



(43) International Publication Date
8 May 2014 (08.05.2014)

(10) International Publication Number
WO 2014/068033 A2

(51) International Patent Classification:

A01K 67/027 (2006.01) *G01N 33/50* (2006.01)
C12N 9/00 (2006.01) *C12N 9/02* (2006.01)

(21) International Application Number:

PCT/EP2013/072772

(22) International Filing Date:

31 October 2013 (31.10.2013)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

12007446.3 31 October 2012 (31.10.2012) EP

(71) Applicant: **UNIVERSITÄTSKLINIKUM FREIBURG**
[DE/DE]; Hugstetter Str. 49, 79106 Freiburg (DE).

(72) Inventors: **SCHÜLE, Roland**; Gauchmattenweg 7, 79367
Weisweil (DE). **DUTEIL, Delphine**; 11 rue de la nieder-
bourg, F-67400 Illkirch (FR). **METZGER, Eric**; 2A, rue
Vauban, F-68600 Neuf-Brisach (FR). **GÜNTHER,**
Thomas; Pochgasse 44, 79104 Freiburg (DE).

(74) Agents: **KALHAMMER, Georg** et al.; Unsöldstr. 2,
80538 München (DE).

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM,
TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM,
ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

Published:

- without international search report and to be republished
upon receipt of that report (Rule 48.2(g))
- with sequence listing part of description (Rule 5.2(a))

(54) Title: ANIMAL MODEL FOR TYPE 2 DIABETES AND OBESITY

(57) Abstract: The present invention relates to the use of a genetically modified non-human animal as an animal model for obesity or obesity-related disorders, wherein the amount of Lysine-specific Demethylase 1 (LSD1) in at least one tissue or at least one cell type of said animal is reduced.



WO 2014/068033 A2

Animal Model for Type 2 Diabetes and Obesity

5 FIELD OF THE INVENTION

The present invention relates to the use of a genetically modified non-human animal as an animal model for type 2 diabetes, obesity and related disorders, wherein the amount of Lysine-specific Demethylase 1 (LSD1) in at least one tissue or at least one cell type of said
10 animal is reduced. The invention further pertains to a method for identifying a compound useful in the treatment and/or prevention of obesity or an obesity-related disorder, and to an LSD1 modulator for use in the treatment and/or prevention of obesity or an obesity-related disorder.

15 BACKGROUND OF THE INVENTION

In industrialized countries, characterized by a sedentary lifestyle and high-caloric diet, energy balance is often deregulated leading to the development of obesity, dyslipidemia, hyperglycemia, and insulin resistance (type 2 diabetes). Among other organs, adipose
20 tissue is an important regulator of energy balance (Langin, 2010). There are two major types of adipose tissue in mammals, white adipose tissue (WAT) and brown adipose tissue (BAT), which are present in different compartments and show distinct metabolic characteristics. Unilocular WAT is highly adapted to store excess energy in the form of triglycerides and is mainly located in the abdominal and subcutaneous areas. Conversely,
25 multilocular cells from BAT, which are mainly located in the interscapular area (iBAT), oxidize chemical energy to produce heat as a defense against hypothermia and obesity (Himms-Hagen, 1990; Langin, 2010). Fatty acid oxidation and heat production by brown adipocytes is due to the intense metabolic activity of mitochondria, which express uncoupling protein 1 (Ucp1) (Ricquier and Bouillaud, 2000). WAT and BAT have long been
30 assumed to have the same embryonic origin. However, recent evidence suggests that brown and white adipocytes are derived from two different precursors (Seale et al., 2008). These precursors can be discriminated by the presence or absence of the transcription factor myogenic factor 5 (Myf5), with brown adipocytes being derived from Myf5-positive

and white adipocytes derived from Myf5-negative cells, respectively (Seale et al., 2008). In response to environmental cues such as cold or treatment with β 3-adrenergic agonists, appearance of brown fat-like cells has been observed in mouse WAT (Himms-Hagen et al., 1994; Himms-Hagen et al., 2000; Young et al., 1984). These brown fat-like cells are called beige or brite cells. Interestingly, these beige fat cells are not derived from Myf5-expressing precursors (Seale et al., 2008), raising questions about their origin. It has been speculated that beige cells might originate from differentiation of a specific pool of precursor cells already present in WAT (Seale et al., 2011; Wu et al., 2012). Alternatively, beige fat cells could arise from direct conversion of white adipocytes (Granneman et al., 2005; Himms-Hagen et al., 2000; Loncar, 1991). Recently, Wu and colleagues proposed that beige cells exhibit a gene expression pattern distinct from either white or brown fat and that previously identified brown fat deposits in adult humans are indeed composed of beige adipocytes (Wu et al., 2012). However, it is neither known whether beige adipocytes constitute metabolically active fat cell nor are the transcriptional cascades that control the transformation of white to beige adipose tissues have been determined so far.

Over the last decade, evidence accumulated that epigenetics contribute to regulation of adipogenesis. In particular, posttranslational modifications of histone H3 lysines have been linked to either transcriptional activation or repression, depending on the modified residue. Methylation of lysine 4 in histone H3 (H3K4) correlates with gene activation, whereas methylation of lysine 9 or 27 in histone H3 (H3K9 or H3K27, respectively) is associated with transcriptional repression. As an example illustrating the key role of lysine methylation in adipocyte differentiation, it was reported that H3K4 methylation was required for Pparg and C/ebpa expression and thus positively regulates adipogenesis (Cho et al., 2009). In contrast, methylation of H3K27 by the methyltransferase Ezh2 promotes adipogenesis by repressing the Wnt signaling (Wang et al., 2010). Lysine-specific demethylase 1 (LSD1), the first histone lysine demethylase described, is an amine oxidase that mediates histone demethylation via a FAD-dependent oxidative reaction. It has been shown that LSD1 selectively removes mono- and dimethyl groups from H3K4 or H3K9, thereby causing either repression or activation of gene transcription (Garcia-Bassets et al., 2007; Lee et al., 2005; Metzger et al., 2010; Metzger et al., 2005; Shi et al., 2004; Wang et al., 2009a; Wang et al., 2009b) (Zhu Ms). Recent in vitro studies suggest that LSD1 might play a role during fat cells differentiation in vitro (Hino et al., 2012). Hino et al. observe upregulation of LSD1 protein levels in mice on a high fat diet. In addition, their ex vivo experiments with

adipocytes from mice on a high fat diet suggest that energy expenditure genes are upregulated upon knockdown of LSD1. This teaches away from the present invention.

SUMMARY OF THE INVENTION

5

The inventors of this application have shown that heterozygous mice in which one allele of the LSD1 gene has been disrupted and which show reduced expression of Lsd1 are prone to obesity and type 2 diabetes. These mice and other non-human animals having a reduced expression of Lsd1 are valuable tools for studying established and potential
10 agents to treat type 2 diabetes and related diseases such as or insulin resistance and obesity.

15

In addition, the inventors found that transgenic overexpression of Lsd1 in mice improved the metabolic profile of the transgenic mice when fed a high-caloric diet, thereby attenuating obesity and diabetes.

The present invention therefore relates to the subject matter defined in items (1) to (30).

20

(1) The use of a modified non-human animal as an animal model for obesity or obesity-related disorders, wherein the amount of Lysine-specific Demethylase 1 (LSD1) in at least one tissue or at least one cell type of said animal is reduced, wherein the modified non-human animal preferably is a genetically modified non-human animal.

25

(2) The use of item (1), wherein the genetically modified non-human animal has a nucleic acid inserted in its genome, wherein the presence of the inserted nucleic acid in the genome of the animal results in reduced expression of LSD1.

30

(3) The use of item (1) or (2), wherein said genetic modification is a disruption of an allele of the endogenous gene encoding LSD1.

(4) The use of any one of the preceding items, wherein said animal is a non-human transgenic animal which is heterozygous for the disruption of the gene encoding LSD1.

35

(5) The use of any one of the preceding items, wherein the amount of LSD1 is reduced in tissue of said animal, preferably in adipose, liver or muscle of said animal.

(6) The use of any one of the preceding items, wherein said animal develops obesity after high fat diet.

5 (7) The use of any one of the preceding items, wherein said animal has at least one symptom of type 2 diabetes.

(8) The use of any one of the preceding items, wherein the animal is a rodent, preferably a mouse.

10

(9) A method for identifying a compound useful in the treatment and/or prevention of obesity or an obesity-related disorder, comprising (a) administering a test compound to a transgenic animal as defined in any one of items (1) to (8), and (b) determining the effect of the test compound on the initiation, maintenance, or progression of at least one obesity-related parameter in said transgenic animal, thereby identifying a compound that inhibits

15

(10) The method of item (9), wherein said obesity-related parameter is selected from the group consisting of the mass of white adipose tissue, the total mass of adipose tissue, glucose intolerance, and expression of a adipose tissue differentiation marker.

20

(11) A compound for use in the treatment and/or prevention of obesity or an obesity-related disorder, wherein said compound is capable of modulating LSD1 protein, the LSD1 gene or a target gene of LSD1.

25

(12) The compound for use according to claim 11, wherein the target gene of Lsd1 is selected from the group consisting of *Nrf1*, *Prdm16* and *Pgc-1 α* .

(13) A method for identifying a compound useful in the treatment and/or prevention of obesity or an obesity-related disorder, comprising (i) contacting a cell with a test compound; (ii) determining expression level of the LSD1 gene and/or of a target gene of LSD1; and (iii) selecting the compound if the test compound is capable of increasing the expression of the LSD1 gene and/or of the target gene of LSD1, as compared to a control cell which has not been contacted with the test compound.

