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An siRNA-based method for efficient silencing of gene expression in mature brown adipocytes

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ABSTRACT

Brown adipose tissue is a promising therapeutic target for opposing obesity, glucose intolerance and insulin resistance. The ability to modulate gene expression in mature brown adipocytes is important to understand brown adipocyte function and delineate novel regulatory mechanisms of non-shivering thermogenesis. The aim of this study was to optimize a lipofection-based small interfering RNA (siRNA) transfection protocol for efficient silencing of gene expression in mature brown adipocytes. We determined that a critical parameter was to deliver the siRNA to mature adipocytes by reverse transfection, i.e. transfection of non-adherent cells. Using this protocol, we effectively knocked down both high- and low-abundance transcripts in a model of mature brown adipocytes (WT-1) as well as in primary mouse brown adipocytes. A functional consequence of the knockdown was confirmed by an attenuated increase in uncoupled respiration (thermogenesis) in response to β-adrenergic stimulation of mature WT-1 brown adipocytes transfected with uncoupling protein 1 siRNA. Efficient gene silencing was also obtained in various mouse and human white adipocyte models (3T3-L1, primary mouse white adipocytes, hMADS) with the ability to undergo "browning." In summary, we report an easy and versatile reverse siRNA transfection protocol to achieve specific silencing of gene expression in various models of mature brown and browning-competent white adipocytes, including primary cells.

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Introduction

Brown adipose tissue (BAT) is specialized in non-shivering thermogenesis, by which energy is used for the generation of heat.\(^1\)\(^-\)\(^4\) The protein responsible for this process is uncoupling protein 1 (UCP1), located in the inner mitochondrial membrane, where it uncouples the electron transport chain from ATP production. BAT activity is important for rodents to defend their body temperature during prolonged cold exposure and has been shown to counteract many of the harmful effects of a high-fat diet, such as obesity, glucose intolerance and insulin resistance.\(^1\)\(^-\)\(^4\) Evidence from rodent studies demonstrates that BAT plays a significant role in glucose and lipid metabolism as well as in whole-body energy homeostasis. The observations that adult humans possess metabolically active BAT, that BAT in humans is recrutable and that BAT mass influences whole-body energy homeostasis make brown adipocytes an interesting target in combating metabolic disease.\(^5\)\(^,\)\(^6\)

Probing the involvement of selected genes in brown adipocyte function can be achieved through loss- and gain-of-function approaches. Generation of transgenic or gene knockout organisms has been of crucial importance for deciphering BAT development and function, but it is both time-consuming and expensive, and moreover, this approach is limited to rodent models. Therefore, an efficient method to silence gene expression in cultured mature brown adipocytes is a relevant supplement to genetically modified mice or rats. RNA interference (RNAi) is a powerful tool to achieve gene silencing; however, using RNAi in mature adipocytes is challenging due to the ineffective delivery of siRNA and short-hairpin RNA (shRNA) by non-viral and viral means, respectively. Using RNAi in pre-adipocytes is straightforward,
but is of limited use if the aim is to understand the function of the targeted gene in the mature adipocyte state: silencing of gene expression by RNAi (by means of siRNA delivery or stable viral expression of shRNA) may affect differentiation per se, and even if differentiation is unaffected, gene silencing by siRNA delivery is transient and is not likely to last until the mature adipocyte state is reached. It is possible to efficiently transduce mature adipocytes with adeno- or lentiviral vectors, however, such an approach is relatively labor intensive and requires special safety precautions. Of non-viral approaches, electroporation has been used for delivery of siRNA into fully differentiated adipocytes, however, this strategy requires large amounts of siRNA and results in a poor transfection and knockdown efficiency. Recently, significant advances have been made by using lipid-based transfection reagents for siRNA transfection of mature white adipocytes. To our knowledge, no studies have reported efficient siRNA-based knockdown of gene expression in mature brown adipocytes. Therefore, based on the protocol reported by Kilroy et al., we set out to develop a protocol for efficient gene silencing in mature brown adipocytes.

