

Regulation of MAP Kinase–Directed Mitogenic and Protein Kinase B–Mediated Signaling by Cannabinoid Receptor Type 1 in Skeletal Muscle Cells

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OBJECTIVE—The endogenous cannabinoid (or endocannabinoid) system (ECS) is part of a central neuromodulatory system thought to play a key role in the regulation of feeding behavior and energy balance. However, increasing evidence suggests that modulation of the ECS may also act to regulate peripheral mechanisms involved in these processes, including lipogenesis in adipose tissue and liver, insulin release from pancreatic β -cells, and glucose uptake into skeletal muscle. It was recently shown that cannabinoid receptor type 1 (CB1) and type 2 (CB2), both key components of the ECS, are expressed in human and rodent skeletal muscle. However, their role in modulating insulin sensitivity in this metabolically active tissue has yet to be determined. Our aim was to establish the role, if any, of these receptors in modulating insulin sensitivity in skeletal muscle cells.

RESEARCH DESIGN AND METHODS—Cultured skeletal muscle cells were exposed to CB1 and/or CB2 pharmacological agonists/antagonists/inverse agonists, and the resulting effects on insulin-regulated phosphatidylinositol 3 kinase (PI 3-kinase)–protein kinase B (PKB) and extracellular signal–related kinases 1/2 (ERK1/2)-directed signaling were determined.

RESULTS—Here, we report that modulating the activity of the ECS in skeletal muscle regulates both insulin-dependent mitogen-activated protein (MAP) kinase (ERK1/2) and the canonical PI 3-kinase/PKB signaling pathways. We show that pharmacological activation or inhibition of CB1 receptor activity exerts a differential effect with regard to MAP kinase– and PKB-directed signaling.

CONCLUSIONS—Our study provides evidence that signaling via cannabinoid receptors can significantly modulate mitogenic and metabolic signaling in skeletal muscle with important implications for muscle growth and differentiation as well as the regulation of glucose and lipid metabolism. *Diabetes* 59:375–385, 2010

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The increasing occurrence of obesity continues to pose major health problems globally and is linked with the growing incidence of conditions such as type 2 diabetes and cardiovascular disease (1,2). The mechanisms involved in the pathogenesis of type 2 diabetes are not yet fully understood and therefore are the focus of intense study. Insulin resistance probably develops due to unfavorable alterations in the insulin signal transduction pathways that are important for controlling glucose homeostasis in target tissues, such as liver, adipose tissue, and skeletal muscle (3,4). Initiation of these pathways stems from the activated insulin receptor kinase that can bind and regulate numerous downstream intracellular targets, such as the insulin receptor substrate (IRS) proteins, phosphatidylinositol 3 kinase (PI 3-kinase), and growth factor receptor–bound protein 2 (5–7).

The endocannabinoid signaling system (ECS) has been shown to influence multiple metabolic pathways, via both its central and peripheral actions (8–10). Key components of this system include the 7-transmembrane endocannabinoid receptors (cannabinoid [CB] receptors) and endogenous lipid-derived endocannabinoid ligands such as anandamide and 2-arachidonoylglycerol (2-AG) (9). From work carried out in neurons, it is widely acknowledged that these endocannabinoids are not stored in cells but are produced “on-demand” from lipid precursors in response to elevated levels of intracellular calcium (11). The mechanisms by which endocannabinoids are synthesized in peripheral tissues have yet to be established.

CB receptors belong to the superfamily of G-protein–coupled receptors, where the two principle subtypes, type 1 (CB1) and type 2 (CB2), are established as the mediators of the majority of the biological effects of cannabinoid ligands. Although these receptors are both $G_{i/o}$ coupled, they do display very different pharmacological profiles and patterns of expression (8). The CB1 receptor, in particular, has been detected in adipose tissue, liver, muscle, and pancreas and is the most abundantly expressed G-protein–coupled receptor in the brain (8,12–14). CB2 receptors, on the other hand, are expressed primarily in spleen and leukocytes (8,15).

The ECS is known to regulate energy balance and initially this was thought to occur via its central effects on feeding behavior, although more recent evidence suggests it may also regulate lipid and glucose metabolism by direct actions on peripheral targets (8,9,12). The generation of genetic mouse knockout models and the discovery of SR141716, a CB1 selective inverse agonist, have greatly contributed to our understanding of the role of the ECS in the regulation of energy metabolism (16,17). Centrally,

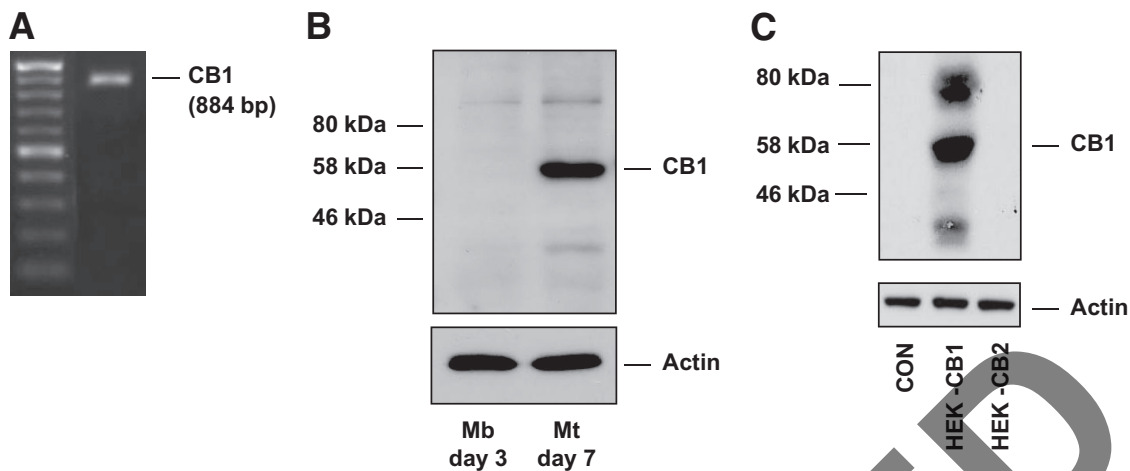


FIG. 1. CB1 expression in myoblasts and myotubes. **A:** The presence of CB1 mRNA was confirmed by conventional RT-PCR analysis of RNA isolated from L6 myotubes. **B:** Expression of CB1 receptor protein was compared in lysates (40 μ g) obtained from L6 myoblasts and myotubes by immunoblotting using a CB1 antibody. **C:** Specificity of this CB1 antibody was confirmed by immunoblot analysis of lysates isolated from HEK-293AD cells transfected with or without (CON) wild-type CB1 (HEK-CB1) or CB2 receptor (HEK-CB2).

antagonism of the CB1 receptor is found to suppress appetite and promote weight loss, effects that are also seen in mice lacking the CB1 receptor (12,17). On the other hand, with regard to peripheral effects, SR141716 acts to suppress lipogenesis in both liver and adipose tissue promoted by endocannabinoids acting via the CB1 receptor (9,18,19). In addition, pharmacological inhibition of the CB1 receptor increases the expression of adiponectin, an insulin-sensitizing adipokine (20). Overall, longer-term SR141716 treatment has been shown to reduce fasting glucose and insulin levels as well as improve lipid profile in both animals and humans (17,21,22). Emphasizing these important regulatory roles of CB1 signaling in metabolism, there is also increasing evidence that the ECS becomes dysregulated during hyperglycemia and obesity (9).