30
35

(14) The method of item (13), wherein the cell is an adipocyte or a preadipocyte, preferably a mouse 3T3-L1 cell, a 3T3-F442 cell or a 10T1/2 cell.

(15) The use according to any one of items (1) to (8), the method of item (9) or (10), the
5 LSD1 inhibitor for use according to item (11) or (12), or the method of item (13) or (14),
wherein said obesity-related disorder is selected from the group consisting of insulin
resistance, type II diabetes, hypertension, hyperuricemia, fatty liver, non-alcoholic fatty
liver disease, polycystic ovarian syndrome, acanthosis nigricans, hyperphagia, endocrine
abnormalities, triglyceride storage disease, Bardet-Biedl syndrome, and Lawrence-Moon
10 syndrome.

(16) The use of a non-human transgenic animal whose genome comprises a stably
integrated transgenic nucleotide sequence encoding Lysine-specific Demethylase 1
(LSD1) operably linked to a promoter for studying metabolism and/or as an animal model
15 for metabolic disorders.

(17) The use of item (16), wherein said LSD1 is human LSD1.

(18) The use of item (16) or (17), wherein said LSD1 comprises at least amino acids 2
20 to 852 of the amino acid sequence as shown in SEQ ID NO:3.

(19) The use according to any one of items (16) to (18), wherein said transgenic
nucleotide sequence comprises nucleotides 4 to 2556 of the nucleotide sequence as
shown in SEQ ID NO:1.
25

(20) The use according to any one of items (16) to (19), wherein said LSD1 is
overexpressed in the transgenic animal.

(21) The use of item (20), wherein said overexpression is present at least in white
30 adipose tissue.

(22) The use according to any one of items (16) to (21), wherein said promoter is a
Rosa26 promoter.

(23) The use according to any one of items (16) to (22), wherein said animal has a reduced weight relative to a wild type mouse.

5 (24) The use according to any one of items (16) to (23), which is a rodent, preferably a mouse.

(25) A use according to any one of items (16) to (24), wherein said animal does not comprise other transgenic nucleotide sequences.

10 (26) A method for identifying a compound useful in the treatment and/or prevention of a metabolic disorder, comprising (a) administering a test compound to a transgenic animal as defined in any one of items (16) to (25) and (b) determining the effect of the test compound on the initiation, maintenance, or progression of at least one metabolic parameter in said transgenic animal, thereby identifying a compound that inhibits the
15 metabolic disorder, wherein said metabolic parameter is selected from the group consisting of the mass of white adipose tissue, the total mass of adipose tissue, glucose intolerance, expression of a adipose tissue differentiation marker.

20 (27) A method according to item (26), wherein said test compound is selected from the group consisting of LSD1 inhibitors or LSD1 modulators, modulators of androgen receptor, modulators of p53, and modulators of Rb.

25 (28) A LSD1 inhibitor or LSD1 modulator for use in the treatment and/or prevention of a metabolic disorder.

(29) The LSD1 inhibitor or LSD1 modulator of item (28), which is siRNA capable of inhibiting expression of the LSD1 gene.

30 (30) The use according to any one of items (16) to (25), the method of item (26) or (27), or the LSD1 inhibitor for use according to item (28) or (29), wherein said metabolic disorder is selected from the group consisting of eating disorders, body weight disorders, cachexia, anorexia, sarcopenia and wasting syndrome or disease.

DETAILED DESCRIPTION OF THE INVENTION

In a first embodiment, the present invention provides an animal model for type 2 diabetes, obesity and related disorders. One aspect of the invention is the use of a modified non-human animal as an animal model for obesity or obesity-related disorders, wherein the amount of Lysine-specific Demethylase 1 (LSD1) in at least one tissue or at least one cell type of said animal is reduced. The modified non-human animal may be a genetically modified non-human animal, preferably it is a transgenic non-human animal. The animals in accordance with this embodiment have a reduced amount of LSD1 in at least one tissue. These animals typically exhibit a reduced expression of LSD1 in one or more tissues. The reduced expression may or may not affect all tissues of the animal. Preferably, the amount of LSD1 protein or Lsd1 mRNA is reduced in fat tissue, e.g. in BAT and/or WAT.

In a second embodiment, the invention provides an animal model for metabolic disorders including, but not limited to, eating disorders, body weight disorders, cachexia, anorexia, sarcopenia and wasting syndrome or disease. This embodiment includes the use of a non-human transgenic animal whose genome comprises a stably integrated transgenic nucleotide sequence encoding Lysine-specific Demethylase 1 (LSD1) operably linked to a promoter for studying metabolism and/or as an animal model for metabolic disorders. The animals in accordance with this embodiment have an increased amount of LSD1 in at least one tissue. These animals typically overexpress LSD1 in at least one tissue. The overexpression may or may not affect all tissues of the animal. Preferably, the amount of LSD1 protein or Lsd1 mRNA is increased in fat tissue, e.g. in BAT and/or WAT.

In both embodiments, the reduced expression and the increased expression (overexpression), respectively, is relative to a control animal. The control animal may be a wild type animal which is substantially identical to the modified animal or transgenic animal, except for the genetic manipulation. The amount of LSD1 may be determined at the protein level, e.g. by immunoassays using antibodies against LSD1. The expression level of Lsd1 may be determined by quantitative RT-PCR, detecting the amount of Lsd1 mRNA.

In the first embodiment, the amount of LSD1 protein, or the amount of Lsd1 mRNA may be reduced relative to the control animal by at least 10%, preferably by at least 20%, more

preferably by at least 30%, more preferably by at least 40%, e.g. by about 50%. For example, the amount of LSD1 protein, or the amount of Lsd1 mRNA may be reduced relative to the control animal by 10% to 90%, preferably by 20% to 80%, more preferably by 30% to 70%, more preferably by 40% to 60%.

5

In the animals of the first embodiment the protein and/or mRNA levels of *Prdm16*, *Pgc-1 α* and *Ucp1* are reduced, e.g. by at least 10%, more preferably by at least 25%, most preferably by at least about 50%, relative to a control animal. Body fat mass in these animals may be increased by about 10% relative to a control animal, in particular after high fat diet. Blood glucose levels in these animal may be increased by about 10% to about 50%, or by about 20% to about 40%, relative to a control animal. Moreover, the animals of the first embodiment typically exhibit reduced insulin sensitivity and glucose uptake relative to a control animal, wherein insulin sensitivity and glucose uptake may be determined according to the tests described in the Examples hereinbelow.

10

In the second embodiment, the amount of LSD1 protein, or the amount of Lsd1 mRNA may be increased relative to the control animal by at least 10%, preferably by at least 25%, more preferably by at least 50%, more preferably by at least 75%, e.g. by about 100%. For example, the amount of LSD1 protein, or the amount of Lsd1 mRNA may be increased relative to the control animal by 10% to 1000%, preferably by 25% to 500%, more preferably by 50% to 200%, more preferably by 75% to 150%. In this embodiment the phrase "LSD1 protein" includes endogenous and exogenous LSD1 protein. The phrase "Lsd1 mRNA" includes endogenous and exogenous Lsd1 mRNA.

15

The transgenic non-human animal may be a transgenic non-human vertebrate animal, preferably a mammal, preferably a rodent, such as a mouse. Suitable animals are available, or easily generated, using conventional methods, in a variety of genera, including rodents (e.g., rats), rabbits, guinea pigs, dogs, goats, sheep, cows, horses, pigs, llamas, camels or the like. Preferably, the non-human transgenic animal is a transgenic mouse.

20

The animal from which the progeny animal is descended is referred to as "progenitor animal". "Progeny" of a progenitor mammal are any animals which are descended from the progenitor as a result of sexual reproduction or cloning of the progenitor, and which have inherited genetic material from the progenitor. In this context, cloning refers to production

25

30

35

of genetically identical offspring from DNA or a cell(s) of the progenitor animal. As used herein, "development of an animal" from a cell or cells (embryonic cells, for example), or development of a cell or cells into an animal, refers to the developmental process that includes growth, division and differentiation of a fertilized egg or embryonic cells (and their progeny) to form an embryo, and birth and development of that embryonic animal into an adult animal.

An animal is "derived from" a transgenic ovum, sperm cell, embryo or other cell if the transgenic ovum, sperm cell, embryo or other cell contributes DNA to the animal's genomic DNA. For example, a transgenic embryo of the invention can develop into a transgenic animal of the invention. A transgenic ovum of the invention can be fertilized to create a transgenic embryo of the invention that develops into a transgenic animal of the invention. A transgenic sperm of the invention can be used to fertilize an ovum to create a transgenic embryo of the invention that develops into a transgenic animal of the invention. A transgenic cell of the invention can be used to clone a transgenic animal of the invention.

As used herein, a "transgenic non-human mammal" is a non-human mammal into which an exogenous recombinant construct has been introduced, or its progeny. Such a mammal may have developed from (a) embryonic cells into which the construct has been directly introduced or (b) progeny cells of (a). As used herein, an "exogenous construct" is a nucleic acid that is artificially introduced, or was originally artificially introduced, into an animal. The term "artificial introduction" excludes introduction of a construct into an animal through normal reproductive processes (such as by cross breeding). However, animals that have been produced by transfer of an exogenous construct through the breeding of a mammal comprising the construct (into whom the construct was originally "artificially introduced") are considered to "comprise the exogenous construct." Such animals are progeny of animals into which the exogenous construct has been introduced.

