p38 Gamma MAPK Regulation of Glucose Transporter Expression and Glucose Uptake in L6 Myotubes and Mouse Skeletal Muscle

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Running head: p38γ regulation of glucose uptake in skeletal muscle
Abstract

Skeletal muscle expresses at least three p38 MAPKs (α, β, γ). However, no studies have examined the potential regulation of glucose uptake by p38γ, the isoform predominantly expressed in skeletal muscle and highly regulated by exercise. L6 myotubes were transfected with empty vector (pCAGGS), activating MKK6 (MKK6CA), or p38γ-specific siRNA. MKK6CA-transfected cells had higher rates of basal 3H-2-deoxyglucose (2DG) uptake (p<0.05), but lower rates of 2,4-dinitrophenol (DNP)-stimulated glucose uptake, an uncoupler of oxidative phosphorylation that operates through an insulin-independent mechanism (p<0.05). These effects were reversed when MKK6CA cells were cotransfected with p38γ-specific siRNA. To determine whether the p38γ isoform is involved in the regulation of contraction-stimulated glucose uptake in adult skeletal muscle, the tibialis anterior muscles of mice were injected with pCAGGS or wild-type p38γ (p38γWT) followed by intramuscular electroporation. Basal and contraction-stimulated 2DG uptake in vivo was determined 14 days later. Overexpression of p38γWT resulted in higher basal rates of glucose uptake compared with pCAGGS (p<0.05). Muscles overexpressing p38γWT showed a trend for lower in situ contraction-mediated glucose uptake (P=0.08) and significantly lower total GLUT4 levels (p<0.05). These data suggest that p38γ increases basal glucose uptake and decreases DNP- and contraction-stimulated glucose uptake, partially by affecting levels of glucose transporter expression in skeletal muscle. These findings are consistent with the hypothesis that activation of stress kinases such as p38 are negative regulators of stimulated glucose uptake in peripheral tissues.

Keywords: MAPK, exercise, GLUT1, GLUT4
**Introduction**

Skeletal muscle represents a significant site for whole-body insulin-stimulated glucose disposal (13) and insulin resistance in this tissue is a characteristic feature in the development of type 2 diabetes mellitus (12,21,44). In addition to diabetes, skeletal muscle insulin resistance is common to other clinical and subclinical conditions of obesity, stress, cachexia, pregnancy, starvation, sepsis and trauma. These conditions are often associated with systemic factors that activate cellular signals, many of which are transmitted via mitogen-activated protein kinases (MAPK). Of the four main MAPK subgroups, the extracellular-signal regulated kinases (ERK) appear to be primarily involved in cellular growth and transformation (41), and the c-Jun NH$_2$-terminal kinases (JNK) and p38 MAPK are regulated by cytotoxic and environmental stress. JNK has recently been implicated in obesity- and TNF$\alpha$-mediated insulin resistance by negative regulation of insulin-stimulated phosphoinositide-3 kinase (PI3K) activity (2,25). For p38 MAPK, numerous activators of these enzymes are associated with insulin resistance, however, data regarding the potential role of p38 MAPK in the regulation of glucose transport in skeletal muscle have been controversial (17,50).

Four p38 MAPK isoforms have been reported: p38$\alpha$ (35), p38$\beta$ (28,49), p38$\gamma$ (34,36) and p38$\delta$ (18). Activation of p38 MAPK occurs via dual phosphorylation of conserved TGY motifs by the MAPK kinases, MKK6 and MKK3 (42). Functional differences between the isoforms are related in part to their differential expression, activation, and substrate specificity. p38$\alpha$ and p38$\beta$ are ubiquitously expressed, while p38$\delta$ is predominantly expressed in glandular tissues, lung, and kidney (29,52). Interestingly, p38$\gamma$ (ERK6, SAPK3) and MKK6 are primarily expressed in skeletal muscle (10,22,34).
In studies using the pyridinyl imidazole class of inhibitors, p38α and p38β activity have been shown to be required for insulin-stimulated glucose uptake through a mechanism that involves increases in the intrinsic activity of GLUT4 (46,47,50). In contrast to these studies, activation of p38 by overexpression of a constitutively active MKK6 decreased insulin signaling, GLUT4 expression and insulin-stimulated glucose uptake in 3T3-L1 adipocytes and L6 cells (16,17). In addition, overexpression of dominant negative p38α or MKK6 lead to increased insulin-stimulated glucose uptake in 3T3-L1 adipocytes (17). Thus, there are data suggesting that p38 is necessary for insulin effects on glucose transport, and other studies suggesting that p38 is a negative regulator of insulin-stimulated glucose uptake (16,17).

