2, arachidonyl-2-chloroethylamide (ACEA), AM251, and AM630 were obtained from Cayman Chemical (Ann Arbor, MI). GFP-HA-tagged CBIR was from K. Mackie (Indiana University). The human IR and G-αi3 cDNA were amplified by RT-PCR from a human pancreas RNA (Stratagene, La Jolla, CA), with oligo-dT (18 bp) for the reverse transcription. The IR cDNA was incorporated into a 3× Flag-vector and the G-αi3 cDNA was incorporated into an mVenus-C1 vector. IR mutant (IR-3YA), whose Tyr1158/1162/1163 residues were substituted to Ala, was developed and backcrossed to a C57Bl/6 J background, as previously described (16). The study used male 2- to 3-month-old CBIR−/− and CBIR+/+ (IR-3YA), whose Tyr1158/1162/1163 residues were substituted to Ala, was generated from wild-type IR (IR WT) using a QuikChange II XL site-directed mutagenesis kit (Stratagene).

Animal experiments. CBIR−/− mice and their WT littermates were developed and backcrossed to a C57Bl/6 J background, as previously described (16). The study used male 2- to 3-month-old CBIR−/− and CBIR+/+ mice. AM251 (10 mg/kg) was administered by daily intraperitoneal injection to 1-month-old normal C57Bl/6 J mice for 4 weeks. FAAH mice were obtained from Dr. Benjamin Cravatt (Scripps Research Institute, CA), and 1-month-old db/db mice were from Jackson Laboratories (Bar Harbor, ME).

DMO, AM251 (10 mg/kg), and AM630 (10 mg/kg) were injected daily for 4 weeks. Then, the pancreata were dissected and blood was collected in the ad lib state of eating. Blood glucose concentration was measured using an Elite glucometer (Bayer Healthcare, Tarrytown NY), and plasma insulin was measured using a rat/mouse insulin ELISA Kit (Crystal Chem, Downers Grove, IL).

Immunostaining and pancreas morphometry. Pancreata were fixed in 4% paraformaldehyde, immersed in 20% sucrose before freezing, and sectioned (7-μm thickness). Human and mouse paraffin-embedded pancreatic sections were immunostained as before (17). After antigen unmasking, the slides were incubated with primary antibodies (Supplementary Table 1), followed by secondary antibodies (Invitrogen, Carlsbad, CA) along with TO-PRO-3 (Invitrogen), in some cases, for nuclear staining.

Slides were viewed using a LSM-710 confocal microscope (Carl Zeiss Microimaging, Munich-Hallbergmoos, Germany). Multiple sections from 3 to 5 mice per group, separated by at least 200 μm from each section, were assessed for signal intensity and the number of nuclear p27 or CB2R staining. Multiple sections from 3 to 5 mice per group were immunostained as before (17). After antigen unmasking, the slides were incubated with primary antibodies (Supplementary Table 1), followed by secondary antibodies (Invitrogen, Carlsbad, CA) along with TO-PRO-3 (Invitrogen), in some cases, for nuclear staining. The relative cross-sectional areas of pancreata and β-cells were determined from multiple sections (n = 5 mice per group), separated by at least 200 μm from each section, using LSM Image Browser software. The relative cross-sectional area of β-cells was determined by quantification of the cross-sectional area covered by insulin-positive cells divided by the cross-sectional area of total pancreas tissue. The β-cell mass per pancreas was estimated as the product of the relative cross-sectional area of β-cells per total tissue and the weight of the pancreas.

Islet isolation and EC levels. Human islets were provided by the Islet Cell Resource Center. Mouse islets were isolated using collagenase digestion, as we previously described (18). Human or mouse islets in Dulbecco’s modified Eagle’s medium (DMEM) containing 4 mmol/L glucose and 1% BSA were pelleted and incubated with DMEM containing 4, 10, or 15 mmol/L glucose, with or without KCl (30 mmol/L) for 10 min. Lipid extraction and tandem mass spectrometry analysis were done next, and details are described in the Supplementary Data.

Western blot analysis. Western blot analysis was done next, and details are described in the Supplementary Data.