In accordance with the first embodiment, the transgenic non-human animal contains a disruption in an endogenous LSD1 gene such that at least one allele of the LSD1 gene is non-functional or does not express a functional LSD1, wherein the disruption is an insertion of a transgene into the endogenous LSD1 gene. The disruption can be, for example, an insertion, missense, frameshift, or deletion mutation. The disruption can also alter a promoter, enhancer, or splice site. The disruption can be insertion of a transgene. The transgene optionally encodes a selectable marker, such as, for example a LacZ

reporter gene operably linked to a LSD1 promoter. The provided non-human animals are preferably heterozygous for LSD1. As used herein, the term heterozygous means that the animal has a disruption in one allele (i.e., endogenous gene) while the second allele is unaffected (i.e., does not contain a disruption). In a most preferred embodiment, the genome of the animal comprises a disruption of only one allele of the gene encoding LSD1. An example of this embodiment is the Lsd+/- mouse described in the Examples.

In accordance with the second embodiment, the invention relates to a non-human transgenic animal (e.g., a rodent, preferably a mouse) whose genome comprises a DNA sequence encoding hLSD1, or encoding a biologically active fragment or variant thereof, which is operably linked to an expression control sequence. Typically, the mouse according to this embodiment will overexpress LSD1 (see, for example, the LSD1-overexpressing mice described in the Examples). In this embodiment, the non-human transgenic animal of the invention is preferably one whose somatic and germ cells comprise at least one genomically integrated copy of a recombinant construct of the invention (a recombinant construct comprising a sequence encoding LSD, preferably hLSD1), or an active fragment or variant thereof, which sequence is operably linked to an expression control sequence. Alternatively, the disclosed transgene construct can also be assembled as an artificial chromosome, which does not integrate into the genome but which is maintained and inherited substantially stably in the animal. Artificial chromosomes of more than 200 kb can be used for this purpose. The present invention is also directed to the creation of transgenic mice in whose tissue specific expression of the hLSD1 transgene is driven by a tissue specific promoter, as is discussed more extensively below.

The invention further provides a transgenic gamete, including a transgenic ovum or sperm cell, a transgenic embryo, and any other type of transgenic cell or cluster of cells, whether haploid, diploid, or of higher zygosity having at least one disruption in the LSD1 gene.

As used herein, the term "embryo" includes a fertilized ovum or egg (i.e., a zygote) as well as later multicellular developmental stages of the organism. The disruption referred to above is preferably in the animal's somatic and germ cells.

Also included herein are progeny of the transgenic animal that preferably comprise a disruption of at least one allele of the LSD1 gene, and transgenic animals derived from a transgenic ovum, sperm, embryo or other cell of the invention.

The transgenic animal may be sterile although, preferably, it is fertile. The present invention further includes a cell line derived from a transgenic embryo or other transgenic cell of the invention, which contains a disruption of at least one allele of the LSD1 gene.

5 Methods of isolating such cells and propagating them are known to those of skill in the art.

Generation of transgenic animals

10 The transgenic non-human animals of the invention are produced by introducing transgenes into the germline of the non-human animal. Embryonal target cells at various developmental stages are used to introduce the transgenes of the invention. Different methods are used depending on the stage of development of the embryonal target cell(s). Such methods include, but are not limited to, microinjection of zygotes, viral integration,
15 and transformation of embryonic stem cells as described below.

Microinjection of zygotes is the preferred method for incorporating transgenes into animal genomes. A zygote, which is a fertilized ovum that has not undergone pronuclei fusion or subsequent cell division, is the preferred target cell for microinjection of transgenic DNA
20 sequences. The murine male pronucleus reaches a size of approximately 20 micrometers in diameter, a feature which allows for the reproducible injection of 1-2 picoliters of a solution containing transgenic DNA sequences. The use of a zygote for introduction of transgenes has the advantage that, in most cases, the injected transgenic DNA sequences will be incorporated into the host animal's genome before the first cell division. Brinster et
25 al., Proc. Natl. Acad. Sci. USA 82:4438 (1985). As a consequence, all cells of the resultant transgenic animals (founder animals) stably carry an incorporated transgene at a particular genetic locus.

Viral integration can also be used to introduce the transgenes of the invention into an
30 animal. The developing embryos are cultured in vitro to the blastocyte developmental stage. The blastomeres may be infected with appropriate retroviruses. Jaenich, Proc. Natl. Acad. Sci. USA 73:1260. Infection of the blastomeres is enhanced by enzymatic removal of the zona pellucida. Transgenes are introduced via viral vectors which are typically replication-defective but which remain competent for integration of viral-associated DNA
35 sequences, including transgenic DNA sequences linked to such viral sequences, into the

host animal's genome. Transfection is easily and efficiently obtained by culture of blastomeres on a monolayer of cells producing the transgene-containing viral vector. Alternatively, infection may be performed using cells at a later developmental stage, such as blastocoeles. In any event, most transgenic founder animals produced by viral
5 integration will be mosaics for the transgenic allele; that is, the transgene is incorporated into only a subset of all the cells that form the transgenic founder animals. Moreover, multiple viral integration events may occur in a single founder animal, generating multiple transgenic alleles which will segregate in future generations of offspring. Introduction of transgenes into germline cells by this method is possible but probably occurs at a low
10 frequency. However, once a transgene has been introduced into germline cells by this method, offspring may be produced in which the transgenic allele is present in all of the animal's cells, i.e., in both somatic and germline cells.

Embryonic stem (ES) cells can also serve as target cells for introduction of the transgenes
15 of the invention into animals. ES cells are obtained from pre-implantation embryos that are cultured *in vitro*. Evans et al., Nature 292:154 (1981). ES cells that have been transformed with a transgene can be combined with an animal blastocyst, after which the ES cells colonize the embryo and contribute to the germline of the resulting animal. Once a transgene has been introduced into germline cells by this method, offspring may be
20 produced in which the transgenic allele is present in all of the animal's cells, i.e., in both somatic and germline cells.

The transgenic nucleic acid may be stably integrated into germ line cells and transmitted to offspring of the transgenic animal as Mendelian loci. Other transgenic techniques result in
25 mosaic transgenic animals, in which some cells carry the transgenes and other cells do not. In mosaic transgenic animals in which germ line cells do not carry the transgenes, transmission of the transgenes to offspring does not occur. Nevertheless, mosaic transgenic animals are capable of demonstrating phenotypes associated with the transgenes.

30 In practicing the invention, animals of the transgenic maintenance line are crossed with animals having a genetic background in which expression of the transgene results in symptoms of obesity or obesity-related disorders. Offspring that have inherited the transgenic nucleic acids of the invention are distinguished from littermates that have not
35 inherited transgenic nucleic acids by analysis of genetic material from the offspring for the

presence of nucleic acid sequences derived from the transgenic nucleic acids of the invention. For example, biological fluids that contain polypeptides uniquely encoded by the transgenic nucleic acids of the invention may be immunoassayed for the presence of the polypeptides. A simpler and more reliable means of identifying transgenic offspring
5 comprises obtaining a tissue sample from an extremity of an animal, such as, for example, a tail, and analyzing the sample for the presence of nucleic acid sequences corresponding to the DNA sequence of a unique portion or portions of the transgenic nucleic acids of the invention. The presence of such nucleic acid sequences may be determined by, e.g., hybridization ("Southern") analysis with DNA sequences corresponding to unique portions
10 of the transgene, analysis of the products of PCR reactions using DNA sequences in a sample as substrates, oligonucleotides derived from the transgene's DNA sequence, and the like.

15 *Targeting vectors*

As used herein, the term "polynucleotide" is interchangeable with "nucleic acid." A polynucleotide of the present invention may be recombinant, natural, or synthetic or semi-synthetic, or any combination thereof. Polynucleotides of the invention may be RNA, PNA,
20 LNA, or DNA, or combinations thereof. As used herein, the terms peptide, polypeptide and protein are also interchangeable.

A "recombinant construct" (also referred to herein as a "construct" for short) or a "transgene" of "transgenic nucleic acid" which is used to generate a transgenic animal of
25 the second embodiment of the invention is a polynucleotide which comprises a sequence encoding LSD1 (preferably hLSD1), or an active fragment or variant thereof, which is operably linked to an expression control sequence. The coding sequence comprises LSD1 exon sequences, although it may optionally include intron sequences which are either derived from an hLSD1 genomic DNA or DNA of an unrelated chromosomal gene. The
30 recombinant construct may comprise a sequence encoding mLSD1 or at least a biologically active fragment thereof. Preferably, the recombinant construct comprises a sequence encoding human LSD1 (hLSD1) or a biologically active fragment thereof. The amino acid sequences of hLSD1 and mLSD1 are shown in SEQ ID NO:3 and 5, respectively. The nucleotide sequence encoding mLSD1 is shown in SEQ ID NO:4. The
35 nucleotide sequence encoding hLSD1 is shown in SEQ ID NO:1. The hLSD1 cDNA

sequence including 5'- and 3'- untranslated regions is shown in SEQ ID NO:2. The nucleotide sequence of an exemplary recombinant construct is shown in SEQ ID NO:6. The amino acid sequence encoded by this construct is shown in SEQ ID NO:7.

- 5 For tissue-specific expression of the transgene in the transgenic animal, the coding sequence must be operably linked to an expression control sequence that drives expression specifically in that tissue. Suitable tissue-specific expression control sequences include the following: MMTV-LTR (for mammary-specific expression), etc.