Like insulin, exercise is known to increase skeletal muscle glucose transport. In adult skeletal muscle, exercise and contractile activity increase the phosphorylation and activity of multiple p38 isoforms via a mechanism that likely involves activation of MKK6/3 (4,19,24). One study has suggested that the well-known effects of contractile activity to stimulate glucose transport in skeletal muscle are impaired when muscles are treated with a p38 inhibitor (48). Interestingly, unlike p38α and p38β, p38γ is resistant to the effects by known p38 inhibitors (11). Compared with the α and β isoforms of p38, we have evidence that p38γ is very highly regulated by muscle contraction (6). Thus, the γ isoform is almost exclusively expressed in skeletal muscle and is highly regulated by skeletal muscle contraction, yet nothing is known about the role of p38γ in the regulation of basal and contraction-mediated glucose uptake.

To elucidate the role of p38γ in the regulation of basal and contraction-stimulated glucose uptake in L6 myotubes and skeletal muscle, we transfected and overexpressed wild-type p38γ or MKK6 into L6 myotubes and/or adult mouse skeletal muscle in vivo. We also utilized vector-based siRNA technology to knock down p38γ in L6 myotubes. Our findings suggest that p38γ is
involved in the regulation of GLUT1 expression and basal glucose uptake in L6 myotubes. Our findings also suggest that p38γ negatively regulates GLUT4 expression and contraction-mediated glucose uptake in adult skeletal muscle \textit{in vivo}. 
Experimental procedures

Materials. Antibodies used were purchased from the following: phospho-p38, MKK6, phospho-ATF-2 (Cell Signaling Technology), p38γ (Upstate Biotechnology), FLAG (Sigma), GLUT1 (Chemicon), and GLUT4 (gift from Robert Smith). Anti-mouse and anti-sheep IgG-HRP were from Upstate Biotechnology. The anti-rabbit IgG-HRP and ECL-Plus western blotting detection kit were purchased from Amersham Pharmacia Biotech. 2-deoxy-D-[3H]glucose was from Perkin Elmer.

Plasmid construction. Currently, there are no p38γ inhibitors available, so to study p38γ function in L6 cells we expressed wild type p38γ (p38γWT) and constitutively active M KK6 (M KK6CA). The human wild type FLAG-p38γ and constitutively active M KK6 mutants (donated by Dr. Jiahui Han) were subcloned from a pcDNA3 vector into a pCAGGS vector (gift from Dr. J. Miyazaki of Osaka University) (39). The M KK6 mutant was created by introducing a constitutive negative charge by replacing serine-207 and threonine-211 with glutamine and has been found to efficiently activate both endogenous and recombinant p38 (43). FLAG-p38 and M KK6 cDNA constructs were excised with HindIII and XbaI, and transferred into the XhoI site between the CAG promoter and a 3′-flanking region of a rabbit β-globin gene of pCAGGS expression vector after blunt-end treatment (38). This expression vector drives a target gene under the CAG (cytomegalovirus immediate-early enhancer-chicken β-actin hybrid) promoter. The CAG promoter has extremely high activity in muscle, as demonstrated in both transgenic mice (40) and intramuscular DNA injection (51). Plasmid DNA was grown in E. coli TOP10 cells, extracted using the Endo-free Plasmid Mega Kit (Qiagen), and the DNA was suspended in saline.
RNA interference. pSilencer vectors harboring the U6 promoter (Imgenex, CA) were used to drive the expression of four different pairs of p38γ-specific oligonucleotides. The siRNA constructs contain a U6 promoter followed by a p38γ-specific, 21-mer sense oligonucleotide, a spacer, the 21mer antisense oligonucleotide, and a U6 termination sequence consisting of five thymidines (Figure 1A). Four pairs of oligonucleotides were generated and cotransfected with the FLAG-p38γWT plasmid in L6 cells. All four RNAi oligos were successful in blocking FLAG-p38γWT expression by more than 85%, and one set, which had greater than 94% knockdown efficiency was used for subsequent experiments. While FLAG-p38γWT expression was dramatically decreased, p38γ-specific siRNA did not affect expression of FLAG-p38β or endogenous expression of p38α and p38β (Figure 1B). Levels of endogenous p38γ were below the limits of detection by immunoblotting, however it is known that p38γ is expressed in differentiating muscle cells as determined by Northern blotting (34).