Cell culture, transfection, and proliferation studies. β-IRWT and β-IRKO cells were established from mice (2,10,20). β-IRWT, β-IRKO, MIN6, β-TC6, and α-TC1 cells were maintained in DMEM with 10% FBS (Invitrogen). CHO-K1 and CHO-IR (CHO-K1 cells stably transfected with IR) cells were maintained in DMEM/F12 with 10% FBS. Human neuroblastoma BR(2)-M17 cells were maintained in OPTI-MEM with 10% FBS. Transfections of small interfering (si) RNAs (Santa Cruz Biotechnology, Santa Cruz, CA) for G-αi3 and CB1R and the expression vectors for CB1, G-αi3, and IR, and were done using lipofectamine RNAiMAX or 2000 (Invitrogen). Scramble siRNA (Silencer Negative Control #1; Ambion, Austin, TX) or empty vector was transfected as the negative control. For exogenous insulin treatment, cells starved overnight in low-glu- cose DMEM containing 0.1% FBS were incubated for 2 h in glucose-free DMEM with 0.1% BSA, followed by pretreatment with CB1R agonists for 15 min and insulin stimulation for 10 min, with or without CB1R agonists. For cell proliferation studies, cells were plated into 96-well plates with complete media. After treatment with CB1R antagonist or agonists, or both, the prolif- eration rate was determined after 48 or 72 h using the CellTiter 96 Aqueous One Solution Cell Proliferation Assay (Promega, Madison, WI), according to the manufacturer’s instructions.

Immunoprecipitation and G-αi activation assay. Cells lysates extracted using radioimmunoprecipitation assay buffer containing protease and phosphatase inhibitor cocktails were incubated with the appropriate antibody and subsequently incubated with protein A/G beads. Beads were washed three times in radioimmunoprecipitation buffer and used for Western blot analysis with the primary antibodies and with an HRP-conjugated secondary antibody. Blots were visualized by enhanced chemiluminescence (GE Health, Berne, Switzerland). For G-αi activation assay, we used the G-αi Activation Assay Kit (NewEast Biosciences, Malvern, PA) as previously described (21). Cells treated with or without ACEA were lysed with ice-cold 1×Assay Lysis buffer and underwent immunoprecipitation with anti-G-αi3–guanosine triphosphate (GTP) antibody and Western blot analysis with anti-G-αi3 antibody. For positive control, β-IRWT cell lysate, not treated with ACEA, was incubated with guanine 5′-y-thio) triphosphate (GTP-γ-S) for 90 min before immunoprecipitation.

Statistical analysis. Quantitative data are presented as the mean ± SEM. Differences between mean values were compared statistically by Student t test. Comparisons were performed by using GraphPad Prism (GraphPad Software, San Diego, CA). A P value of < 0.05 was considered statistically significant.

RESULTS

Islets have a self-contained ECS. CB1Rs are present in β- and α-cells in both mouse (Fig. 1A) and human (Fig. 1B) islets. To confirm specificity of staining, we used pancreata from CBIR−/− mice (16) (Fig. 1A) and the corresponding blocking peptides (Fig. 1A). For added proof of our findings, we microdissected β-cells from islets of CBIR−/− and CBIR+/+ mice by laser-capture microscopy, and using qRT-PCR of the captured cells, we confirmed CBIR expression (Fig. 1C). Western blot analysis showed that CB1Rs are expressed in mouse insulinoma (βTC6 and MIN6) and glucagonoma (αTC1) cells (Supplementary Fig. 1A). CB2Rs are absent in β- and α-cells, but cellular CB2R staining is evident in islets (Fig. 1D). Of general interest, and as previously reported (10), the CB2Rs are present in somatostatin-containing cells in islets (Fig. 1E).

Also as previously reported (11), EC synthetic enzymes, N-acylphosphatidyl ethanolamine phospholipase D (NAPE-PLD; Fig. 2A) and diacylglycerol lipase-α (Fig. 2B) are present mainly in β-cells, with little if any expression in α-cells in both human and mouse islets. The EC-degrading enzyme, fatty acid amide hydrolase (FAAH), is present mainly in β-cells (Fig. 2C), and monoacyl glycerol lipase (MAGL) is present in both β- and α-cells (Fig. 2D) in human and mouse islets. In agreement with previous literature (9,10), increasing glucose concentrations increased 2-AG and AEA levels in human (Fig. 2E) and mouse (Fig. 2F) islets, and membrane depolarization with KCl also increased 2-AG and AEA levels in human islets (Fig. 2E). Consistently, glucose and KCl also increased 2-AG levels in insulin-secreting immortalized β-cells (β-IRWT) established...
from mice (2,19,20) (Supplementary Fig. 1B). Thus, these results favor the presence of an entire self-contained ECS in mouse and human islets.