10 *Inducible/Repressible Expression Control Systems*

An inducible promoter is one which, in response to the presence of an inducer, is activated. Hence, a coding sequence driven by an inducible promoter can be turned on or off by providing or withdrawing the inducer. A promoter may be homologous, derived from
15 the same species as the coding sequence. Preferably, the promoter is heterologous, that is, derived from another species, or even from a virus. hLSD1 constructs in accordance with the present invention may be operably linked to an inducible or repressible control elements. An repressible system, described by Gossen, M. et al., Proc Natl Acad Sci USA 89:5547-51 (1992), is based on the use of control elements of the tetracycline-resistance
20 operon encoded in Tn10 of E. coli. The tet repressor is fused with the activating domain of Herpes simplex virus VP16 to generate a tetracycline-controlled transactivator. Such a transactivator is used to stimulate transcription from a promoter sequence, such as the CMV promoter IE.

- 25 A gene controlled by a promoter acting under the influence of the tetracycline-controlled transactivator can be constitutively expressed and turned off by using an effective concentration of tetracycline. Such a system can regulate a gene over about five orders of magnitude. The tetracycline-repressible system functions in vivo in mice, where tetracycline administration via the diet is used to keep the expression of the inducible gene
30 off. Tetracycline analogs which cross the blood-brain barrier can be used if gene activity is desired in the brain.

Two steps of transfection may be used to produce the appropriate system. A first transfection is used to isolate clones expressing the transactivator. The best clones are
35 identified by testing each in a transient transfection assay for the ability to express a

marker gene, such as an estrogen-dependent luciferase. The second transfection involves the hLSD1 coding sequence under control of an inducible promoter into a transactivator-containing clone. One strategy involves first isolating a stable cell line expressing the inducible hLSD1 protein or peptide by cotransfection of both plasmids into appropriate target cells. After selection, for example with G418, clones showing estrogen-dependent expression of hLSD1 may be detected by an immunoassay or biological assay. To increase the rate of plasmid integration and to stabilize the integrated plasmids in the host genome, the plasmids are preferably linearized and cotransfected into cells in the presence of mammalian high molecular weight DNA as a carrier.

The relative advantages of a two vector system, as described above, over a single vector system involving a larger plasmid is that in a two vector system, multiple copies of the reporter plasmid (encoding the gene of interest) may be needed to obtain a detectable biological effect in a cell, while one or only a few copies of the transactivator-carrying plasmid may suffice.

According to the present invention, the hLSD1 DNA molecule is placed under the control of a promoter subject to regulation by a tetracycline-controlled transactivator. Such a construct (in a single vector or preferably two vector form) is delivered into target cells, whether embryonic, adult normal or tumor, either in vitro or in vivo. To express the hLSD1, tetracycline is withheld so that the hLSD1 DNA is expressed. To prevent the action of the hLSD1, for example, locally, tetracycline or an active congener of tetracycline is administered locally to the cells transfected with the constructs. Effective systemic doses (oral or parenteral) of tetracycline are in the range of about 0.1 mg to 1 g per day. In a preferred embodiment, the transactivator is maintained in the "on" position by withholding tetracycline.

An estrogen-inducible system described by Braselmann, S. et al. Proc Natl Acad Sci USA (1993) 90:1657-61, is based on the fact that most mammalian cells neither express any Gal4-like activity nor endogenous estrogen receptor (ER), thus rendering estrogen an inert signal for them. The authors developed a selective induction system based on the estrogen-regulatable transcription factor Gal-ER. Gal-ER consists of the DNA-binding domain of the yeast Gal4 protein fused to the hormone-binding domain of the human ER and hence exclusively regulates a transfected coding sequence under the control of a Gal4-responsive promoter in mammalian cells. This system includes a synthetic Gal4-

responsive promoter which consists of four Gal4-binding sites, an inverted CCAAT element, a TATA box, and the adenovirus major late initiation region. This promoter shows extremely low basal activity in the absence of, and high inducibility in the presence of, ligand-activated Gal-ER. The transcription factor Gal-ER is rendered more potent and less susceptible to cell type-specific variation by fusing the strong activating domain of the herpesvirus protein VP16 onto its C-terminus. In response to estrogen, e.g., 17- β estradiol, Gal-ER-VP16 may induce the Gal4-responsive promoter at least 100-fold in transfected cells. Thus, the Gal-ER induction system is a powerful genetic switch for regulating heterologous genes. For induction of expression of the DNA molecules of the present invention in an estrogen inducible system in an animal, local or systemic treatment with estrogen would be required. An effective dose of an estrogen is a dose which would trigger the expression of an hLSD1-encoding nucleic acid of the present invention to produce hLSD1 and promote growth of hLSD1-expressing adipose cells. Such doses can be ascertained by one skilled in the art. Preferably, doses in the range of about 0.05 to 100 mg/kg of an estrogen are used in a single dose or in multiple doses over a period of about one week days to about 6 months, or even longer. Forms and preparations of estrogen and their usage in animals, particularly in humans, are well-known in the art. Estrogen analogues which are capable of specifically activating the exogenous transactivator while having fewer biological effects and side effects are preferred.

Ionizing radiation has been used to activate the transcription of exogenous genes, for example, encoding a cytotoxic protein TNF-I (Weichselbaum, R R et al., *Int J Radiation Oncology Biol Phys* 24:565-67 (1992)) This may be accomplished through the use of radiation-responsive elements distal to the transcription start site of such genes. See, for example, Hallahan, D et al., *Proc Natl Acad Sci USA* 88:2152-20 (1991); Datta, R et al., *Proc Natl Acad Sci USA* 89:10149-53 (1992); Weichselbaum et al., *supra*; Hallahan, D E et al. *J Biol Chem* 268:4903-07 (1993); Weichselbaum, R R et al., *Intl J Radiation Oncology Bio. Phys* 30:229-34 (1994); Hallahan, D E et al. *Nature Med* 1:786-91 (1995), which references are hereby incorporated by reference in their entirety. Thus, the present invention provides methods for the spatial and temporal control of gene expression with such radiation-inducible promoters to activate hLSD1. The hLSD1 coding sequence is placed in a vector under control of a radiation-inducible promoter.

In a preferred embodiment, the expression control sequence (either a ubiquitously acting expression control sequence or a tissue-specific one) is expressed in a regulatable

fashion, meaning that it is preferably a component of any of a number of well-known regulatable expression systems.

Methods of making recombinant constructs are conventional. Such methods, as well as many other molecular biological methods used in conjunction with the present invention, are discussed, e.g., in Sambrook, et al. (1989), *Molecular Cloning, a Laboratory Manual*, Cold Harbor Laboratory Press, Cold Spring Harbor, N.Y.; Ausubel et al. (1995). *Current Protocols in Molecular Biology*, N.Y., John Wiley & Sons; Davis et al. (1986), *Basic Methods in Molecular Biology*, Elsevier Sciences Publishing, Inc., New York; Hames et al. (1985), *Nucleic Acid Hybridization*, IL Press; Dracopoli et al. *Current Protocols in Human Genetics*, John Wiley & Sons, Inc.; and Coligan et al. *Current Protocols in Protein Science*, John Wiley & Sons, Inc. See, also, the Examples herein.

In a specific embodiment of this invention, the transgenic animal does not comprise additional transgenic sequences. This means that the transgenic construct present in the transgenic animal is the only transgenic construct present in the animal of this invention. The transgenic animal preferably does not comprise further genetic germ line modifications other than that described hereinabove. The genetic background of the transgenic animal of the invention is 'wild type' except for the genetic modifications described hereinabove. This embodiment is preferred, as it allows studying the effect of any methods interfering with the action of LSD1.

Method for identifying potential therapeutic agents

Another aspect of this invention is a method for identifying a compound which inhibits the growth of adipose tissue, comprising (a) administering a test compound to a transgenic animal according to the present invention and (b) determining the effect of the test compound on the growth or survival of the adipocytes or adipose tissue in said transgenic animal, thereby identifying a compound that inhibits the growth of adipose tissue.

Another aspect of this invention is a method for identifying a compound which is useful in the treatment of type 2 diabetes, obesity and/or a related disorder, comprising (a) administering a test compound to a transgenic animal according to the first embodiment of the present invention and (b) determining the effect of the test compound on at least one metabolic parameter, at least one obesity-related parameter or at least one diabetes-

related parameter, and optionally (c) selecting the compound if the effect is indicative of inhibition or amelioration of type 2 diabetes, obesity and/or a related disorder.

The methods may comprise the steps (i) administering a test compound to a transgenic animal according to the present invention, (ii) administering the same test compound to a control animal, and (iii) determining the effect of the test compound on the transgenic animal as compared to said control animal. The control animal is preferably an animal of the same species as the transgenic animal. The control animal does not show reduced or increased expression of LSD1 or only to a significantly lower degree, relative to a wild type animal. In one embodiment, the control animal does not carry the transgenic nucleotide sequence present in the test animal of step (i). In another embodiment, the control animal is also carrying the same transgenic nucleotide sequence as the transgenic animal used in step (i) but there is no or only a slight reduction or increase in expression. This can be achieved by the use of inducible transgene constructs, see *supra*.