Cells and transfections. L6 cells were seeded into 12-well plates and maintained in growth medium consisting of αMEM supplemented with 10% fetal bovine serum in a humidified atmosphere containing 5% CO₂ and 95% air at 37°C. Myoblasts were grown in monolayers and allowed to reach confluence. Myoblasts were induced to differentiate by exposure to 2% fetal bovine serum for 6 days. Transient transfections were performed using a total of 2 µg of DNA per well, using lipofection (Lipofectamine 2000, Invitrogen). Recombinant protein expression was allowed for 48 h, at which time cells were used for the determination of glucose transport and immunoblotting.

Glucose uptake in L6 myotubes. L6 myotubes were serum-starved for 5 h in αMEM prior to any treatment. Cells were washed twice in PBS and incubated in 2,4-dinitrophenol (DNP, 500 µM; 10 min). Following stimulation, 2-deoxy-D-[³H]glucose uptake was measured by
incubating cells at room temperature for 5 min in transport solution (140 mM NaCl, 20 mM Hepes-Na, pH 7.4, 5 mM KCl, 0.5 µCi/ml 2-deoxy-D-[³H]glucose, 2.5 mM MgSO₄, 1.0 mM CaCl₂). Non-facilitated glucose uptake was determined in the presence of 10 µM cytochalasin B. Net accumulation of ³H-2-deoxyglucose was determined and rates of uptake calculated.

Sensitivity to stimulated glucose uptake of L6 cells increases, but transfection efficiency decreases with differentiation. Therefore, we determined the optimal stage at which myotubes could be both effectively transfected and stimulated by DNP. By the eighth day of differentiation, we were able to measure a twofold increase in glucose uptake with DNP stimulation. Transfection efficiency of approximately 45% was observed on day 8 of differentiation judged by LacZ transfection (on day 6) and X-gal staining for β-galactosidase expression. Therefore, all subsequent experiments were performed according to this protocol.

**DNA injection into skeletal muscle and in vivo electroporation.** Animal protocols were approved by the Joslin Diabetes Center Institutional Animal Care and Use Committee and were in accordance with National Institutes of Health guidelines. DNA injection and in vivo electroporation were performed by a modification of the method of Aihara and Miyazak (3). Mice (ICR, Taconic) weighing 25-30g were anesthetized with an intraperitoneal injection of sodium pentobarbital (90 mg/kg) and 100 µg of FLAG-p38/pCAGGS plasmid in 25 µl of saline was injected into the tibialis anterior muscle of one leg using an insulin syringe with a 29-gauge needle. For the control, empty pCAGGS vector in 25 µl of saline was injected into the opposite leg. Square-wave electrical pulses (200 V/cm) were applied eight times at a rate of one pulse per second with each pulse being 20 ms in duration using an electric pulse generator. The electrodes consist of a pair of stainless needles inserted and fixed 5 mm apart into the tibialis anterior muscles.
Previous work in our lab has determined the distribution and efficiency of gene transfer by x-gal staining to detect the activity of β-galactosidase (the lacZ gene product). Our results show that β-galactosidase activity is detected in almost all areas of the tibialis anterior and that β-galactosidase expression is observed not only on the surface but also deep within the tissue. The percentage of fibers expressing β-galactosidase was estimated as 85.7±2.3%. Our data demonstrate that a very high proportion of muscle fibers express the foreign gene using the parameters in the in vivo electroporation section above (15).

**In situ contraction.** Fourteen days following the in vivo electroporation protocol, 12-hr overnight fasted mice were anesthetized with an intraperitoneal injection of sodium pentobarbital (90 mg/kg). The sciatic nerves were bilaterally isolated, electrodes placed around each nerve, and then interfaced with a Grass model S88 electrical stimulation unit. Hindlimb muscles were either stimulated to induce contractions for 15 minutes (1 train/sec, 500 ms train duration, 100 Hz, 0.1 ms duration, 1V), or remained unstimulated to serve as sham controls.