**Enhanced IR signaling and β-cell proliferation due to CB1R antagonism.** The CB1R<sup>−/−</sup> mice are known to have a lean phenotype and are resistant to weight gain, even when fed a high-fat diet, and to have improved glucose tolerance and insulin sensitivity compared with WT mice (22,23). Consistently, treatment with CB1R ligands leads to glucose intolerance and insulin resistance in rodents (23–25) and conversely, peripheral, but not central, CB1R antagonism caused weight-independent improvement in glucose tolerance, insulin sensitivity, fatty liver, and plasma lipid profile even in mice with genetic or diet-induced obesity (23,25,26). These effects are independent of food intake or central CB1R activation (6,23,26).

Their pancreata have not been previously studied. We found that the amount of phosphorylated IR at Y1162/1163 (p-IR), IRS1/2 at Y612 (p-IRS1/2), and AKT at S473 (p-AKT) were all higher in the islets of CB1R<sup>−/−</sup> mice compared with age-matched CB1R<sup>+/+</sup> mice (Fig. 3A). Because IR signaling is a key regulator of β-cell proliferation (1–4,27–29), we investigated β-cell area and islet size in CB1R<sup>−/−</sup> mice. In keeping with enhanced IR signaling in isolated islets of CB1R<sup>−/−</sup> mice, β-cell area (Fig. 3B) and islet size (Fig. 3C), but not pancreas wet weight of CB1R<sup>−/−</sup> (0.216 g ± 0.02 g) versus CB1R<sup>+/+</sup> (0.196 ± 0.02 g, n = 6 per genotype, P = 0.48), were increased, and the distribution of islet size (Fig. 3D) was shifted toward bigger islets in CB1R<sup>−/−</sup> compared with CB1R<sup>+/+</sup> mice. Proliferating-cell nuclear antigen (PCNA), a marker of cell proliferation, was more readily apparent in nuclei of β-cells in CB1R<sup>−/−</sup> mice than in CB1R<sup>+/+</sup> mice (Fig. 3E). Ki-67 staining, another marker of
cell proliferation, generated similar results (data not shown). Concordant with these observations, CB1R blockade by AM251 also led to increases in β-cell area (Fig. 3F) and PCNA+ β-cells (Fig. 3G), compared with DMSO-treated animals.

CB1R blockade leads to increased β-cell mass in db/db mice. Genetic and pharmacologic blockade of CB1R in mice with diet-induced obesity results in improved glucose tolerance and insulin sensitivity (23,25,26,30). Because genetic CB1R ablation resulted in larger islets and enhanced β-cell proliferation, despite improved insulin sensitivity, we investigated if CB1R modulation would be beneficial to β-cells in a mouse model of type 2 diabetes. We injected DMSO, AM251, or AM630 (a CB2R antagonist) daily into 4-week-old db/db mice for 4 weeks (Fig. 4A).

Consistent with previous reports (23,25,26,30), AM251-treated mice had lower body weight (Fig. 4B) and blood glucose (Fig. 4C) and plasma insulin (Fig. 4D) levels than DMSO-treated mice, whereas AM630 had no obvious effects (Fig. 4B–D). Pancreatic sections showed increased intraislet insulin content and total β-cell mass in AM251-treated mice compared with DMSO-treated mice (Fig. 4E–G), which was most likely due to enhanced β-cell proliferation (Fig. 4H).

Given that AKT regulates p27Kip1 (p27) activity, an inhibitor of cell cycle progression, by affecting its abundance and subcellular localization (31,32), and that accumulation of p27 in the nuclei of β-cells contributes to deficient β-cell mass and proliferation during the development of type 2 diabetes in Irs2−/− and db/db mice (28), we examined the
expression and subcellular localization of p27. Immuno-
staining of pancreatic sections from AM251-treated mice showed a significant decrease in the total amount and nuclear localization of p27 in β-cells, with most of the protein being localized in cytoplasm, compared with DMSO-treated mice (Fig. 4I). To evaluate whether the increased β-cell proliferation seen by CB1R antagonism associates with any changes in IR signaling, we examined phosphorylation levels of IR. The amount of p-IR was significantly increased in AM251-treated mice compared with DMSO-treated mice (Fig. 4G).