We here report an easy and versatile reverse siRNA transfection protocol to silence specific gene expression in mature brown adipocytes and in mature white adipocytes capable of undergoing “browning.” Importantly, the protocol works well in human adipocytes as well as in primary mouse adipocytes, and it can be used in combination with downstream analyses such as studies of insulin signaling, lipolysis and thermogenesis.

**Results**

**Efficient silencing of gene expression in mature mouse brown adipocytes by reverse siRNA transfection**

In order to silence specific genes in mature brown adipocytes without interfering with adipogenesis, we set out to optimize a lipofection-based siRNA transfection protocol. We based our optimization on a protocol developed by Kilroy et al. to obtain effective silencing of gene expression in white adipocytes. Using the Lipofectamine RNAiMAX Transfection Reagent, we probed the importance of experimental parameters such as siRNA concentration and incubation time. For various immortalized cell models, we found that the optimal final concentration of siRNA was 50 nM and the optimal incubation time of the siRNA/RNAiMAX mix was 25 min. As described below, optimal conditions for primary mouse adipocytes were slightly different. In 96-well format, we compared siRNA transfection of adherent (forward transfection) and non-adherent (reverse transfection) pre-adipocytes and adipocytes. An overview of the reverse transfection workflow is shown in Figure 1. We used an siRNA targeting pyruvate kinase M (Pkm) and a non-silencing (negative) siRNA as control. Forward transfection of immortalized WT-1 brown pre-adipocytes and mature adipocytes with siRNA resulted in a similar Pkm knockdown efficiency of ~55% as determined by reverse transcription-quantitative polymerase chain reaction (RT-qPCR) (Fig. 2A and B). Reverse transfection with Pkm siRNA yielded a 74% and 93% knockdown in pre-adipocytes and mature adipocytes, respectively (Fig. 2A and B). Thus, the reverse transfection protocol proved overall to be most efficient, particularly in the mature WT-1 brown adipocytes.

To render probable that the reverse transfected cells were primarily fully differentiated adipocytes, we confirmed that mature WT-1 adipocytes were able to attach after replating. Micrographs of an oil red O-stained 10-cm dish before replating and 48-well after replating showed that most of the adherent cells stained positive, demonstrating that mature adipocytes were able to reattach after replating (Fig. 2C).

In accordance with the decrease in Pkm mRNA levels, transfection with Pkm siRNA resulted in a substantial decrease in PKM protein levels (Fig. 3A and B). To verify that the knockdown did not affect basic adipocyte function or affected the maturity of the adipocytes, we evaluated the effect of Pkm siRNA transfection on selected parameters. Knockdown of Pkm did not affect expression of typical adipocyte-enriched genes, such as fatty acid-binding protein 4 (Fabp4) and glucose transporter 4 (Glut4) (Fig. 3C and 3D), suggesting that the ratio of mature adipocytes to undifferentiated cells that reattached after reverse transfection was similar irrespective of the siRNA used. Stimulation with insulin demonstrated that insulin signaling, measured by Ser473 phosphorylation of AKT, was not influenced by Pkm siRNA compared to negative control siRNA (Fig. 3B). Similarly, Pkm knockdown had no effect on adrenergically induced lipolysis, since a 6–7-fold increase in glycerol release after stimulation with the β-adrenergic agonist isoproterenol (ISO) was observed both in control and Pkm siRNA-transfected cells (Fig. 3E).

In summary, WT-1 brown adipocytes reverse transfected with siRNA displayed a normal response to insulin and β-adrenergic stimulation.