Skeletal muscle plays a crucial role in glucose homeostasis by being the primary site of glucose disposal and fatty acid oxidation, processes that are acutely regulated by insulin (23,24). It is now known that CB1 receptors are expressed in human skeletal muscle (13), and preliminary evidence suggests that the ECS may have a role in regulating pathways involved in oxygen consumption and oxidation as well as glucose metabolism (25–27). However, as yet, little is known with regard to the effects of manipulating ECS activity on muscle insulin sensitivity. Here we demonstrate that the CB1 receptor is expressed in cultured rat skeletal muscle cells in a differentiation-dependent manner and show for the first time that whereas activating CB1 receptor activity pharmacologically produces differential effects on the insulin-dependent regulation of mitogen-activated protein (MAP) kinase (extracellular signal-related kinases 1/2 [ERK1/2]) and canonical PI 3-kinase/protein kinase B (PKB) signaling, CB1 receptor inverse agonism leads to the insulin sensitization of both pathways.

RESEARCH DESIGN AND METHODS

Materials. Bovine insulin was purchased from Sigma-Aldrich (Munich, Germany). WIN55,212-2 (R-(+)-[2,3-dihydro-5-methyl-3-(4-morpholinylmethyl)-pyrrolo-[1,2,3-de]-1,4-benzoxazin-6-yl]-1-naphthalenylmethanone mesylate), AM630 (6-Iodo-2-methyl-1-[2-(4-morpholinyl)ethyl]-1H-indol-3-yl](4-methoxyphenyl)-methanone), JWH015 (2-Methyl-1-propyl-1H-indol-3-yl)-1-naphthalenylmethanone), and ACEA (N-(2-Chloroethyl)-5Z,8Z,11Z,14Z-eicosatetraenamide) were all purchased from Tocris Bioscience (Bristol, U.K.). SR141716 (N-

(Piperidin-1-yl)-5-(4-chlorophenyl)-1-(2,4-dichlorophenyl)-4-methyl-1H-pyrazole-3-carboxamide) was a gift from sanofi-aventis (Frankfurt, Germany). All antibodies were from Cell Signaling Technology (Beverly, MA) unless stated otherwise. Anti-actin was purchased from Sigma-Aldrich (St. Louis, MO). Both IRS-1 and p85 (PI 3-kinase) antibodies were from Millipore (Watford, U.K.). The antibody against the CB1 receptor together with rat CB1 and rat CB2 cDNA were generated by the Mackie laboratory (Indiana University) (28). Horseradish peroxidase-conjugated anti-(rabbit IgG) and anti-(mouse IgG) were obtained from New England Biolabs (Beverly, MA).

Cell culture and transient transfection. L6 cells were cultured to myotubes in α -minimum essential medium containing 2% (vol/vol) FBS (Life Technologies, Paisley, U.K.) and 1% (vol/vol) antibiotic/antimycotic solution (100 units/ml penicillin, 100 μ g/ml streptomycin, and 250 ng/ml amphotericin B) at 37°C with 5% CO₂. HEK-293AD and HEK-293T cells were maintained in a humidified 5% CO₂, 37°C incubator in Dulbecco's modified Eagle's medium/F12 with 10% (vol/vol) FBS. Transient transfections in HEK-293 cells were carried out using Lipofectamine 2000 (Invitrogen), according to manufacturer's instructions.

Cell lysis and immunoblotting. L6 myotubes were lysed after experimental treatment in an appropriate volume of lysis buffer (29). Cell lysates (40 μ g) were subjected to SDS/PAGE on a 10% resolving gel and immunoblotted as previously described (29). Immobilon-P membranes (Millipore, Bedford, MA) were probed with different primary antibodies as described in the figure legends. Primary antibody detection was performed with the appropriate horseradish peroxidase-conjugated anti-rabbit or anti-mouse IgG and resulting signals visualized using enhanced chemiluminescence by exposure to Konica Minolta X-ray autoradiographic film.

Immunoprecipitation. L6 myotubes were lysed as described above. IRS-1 was immunoprecipitated overnight at 4°C from 400 μ g of cell lysate protein using an anti-IRS-1 antibody. The resulting immunocomplex was conjugated to protein-G-Sepharose beads and solubilized in Laemmli sample buffer prior to immunoblotting.

RNA isolation and semiquantitative RT-PCR. Total RNA was extracted from L6 myoblasts or myotubes using TRI Reagent (Sigma-Aldrich, Dorset, U.K.) according to the manufacturer's instructions. The extracted RNA (1 μ g) was used as the template for cDNA synthesis performed using the Improm-II Reverse Transcription System (Promega, Madison, WI) according to manufacturer's instructions. Primers used for PCR amplification were from previously published sequences and were as follows: Forward 5'-3', GGCATCTCTTCTCAGTCAC, reverse 5'-3', ATCAGGTAGGTCTCGTCAAT (30). PCR amplification was performed using the following cycling conditions: 94°C for 2 min followed by (for 28 cycles) 94°C for 1 min, 60°C for 1 min, and 72°C for 2 min. Final extension was carried out at 72°C for 5 min. The amplification reaction was carried out using GoTaq Flexi DNA polymerase according to manufacturer's instructions (Promega). PCR products were then analyzed by agarose gel electrophoresis.

Design and cloning of short hairpin RNAs. Short hairpin RNA (shRNA) sequences were inserted into the pLKO.1-puro lentiviral vector (Sigma-Aldrich, St. Louis, MO) as follows. Each hairpin consisted of a 21-nucleotide sense sequence, a short hairpin sequence (CTCGAG), a 21-nucleotide antisense sequence, and five thymidines (a stop signal for RNA polymerase). Oligonucleotides (oligos)