**CB1R inhibits β-cell proliferation by impeding IR autophosphorylation.** Because pharmacologic and genetic blockade of CB1Rs led to enhanced IR signaling and β-cell proliferation, we next investigated the potential role of IRs as a mediator of CB1R-controlled β-cell proliferation. We used β-cells established from control (β-IRWT) and β-cell–specific IR knockout (β-IRKO) mice (2,19,20) in which expression levels of CB1Rs are similar (Fig. 5A).

![Image](https://example.com/image.png)

**FIG. 3.** Effects of CB1R antagonism on β-cell proliferation. A: Western blot analysis for the indicated proteins in isolated islets from overnight-fasted CB1R+/+ and CB1R−/− mice. Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) was used as a loading control. B: Representative immunostaining for insulin in CB1R+/+ and CB1R−/− mice. Scale bar = 200 μm. Mean β-cell area is shown on the right. C and D: Mean islet size (C) and islet size distribution (D) of CB1R+/+ and CB1R−/− mice. The data were estimated from at least 225 islets per genotype. E: Pancreatic sections of cohorts in (panel B), showing PCNA+ β-cells as indicated by arrows. Scale bar = 50 μm. Quantification of PCNA+ β-cells is shown on the right. The number of cells that are positive for both PCNA and insulin were quantified as a percentage of the total number of insulin-positive cells in the sections. F: Representative immunostaining for insulin in DMSO- and AM251-injected mice. Scale bar = 200 μm. Mean β-cell area of DMSO- and AM251-treated mice is shown on the right. G: Pancreatic sections of cohorts in F, showing PCNA+ β-cells as indicated by arrows. Scale bar = 50 μm. Quantification of PCNA-positive β-cells is shown on the right. The number of cells that are positive for both PCNA and insulin were quantified as a percentage of the total number of insulin-positive cells in the sections. Data are shown as the mean ± SEM in all panels (n = 3–5 animals per group). *P < 0.05; **P < 0.01. (A high-quality digital representation of this figure is available in the online issue.)
FIG. 4. Increased β-cell mass and proliferation in AM251-treated db/db mice. A: Experimental timeline for DMSO, AM251, or AM630 (CB2R antagonist) treatment in 4-week-old db/db mice. DMSO, AM251 (10 mg/kg), or AM630 (10 mg/kg), were administrated by daily intraperitoneal injection for 4 weeks. B: Body weight of DMSO-, AM251-, or AM630-treated db/db mice. C: Blood glucose levels at the end of the 4-week period. D: Plasma insulin levels of DMSO-, AM251-, or AM630-treated db/db mice. E: Representative images for insulin in db/db mice injected with DMSO or AM251 for 4 weeks. F: Quantification of insulin intensity in islets of cohorts in E. G: Morphometric assessment of β-cell mass of cohorts in E. H: Representative images for PCNA+ β-cells in islets of cohorts in E. Arrows denote PCNA+ β-cells. Scale bar = 50 μm. Quantification of PCNA+ β-cells is shown on the right. The number of cells that are positive for both PCNA and insulin were quantified as a percentage of the total number of insulin-positive cells in the sections. I: Representative immunostaining for insulin and p27 in islets of cohorts in E. Scale bar = 50 μm. Relative signal intensity for p27 in islet is shown on the right. J: Representative immunostaining for IR and p-IR in islets of cohorts in E. Scale bar = 50 μm. Relative signal intensity for p-IR was normalized to that for total IR. Data are shown as the mean ± SEM in all panels (n = 5 animals per group). *P < 0.05; **P < 0.01. (A high-quality digital representation of this figure is available in the online issue.)
in β-IRWT cells, but not in β-IRKO cells. CB1R blockade by AM251 in normal mice also resulted in a significant decrease in both the amount and nuclear localization of p27 (Fig. 5G) compared with DMSO-treated animals. These results suggest that CB1R signaling functions as a negative regulator of the proliferative effects of endogenously secreted insulin from β-cells.