The effect to be determined in step (iii) may be any change in any clinically or biologically relevant parameter including body weight, adipose tissue mass, adipose tissue size, presence of WAT markers, number of adipocytes, presence of lipomas, survival rate and the like (relative to the control animal). The methods of analysis include but are not limited to determining the body weight, adipose tissue mass, adipose tissue size, presence of WAT markers, number of adipocytes, presence of lipomas, survival rate and the like, e.g. by histological methods and/or biochemical methods. A particularly preferred parameter is insulin sensitivity and glucose tolerance.

The test compound may be selected as a compound which is useful in the treatment of type 2 diabetes, obesity or a related disorder if there is a significant difference in at least one of the clinically or biologically relevant parameters tested, for example when the parameter (e.g. adipose tissue mass, adipose tissue size, presence of WAT markers, number of adipocytes, presence of lipomas, survival rate etc.) in the transgenic test animal used in step (i) is significantly reduced (e.g. by at least 10%, preferably by at least 25%, more preferably by at least 50%) relative to that of the control animal.

The test compound may be selected as a compound which is useful in the treatment of type 2 diabetes, obesity or a related disorder if blood glucose levels are reduced by the test compound, or if insulin sensitivity and/or glucose uptake are significantly increased.

The compound may be selected if any one the the target genes of LSD1 (e.g. *Nrf1*, *Prdm16* and *Pgc-1 α*) is upregulated by the test compound, e.g. by at least about 10% or at least about 25%, or at least about 50%, or at least about 100%. The quantitation is preferably done via RT-PCR.

In another embodiment, the compound may be selected if any one the the target genes of LSD1 (e.g. *Nrf1*, *Prdm16* and *Pgc-1 α*) is downregulated by the test compound, e.g. by at least about 10% or at least about 25%, or at least about 50%. The quantitation is preferably done via RT-PCR.

The compounds used as test compounds may be modulators of the LSD1 gene, of the LSD1 protein, or of any target gene of LSD1. Modulators include activators and inhibitors. The modulators are preferably activators of the LSD1 protein or activators of the LSD1 gene (see *infra*).

The invention further pertains to a method for identifying a compound which inhibits adipose cell or tissue growth, the method comprising

- providing a cell expressing LSD1
- contacting the cell with a test compound
- determining the amount of LSD1 protein or LSD1 mRNA expressed by the cell
- selecting the test compound as a compound which inhibits adipose cell or tissue growth if the amount of LSD1 protein or LSD1 mRNA expressed by the cell is greater than that expressed by a control cell.

The invention further relates to a LSD1 modulator for use in the treatment and/or prevention of type 2 diabetes, obesity or an obesity-related disorder. The invention further relates to a method of treating type 2 diabetes, obesity or an obesity-related disorder, comprising administering to an individual in need thereof, a pharmaceutically effective amount of a LSD1 modulator. Obesity-related disorders include, but are not limited to, insulin resistance, hypertension, hyperuricemia, fatty liver, non-alcoholic fatty liver disease, polycystic ovarian syndrome, acanthosis nigricans, hyperphagia, endocrine abnormalities, triglyceride storage disease, Bardet-Biedl syndrome, and Lawrence-Moon syndrome. Preferably, the disorder is type II diabetes. In certain embodiments, the obesity-related disorder is not hypertension.

LSD1 modulators

An LSD1 activator to be used in accordance with this invention is a compound capable of increasing the amount of LSD1 mRNA or LSD1 protein in a cell and/or activating at least one function or activity of the LSD1 gene or the LSD1 protein. These functions include (1) the ability of LSD1 to interact with androgen receptor, (2) the ability of LSD1 to assemble with other proteins, in particular transcription factors into protein complexes, and (3) the catalytic activity of LSD1. The protein complexes may be important for transcriptional activation.

An LSD1 inhibitor to be used in accordance with this invention is a compound capable of reducing the amount of LSD1 mRNA or LSD1 protein in a cell and/or inhibiting at least one function of the LSD1 gene or the LSD1 protein. These functions include (1) the ability of LSD1 to interact with androgen receptor, (2) the ability of LSD1 to assemble with other proteins, in particular transcription factors into protein complexes, and (3) the catalytic activity of LSD1. The protein complexes may be important for transcriptional activation.

The LSD1 modulator to be used in accordance with this invention may be a compound capable of activating or inhibiting expression of the LSD1 gene in a cell. Various methods for activating or inhibiting expression of genes in a cell are known to one of skill in the art (e.g. RNA interference or antisense technology).

In another embodiment the invention, the LSD1 modulator is capable of modulating the interaction of LSD1 protein with the androgen receptor. Such activators include "small molecules," also referred to herein as "compounds," which are isolated from natural sources or made synthetically. In general, such molecules may be identified from large libraries of natural products or synthetic (or semi-synthetic) extracts or chemical libraries according to methods known in the art. Those skilled in the field of drug discovery and development will understand that the precise source of test extracts or compounds is not critical to the methods of the invention. Accordingly, virtually any number of chemical extracts or compounds can be used in the methods described herein. The types of extracts or compounds that may be tested include plant, fungal, prokaryotic or eukaryotic cell or organism-based extracts, fermentation broths, and synthetic compounds including modifications of existing compounds. Numerous methods are also available for generating random or directed synthesis (e.g., semi-synthesis or total synthesis) of any number of

chemical compounds, including, but not limited to, saccharides, lipids, peptides, polypeptides and nucleic acids and derivatives thereof. Synthetic compound libraries are commercially available.

- 5 In yet another embodiment, the LSD1 modulator may modulate (promote or inhibit) the stability the the LSD1 protein or Lsd1 mRNA.

In yet another embodiment, the LSD1 modulator may modulate (promote or inhibit) degradation of LSD1 protein or Lsd1 mRNA. For example, the pathways leading to
10 degradation of LSD1 protein or Lsd1 mRNA in the cells may be inhibited, thus leading to an increased amount of LSD1 protein or Lsd1 mRNA in the cells.

In yet another embodiment, the LSD1 modulator may modulate (promote or inhibit) the translation efficiency of the Lsd1 gene.

15

Alternatively, libraries of natural compounds in the form of bacterial, fungal, plant, and animal extracts are commercially available from a number of sources. In addition, natural and synthetically produced libraries can be generated according to methods known in the art, e.g., by standard extraction and fractionation methods. Furthermore any library or
20 compound may readily be modified using standard chemical, physical, or biochemical methods.

Another class of agents that can be screened are antibodies, in particular monoclonal antibodies.

25

The LSD1 activators are preferably useful in the treatment and/or prevention of type 2 diabetes, obesity and/or related disorders. LSD1 inhibitors may be useful in the treatment and/or prevention of metabolic disorders such as eating disorders, body weight disorders, cachexia, anorexia, sarcopenia and wasting syndrome or disease.

30

"Cachexia" refers to a state of general ill health and malnutrition. It is often associated with and induced by malignant cancer, and is characterized by loss of appetite, lass of body mass, especially lean body mass, and muscle wasting.

"Anorexia" refers simply to a loss of appetite, whether brought on by medical or psychological factors. Anorexia is often closely associated with, and generally contributes to, the cachexia seen in patients with advanced cancers.

5 *Modulators of target genes of LSD1*

Target genes of LSD1 include, but are not limited to, *Nrf1*, *Prdm16* and *Pgc-1 α* .

10 In one embodiment, the modulator of a target gene of LSD1 is an activator of the target gene.

In another embodiment, the modulator of a target gene of LSD1 is an inhibitor of the target gene.

In another embodiment, the modulator of a target gene of LSD1 is an activator of *Nrf1*.

In another embodiment, the modulator of a target gene of LSD1 is an activator of *Prdm16*.

15 In another embodiment, the modulator of a target gene of LSD1 is an activator of *Pgc-1 α* .

In another embodiment, the modulator of a target gene of LSD1 is an inhibitor of *Nrf1*.

In another embodiment, the modulator of a target gene of LSD1 is an inhibitor of *Prdm16*.

In another embodiment, the modulator of a target gene of LSD1 is an inhibitor of *Pgc-1 α* .

20 Preferably, an activator is capable of increasing the expression of the target gene, or activating a function of the gene product of said target gene. Typically, an inhibitor is capable of inhibiting the expression of the target gene, or inhibiting a function of the gene product of said target gene.

25 The above-mentioned modulators are useful in the treatment and/or prevention of type 2 diabetes, obesity and/or related disorders. The above-mentioned modulators may further be useful in the treatment and/or prevention of a metabolic disorder.

30 One of skill in the art will appreciate that the LSD1 modulators can be used alone or in combination with other compounds and therapeutic regimens to inhibit obesity or obesity-related disorders or obesity-related symptoms, or metabolic disorders.

35 An effective amount of the activator will be determined by the existence, nature, and extent of any adverse side-effects that accompany the administration of the composition; the LD₅₀ of the composition; and the side-effects of the composition at various concentrations.

Typically, the amount of the composition administered will range from about 0.01 to about 20 mg per kg, more typically about 0.05 to about 15 mg per kg, even more typically about 0.1 to about 10 mg per kg body weight.

- 5 The activator can be administered, for example, by intravenous infusion, orally, intraperitoneally, or subcutaneously. Oral administration is the preferred method of administration. The formulations of compounds can be presented in unit-dose or multi-dose sealed containers, such as ampoules and vials.
- 10 The LSD1 activators are typically formulated with a pharmaceutically acceptable carrier before administration to an individual or subject. Pharmaceutically acceptable carriers are determined, in part, by the particular composition being administered, as well as by the particular method used to administer the composition. Accordingly, there are a wide variety of suitable formulations of pharmaceutical compositions of the present invention (see, e.g.,
- 15 Remington's Pharmaceutical Sciences, 17th ed., 1989).