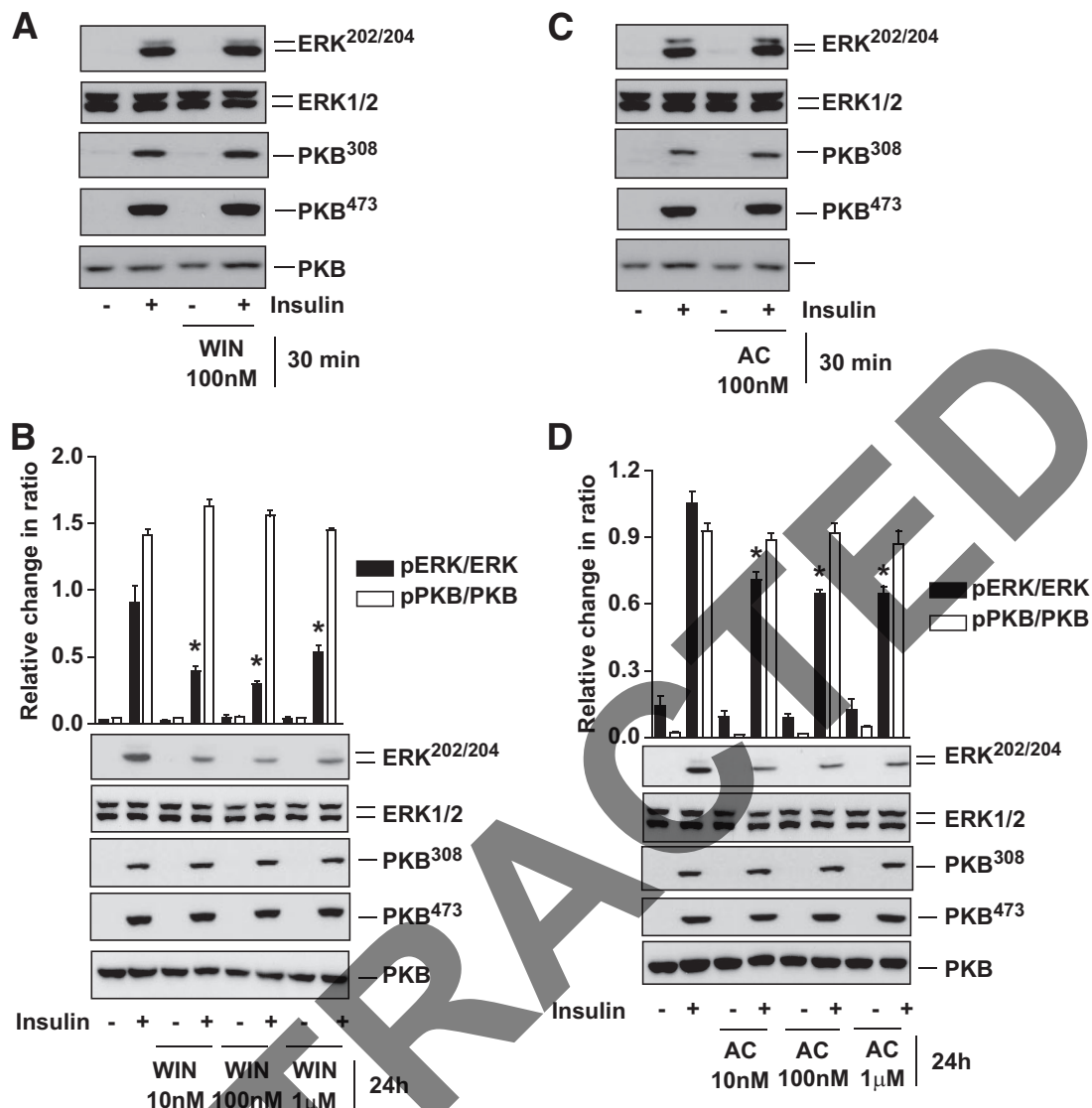


FIG. 2. Effects of WIN55,212-2 and ACEA incubation upon insulin-stimulated PKB and ERK1/2 activation. L6 myotubes were incubated in the absence or presence of either the CB1/2 mixed agonist WIN55,212-2 (WIN) or the CB1 selective agonist ACEA (AC) at the concentrations indicated for either 30 min (A and C) or 24 h (B and D) including a 2-h serum starvation period prior to insulin stimulation (100 nmol/l for 10 min). Cell lysates were then analyzed by immunoblotting with phospho-PKB (Thr308 and Ser473), PKB, phospho-ERK1/2, and ERK1/2. Each bar represents mean \pm SD of three independent experiments. Asterisks indicate statistically significant differences versus untreated cells ($*P < 0.05$).

were constructed for rat CB1 (sense and antisense strands underlined, hairpin loop is indicated by italics): forward CGGAACAAGTCTCTCGTCGT TCAACTCGAGTTGAACGACGAGAGAGACTTGTTTTTTTG, reverse AATTC AAAAAAGAGCACCGTTAAGATCGCGAACTCGAGTTCGCGATCTTAACGGT GCTCTT. Additional nucleotides were added to the ends of the oligos as shown, such that annealing of the two complementary oligos resulted in overhangs consistent with those generated by *EcoRI* and *AgeI*. Oligos were annealed by mixing 2 μ g of each oligo, heating to 94°C for 10 min, followed by cooling at a rate 1°C per minute until 21°C is reached. The final double-stranded DNA sequences were then inserted into pLKO.1-puro at the *EcoRI* and *AgeI* sites. Correct insertions of shRNA were confirmed by sequencing. **Lentivirus production and generation of stable CB1 knockdown L6 cell lines.** Recombinant lentiviruses were produced by cotransfecting HEK-293T cells with the empty pLKO.1-puro vector, pLKO.1-puro/scramble, or pLKO.1-puro/CB1 plasmids with the envelope vector pCMV-VSVg and the packaging vector pHR-CMV8.2AR at ratios of 3:2:2, respectively, according to mass. Infectious lentiviral particles were harvested by collecting the cell culture media 72 h later and filtered through 0.45- μ m Minisart cellulose-acetate filters. Infection of L6 myoblasts was carried out by adding 1 ml crude lentivirus preparation to L6 myoblasts seeded in 6-cm dishes in the presence of 8 μ g/ml polybrene. Medium was replaced with standard growth medium containing 3 μ g/ml puromycin 24 h after transduction and cells were maintained in this selective medium until fully selected.

Statistical analysis. All statistical analysis was performed using one-way ANOVA. Data analysis was performed using GraphPad Prism software and considered statistically significant at P values < 0.05 .

RESULTS

CB1 receptors are expressed in differentiated L6 skeletal myotubes. CB1 receptor expression was originally thought to be exclusive to the brain. However, an increasing number of studies suggest that these receptors are also expressed in peripheral tissues, including skeletal muscle (13). However, to date, no specific function(s) has been attributed to these cannabinoid receptors, and their roles in skeletal muscle physiology remain largely unknown. In an attempt to address this, we initially assessed expression of the CB1 receptor in L6 rat skeletal muscle cells. Using RT-PCR and Western blot analysis, respectively, the expression of the CB1 receptor was confirmed in fully differentiated L6 myotubes at both the mRNA (Fig. 1A) and protein (Fig. 1B) level. However, CB1 receptor protein

was not detected in L6 myoblasts (Fig. 1B), supporting the view that its expression is differentiation dependent in skeletal muscle (31). Specificity of the CB1 antibody used was confirmed by immunoblot analysis performed using lysates obtained from HEK-293AD cells transiently overexpressing rat CB1 and CB2 receptors (Fig. 1C).

The mixed CB1/CB2-receptor agonist WIN55,212-2 downregulates insulin-stimulated ERK1/2 activity but not PKB activation in skeletal L6 myotubes.