To test the direct effect of CB1R activation on IR activity, isolated mouse islets (Fig. 6A) and β-IRWT cells (Fig. 6B) were pretreated with AEA or 2-AG and ACEA, respectively, before addition of exogenous insulin. All agonists markedly prevented exogenous insulin-stimulated IR autophosphorylation and downstream signaling. This was also true in BE(2)-M17 human neuroblastoma cells (data not shown), which express CB1Rs (Supplementary Fig. 1A). In addition, ACEA diminished exogenous insulin-stimulated IR autophosphorylation and levels of p-IRS1/2, p-PDK1, p-AKT, and p-FoxO1 in MIN6 cells (data not shown). The inhibitory effects of CB1R agonists on IR autophosphorylation and p-AKT were not observed in CHO cells (CHO cells lack CB1Rs, see Supplementary Fig. 1A; Fig. 6C), but ACEA treatment in CHO-IR (CHO cells stably transfected with IR) cells transfected with the expression

![Image]

**FIG. 5.** Inhibitory effects of CB1R on β-cell proliferation depends on IR. **A**: Levels of CB1R, p27, and IR in β-IRWT and β-IRKO cells exposed to a selective synthetic CB1R agonist ACEA for 40 h. **B**: Proliferation rates of β-IRWT cells exposed to ACEA with or without AM251 for 48 h. Data are shown as the mean ± SEM from three independent experiments. **P < 0.01. **C**: Proliferation rates of β-IRWT and β-IRKO cells 5 days after plating. Data are shown as the mean ± SEM from three independent experiments. **P < 0.01. **D**: Effects of AM251 on the proliferation of β-IRWT and β-IRKO cells. Data are shown as the mean ± SEM from three independent experiments. *P < 0.05; **P < 0.01. **E**: Effects of ACEA (48 h) on the proliferation of β-IRWT and β-IRKO cells. Data are shown as the mean ± SEM from three independent experiments. **P < 0.01. **F**: Levels of the indicated proteins in β-IRWT and β-IRKO cells exposed to ACEA for 40 h. **G**: Representative immunostaining of insulin and p27 in pancreatic sections from DMSO- and AM251-injected mice. Scale bar = 50 μm. Quantification of p27 intensity and nuclear p27+ β-cells in islets is shown on the bottom. Data are shown as the mean ± SEM (n = 3 per group). **P < 0.01. (A high-quality digital representation of this figure is available in the online issue.)
vector containing GFP-HA–tagged CB1R led to reduced IR autophosphorylation (Fig. 6D).

To directly confirm the inhibitory effects of CB1R on IR autophosphorylation, we transfected Flag-tagged IR-WT and IR mutant (IR-3YA), whose Tyr1158/1162/1163 residues were substituted to Ala (Fig. 6E), into β-IRKO cells and then treated the cells with ACEA for 40 h (Fig. 6F). IR autophosphorylation was detected in IR-WT–transfected β-IRKO cells, presumably due to endogenous insulin secretion, and ACEA reduced levels of p-IR and p-AKT in those cells, but in IR-3YA–transfected β-IRKO cells, p-AKT levels were not altered (Fig. 6F). In sum, these results suggest a functional interaction between CB1R and IR signaling upon IR autophosphorylation.

**Inhibitory effect of CB1R on IR signaling depends on G-αi.** Activated CB1Rs mediate their intracellular actions through G-αi proteins (5). G-αi-3 appears to be expressed mainly in β-cells of both human and mouse (Fig. 7A), and its activity was increased by CB1R activation in both β-IRWT and β-IRKO cells (Fig. 7B). ACEA dose-dependently increased the association between G-αi-3 and IR (Fig. 7C), whereas siRNA-mediated attenuation of CB1Rs (Supplementary Fig. 2A) reduced the association (Fig. 7C). Furthermore, exogenous insulin treatment led to a decrease in G-αi-3/IR association, which was impeded by ACEA (Fig. 7D).

We further confirmed an EC-mediated G-αi-3/IR association using IR-WT and IR-3YA–transfected β-IRKO cells with or without ACEA treatment for 15 min. As shown in Fig. 7E, ACEA reduced levels of p-IR and p-AKT in IR-WT–transfected β-IRKO cells, but p-AKT was not reduced in IR-3YA–transfected β-IRKO cells (Fig. 7E), and most interestingly, G-αi-3 association with IR-3YA was actually increased compared with IR-WT (Fig. 7F and G). ACEA increased G-αi-3/IR association (Fig. 7F), which conversely was reduced by AM251 (7G). These results suggest that G-αi mediates the inhibitory effect of CB1R activation on IR autophosphorylation by its association with IR. Furthermore, over-expression of G-αi-3 in β-IRWT cells led to decreased levels of p-IR and p-IRS1/2 (Fig. 8A) and knockdown of CB1Rs (Supplementary Fig. 2A) or G-αi-3 (Supplementary Fig. 2B) by siRNA in β-IRWT cells abolished the ability of ACEA to inhibit insulin-stimulated phosphorylation of IR, IRS1/2, and AKT (Fig. 8B) as well as its ability to increase p27 expression (Fig. 8C). Consistently, knockdown of CB1Rs or G-αi-3 resulted in an