**Glucose uptake in skeletal muscle in vivo.** Baseline blood samples were collected from the tail, the jugular vein was catheterized and an intravenous bolus of 2-deoxy-D-[3H]glucose (10 μCi/mouse) was administered. Following the injection of the tracer, mice were subjected to the in situ muscle contraction protocol (15 min). A matched group of animals were used as controls (no contraction) for the determination of basal glucose uptake. Blood samples were obtained at 5, 10, 15, 25, 35 and 45 minutes for the determination of blood glucose and 2-deoxy-D-[3H]glucose specific activity. After collection of the last blood sample, animals were sacrificed, the tibialis anterior muscle was removed and snap frozen in liquid nitrogen. Accumulation of 3H-2-deoxyglucose in the tissue was determined and rates of uptake calculated (27).
**Immunoblotting.** Following the experimental protocols skeletal muscle samples were homogenized in lysis buffer (20 mM Tris-HCl, 5 mM EDTA, 10 mM Na₄P₂O₇, 100 mM NaF, 2 mM NaVO₄, 1% NP-40, 10 µg/ml aprotinin, 10 µg/ml leupeptin, 3 mM benzamidine, 1 mM PMSF) and total protein concentrations were determined by the Bradford method (Biorad). Samples were resolved by 8% SDS-PAGE, transferred to nitrocellulose membranes, blocked in 5% milk and probed using the respective antibodies. Immunocomplexes were detected using chemiluminescence.

**Statistical analysis.** Results are expressed as means ± S.E. or transformed and expressed relative as a percent of the mock transfected control. Analysis of variance and Student’s paired and unpaired t tests were used (p<0.05).
Results

**Overexpression of constitutively active MKK6 increases basal glucose uptake in L6 myotubes.** To study the regulation of basal glucose uptake by p38γ, we transfected L6 myotubes with MKK6CA alone or with p38γ-specific siRNA. Expression of the activating MKK6 mutant resulted in an increase in basal rates of glucose uptake in the myotubes (Figure 2A). These changes in basal glucose uptake were likely due to alterations in GLUT1 protein expression, as there was a tendency for GLUT1 expression to be higher in cells overexpressing MKK6CA compared to pCAGGS transfected cells. (Figure 2B). Because MKK6 activates all p38 isoforms we also designed vector-based siRNA constructs to selectively knockdown p38γ expression in L6 cells. The increases in basal glucose uptake in response to MKK6CA overexpression were reversed when cells were cotransfected with the p38γ-specific siRNA (Figure 2A).

**Overexpression of p38 in injected muscles.** In adult skeletal muscle, the expression of FLAG-p38γ was 10-fold higher compared with the endogenous expression of p38γ (Figure 3A). The high degree of overexpression did not affect endogenous p38γ expression (Figure 3A). Using a pan-p38 antibody that recognizes all p38 isoforms, Figure 3B shows that overexpression of FLAG-p38γ did not affect total expression of endogenous p38 isoforms. Recombinant FLAG-p38γ is functional, as evidenced by the finding that it is phosphorylated in response to in situ muscle contractions (Figure 3C). Total (endogenous + recombinant) p38 phosphorylation under both the basal and contraction-stimulated conditions was significantly increased in FLAG-p38WT muscles compared with pCAGGS controls (Figure 3C). The changes in p38 phosphorylation in muscles overexpressing p38γWT were associated with increases in phosphorylation of the p38 downstream substrate ATF-2 (Figure 3D).
**p38γ positively regulates basal glucose uptake in adult skeletal muscle.** We next used this gene transfer method to overexpress p38γWT in skeletal muscle of free-living animals to determine whether basal glucose uptake and GLUT1 expression are regulated by p38γ. Skeletal muscles overexpressing p38γWT exhibited significantly higher basal rates of glucose uptake compared with pCAGGS transfected muscles (Figure 4A). This increase was not due to detectable changes in GLUT1 expression in the muscle (Figure 4B, 85.8 ± 13.5% vs. 100.0 ± 17.9%, p=0.54), nor was it due to increases in GLUT4 (described below). Collectively, the data from L6 cells and adult skeletal muscle suggest that p38γ positively regulates basal glucose uptake.