DESCRIPTION OF THE DRAWINGS

- 20 **Figure 1. Expression of LSD1 in transgenic mice induces the formation of functional beige fat in white adipose tissue.** **a**, Macroscopic view of epididymal fat and haematoxylin and eosin staining (H&E) of interscapular brown adipose tissue (BAT), epididymal (epWAT), inguinal (ingWAT), perimuscular (pmWAT), and retroperitoneal (rpWAT) white adipose tissue of control (Ctrl) and LSD1 transgenic (Tg) mice. Black
- 25 arrows indicate beige fat islets. **b**, Western blot analyses of LSD1, Prdm16, Ucp1, and Khl13 in the indicated adipose tissues of Ctrl and Tg mice. β -Tubulin was used as a loading control. **c**, **d**, Relative transcript levels of the indicated (**c**) oxidative, (**d**) beige fat-selective, brown fat-selective, adipogenic, and white fat-selective markers in ingWAT of Ctrl, Tg, and transgenic mice expressing enzymatically inactive LSD1 mutant (Tg^{Mut}). **e**,
- 30 Ultrastructure analysis of ingWAT of Ctrl and Tg mice. Black arrows indicate mitochondria. LV: lipid vesicle. Magnified regions are delimited by squares. **f**, Density of mitochondria determined from ultrastructure analysis of indicated adipose tissues of Ctrl and Tg mice. **g**, Determination of Sdh (mitochondrial respiratory chain complex II) and Cox (mitochondrial respiratory chain complex IV) activities in pmWAT of Ctrl and Tg mice. BAT of Ctrl mice

was used as a positive control. **a-d**, n=10 mice. **e-g**, n=5 mice. Standard deviation represents + SEM, * p<0.05.

Figure 2. LSD1 is induced in white fat pads after cold exposure or β 3-adrenergic treatment of mice.

a, (left panel) Western blot analysis showing LSD1 in ingWAT of mice on regular diet (RD) or high-fat diet (HFD). β -Tubulin was used as a loading control. (right panel) Amount of LSD1 protein relative to β -Tubulin. **b, c**, H&E staining of ingWAT of mice (**b**) maintained at either 24 or 10 °C, or (**c**) treated with vehicle or the β 3-adrenergic agonist CL316,243. Black arrows show beige fat islets. **d, e**, (left panels) Western blot analysis of LSD1 and Ucp1 in ingWAT of mice (**d**) maintained at either 24 or 10 °C, or (**e**) treated with vehicle or CL316,243. β -Tubulin was used as a loading control. (right panels) Amount of LSD1 protein relative to β -Tubulin. Standard deviation represents + SEM (n=10 mice), *** p<0.001.

Figure 3. β 3-adrenergic signalling promotes the beige fat programme through LSD1.

***LSD1*^{+/-} mice are prone to obesity and type-2 diabetes due to decreased oxidative capacities in adipose tissue.** **a**, Western blot analysis of LSD1 and Ucp1 in ingWAT of control (Ctrl) and heterozygous LSD1 (*LSD1*^{+/-}) mice treated with vehicle (-) or CL316,243 (+). β -Actin was used as a loading control. **b**, Immunofluorescent staining of LSD1 (yellow arrows, left panel) and H&E staining (right panel) of ingWAT of Ctrl and *LSD1*^{+/-} mice treated with vehicle or CL316,243. Black arrows indicate beige fat islets. **c**, Relative transcript levels of the indicated genes in ingWAT of Ctrl and *LSD1*^{+/-} mice treated with vehicle or CL316,243. **d**, Relative body weight of Ctrl and *LSD1*^{+/-} mice fed a HFD. **e**, Western blot analysis showing LSD1 and Ucp1 in ingWAT of Ctrl and *LSD1*^{+/-} mice fed a HFD. β -Tubulin was used as a loading control. **f**, H&E staining of ingWAT of Ctrl and *LSD1*^{+/-} mice fed a HFD. **g, h**, Intraperitoneal insulin sensitive test (**g**, IPIST), and intraperitoneal glucose tolerance test (**h**, IPGTT) of Ctrl and *LSD1*^{+/-} mice fed a HFD. Standard deviation represents + SEM (n=6 mice), *: p<0.05.

Figure 4. LSD1 promotes the formation of functional beige adipocytes in vitro.

a, Relative transcript levels of the indicated oxidative and beige fat-selective markers in in vitro differentiated primary adipocytes isolated from stromal-vascular fraction of control (Ctrl) and LSD1 transgenic (Tg) mice. **b**, Relative transcript levels of the indicated oxidative and beige fat-selective markers in undifferentiated (day 0) and differentiated (day 7) control (Ctrl) and LSD1 overexpressing (Tg) 3T3-L1 cells. **c**, Mitochondrial activity in 3T3-L1(Ctrl)

and 3T3-L1(Tg) cells at day 7 reflected by red fluorescent JC-1 aggregates (FL-2). Black curves represent the background staining (CCCP). Numbers in red show the percentage of cells with increased mitochondrial activity. Standard deviation represents + SEM (n=6), * p<0.05, *** p<0.001.

5

Figure 5. LSD1 positively regulates multiple metabolic pathways to promote beige fat formation. **a, b**, Pie charts displaying genomic distribution of LSD1 peaks in **(a)** control (Ctrl) and **(b)** LSD1 overexpressing (Tg) 3T3-L1 cells determined by ChIP-seq analysis. **c, d**, Venn diagram showing the number of genes with LSD1 peaks at promoters in **(c)** 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation, and **(d)** in 3T3-L1(Ctrl) cells at day 7 and 3T3-L1(Tg) cells at day 0 of differentiation. **e, f**, Venn diagram showing the number of genes with LSD1 peaks at promoters and differentially regulated genes deduced from RNA-seq data in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at **(e)** day 0 and **(f)** day 7 of differentiation.

15

Figure 6. LSD1 controls beige fat formation through Nrf1, C/ebp β and Ppar γ /Rrx α . **a**, HOMER motif analyses of LSD1 ChIP-seq data unravel Nrf1, C/ebp β , Ppar γ , and Rrx α binding sites among the top scoring motifs. ND: motif not determined by HOMER. **b**, Pie charts displaying genomic distribution of Nrf1 peaks in 3T3-L1 cells at days 0 and 7. **c**, Venn diagram showing number and intersection of genes with Nrf1 promoter peaks in 3T3-L1 cells at days 0 and 7. **d, e**, Venn diagram depicting the number of genes with LSD1 and Nrf1 peaks at promoters in 3T3-L1 cells at days 0 and 7 of differentiation. **f, g**, Venn diagram depicting the number of genes with LSD1 and **(f)** C/ebp β , or **(g)** Ppar γ and Rrx α peaks at promoters in 3T3-L1 cells at days 3 and 7 of differentiation.

25

Figure 7. Expression of LSD1 in transgenic mice promotes the formation of functional beige fat in white adipose tissue. **a**, Schematic representation of the Rosa26-LSD1 transgene. Arrows indicate the location of primers used to characterize the LSD1 allele. **b**, QRT-PCR analyses of total LSD1 (human and mouse) levels in interscapular brown adipose tissue (BAT), epididymal (epWAT), inguinal (ingWAT), perimuscular (pmWAT), and retroperitoneal (rpWAT) white adipose tissue of control (Ctrl) and transgenic (Tg) mice. **c**, Western blot analyses of Ear2 and Fabp4 in the indicated adipose tissues of Ctrl and Tg mice. Flag antibody was used to detect expression of the LSD1 transgene. β -Actin served as a loading control. **d**, Immunofluorescence analysis of LSD1 (yellow) in the indicated adipose tissues of Ctrl and Tg mice. Rabbit IgG was used

30

35

as a negative control. **e**, Immunofluorescence analysis of Prdm16 and Ucp1 (yellow arrows) in ingWAT and of Myf5 in ingWAT and BAT of Ctrl and Tg mice. Rabbit IgG was used as a negative control. n=10 mice. Standard deviation represents + SEM, * p<0.05.

5 **Figure 8. Expression of LSD1 in transgenic mice promotes oxidative capacities in white adipose tissue.** Relative transcript levels of oxidative markers in the indicated adipose tissues of control (Ctrl), transgenic (Tg), and transgenic mice expressing enzymatic inactive LSD1 (Tg^{Mut}). BAT of Ctrl mice was used as a control. n=10 mice. Standard deviation represents + SEM, * p<0.05 between Ctrl and Tg WAT.

10

Figure 9. Expression of LSD1 in transgenic mice does not promote oxidative capacities in brown adipose tissue, skeletal muscle, and liver. Relative transcript levels of oxidative markers in the indicated tissues of control (Ctrl) and transgenic (Tg) mice. n=10 mice. Standard deviation represents + SEM. ND: Not detected.

15

Figure 10. Expression of enzymatic inactive LSD1 in transgenic mice does not promote the formation of functional beige fat in white adipose tissue. a, Schematic representation of the *Rosa26-LSD1^{Mut}* transgene. Arrows indicate the location of primers used to characterize the *LSD1^{Mut}* allele. **b**, Macroscopic view of epididymal fat and haematoxylin and eosin staining (H&E) of BAT, epWAT, ingWAT, pmWAT, and rpWAT of Ctrl and Tg^{Mut} mice. **c**, Western blot analyses of LSD1, Prdm16, Ucp1, Khlh13, Ear2, and Fabp4 in the indicated adipose tissues of Ctrl and Tg^{Mut} mice. Flag antibody was used to detect expression of the *LSD1^{Mut}* transgene. β -Tubulin served as a loading control.