**Efficient knockdown irrespective of target mRNA abundance**

Pkm is expressed at relatively high levels in mature brown adipocytes (C, value ~20). To compare the knockdown
| Step | Procedure | Specific instructions |
|------|-----------|-----------------------|
| 0    | Differentiate pre-adipocytes by cell type specific protocol in 10 cm dishes | Carry out transfection after 6, 8 or 9 days (mouse cell lines, primary mouse cells or human cell lines, respectively) of differentiation |
| 1    | Dilute Lipofectamine RNAiMAX in Opti-MEM Medium | Seahorse: 5 μl/ml 96 well: 5 μl/ml 48 well: 9 μl/ml |
| 2    | Dilute siRNA in Opti-MEM medium | Seahorse: 50 nM 96 well: 50 nM 48 well: 90 nM |
| 3    | Add diluted siRNA to diluted Lipofectamine RNAiMAX mixture 1:1 |  |
| 4    | Add siRNA-lipofectamine mix to plate pre-coated with gelatin | Seahorse: 15 μl 96 well: 30 μl 48 well: 92.5 μl |
| 5a   | Incubate plate for 25 min |  |
| 5b   | During incubation (step 5a) trypsinize cells, count and resuspend in culture medium |  |
| 6    | Add cell suspension to plate on top of siRNA-Lipofectamine RNAiMAX complex | Seahorse: 20,000 cells/well 96 well: 80,000 cells/well 48 well: 200,000 cells/well |

**Figure 1.** Schematic overview of the reverse siRNA transfection protocol.
efficiency of high- and low-abundance mRNAs using reverse transfection of mature WT-1 adipocytes, we applied siRNA targeting Pkm or calcium/calmodulin-dependent protein kinase IIα (Camk2a), the latter being expressed at relatively low levels as determined by RT-qPCR (Ct value > 27). Pkm mRNA was knocked down by 89% upon transfection with Pkm siRNA (Fig. 4A), whereas Camk2a mRNA was reduced by 82% in response to Camk2a siRNA (Fig. 4B). Hence, both high- and low-abundance mRNAs were efficiently silenced in mature brown adipocytes by reverse siRNA transfection. Expression of Fabp4 and Glut4 mRNAs was not differentially influenced by the siRNAs (Fig. 4C and 4D).

**Silencing of gene expression in human multipotent adipose-derived stem cell (hMADS), in the 3T3-L1 cell line and in primary mouse adipocytes**

We further analyzed the efficiency and applicability of the reverse transfection protocol in 4 additional adipocyte cell models of human and mouse origin: hMADS, 3T3-L1 and primary mouse adipocytes from BAT and the inguinal white adipose tissue (iWAT) (Fig. 5). hMADS, 3T3-L1 and primary iWAT adipocytes are considered models of white adipogenesis, but all have the ability under specific conditions to convert into UCP1-positive, thermogenic adipocytes, a process known as “browning.”16-18 Reverse transfection of hMADS and 3T3-L1 adipocytes was carried out as for WT-1 adipocytes (Fig. 1). In order to obtain sufficient material for downstream analyses, primary mouse adipocytes were reverse transfected in 48-well plates, using 2.5-fold more cells per well and 90 nM siRNA (Fig. 1). We used siRNA against glyceraldehyde-3-phosphate (GAPDH) in the human hMADS adipocytes and Pkm siRNA in the 3 mouse adipocyte models. GAPDH mRNA was knocked down by 90% in hMADS adipocytes, and knockdown efficiencies of Pkm mRNA in 3T3-L1 and primary BAT and iWAT adipocytes were 90%, 73% and 80%, respectively (Fig. 5A-D). Hence, the
optimized protocol was also applicable to human adipocytes (hMADS), mouse white adipocytes (3T3-L1 and primary iWAT) and primary mouse brown adipocytes.