**Overexpression of constitutively active MKK6 decreases DNP-stimulated glucose uptake in L6 myotubes.** We next investigated the role of p38γ in stimulated glucose uptake. L6 myotubes were transfected with MKK6CA and stimulated with DNP, an uncoupler of oxidative phosphorylation, to determine whether p38γ regulates increases in glucose uptake caused by cellular energy demand. DNP-stimulated glucose uptake was significantly lower in cells overexpressing MKK6CA compared with pCAGGS transfected cells (Figure 5). Interestingly, the effect of MKK6CA on DNP-stimulated glucose uptake was reversed when cells were cotransfected with p38γ-specific siRNA (Figure 5). Thus, knockdown of p38γ completely restores the impairment in glucose uptake caused by overexpression of MKK6CA. While the effects of MKK6 and p38γ-siRNA on basal glucose uptake are paralleled by changes in GLUT1 expression, the effects on DNP-stimulated glucose uptake were not associated with detectable changes in GLUT4 protein levels (data not shown).

**p38γ negatively regulates contraction-mediated glucose uptake.** Contractile activity also increases glucose uptake through a mechanism that may also involve cellular energy demand.
Since p38γ is highly activated by exercise, we determined whether p38γ regulates glucose uptake in contracting skeletal muscle. Mice injected with empty vector or p38γWT into the tibialis anterior muscle were anesthetized and in situ contraction-stimulated glucose uptake was determined. The mean contraction-mediated glucose uptake was 16% lower in skeletal muscle overexpressing wild type p38γ compared with pCAGGS transfected muscles, and this effect was close to reaching statistical significance (P=0.08, Figure 6A). Total GLUT4 expression was significantly lower in skeletal muscle overexpressing FLAG-p38γWT (Figure 6B). Thus, these data suggest that p38γ is a negative regulator of GLUT4 expression and, subsequently, attenuates the increases in glucose uptake in response to changes in cellular energy demand (DNP stimulation and contractile activity in L6 cells and adult skeletal muscle, respectively).
Discussion

Mitogen activated protein kinases, particularly JNK and p38 MAPK, are activated under conditions of environmental and cellular stress. These physiological and cellular perturbations are commonly associated with skeletal muscle insulin resistance and recent studies suggest that JNK is a negative regulator of insulin signaling in 3T3-L1 adipocytes (25). However, previous data regarding the role of p38 in the regulation of glucose uptake in skeletal muscle are controversial. The majority of these studies have focused exclusively on the ubiquitously expressed p38α and p38β isoforms using p38 inhibitors. The workhorse among p38 inhibitors has been the pyridinyl imidazole derivatives (SB compounds), which are only effective against p38α and p38β activity. Unfortunately, these compounds have also been shown to inhibit Akt (33), JNK (9), ERK (37,45) and nucleoside transporters (26) in a variety of cell lines. Skeletal muscle p38γ is unique in that it is insensitive to inhibition by known p38 inhibitors (18).

In the current study we suggest that p38γ positively regulates basal glucose uptake in L6 myotubes. Overexpression of constitutively active MKK6, which activates all p38 isoforms, resulted in increases in rates of basal glucose uptake. This increase was associated with a trend for higher cellular GLUT1 content. Our data support previous findings that overexpression of a constitutively active MKK6 mutant upregulated GLUT1 expression and increased basal glucose uptake in 3T3-L1 adipocytes and L6 myotubes (17). Increases in GLUT1 in 3T3-L1 adipocytes and L6 cells have also been reported using a constitutively active MKK3 mutant, which unlike MKK6, does not activate p38β (14,28). Therefore, it appears that p38β is not required for the regulation of GLUT1. Interestingly, the effects of overexpression of the activating MKK6 mutant on basal glucose uptake and GLUT1 expression observed in the present study were completely reversed by cotransfection with p38γ-specific siRNA oligonucleotides. These results
suggest that the effects of MKK6 activity on basal glucose uptake and GLUT1 expression in L6 myotubes are primarily mediated by the p38γ isoform.