20

25 **Figure 11. Expression of LSD1 in transgenic mice promotes beige fat-selective markers in white adipose tissue.** Relative transcript levels of beige fat-selective markers in the indicated adipose tissues of Ctrl, Tg, and Tg^{Mut} mice. n=10 mice. Standard deviation represents + SEM, * p<0.05 between Ctrl and Tg WAT.

30 **Figure 12. Expression of LSD1 in transgenic mice does not foster the beige fat-selective gene programme in brown adipose tissue, skeletal muscle, and liver.** Relative transcript levels of beige fat-selective markers in the indicated tissues of Ctrl and Tg mice. n=10 mice. Standard deviation represents + SEM. ND: Not detected.

Figure 13. Expression of LSD1 in transgenic mice does not promote brown fat-selective markers in white adipose tissue. Relative transcript levels of brown fat-selective markers in the indicated adipose tissues of Ctrl, Tg, and Tg^{Mut} mice. BAT of Ctrl mice was used as a control. n=10 mice. Standard deviation represents + SEM, * p<0.05 between Ctrl and Tg WAT.

Figure 14. Expression of LSD1 in transgenic mice does not alter white adipogenesis in white adipose tissue. a,b, Relative transcript levels of adipogenic (a), and white fat-selective (b) markers in the indicated adipose tissues of Ctrl, Tg, and Tg^{Mut} mice. BAT of Ctrl mice was used as a control for adipogenic markers. n=10 mice. Standard deviation represents + SEM.

Figure 15. Expression of LSD1 in transgenic mice promotes mitochondrial biogenesis in white adipose tissue. a, Distribution of mitochondria size determined from ultrastructure analysis. **b,** Ratio of mitochondrial to nuclear DNA content assessed by quantitative PCR of the mitochondrial-encoded *Cox2* and the nuclear-encoded *Fasn* gene in the indicated adipose tissues of Ctrl and Tg mice. **c,** Determination of Sdh (mitochondrial respiratory chain complex II) and Cox (mitochondrial respiratory chain complex IV) activities in rpWAT of Ctrl and Tg mice. BAT of Ctrl mice was used as a positive control. n=5 mice. Standard deviation represents + SEM, * p<0.05.

Figure 16. LSD1 Tg mice display limited weight gain in response to a high-fat diet. a, Body weight of Ctrl and Tg mice fed a regular diet (RD). **b,** Weight of the indicated tissues of Ctrl and Tg mice fed a RD. **c,** Food consumption of Ctrl and Tg mice fed a RD. **d,** Body weight of Ctrl and Tg mice fed a high-fat diet (HFD). **e,** Fat, lean, and free body fluid (FBF) content of Ctrl and Tg mice fed a HFD. **f,** Weight of the indicated tissues of Ctrl and Tg mice fed a HFD. **g,** H&E staining of indicated adipose tissues of Ctrl and Tg mice fed a HFD. **h,** Western blot analyses of LSD1, Ucp1, and Fabp4 in the indicated adipose tissues of Ctrl and Tg mice fed a RD or HFD. β -Tubulin was used as a loading control. n=10 mice. Standard deviation represents + SEM, * p<0.05.

Figure 17. LSD1 Tg mice are more resistant to high-fat diet-induced obesity and type-2 diabetes. a-h, (a) Food consumption, (b) spontaneous activity, (c) VO_2 , (d) VCO_2 , (e) respiratory quotient (RQ), (f) heat production, (g) serum glucose, triglyceride, free fatty acid (FFA), and cholesterol (Total: total cholesterol, HDL: high density lipoprotein, and

LDL: low density lipoprotein) levels of Ctrl and Tg mice fed a HFD. **h,i**, Intraperitoneal glucose tolerance test (**h**, IPGTT), and intraperitoneal insulin sensitive test (**i**, IPIST) of Ctrl and Tg mice fed a HFD. **j**, Serum glucose, triglyceride, free fatty acid (FFA), and cholesterol (Total: total cholesterol, HDL: high density lipoprotein, and LDL: low density lipoprotein) levels of Ctrl and Tg mice fed a RD. **k,l**, (**k**) IPGTT and (**l**) IPIST of Ctrl and Tg mice fed a RD. n=10 mice. Standard deviation represents + SEM, * p<0.05.

Figure 18. LSD1 is induced in white fat pads after cold exposure or β 3-adrenergic treatment of mice. **a,b**, H&E staining of indicated adipose tissues of mice (**a**) maintained at either 24 or 10 °C, or (**b**) treated with vehicle or the β 3-adrenergic agonist CL316,243. Black arrows show beige fat islets. **c**, Western blot analysis of LSD1 and Ucp1 in the indicated tissues of mice maintained at 24 or 10 °C. Indicated LSD1 levels were normalized to β -Tubulin.

Figure 19. Fat-specific deletion of LSD1 impairs WAT adipogenesis. **a**, Immunofluorescence analysis of LSD1 (red) in interscapular brown adipose tissue (BAT) of control (Ctrl) and *LSD1^{aP2-Cre}* mice. Nuclei were counterstained with DAPI. **b-d**, Macroscopic view of (**b**) epWAT and (**c**) BAT of Ctrl and *LSD1^{aP2-Cre}* mice. Fat depots are indicated by arrow heads (**d**) H&E staining of BAT of Ctrl and *LSD1^{aP2-Cre}* mice. **e**, Microscopic view of stromal vascular fraction of fat from Ctrl and *LSD1^{Rosa26-CreERT}* mice treated for five days with tamoxifen and differentiated into adipocytes. Magnification: 200 x. **f**, Relative transcript levels of *LSD1* and the indicated adipogenic and white fat-selective markers in differentiated Ctrl and *LSD1^{-/-}* primary adipocytes. **a-d**, n=6; **e,f**, n=5. Standard deviation represents + SEM, ** p<0.01.

25

Figure 20. β 3-adrenergic signalling is impaired in *LSD1^{+/-}* mice. **a**, Schematic representation of the *Rosa26-Cre* transgene and the floxed L2 *LSD1* allele. Arrows indicate the locations of primers used to characterize the different alleles. Yellow flags show LoxP sites. **b**, Relative *LSD1* transcript levels in the indicated adipose tissues of control (Ctrl) and heterozygous *LSD1* (*LSD1^{+/-}*) mice treated with vehicle or CL316,243. **c**, H&E staining of indicated adipose tissues of Ctrl and *LSD1^{+/-}* mice treated with vehicle or CL316,243. Black arrows indicate beige fat islets. **b** and **c**, n=5 mice. Standard deviation represents + SEM, * p<0.05.

30

Figure 21. β 3-adrenergic signalling promotes the beige fat programme through LSD1. Relative transcript levels of (a) oxidative, (b) adipogenic, (c) white, and (d) beige fat-selective markers in the indicated adipose tissues of Ctrl and $LSD1^{+/-}$ mice treated with vehicle or CL316,243. n=10 mice. Standard deviation represents + SEM, * p<0.05.

5

Figure 22. $LSD1^{+/-}$ mice are prone to obesity due to decreased oxidative capacities in adipose tissue. a-e, (a) Food consumption, (b) fat, lean, and FBF content, (c) H&E staining of indicated adipose tissues, (d) histochemical staining of NADH dehydrogenase activity in gastrocnemius muscle, (e) spontaneous activity of Ctrl and $LSD1^{+/-}$ mice fed a HFD. n=6 mice. Standard deviation represents + SEM, * p<0.05.

10

Figure 23. $LSD1^{+/-}$ mice are prone to obesity and type-2 diabetes. a-e, (a) VO_2 , (b) VCO_2 , (c) respiratory quotient (RQ), (d) heat production, (e) serum glucose, triglyceride, levels, free fatty acid (FFA), and cholesterol (Total: total cholesterol, HDL: high density lipoprotein, and LDL: low density lipoprotein) levels of Ctrl and $LSD1^{+/-}$ mice fed a HFD. f,g, (f) IPIST and (g) IPGTT of Ctrl and $LSD1^{+/-}$ mice fed a RD. h, Serum glucose, triglyceride, levels, FFA, and cholesterol levels of Ctrl and $LSD1^{+/-}$ mice fed a RD. n=6 mice. Standard deviation represents + SEM, * p<0.05.

15

Figure 24. LSD1 is essential to maintain oxidative capacities of adipocytes. a, Microscopic view of primary adipocytes isolated from the stromal vascular fraction of fat from Ctrl and $LSD1^{+/-}$ mice and differentiated in vitro. Magnification: 200 x. **b,** Relative transcript levels of the indicated adipogenic, white fat-selective, and oxidative markers in differentiated Ctrl and $LSD1^{+/-}$ primary adipocytes. **c,** Preadipocytes isolated from the stromal vascular fraction from Ctrl and Tg $LSD1$ mice were differentiated in vitro. Relative transcript levels of the indicated adipogenic, white, and brown fat-selective markers in differentiated Ctrl and Tg primary adipocytes. Standard deviation represents + SEM (n=5), * p<0.05, ** p<0.01, *** p<0.001.