**Attenuation of β-adrenergically stimulated oxygen consumption in mouse brown adipocytes by Ucp1 knockdown**

To demonstrate a functional consequence of gene silencing in brown adipocytes, we reverse transfected mature WT-1 adipocytes with an siRNA against Ucp1, which resulted in a 78% decrease in Ucp1 mRNA levels, or with a control siRNA (Fig. 6A). Since Ucp1 is barely expressed in pre-adipocytes, the Ucp1 knockdown demonstrated that mature adipocytes had been transfected. To investigate the efficiency of the UCP1 knockdown on adrenergically induced thermogenesis, we performed the reverse transfection with Ucp1 siRNA directly in gelatin-coated XF96 Cell Culture Microplates, to be used for analysis on the Seahorse XF analyzer. Four days after transfection, we determined oxygen consumption rate (OCR) during sequential addition of ISO, carbonyl cyanide p-(trifluoromethoxy) phenylhydrazone (FCCP) and rotenone/antimycin A (Fig. 6B). This was carried out under experimental conditions where it has been demonstrated that adrenergically induced OCR is UCP1-dependent.19 Brown adipocytes transfected with the control siRNA increased their OCR by 70% in response to acute stimulation with ISO, whereas Ucp1 siRNA-transfected cells increased their OCR only 30% (Fig. 6B and C), demonstrating both the functional efficiency of the knockdown and the significance of UCP1 for the induced thermogenesis. Ucp1 knockdown cells pretreated with oligomycin failed to increase oxygen consumption in response to ISO, whereas OCR increased with 30% in oligomycin-pretreated control cells (data not shown). Similar to the situation in freshly isolated mouse brown adipocytes,20 this demonstrates that UCP1 is essential for adrenergically induced thermogenesis in mature WT-1 cells.
Discussion

Brown adipocytes are considered promising targets in combatting obesity and diabetes. The ability to tinker with specific genes in mature brown adipocytes is of importance for discovering novel information about brown adipocyte biology. Here we report an easy, rapid and versatile lipofection-based reverse siRNA transfection protocol with which specific genes can be effectively silenced in mature adipocytes of various origins.

Transflecting the mature adipocytes while still in suspension, followed by reattachment, greatly increases knockdown efficiency. This reverse transfection protocol is effective using pre-adipocytes, but surprisingly is more effective using mature adipocytes. The presented protocol, as summarized in Figure 1, has an easy workflow, is time and cost efficient and requires no special equipment. The protocol is easily adaptable to various adipocyte cell models, as demonstrated by its effectiveness in different mouse and human adipogenic cell lines as well as in primary mouse adipocytes. Equally efficient gene silencing was observed in mature brown adipocytes and mature white adipocytes with the ability to undergo browning.

We also demonstrate that the knockdown procedure can be combined with functional assays, as shown by the normal response to insulin and β-adrenergic stimulation after reverse siRNA transfection, and the reduced β-adrenergically induced oxygen consumption following knockdown of Ucp1 expression. Finally, the reverse siRNA transfection protocol has been optimized and standardized for 96-well plates and is therefore adaptable to high-throughput screening of siRNA libraries.

Figure 4. Knockdown efficiency of high- and low-abundance targets. Reverse siRNA transfections of mature WT-1 adipocytes with siRNA against Pkm, Camk2a or a universal negative siRNA as control. The transfections were performed at day 6 of differentiation and adipocytes were harvested 4 d later. Relative mRNA expression levels (RT-qPCR) of (A) Pkm, (B) Camk2a, (C) Fabp4, and (D) Glut4 were determined by normalization to expression levels of Tbp. Data represent mean of means ±SEM (n = 4). * p < 0.05 versus universal negative siRNA.
We hope that the reported protocol will be an easily accessible and useful tool for deciphering novel aspects of brown adipocyte biology and browning of white adipocytes in vitro.

Materials and methods

Culture of cell lines

The WT-1 cell line established by immortalization of brown pre-adipocytes from newborn mice with SV40 large T antigen was kindly provided by Dr. C. Ronald Kahn. WT-1 cells were propagated in Dulbecco’s Modified Eagle’s Medium (DMEM) (Life Technologies, 52100) supplemented with 10% fetal bovine serum (FBS) (Life Technologies, 10270), 62.5 µg/ml penicillin and 100 µg/ml streptomycin (Life Technologies, 15140–122).