In agreement with our data from L6 cells, we also found that p38γ increases basal glucose uptake in adult skeletal muscle. Overexpression of wild-type p38γ resulted in significantly elevated rates of basal glucose uptake, however, this was not accompanied by detectable changes in levels of total GLUT1 expression compared with pCAGGS transfected muscles. Our data are consistent with previous reports suggesting that p38 is involved in the regulation of basal glucose uptake, and demonstrate that the γ isoform is pivotal in mediating this effect in skeletal muscle (14,17,26).

We also show that overexpression of constitutively active MKK6 significantly attenuated DNP-stimulated glucose uptake in L6 myotubes. These data suggest that the p38γ isoform is primarily responsible for this effect since full recovery of DNP-stimulated glucose uptake resulted when L6 cells were cotransfected with p38γ-specific siRNA oligos. We did not observe significant changes in GLUT4 expression in response to overexpression of MKK6CA or p38γ-siRNA, however L6 cells are known to exhibit relatively low levels of GLUT4 and changes in protein expression may be below the limits of detection by immunoblotting.

We have previously reported that compared to the p38α and p38β isoforms, p38γ was highly activated following prolonged exercise in humans (6), however the physiological role of exercise-stimulated p38γ signaling in skeletal muscle has remained obscure. Here, we demonstrate that total GLUT4 expression is significantly lower in skeletal muscle overexpressing wild type p38γ in vivo. This was associated with decreases in in situ contraction-mediated glucose uptake, suggesting that p38γ negatively influences contraction-mediated glucose uptake in skeletal muscle in vivo. The effect of p38γ activation on contraction-
stimulated glucose uptake is at least partially due to the negative regulation of GLUT4 protein expression in skeletal muscle. Our data agree with a previous report which showed that constitutively active MKK6/3 mutants down-regulated GLUT4 expression in 3T3-L1 adipocytes (17). Recent studies have shown an upregulation of MAPK (including p38) in adipose tissue from individuals with type 2 diabetes, and have suggested that the p38 pathway, in particular, might contribute to the loss of GLUT4 expression observed in adipose tissue from type 2 diabetic patients (8,32). However, these studies have did not determine isoform specific effects of p38 signaling in the regulation of GLUT4 expression. Our data indicate that p38γ is involved in the regulation of GLUT4 expression in skeletal muscle in vivo and, therefore, may represent a novel target for the regulation of glucose homeostasis in this tissue.

While the present data are the first to suggest that p38γ is a negative regulator of GLUT4 expression in adult skeletal muscle in vivo, the effect of p38α and p38β on stimulated glucose transport has yet to be resolved. Klip and colleagues have reported that insulin-activated p38, and the stimulation of glucose uptake, was reduced by preincubation of 3T3-L1 adipocytes and L6 myotubes with p38 inhibitors (50). These authors concluded that insulin activates GLUT4 intrinsic activity, most likely by utilizing a p38-dependent signal in L6 cells. The same group has shown that contraction-stimulated 2-deoxyglucose glucose transport was reduced by up to 50% when isolated muscles were pretreated with SB203580 (48). On the other hand, studies have indicated that increases in glucose uptake resulting from hyperosmolarity, insulin or osmotic shock are not impaired by treatment with p38 inhibitors (5,31). Another study reported that activation of p38 by treatment of cells with anisomycin did not stimulate glucose transport (31). Interestingly, both ERK and JNK are activated by exercise (20) and, like p38γ described here, ERK and JNK have been shown to positively regulate GLUT1 expression and negatively
regulate insulin-stimulated glucose uptake in cell systems (2,7,16,17). While our data indicate that p38γ negatively regulates DNP-stimulated glucose uptake in L6 cells and contraction-mediated glucose uptake in skeletal muscle, the possibility remains that p38α and p38β may have the opposite effect. This is plausible considering different isoform-specific tissue expression, cellular localization, activation, and downstream signaling. For example, p38γ is the only known MAPK to exhibit a PSD-95, discs-large, ZO-1 (PDZ) binding domain (23), which confers the ability for specific downstream signaling to proteins such as syntrophin (23), aquaporin-4 (1), and potentially nitric oxide synthase (30).