FIG. 6. Regulation of IR activity by CB1R. A: Phosphorylation levels of p-IR in isolated mouse islets exposed to insulin (10 nmol/L) for 10 min with vehicle, AEA or 2-AG. B: Western blot analysis of the indicated proteins in β-IRWT cells exposed to insulin (10 min) with ACEA or vehicle. C: Levels of p-IR and p-AKT in CHO-K1 cells exposed to insulin with or without ACEA. D: Effects of CB1R over-expression on insulin-stimulated IR autophosphorylation. CHO-IR cells transiently transfected with the indicated plasmids were preincubated with ACEA for 20 min before insulin treatment (10 min), after which their lysates were subjected to Western blot analysis for the indicated proteins. E: Substitution of IR autophosphorylation sites (Tyr1158/1162/1163) with Ala. F: Western blot analysis for the indicated proteins in βIRKO cells exposed to ACEA for 40 h after transfection with empty vector, IR-WT, or IR-3YA. (A high-quality color representation of this figure is available in the online issue.)
increase in β-cell proliferation (Fig. 8D) and a loss of the inhibitory actions of ACEA (Fig. 8E). These results suggest that the CB1R-mediated effects on IR and downstream signaling involve EC-induced activation of G-αi.

DISCUSSION

In contrast to adipose tissue, liver, and muscle, the presence and effects of CB1Rs in β-cells have been inconclusive. Here, we demonstrate that β-cells contain all of the components of a self-contained ECS: CB1R, the necessary enzymes for catalyzing EC biosynthesis and degradation, and the capacity to generate ECs in response to glucose stimulation and depolarization, even when isolated from the pancreas. We used several antibodies (33,34), including the L15 antibody to the C-terminus of CB1R that exhibits the expression pattern most consistent with in-situ hybridization (33) as well as qRT-PCR of laser-captured β-cells from islets, to affirm that CB1Rs, but not CB2Rs, are present on β-cells of mice and men. Bermúdez-Silva et al. (14) have very recently written that using the L15 antibody they also found a CB1R signal with insulin costaining; after using a commercially available CB1R antibody, they reported that CB1Rs were mainly expressed in α-cells (10). CB2Rs are absent from α- and β-cells. Most reports, including this study, found that β-cells contain EC synthetic and degrading enzymes (9–11,14).

Since at least 1979, insulin mediators, also referred to as insulin second messengers, are known to be generated from lipid precursors present on plasma membranes in response to IR activation and consequent downstream phospholipase activation (35). We are now suggesting that ECs, also generated from lipid precursors in β-cells, influence IR activation (Supplementary Fig. 3). This is especially relevant because insulin concentrations would be expected to be at their highest levels surrounding β-cells and therefore the islet ECS potentially evolved to prevent an over-exuberant β-cell IR signaling cascade. Favoring this view are our findings that in various β-cell lines, isolated islets and a mouse model of diabetes CB1R signaling counteracts the effects of insulin on β-cells by preventing IR autophosphorylation and downstream signals. This finding was not unique to pancreatic β-cells because activation of CB1Rs also impeded exogenous insulin-stimulated IR autophosphorylation in non-insulin-secreting cells.

We also found that G-αi, which is involved in the regulation of insulin secretion (36) and β-cell proliferation (37), mediates the inhibitory effect of CB1R activation on IR...
activity by its association with IR. CB1R activation increased G-α-3 activity and G-α-3/IR association was strengthened by CB1R activation and substitution of Tyr1158/1162/1163 residues of IR with Ala, which, conversely, was weakened by suppression of CB1R activity and by insulin. Furthermore, knockdown of G-α-3 by siRNA abolished the ability of CB1R to inhibit exogenous insulin-stimulated IR autophosphorylation and β-cell proliferation.