The 3T3-L1 white pre-adipocyte cell line was propagated as WT-1 cells, except that 10% calf serum (PPA Laboratories, B15-004) was used instead of FBS. Two days post-confluent WT-1 and 3T3-L1 cells (designated day 0) were induced to differentiate in WT-1 propagation medium supplemented with 1 µM dexamethasone (Sigma-Aldrich, D1756), 0.5 mM isobutylmethylxanthine (Sigma-Aldrich, I5879), 5 µg/ml insulin (Roche, 11376497001) and 1 µM rosiglitazone (Cayman Chemicals, 71740). At day 2, cells were refreshed with medium containing 5 µg/ml insulin and 1 µM rosiglitazone. From day 4, the cells were cultured in WT-1 propagation medium.

hMADS cells were obtained from Dr. Christian Dani and propagated in Advanced DMEM/F12 (Life Technologies, 12634) supplemented by 10% FBS, 2 mM

Figure 5. Knockdown efficiency in different adipocyte cell models. Reverse siRNA transfections of mature adipocytes with siRNA against Pkm for mouse cell models, GAPDH for human hMADS cells or a universal negative siRNA as control. The transfections were performed in (A) 3T3-L1, (B) hMADS, and (C) primary brown and (D) primary white adipocytes. The reverse siRNA transfections were performed at day 6 (3T3-L1), day 9 (hMADS) or day 8 (primary cells) of differentiation and were harvested 4 d, 3 d and 2 d later, respectively. Relative mRNA expression levels (measured by RT-qPCR) of Pkm or GAPDH were determined by normalization to expression levels of Tbp. Data represent mean of means ± SEM (n = 3 for panels A and B, n = 4 for panels C and D). *, p < 0.05 vs. universal negative siRNA.
L-glutamine (Life Technologies, 25030), 62.5 μg/ml penicillin and 100 μg/ml streptomycin. Two days post-confluent cells (day 0) were induced to differentiate in Advanced DMEM/F12 with 2% FBS and 1 μM dexamethasone, 0.5 mM isobutylmethylxanthine, 5 μg/ml insulin, 1 μM rosiglitazone, 1 μM cortisol (Sigma-Aldrich, H0135) and 1 nM thyroid hormone (T3) (Sigma-Aldrich, T6397). This treatment was repeated at day 3. On day 6, the cells were refed with Advanced DMEM/F12 with 2% FBS containing 1 μM rosiglitazone and 1 nM T3.

Cell cultures were kept at 37°C in a humidified atmosphere with 5% CO₂. Cells used for reverse siRNA transfections were cultured in 10 cm dishes until transfection.

**Isolation and culture of primary adipocytes**

Primary brown (from interscapular, cervical and axillary BAT) and inguinal white pre-adipocytes, from 3 to 4 weeks old NMRI mice (males and females), were isolated and cultured essentially as described. After the tissue was minced and transferred to a HEPES-buffered solution (pH 7.4) containing 0.2% crude collagenase type II (Sigma-Aldrich, C6885), it was digested at 37°C for 30 min with constant shaking. The cell suspension was filtered through a 50-μm filter. After centrifugation (10 min, 700 g), the pellet was resuspended in culture medium (DMEM, 4.5 g D-glucose/liter) (Sigma-Aldrich, D6429), 10% newborn calf serum (Life Technologies, 16010-159), 2.4 nM insulin (Novo Nordisk, 8-0204), 4 mM L-glutamine, 10 mM HEPES (Lonza, BE17-737E), 25 μg/ml sodium ascorbate (Sigma-Aldrich, A4034), 50 IU/ml penicillin and 50 μg/ml streptomycin and centrifuged. The pellet was resuspended in culture medium and plated in 6-well plates. Cultures were incubated in a humidified atmosphere of 8% CO₂ at 37°C. The cell culture medium was changed at days 1, 3, 5 and 7 after isolation.