Treatment of rat skeletal L6 myotubes with 100 nmol/l insulin for 10 min after short-term (2-h) serum starvation leads to robust activation of PKB and ERK1/2 (p42/44 MAPK), as measured by the extent of phosphorylation of PKB at Thr308 and Ser473, and of ERK1/2 at Thr202/Tyr204 (Fig. 2A). Acute pretreatment (up to 30 min) using the mixed CB1/CB2 agonist WIN55,212-2 (100 nmol/l) has no effect on insulin-stimulated ERK1/2 or PKB activation (Fig. 2A). However, pretreating L6 myotubes with WIN55,212-2 (100 nmol/l) for 24 h prior to insulin treatment substantially perturbs the activation of ERK but not that of PKB (Fig. 2B). Therefore, chronic WIN55,212-2 treatment selectively suppresses insulin-induced activation of the ERK1/2 pathway, but has no effect on PKB activation. This is in contrast to a previous study carried out in glioma cells, demonstrating that longer-term (> 12 h) treatment with WIN55,212-2 used at a higher concentration (15 μ mol/l) can downregulate both ERK1/2 and PKB activity, although this was done in the absence of any external hormonal stimulus (32). In another study performed in primary human skeletal muscle, acute exposure with the endogenous CB1 agonist anandamide alone was found to transiently activate ERK1/2. However we did not observe this same effect in the L6 myotubes using the synthetic CB1 agonists WIN55,212-2 and ACEA, but it is noteworthy that the effects reported by Eckardt et al. (31) were observed using a high concentration (10 μ mol/l) of anandamide, which may potentially modulate a number of cellular responses independently of its effect on cannabinoid receptors.

WIN55,212-2 mediates its inhibitory effects on ERK1/2 specifically through the CB1 receptor. To determine whether the effect of WIN55,212-2 is mediated through the CB1 and/or CB2 receptors, we tested the CB1 and CB2 selective agonists ACEA and JWH015, respectively. Acute (30 min) treatment with ACEA (10 nmol/l) had no effect on either ERK1/2 or PKB activation in response to insulin (Fig. 2C). However, similar to the application of WIN55,212-2, a 24-h treatment with ACEA (10 nmol/l) also led to the inhibition of insulin-stimulated ERK1/2 activity but had no effect on PKB activation (Fig. 2D). In contrast to the effects of WIN55,212-2 and ACEA, treating L6 myotubes with JWH015 either acutely (100 nmol/l, 30 min) or with various concentrations longer term (10 nmol/l to 1 μ mol/l, 24 h) does not alter insulin-stimulated activation of ERK1/2 or PKB (Fig. 3), suggesting that the inhibitory effect of WIN55,212-2 on ERK1/2 signaling is mediated selectively through the CB1 receptor. It should be noted that concentrations of JWH015 less than 100 nmol/l have been shown to inhibit cAMP production and those less than 1 μ mol/l, to evoke calcium transients in HEK-293 cells expressing either the human or rat forms of the CB2 receptor (33,34).

The CB1 receptor inverse agonist SR141716 sensitizes PKB- and ERK1/2-directed signaling in L6 myotubes. SR141716 (rimonabant) is a selective CB1 receptor inverse agonist (trade name Acomplia) that has been used

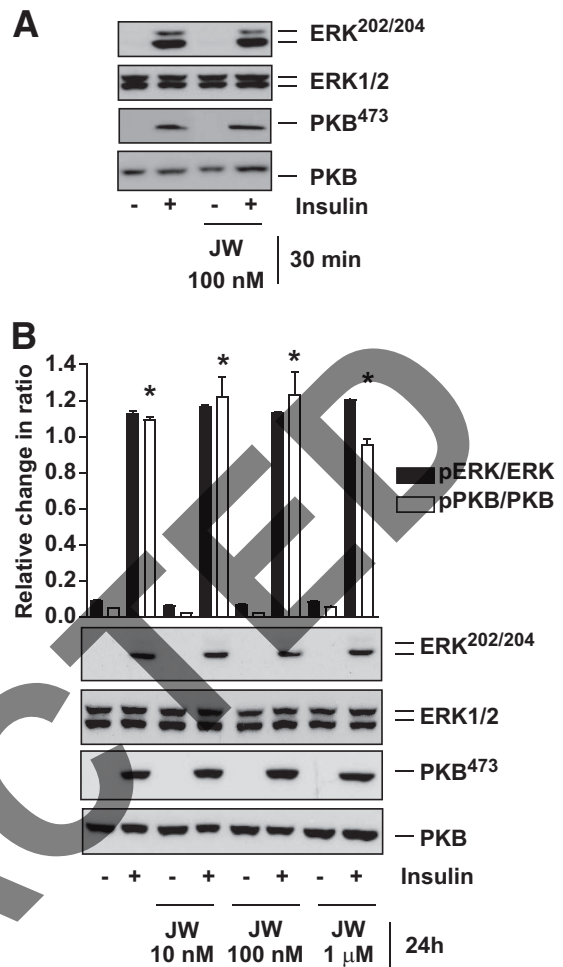


FIG. 3. The CB2 agonist JWH015 does not modulate insulin-stimulated ERK1/2 and PKB activation. L6 myotubes were incubated in the absence or presence of the CB2 selective agonist JWH015 (JW) for the concentrations indicated for either 30 min (A) or 24 h (B) including a 2-h serum starvation period prior to insulin stimulation (100 nmol/l for 10 min). Cell lysates were then analyzed by immunoblotting with phospho-PKB (Ser473), PKB, phospho-ERK1/2, and ERK1/2. Each bar represents mean \pm SD of three independent experiments. Asterisks indicate statistically significant differences versus untreated cells (* P < 0.05).

to treat obesity (35). Administration of SR141716 causes a transient reduction in food intake and sustained reduction in body weight gain as well as decreases hyperinsulinemia and reduces circulating levels of free fatty acids in diet-induced obese rodents and in humans (17,22). Predictably, these effects of SR141716 are not observed in CB1 receptor-deficient mice fed a high-fat diet (17). To our knowledge, the effects of SR141716 on insulin-induced signaling responses in skeletal muscle have not yet been fully elucidated. Therefore, we investigated whether exposing L6 myotubes to SR141716 would abrogate the effects of CB1 activation on insulin-stimulated PKB and ERK1/2 activation. Our data demonstrate that SR141716 prevents the loss in ERK1/2 activity in response to both WIN55,212-2 and ACEA in a concentration-dependent manner, with the effects of the agonists completely blocked by 100 nmol/l SR141716 (Figs. 4 and 5). In contrast, application of the CB2 selective antagonist AM630 (100 nmol/l) had no effect on WIN55,212-2 and ACEA-mediated loss in ERK1/2 activity, again implying that the modulation of ERK1/2 signaling is selectively mediated through the CB1 receptor (Fig. 4A).