In conclusion, our results demonstrate that p38γ MAPK signaling positively regulates GLUT1 expression and basal glucose uptake in L6 myotubes and adult skeletal muscle. Our results also identify p38γ as a negative regulator of GLUT4 expression and DNP- and contraction-stimulated glucose uptake in L6 myotubes and adult skeletal muscle, respectively. MAPKs are involved in the regulation of numerous cytokine signaling networks, which have commonly been associated with peripheral insulin resistance. Here, we demonstrate the isoform-specific involvement of p38γ in the regulation of glucose uptake in L6 myotubes and skeletal muscle in vivo.
Acknowledgements

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References


Ref Type: In Press


Figure Legends

**Figure 1. Overexpression of p38γ in L6 myotubes.** L6 myoblasts were seeded and differentiated in 2% FBS. Myotubes were transfected on day 6 of differentiation and subsequent experiments were performed 48 hours later. (A) Four pairs p38γ-specific oligonucleotides were cloned into the pSilencer vector. FLAG-p38γ was reduced by 89.6, 97.2, 94.5, and 94.7% response to the four different p38g-siRNAs. Pair #2 exhibited the maximum silencing effect and was used for all subsequent experiments. (B) Representative immunoblot with a total p38 antibody showing the specificity of p38γ-specific siRNA. Expression of p38γWT was reduced over 90% in response to p38γ-specific siRNA, while expression of endogenous p38α/β and overexpression of FLAG-p38βWT was unaffected. Results are from one representative experiment with at least two replicates.

**Figure 2. Overexpression of constitutively active MKK6 in L6 myotubes.** L6 myoblasts were seeded and differentiated in 2% FBS. Myotubes were transfected on day 6 of differentiation and subsequent experiments were performed 48 hours later. (A) Levels of constitutively active MKK6 (MKK6CA) overexpression in L6 myotubes were similar to endogenous skeletal muscle MKK6 expression. Endogenous levels of MKK6 in L6 cells are below the detection limit by immunoblotting. Overexpression of MKK6CA significantly increased basal glucose uptake in L6 myotubes. Cotransfection with p38γ-specific siRNA reversed the effect of MKK6CA on basal glucose uptake in L6 myotubes. (B) The changes in basal glucose uptake associated with overexpression of MKK6CA and p38γ-specific siRNA were paralleled by changes in total GLUT1 protein expression. Results shown are the mean ± S.E. of at least three independent experiments within which each point was assayed in duplicate.

*Significant difference (p<0.05).
Figure 3. Overexpression of p38γ in adult mouse skeletal muscle. Empty vector or FLAG-p38γ constructs were injected into the tibialis anterior muscles of anesthetized mice (n=6). Animals were allowed to recover and recombinant proteins were overexpressed for 14 days. (A) In vivo transfection or overexpression of FLAG-p38γ do not affect endogenous expression of p38γ (lower band), Lane 1= nontransfected control (NT), Lane 2=empty vector transfection (pCAGGS), Lane 3=FLAG-p38γ transfection. Expression of FLAG-p38γWT in Lane 3 was 10-fold higher compared with endogenous p38γ (Lanes 1 and 2). (B) Overexpression of FLAG-p38γWT did not affect endogenous expression of other p38 isoforms. (C) Using an antibody that recognizes the activating phosphorylation sites of all p38 isoforms, recombinant FLAG-p38γWT was phosphorylated and regulated by 15 minutes of in situ contraction. Overexpression of FLAG-p38γ results in significant increases in both basal and in situ contraction-stimulated p38 phosphorylation. (D) ATF-2 phosphorylation is increased by in situ contraction. Increased p38γ from muscles overexpressing FLAG-p38γWT is shown by elevations in ATF-2 phosphorylation compared with pCAGGS controls. *Significant difference (p<0.05).

Figure 4. Overexpression of p38γWT increases basal glucose uptake in skeletal muscle. Empty vector or FLAG-p38γ constructs were injected into the tibialis anterior muscles of anesthetized mice. Animals were allowed to recover and recombinant proteins were overexpressed for 14 days. (A) Anesthetized mice (n=6) were injected with 3H-2-deoxyglucose and tibialis anterior muscles were removed 45 minutes later. Accumulation of 3H-2-deoxyglucose was determined and basal rates of glucose uptake were calculated. Muscles overexpressing FLAG-p38γWT exhibited significantly higher rates of basal glucose uptake compared with pCAGGS transfected muscles. (B) Levels of total GLUT1 protein were not different between the groups. *Significant difference (p<0.05).
Figure 5. Overexpression of constitutively active MKK6 decreases DNP-stimulated glucose uptake in L6 myotubes. Overexpression of MKK6CA significantly decreased DNP-stimulated glucose uptake. Cotransfection of MKK6CA with p38γ-specific siRNA reversed the negative effect of MKK6CA alone on DNP-stimulated glucose uptake. Results shown are the mean ± S.E. of at least three independent experiments within which each point was assayed in duplicate. *Significant difference (p<0.05). Basal glucose uptake values from Figure 2 included as reference.