**Reverse siRNA transfections**

Pre-adipocytes and mature adipocytes were reverse transfected with siRNA as follows: siRNA and Lipofectamine RNAiMAX (Life Technologies, 13778–150) were diluted in Opti-MEM I Reduced Serum Medium (Life Technologies, 31985-062) separately before being mixed by pipetting. The siRNA-RNAiMAX mix was added to gelatin-coated 96- or 48-well cell culture plates or 96-well Seahorse plates, and left to incubate for 25 min at room temperature. The final concentrations of Lipofectamine RNAiMAX and siRNA were 5 μl/ml and 50 nM, respectively, in 96-well cell culture and Seahorse plates, and 9 μl/ml and 90 nM, respectively, in 48-well plates. The final amount of medium per well was 90 μl in a Seahorse plates, 180 μl in 96-well culture plates and 250 μl in 48-well plates.

Pre-adipocytes were reverse transfected when the cells were 70% confluent. Pre-adipocytes were detached with 0.05% trypsin (Sigma-Aldrich, T3924) for 5 min, counted and spun down (5 min, 300 g). The cells were resuspended in culture medium and added (20,000 cells per well) to 96-well plates on top of the pre-incubated siRNA-RNAiMAX mix. The cells were harvested 2 d after transfection.

Mature adipocytes were transfected at day 6 of differentiation for mouse cell lines (WT-1 and 3T3-L1), day 8 for primary cultures or day 9 for hMADS cells. Mature adipocytes were trypsinized with 0.25% trypsin (Life Technologies, 25200-072) for 15–20 min, counted and
spun down (5 min, 300 g). The cells were resuspended in culture medium and added to Seahorse, 96- or 48-well plates on top of the pre-incubated siRNA-RNAiMAX mix. The final number of cells per well was 20,000, 80,000 and 200,000 in Seahorse, 96- and 48-well culture plates, respectively. Reverse transfection and replating were performed in 96-well plates for mouse and human cell lines and in 48-well plates for primary cells. Figure 1 illustrates the protocol for reverse siRNA transfection.

Mature mouse primary adipocytes and hMADS cells were harvested 2 and 3 d after transfection, respectively. For the mouse cell lines (WT-1 and 3T3-L1 cells) the medium was changed after 2 d and the cells were harvested 4 d after transfection.

The MISSION® siRNAs (Sigma-Aldrich) used were mouse Pkm (SASI_Mm01_00036294), mouse Camk2a (SASI_Mm01_00347598) and mouse Ucp1 (SASI_Mm01_00067600). For hMADS cells, the Silencer Select siRNA against human GAPDH (Life Technologies, 4427038) was used. The MISSION® siRNA Universal Negative Control #1 (Sigma-Aldrich, SIC001) was used as control in all mouse experiments and Negative Control #1 (Life Technologies, 4390843) was used as control in hMADS cells.

**Forward siRNA transfections**

Pre-adipocytes and mature adipocytes were forward transfected with siRNA when the cells were 70% confluent or at day 6 of differentiation, respectively. As with the reverse siRNA transfection, the siRNA and Lipofectamine RNAiMAX were diluted separately and mixed by pipetting. The siRNA-RNAiMAX mix was left to incubate for 25 min at room temperature after which the siRNA-RNAiMAX mix was added on top of the adherent cells. The concentration of Lipofectamine RNAiMAX and siRNA was as described for the reverse siRNA transfection in 96-wells culture plates. The pre-adipocytes were harvested 2 d after transfection. For mature adipocytes the medium was changed after 2 d and the cells were harvested 4 d after transfection.

**Oil red O staining**

Oil red O staining was performed as previously described.

**Seahorse measurements**

Four days after transfection, real-time measurements of OCR were performed using the Seahorse XF96 Extracellular Flux Analyzer (Seahorse Bioscience). One h before the first measurement, the cell culture medium was changed to DMEM (Seahorse Bioscience, 102352) supplemented with 5 mM glucose (Sigma-Aldrich, G7021) and 2% bovine serum albumin (Sigma-Aldrich, A9647) (adjusted to pH 7.4). OCR was measured under basal conditions and during successive addition of 1 μM ISO (Sigma-Aldrich, I5627), 1 μM FCCP and a mixture of 1 μM rotenone and 1 μM antimycin A (Seahorse Bioscience, 101706–100).