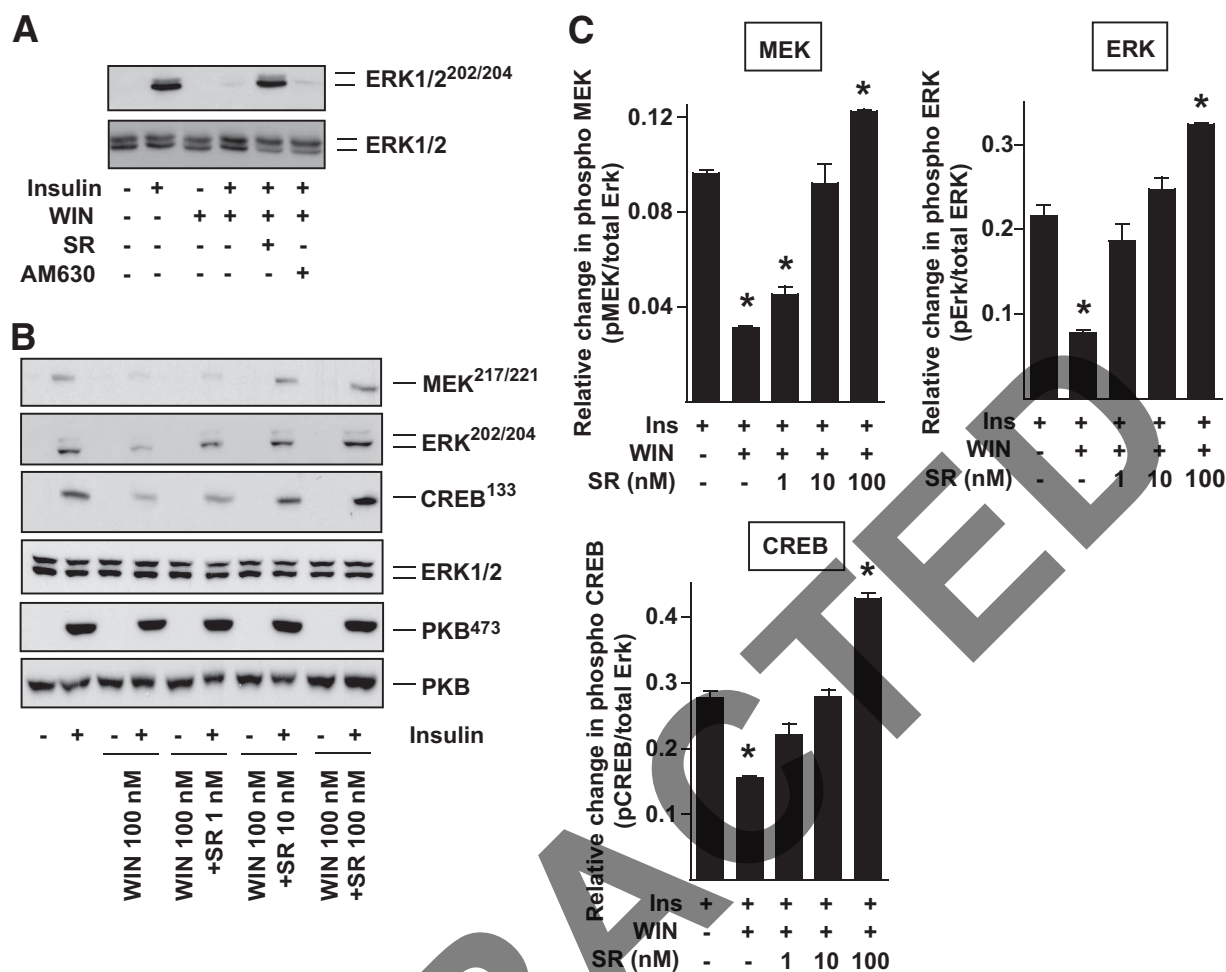


FIG. 4. The inhibitory effects of WIN55,212-2 on ERK1/2 activity are prevented by the CB1 receptor antagonist SR141716. L6 myotubes were incubated with 100 nmol/l WIN55,212-2 (WIN) in the absence or presence of the CB1 inverse agonist SR141716 (SR; 100 nmol/l) or the CB2 antagonist AM630 (100 nmol/l), respectively, for 24 h (A) including a 2-h serum starvation period prior to insulin stimulation (100 nmol/l for 10 min). L6 myotubes were also pretreated with WIN55,212-2 (100 nmol/l) for 24 h in the presence of SR141716 at the different concentrations indicated. Cell lysates were then analyzed by immunoblotting for phospho-ERK1/2, ERK1/2, phospho-MEK1/2, phospho-CREB, phospho-PKB, and PKB as indicated (B), with quantification of three independent experiments (mean \pm SD) shown (C). Asterisks indicate statistically significant differences versus untreated cells (* P < 0.05).

Consistent with the inhibition of ERK1/2, WIN55,212-2 or ACEA treatment (both 100 nmol/l) for 24 h also leads to suppression of insulin-induced cAMP-responsive element-binding protein (CREB) phosphorylation at Ser133, a downstream target of ERK1/2 as well as activation of MAP kinase kinase (MEK) 1/2, the immediate upstream kinase of ERK (Figs. 4 and 5). Again, similarly to the effects on ERK1/2, the responses on MEK1/2 and CREB phosphorylation are abrogated by coapplication of SR141716 in a concentration-dependent manner. Interestingly, our data also demonstrate that the level of insulin-mediated activation of MEK1/2, ERK1/2, and CREB with coapplication of SR141716 with WIN55,212-2 was higher than that observed with insulin alone (Fig. 4B). However, this did not appear to be the case in the presence of ACEA, possibly due to the higher affinity of this agonist toward the CB1 receptor thereby possibly competing more effectively with SR141716 with regard to receptor binding.

In addition to the antagonistic effects of SR141716, we also investigated whether application of SR141716 alone would modulate insulin sensitivity in L6 myotubes. Interestingly, pretreatment with SR141716 (100 nmol/l) for 24 h significantly enhances both insulin-stimulated PKB and ERK activity (Fig. 6), with an approximately twofold and

threefold greater stimulation observed, respectively. This is despite the lack of any effect of pharmacological CB1 activation on insulin-regulated PKB activity. Consistent with the increased activation of PKB, the insulin-induced phosphorylation of forkhead transcription factor in rhabdomyosarcoma-like 1 (FKHRL1)/Foxo3a (Thr32) and glycogen synthase kinase (GSK) 3 α /3 β (Ser21/Ser9), two important downstream targets of PKB, was also further enhanced after SR141716 pretreatment. It must also be noted that despite mediating the enhancement of insulin-stimulated PKB activity, exposure of L6 myotubes to SR141716 alone does not induce activation of this kinase, contrary to previously published data (27).