These results suggest a functional and physical crosstalk between CB1R and IR signaling upon IR autophosphorylation in a G-αi-dependent manner. Given that binding of insulin to the extracellular α-chains of IR causes a change within the quaternary structure of IR that places the phosphorylation sites of one β-chain within reach of the active site of the other β-chain and that results in auto-phosphorylation at Tyr1158/1162/1163 residues of IR (38,39), we propose that G-αi-3 activated by CB1R associates with unphosphorylated IR at the Tyr1158/1162/1163 residues, preventing a conformational change that secures the activation loop in a catalytically competent configuration upon ligand binding.

Because these receptors are found to be present within caveolae, a cholesterol-rich microdomain that performs a number of signaling functions (40), it is possible that the closeness of the CB1Rs causes them to be involved in modulating IR-mediated signaling. Although the detailed molecular mechanism underlying CB1R and G-αi-3 as regulatory components in the IR signaling pathway awaits further exploration, collectively, our results imply that the alteration in IR activity by CB1Rs is a reflection of a direct inhibition of IR autophosphorylation in a Gαi-dependent manner and that ECs directly regulate proliferation through activation of CB1Rs expressed in β-cells. Through these actions, CB1Rs are likely to set a threshold level for IR-mediated responses, which depends on the level of expression or activation of CB1R. Alteration in IR activity by CB1Rs may additionally be due to the change in autocrine activation because of altered insulin secretion. CB1R-mediated suppression of insulin secretion in a Ca2+-dependent manner has been reported (12,41); however, there are also reports to the contrary (9,10,15,42,43).

We demonstrate the therapeutic advantage of CB1R modulation in a type 2 diabetic condition. Inhibition of CB1R activity in db/db mice led to reduced blood glucose and increased β-cell proliferation, coupled with enhanced IR signaling. There is also evidence that insulin itself reduces glucose-stimulated EC synthesis in β-cells, which would serve as a negative feedback loop to reduce intracellular EC levels (9). This would logically mean that when IR function is reduced, as in type 2 diabetes, such a robust feedback would also be impaired, leading to nonphysiologic
EC levels in islets (in addition to in fat and liver) and consequent CB1R-mediated β-cell dysfunction through further impeding IR activity. Blocking CB1Rs would therefore be expected to improve β-cell function in db/db mice, as we found. CB2R antagonism had no such effects.

An inadequate expansion of β-cell mass or failure of the existing β-cell mass to compensate for the changing insulin demand are hallmarks of type 2 diabetes, and these prominent features may result from defective IR signaling (1–4,27–29). Therefore, our data should result in the resumption of attention being paid to ECS as a key factor in β-cell physiology and may lead to development of a new therapeutic strategy aiming to preserve better functioning β-cells.

EC levels, not only in the circulating blood but also in the pancreas, are said to be elevated in diabetes and obesity (9,11,44,45), and elevated EC levels are associated with increased diacylglycerol lipase-α and decreased FAAH levels in β-cells (11). Thus, it is possible that increased EC tone (due to increased EC synthesis, receptor expression or activity) affects the well-described glucose-unresponsiveness of β-cells and the development of insulin resistance by impeding IR autophosphorylation in insulin-sensitive tissues. Indeed, AEA was recently found to impair insulin-stimulated AKT phosphorylation and decrease glucose uptake in skeletal muscle cells (7), and CB1R antagonism enhanced insulin responsiveness of skeletal muscle (8).

In addition, pharmacologic blockade of CB1R in obese fa/fa Zucker rats decreased blood glucose levels and preserved β-cell mass (46), and eliminating CB1Rs in liver protected against fatty liver and improved glucose tolerance and insulin sensitivity in high-fat fed mice (23); IR function in those mice was not investigated. Peripheral, but not central, blockade of CB1R was recently reported to improve overall insulin sensitivity and glucose homeostasis (26) and a non-brain-penetrant CB1R antagonist improved glucose homeostasis, insulin sensitivity, and fatty liver in a weight-independent manner (25). This is a very important point, because a centrally acting CB1R antagonist, rimonabant, used for treating obesity, was removed from patient use because of potentially life-threatening psychiatric problems (47). Therefore, CB1R antagonists with poor brain penetrance might be useful therapies in type 2 diabetes where they would be expected to lessen insulin resistance in skeletal muscle and liver, ameliorate or prevent fatty liver, and improve β-cell function/proliferation.

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