Figure 6. Overexpression of wild type p38γ results in decreases in in situ contraction-mediated glucose uptake in adult mouse skeletal muscle. Empty vector or wild type p38γ (p38γWT) constructs were injected into the tibialis anterior muscles of anesthetized mice. Animals were allowed to recover and recombinant proteins were overexpressed for 14 days. Anesthetized mice (n=6) were injected with 3H-2-deoxyglucose and in situ contraction by peroneal nerve stimulation was conducted for 15 minutes. The tibialis anterior muscles were removed 30 minutes following contraction. (A) Accumulation of 3H-2-deoxyglucose was determined and rates of contraction-stimulated glucose uptake were calculated. (B) Muscles overexpressing wild type p38γ exhibited significantly lower total GLUT4 levels. *Significant difference (p<0.05).
p38γ regulation of glucose uptake in skeletal muscle

FIGURE 1.

A.

#1: 5'-TCGACGTCTCTGACCAACGCAAGCCAAAGCTTTGGCATTGGTCA GGACTTTTTT
#2: 5'-TCGACGCTCATGAACATGAGAAGAAGCTTCTTCTTTCTCAGCTTTTT
#3: 5'-TCGACGCGCCGTGTACAAGACCTAGCTTTGGTAC ACGGCGCTTTTT
#4: 5'-TCGACGACTGTGAGCTG AAGATCCAAGCTTTGGATCTTC AGCTCACAGTCTTTTT

B.

- pCAGGS + pSilencer
- pCAGGS + siRNA
- p38γWT + pSilencer
- p38γWT + siRNA
- p38βWT + pSilencer
- p38βWT + siRNA

αp38α,β,γ
FIGURE 2.

A.

![Bar chart showing basal glucose uptake in different conditions.](image)

- **x-axis**: pCAGGS, MKK6CA, MKK6CA
- **y-axis**: Basal glucose uptake (pmol/mg/min)
- **Conditions**: pCAGGS, MKK6CA, MKK6CA + pSilencer, MKK6CA + pSilencer, MKK6CA + p38γ-siRNA
- **Statistical Comparisons**: *p* = 0.14, *p* = 0.07

B.

![Bar chart showing GLUT 1 expression in different conditions.](image)

- **x-axis**: pCAGGS, MKK6CA, MKK6CA
- **y-axis**: GLUT 1 expression (% control)
- **Conditions**: pCAGGS, MKK6CA, MKK6CA + pSilencer, MKK6CA + pSilencer, MKK6CA + p38γ-siRNA
- **Statistical Comparisons**: *p* = 0.14, *p* = 0.07
FIGURE 3.

A.

1 2 3

αp38γ

Recombinant p38γ
Endogenous p38γ

AU

Recombinant p38γ
Endogenous p38γ

pCAGGS p38γWT

B.

pCAGGS FLAG-p38γ

αp38α,β,γ

Recombinant FLAG-p38γ
Endogenous p38α,β,γ
C. | pCAGGS | FLAG-p38γ |
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*In situ contraction*

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<td>Endogenous p38</td>
</tr>
<tr>
<td>Recombinant p38γ</td>
<td>Endogenous p38 γ</td>
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</tbody>
</table>

D. | pCAGGS | p38γWT |
<table>
<thead>
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<td>+</td>
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αP-ATF-2

<table>
<thead>
<tr>
<th>AU</th>
<th>Basal</th>
<th>Contraction</th>
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<td>p38γWT</td>
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<tr>
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<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

* | * | * | * | * | *
FIGURE 4.

A.

B.
FIGURE 5.

![Bar graph showing glucose uptake in different conditions.](image-url)
FIGURE 6.

A. 

Fold increase in glucose uptake vs. pCAGGS basal

B. 

GLUT4 expression (% control)