The CB1 receptor inverse agonist SR141716 sensitizes PKB- and ERK1/2-directed signaling in L6 myotubes via the CB1 receptor. To determine whether the insulin-sensitizing effects of SR141716 are mediated through the CB1 receptor, we generated stable CB1 knock-down L6 cells using shRNA expression vectors and confirmed suppression of CB1 expression by \sim 70% (Fig. 7). As in normal wild-type L6 cells, those transfected with silencer-negative control small interfering RNA also show enhanced PKB and ERK1/2 activation in response to insulin after SR141716 treatment (Fig. 7). In contrast, genetic

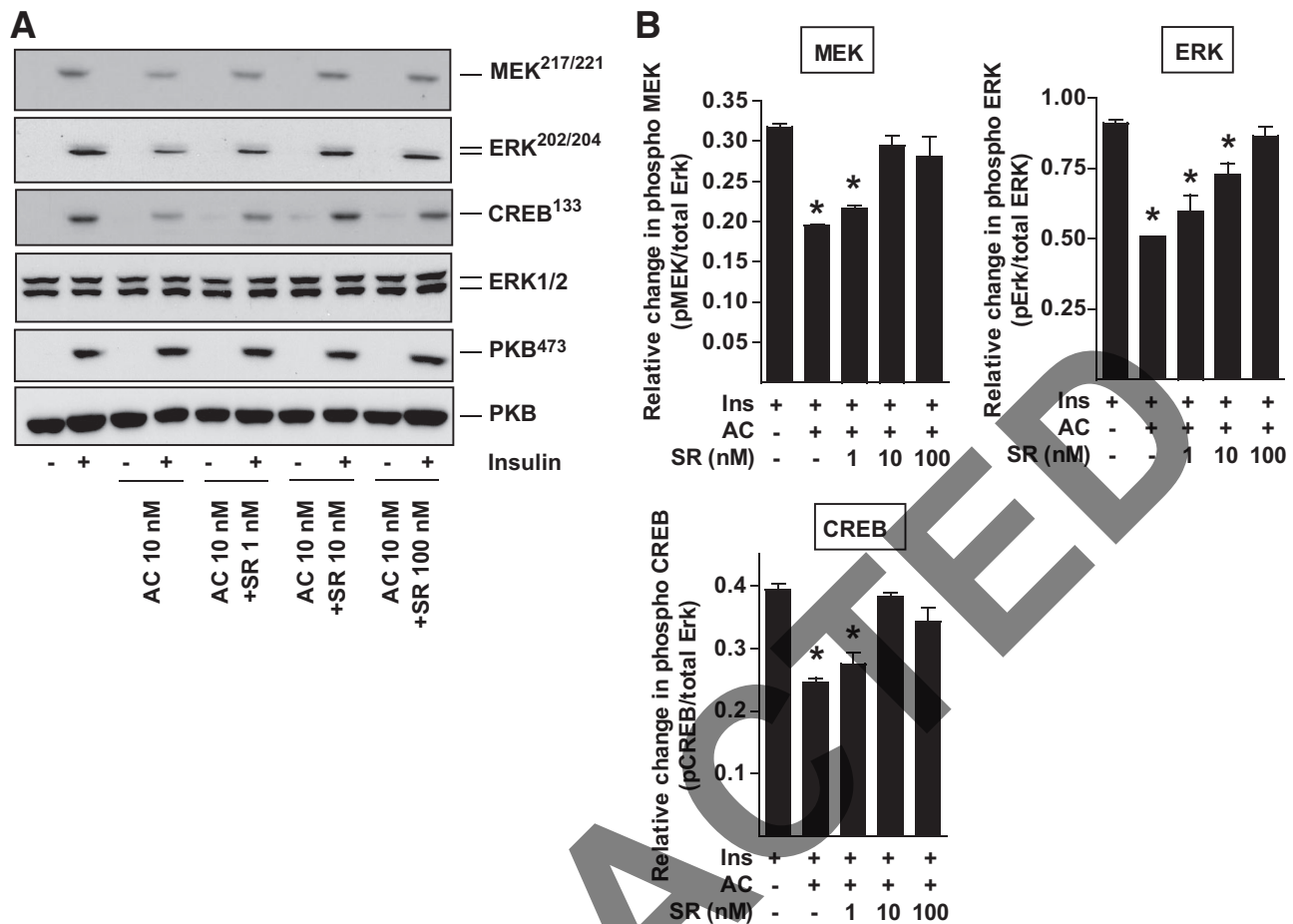


FIG. 5. The inhibitory effects of ACEA on ERK1/2 activity are prevented by the CB1 receptor antagonist SR141716. L6 myotubes were incubated with 10 nmol/l ACEA (AC) in the absence or presence of various concentrations of the CB1 inverse agonist SR141716 (SR; 100 nmol/l) for 24 h including a 2-h serum starvation period prior to insulin stimulation (100 nmol/l for 10 min). Cell lysates were then analyzed by immunoblotting for phospho-ERK1/2, ERK1/2, phospho-MEK1/2, phospho-CREB, phospho-PKB, and PKB as indicated (A), with quantification of three independent experiments (mean \pm SD) shown (B). Asterisks indicate statistically significant differences versus untreated cells (* P < 0.05).

silencing of CB1 leads to a loss in SR141716-mediated insulin sensitization in L6 cells with respect to the activation of both ERK1/2 and PKB.

Effects of SR141716 on insulin-induced IRS-1/p85 association and PKB phosphorylation/dephosphorylation. Insulin-stimulated activation of PI 3-kinase is dependent largely on the interaction of its regulatory subunit, p85, with the IRS proteins. Therefore, by immunoprecipitation, we assessed whether the interaction between p85 (PI 3-kinase) and IRS-1 was altered by modulation of CB1 receptor function. Treatment of L6 myotubes with either the CB1 selective agonist ACEA (10 nmol/l) or the CB1 inverse agonist SR141716 (100 nmol/l) for 24 h did not alter IRS-1/p85 association either under basal or insulin-stimulated conditions (Fig. 8A). This is also consistent with the lack of detectable activation of PKB when SR141716 is applied alone (Fig. 6), and suggests that regulation of CB1 receptor function does not by itself alter PI 3-kinase activity.

Another potential explanation for SR141716-mediated sensitization of insulin-regulated signaling may involve the suppression of phosphatase activity toward target kinases. To explore this possibility, L6 myotubes were treated with or without SR141716 for 24 h prior to insulin stimulation, followed by insulin washout for up to 30 min in the presence of a PI 3-kinase inhibitor, to determine the level of PKB activity under postinsulin washout conditions. In

contrast to control (vehicle-treated) cells, those incubated with SR141716 display a significantly delayed loss in PKB phosphorylation at Ser473 during postinsulin washout (Fig. 8B). This therefore suggests that SR141716 acts through CB1 to suppress phosphatase activity toward this site, thereby maintaining PKB in its active state.