**RT-qPCR**

Total RNA was purified using TRI Reagent (Sigma-Aldrich, T9424) according to the instructions of the manufacturer, and reverse transcription and qPCR were performed as previously described, except that the SensiFAST SYBR Lo-ROX Kit was used (Bioline, BIO-94005). Primers used were: mouse Camk2a, fwd-TCTTC TGAGAGCAAAAC, rev-GGTCCGATATGCCTCGT GTA (136 bp); mouse Fabp4, fwd-TGGAAGCTTG TCTCCAGTGA, rev-AATCCCCATTTACGCTGATG (111 bp); mouse Glut4, fwd-ATCATCCGGAACCTGGAGG, rev-CGGTCAGGCGCTTTAGACTC (52 bp); mouse Pkm, fwd-CTGTGGAGATGCTGAAGGAG, rev-CAACAGGACGGTAGAATGG (156 bp); mouse Tbp, fwd-ACCCCTCCAAATCAGCTCCTATG, rev-ATGATGACTGCGAAATCAG (190 bp); mouse Ucp1, fwd-AAGCGGCCCTAAATCCTGAG, rev-CTCAT GGCAACTGCTGAGG (103 bp); human GAPDH, fwd-GCAAGAGGAGAGAAGAG, rev-CTCATGGCACTGCTGAGG (83 bp). Antibodies used were against Ser473 phosphorylated AKT (Cell Signaling Technologies, 4058), GAPDH (Abcam, Ab8245) and PKM (Sigma-Aldrich, SAB4200095).

**Whole cell extracts and immunoblotting**

Cells transfected with Pkm siRNA were harvested 4 d after transfection. Preparation of whole-cell extracts and immunoblotting were done as described. Antibodies used were against Ser473 phosphorylated AKT (Cell Signaling Technologies, 4058), GAPDH (Abcam, Ab8245) and PKM (Sigma-Aldrich, SAB4200095).

**Glycerol release**

Four days after transfection with control or Pkm siRNA, following addition of fresh medium, cells were stimulated with 1 μM ISO. Cell culture medium was collected after 6 h of stimulation and stored at −20°C. Glycerol release was measured using the Adipolysis Assay Kit (Cayman Chemical, 10009381) essentially following the instructions of the manufacturer.
**Statistical analyses**

For all cell culture studies, 3 samples were harvested for each condition in each experiment, except for primary cultures where only 2 wells were harvested. Data represent mean of means of 3 to 4 independent experiments + standard error of the mean (SEM). Statistical significance in RT-qPCR data and fold change in OCR was determined through 95% confidence intervals as calculated by an unpaired Student’s t-test. Bonferroni correction was used when multiple comparisons were applied.

**Abbreviations**

- **BAT** brown adipose tissue
- **Camk2a** calcium/calmodulin-dependent protein kinase IIα
- **DMEM** Dulbecco’s Modified Eagle’s Medium
- **Fabp4** fatty acid-binding protein 4
- **FBS** fetal bovine serum
- **FCCP** carbonyl cyanide p-(trifluoromethoxy) phenylhydrazone
- **GAPDH** glyceraldehyde-3-phosphate
- **Glut4** glucose transporter 4
- **hMADS** human multipotent adipose-derived stem cells
- **ISO** isoproterenol
- **iWAT** inguinal white adipose tissue
- **OCR** oxygen consumption rate
- **Pkm** pyruvate kinase, muscle
- **RNAi** RNA interference
- **RT-qPCR** reverse transcription-quantitative polymerase chain reaction
- **SEM** standard error of the mean
- **shRNA** short-hairpin RNA
- **siRNA** small interfering RNA
- **SV** stromal vascular
- **T3** thyroid hormone
- **Tbp** TATA-binding protein
- **Ucp1** uncoupling protein 1

**Disclosure of potential conflicts of interest**

No potential conflicts of interest were disclosed.

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