DISCUSSION

The endocannabinoid system (ECS) has emerged as a key regulator of energy balance, and inhibiting CB1 receptor function is a potential treatment for obesity. Although the effects of the ECS on metabolism are mediated both centrally and peripherally, recent studies have shown that CB1 inverse agonists/antagonists such as SR141716 (Acomplia) do not need to act centrally to improve circulating lipid profile and glucose metabolism in the obese state (10,36). The clinical implementation of SR141716 as a counter-obesity drug has, however, been hindered by its central nervous system side effects, resulting in an unfavorable risk-benefit ratio. Nevertheless, a new generation of peripherally acting CB1 inverse agonists/antagonists is currently under clinical development. Identifying skeletal muscle as a potential site of action for the effects of CB1 antagonists/inverse agonists on metabolic processes supports the idea that peripheral cannabinoid targets may be of therapeutic benefit. Indeed, previous studies have dem-

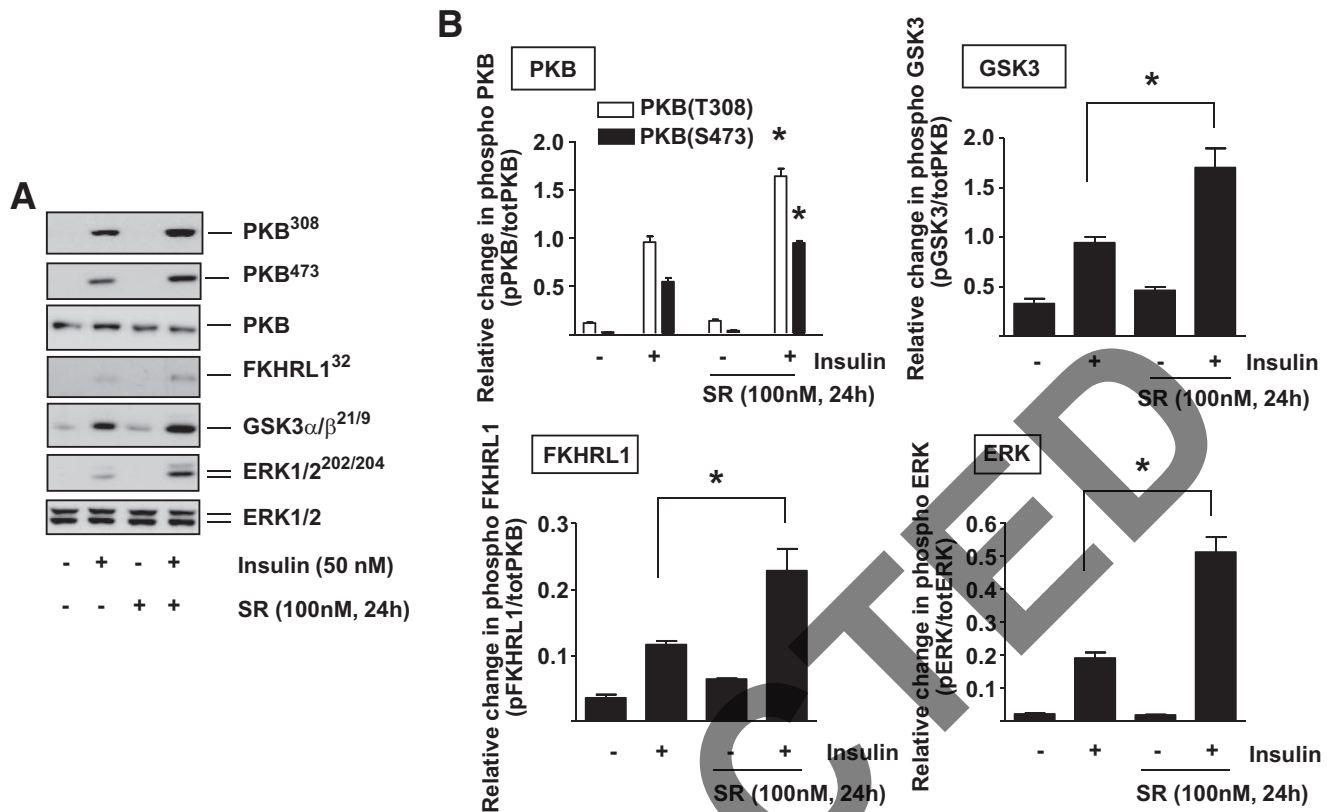


FIG. 6. The CB1 receptor antagonist SR141716 enhances insulin-stimulated ERK1/2 and PKB-associated activity. L6 myotubes were incubated with the CB1 receptor selective antagonist SR141716 (SR; 100 nmol/l) for 24 h including a 2-h serum starvation period prior to insulin stimulation (50 nmol/l for 10 min). Cell lysates were then analyzed by immunoblotting with phospho-PKB (Thr308 and Ser473), phospho-ERK1/2, phospho-GSK3, phospho-FKHRL1, PKB, and ERK1/2 antibodies as indicated (A), with quantification of three independent experiments (mean \pm SD) shown (B). Asterisks indicate statistically significant differences between insulin-stimulated SR141716-treated and untreated cells (* P < 0.05).

onstrated that application of the CB1 receptor inverse agonist SR141716 elevates glucose uptake in soleus muscle isolated from leptin-deficient obese mice as well as in cultured L6 skeletal muscle cells (25,27). These studies were the first to implicate a role for the CB1 receptor in skeletal muscle function and suggest that tonic CB1 receptor activity influences glucose metabolism in this tissue. In this study, we have manipulated CB receptor function by pharmacological means in an attempt to evaluate the importance of the ECS upon insulin action in muscle cells.

Our findings indicate that modulating CB1 receptor function by selective agonists/inverse agonists can regulate the responsiveness of skeletal muscle toward insulin through its action on two key signaling pathways, namely PI 3-kinase/PKB and the Raf-MEK1/2-ERK1/2 phosphorylation cascade. This is an important finding that suggests that the upregulation of endocannabinoid/CB1 tone, as observed in obese animal models and humans, may lead to altered insulin sensitivity in peripheral tissues such as skeletal muscle. Crucially, endocannabinoid levels have previously been shown to be elevated in soleus muscle of mice fed a high-fat diet in accordance with hyperglycemia (37). This work also raises the likelihood of cross talk between CB1 receptor function and upstream components of insulin signaling involved in the regulation of PKB and ERK1/2.

Our data demonstrate that longer-term pharmacological activation of the CB1 receptor function leads to the selective inhibition of ERK1/2-mediated signaling, while having little or no effect on PKB activity. Furthermore, we

have shown for the first time that treatment with the CB1 inverse agonist SR141716 alone can improve insulin sensitivity in skeletal muscle as determined by its ability to enhance both insulin-stimulated PKB- and ERK1/2-directed signaling. However, although activation and inhibition of CB1 are consistent with the inhibitory and stimulatory effects on ERK1/2 activation, respectively, a discrepancy arises when comparing the effects of CB1 agonism and inverse agonism with regard to modulating PKB activity.

It remains unclear what accounts for the distinct effects of CB1 receptor modulation toward PKB- and ERK1/2-directed signaling, but there are a number of possibilities that may help explain the basis of this differential control. It is plausible, for example, that some level of cross-talk exists between the CB1 receptor and insulin receptor signaling, resulting in the specific downregulation of the Ras/Raf/ERK cascade—for instance, this may be due to interference with the ability of adapter molecules such as growth factor receptor-bound protein 2 and Shc to bind to the insulin receptor, or possibly involving the downregulation in expression or activity of one or more of these components. Furthermore, this might occur without altering IRS protein functionality, thereby maintaining PI 3-kinase/PKB signaling capability. Second, CB1 activation may lead to increased phosphatase activity toward the Ras/Raf/ERK cascade, resulting in its inhibition, while having little or no effect toward components of the PI 3-kinase/PKB pathway.

In contrast to the effects observed with the CB1 ago-

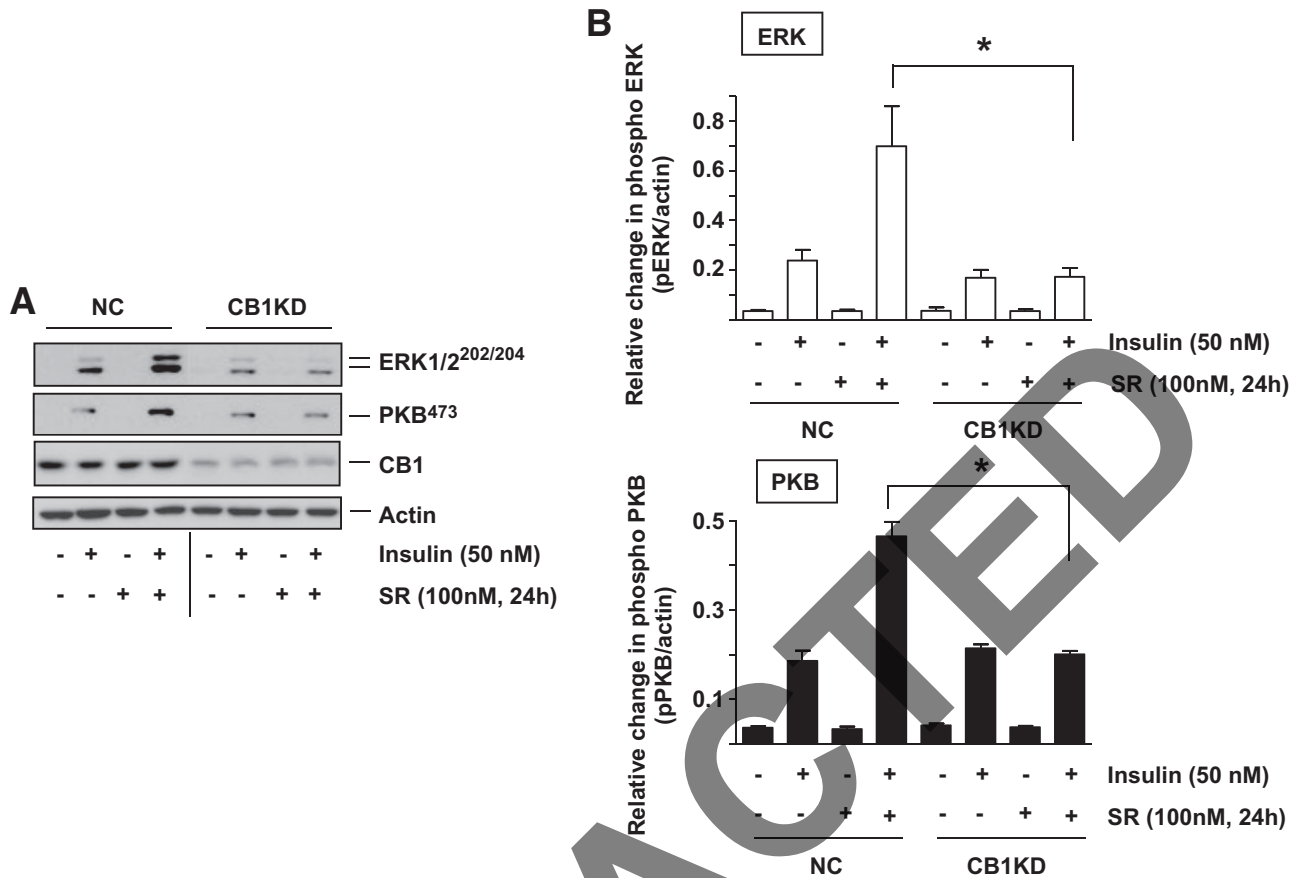


FIG. 7. Silencing CB1 abrogates the insulin-sensitizing effect of SR141716. Fully differentiated stable CB1 receptor knockdown L6 cells (CB1KD) along with corresponding silencer-negative control cells (NC) were incubated with SR141716 (SR; 100 nmol/l) for 24 h including a 2-h serum starvation period prior to insulin stimulation (50 nmol/l for 10 min). Cell lysates were then analyzed by immunoblotting with phospho-PKB, phospho-ERK1/2, CB1, and actin antibodies as indicated. Autoradiographs (A) and quantifications (B) shown are representative of three independent experiments, with each bar representing mean \pm SD. Asterisks indicate statistically significant differences between CB1KD and NC cells (* $P < 0.05$).

nists, applying SR141716 alone potentiated both insulin-stimulated PKB and ERK1/2 activity. In view of our data showing that applying SR141716 alone does not activate PKB to any appreciable extent, we would discount any additive effect of insulin and SR141716. Instead, our observations support the notion that SR141716 acts to potentiate insulin-stimulated PKB activity and because this enhancement in PKB activation is not observed in cells where CB1 expression has been silenced (Fig. 7), it implicates a role for the CB1 receptor in this sensitization.

The potentiation of PKB and ERK1/2 activation by longer-term SR141716 treatment may arise through several different mechanisms. First, it may be due to an increase in the expression of the upstream components of insulin signaling such as the insulin receptor, IRS-1/2, or the regulatory and catalytic subunits of PI 3-kinase. However, we do not observe any detectable elevation of PKB or ERK1/2 activity when SR141716 is applied alone, as measured by the extent of their phosphorylation as would be expected in such a scenario. In addition, there is no observed enhancement in association between IRS-1 and the p85 regulatory subunit of PI 3-kinase, implying that it is unlikely that SR141716 is acting via the modulation of PI 3-kinase activity. Nevertheless we cannot rule out the possibility that a marginal increase in these upstream components may contribute to the insulin sensitization (27). Another possible explanation may involve SR141716 "priming" the cell for stimulation by insulin by disrupting

the inhibitory environment acting on PKB and ERK1/2 under basal conditions. For instance, this may involve relieving the inhibitory action of various phosphatases that can negatively regulate insulin responses (38–43). We have observed that SR141716 does not alter expression of phosphatase and tensin homolog (PTEN) in L6 myotubes (data not shown), although the possibility that it may change the expression and/or activity of other important protein phosphatase(s) such as protein tyrosine phosphatase 1B (PTP-1B) or Src homology domain 2 (SH2)-containing tyrosine phosphatase-1 (SHP-1) cannot be excluded. Indeed, our data demonstrating that SR141716 delays dephosphorylation of PKB at Ser473 during insulin washout provide evidence in support of such a mechanism. However, further work will be required to elucidate the identity of the phosphatase(s) involved. Another explanation may arise from the localization of CB1 receptors at the plasma membrane. For example, these receptors are found to be present within caveolae, well-characterized lipid rafts that perform a number of signaling functions (44). Caveolae are cholesterol-rich microdomains that act to retain PKB in a repressed state via the action of atypical protein kinase Cs (45). Because insulin receptors are also known to reside within caveolae, it is possible that the close proximity of the cannabinoid receptors causes them to be involved in modulating insulin receptor-mediated signaling. One way to test this idea would be to determine

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