25

Figure 25. LSD1 promotes the formation of functional beige adipocytes in vitro. a, Western blot analysis of LSD1 in undifferentiated (day 0) and differentiated (day 7) control (Ctrl) 3T3-L1 and LSD1 overexpressing (Tg) cells. Flag antibody was used to detect expression of the transgene. β -Actin served as a loading control. **b,** Relative transcript levels of $LSD1$, oxidative, and beige fat-selective markers in differentiated C3H-10T1/2 control (Ctrl), LSD1 (Tg), or inactive LSD1 (Tg^{Mut}) overexpressing cells. **c,** Relative

35

transcript levels of oxidative markers in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 0 and 7 of differentiation. **d**, Relative transcript levels of white fat-selective, and adipogenic markers in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 0 and 7 of differentiation. **e**, Relative transcript levels of white fat-selective and adipogenic markers in differentiated Ctrl, Tg, and Tg^{Mut} C3H-10T1/2 cells. Standard deviation represents + SEM (n=6), * p<0.05, ** p<0.01, *** p<0.001.

Figure 26. LSD1 promotes mitochondrial biogenesis and function. a,b, (a) Relative mitochondrial activity determined by red fluorescence intensity of JC-1 aggregates (FL-2) and (b) relative mitochondrial mass determined by green fluorescence intensity of JC-1 aggregates (FL-1) in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at day 7 of differentiation. Samples treated with the mitochondrial membrane potential disrupter CCCP represent background staining. **c**, Ratio of mitochondrial activity (FL-2) relative to mitochondrial mass (FL-1) in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at day 7 of differentiation. Standard deviation represents + SEM (n=6), *** p<0.001.

Figure 27. LSD1 does not promote transdifferentiation of white adipocytes. Relative transcript levels of (a) *LSD1* and oxidative, (b) adipogenic, (c) white fat-selective, and (d) beige fat-selective markers in 3T3-L1 cells infected with either control virus (Ctrl) or virus expressing *LSD1* upon doxycyclin (dox) treatment (*LSD1*^{Ind}). Time points of dox treatment are indicated by +. Standard deviation represents + SEM (n=6), ** p<0.01, *** p<0.001.

Figure 28. LSD1 promotes oxidative metabolic pathways. a,b, Venn diagram depicting the number of genes with *LSD1* peaks at promoters in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at (a) day 0 and (b) day 7 of differentiation. **c-e**, Enriched pathways obtained from GOterm analyses for the indicated sets of genes. **f**, Venn diagram depicting the number of genes with *LSD1* peaks at promoters in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 7 and 0, respectively, and differentially expressed genes between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at day 7 of differentiation. **g**, Enriched pathways obtained from a GOterm analysis for the indicated sets of genes.

Figure 29. LSD1 promotes mitochondrial functions. a, Localization of *LSD1* at promoters of *Cpt1* and *Cpt2* in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at day 0. Differential expression of the indicated genes between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation. (FC) Logarithmic fold change. **b**, Relative transcript levels of

representative genes encoding the mitochondrial electron transport chain in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 0 and 7. **c,d**, (left panel) Relative transcript levels of representatives of **(c)** glycolysis and **(d)** TCA cycle in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 0 and 7, and (right panel) in the indicated adipose tissues of Ctrl and Tg mice. **b-d**,
 5 n=6; **c,d**, n=10 mice. BAT served as a positive control. Standard deviation represents + SEM, * p<0.05.

Figure 30. LSD1 fosters oxidative metabolism. **a**, Modified “energy metabolism pathway” from Hood et al⁶⁴. **b**, Localization of LSD1 at promoters of *Acaca*, *Pgc-1 α* , *Pgc-1 β* , *Nrf1*, and *Tfam* in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at day 0. Differential expression of the indicated genes between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation. (FC) Logarithmic fold change.

Figure 31. LSD1 induces expression of Nrf1, Tfam, and Ucp. **a**, (left panel) Relative transcript levels of *Nrf1* in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 0 and 7, and (right panel) in the indicated adipose tissues of Ctrl and Tg mice. **b**, Western blot analysis of LSD1 and Nrf1 of 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at indicated days. β -Actin served as a loading control. **c**, Western blot analysis of Nrf1 in the indicated adipose tissues of Ctrl and Tg mice. β -Actin was used as a loading control. **d**, (left panel) Relative transcript levels of *Tfam* in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 0 and 7, and (right panel) in the indicated adipose tissues of Ctrl and Tg mice. **e**, Localization of LSD1 at promoters of *Ucp1*, *Ucp2*, and *Ucp3* in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at day 0, and differential expression of the *Ucp* genes between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation. **a,b,d**, n=6; **a,c,d**, n=10 mice. BAT served as a positive control. Standard
 25 deviation represents + SEM, * p<0.05.

Figure 32. LSD1 and Nrf1 control the OXPHOS gene programme. Overlap of LSD1 and Nrf1 peaks at promoters of representative mitochondrial electron transport chain (complex I-V) genes in 3T3-L1 cells at indicated time points of differentiation, and differential
 30 expression of the representatives between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation. (FC) Logarithmic fold change.

Figure 33. Tissue-specific action of LSD1. **a,b**, Relative transcript levels of the indicated genes in **(a)** quadriceps muscle and **(b)** liver of Ctrl and Tg mice. n=10 mice. Standard
 35 deviation represents + SEM, * p<0.05.

Figure 34. LSD1 and Nrf1 control the OXPHOS gene programme. Relative transcript levels of the indicated genes in 3T3-L1(Tg) cells at days 0 and 7, treated with unrelated control siRNA or siRNA directed against Nrf1. Standard deviation represents + SEM n=6, * p<0.05, ** p<0.01, and *** p<0.001.

Figure 35. Genome-wide binding pattern of LSD1 and C/ebp β . **a**, Venn diagram showing the number of genes occupied by LSD1 or C/ebp β in 3T3-L1(Ctrl) cells at day 0. **b**, Enriched pathways identified by a GOterm analysis of the common target genes at day 3 of differentiation **c**, LSD1 occupancy of the indicated *C/ebp* promoters in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at day 0 of differentiation, and differential expression of the indicated *C/ebp* genes between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation. (FC) Logarithmic fold change. **d**, Relative transcript levels of *C/ebp α* , *C/ebp β* , and *C/ebp δ* from undifferentiated (day 0) and differentiated (day 7) 3T3-L1(Ctrl) and 3T3-L1(Tg) cells. **e**, Western blot analysis of LSD1 and C/ebp β of 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at indicated days. β -Actin served as a loading control. **f**, Relative transcript levels of *C/ebp α* , *C/ebp β* , and *C/ebp δ* in the indicated adipose tissues of Ctrl and Tg mice. **d,e**, n=6; **f**, BAT served as a positive control, n=10 mice. Standard deviation represents + SEM, * p<0.05 between Ctrl and Tg WAT (for **f**).

Figure 36. LSD1 controls beige adipogenesis via C/ebp β . Relative transcript levels of the indicated genes in 3T3-L1(Tg) cells at days 0 and 7, treated with unrelated control siRNA or siRNA directed against *C/ebp β* . Standard deviation represents + SEM (n=6), * p<0.05, ** p<0.01, and *** p<0.001.

Figure 37. a, Genome-wide binding pattern of LSD1, Ppar γ , and Rxr α . Venn diagram showing the number of genes occupied by LSD1, Ppar γ , and Rxr α in 3T3-L1 cells at day 0. **b**, Enriched pathways identified by a GOterm analysis of the common target genes in 3T3-L1 cells at day 7 of differentiation. **c**, Overlap of LSD1, Ppar γ , and Rxr α peaks at promoters of representative genes of fatty acid β -oxidation at indicated days of differentiation in 3T3-L1 cells, and differential expression of representative between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation. (FC) Logarithmic fold change.

Figure 38. Control of gene expression by LSD1. **a**, LSD1 occupancy of *Ppar γ* and *Rxr α* promoters in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 0 and 7 of differentiation. **b**, Relative transcript levels of *Ppar γ* and *Rxr α* from undifferentiated (day 0) and differentiated (day 7) 3T3-L1(Ctrl) and 3T3-L1(Tg) cells. **c**, Western blot analysis of LSD1, *Ppar γ* , and *Rxr α* of 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at indicated days. β -Actin served as a loading control. **d**, Relative transcript levels of *Ppar γ* and *Rxr α* in the indicated adipose tissues of Ctrl and Tg mice. **b,c**, n=6; **d**, BAT served as a positive control, n=10 mice. Standard deviation represents + SEM, * p<0.05 between Ctrl and Tg WAT (for **d**).

Figure 39. LSD1 controls beige adipogenesis. LSD1 levels are regulated by environmental cues. LSD1 levels are increased by cold exposure or β 3-adrenergic stimulation and decreased on a HFD. During early phase of differentiation, LSD1 controls adipogenesis via cooperation with C/ebp β . C/ebp β in concert with Prdm16 induces the beige fat programme. In cooperation with Nrf1 and Pgc-1 α , LSD1 promotes mitochondrial biogenesis and OXPHOS. LSD1 reinforces adipogenesis via *Ppar γ* /*Rxr α* /Pgc-1 α by positively regulating metabolism (glycolysis, TCA cycle, and β -oxidation).

Figure 40. LSD1 occupancy of the indicated promoters of beige adipogenesis inducers in 3T3-L1(Ctrl) and 3T3-L1(Tg) cells at days 0 and 7 of differentiation, and differential expression of the indicated genes between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation. (FC) Logarithmic fold change.

EXAMPLES

Results

LSD1 promotes formation of functional beige fat

To investigate physiological functions of LSD1 in vivo, we analysed transgenic (Tg) mice ubiquitously expressing human LSD1 under the control of the Rosa26 promoter (Fig. 7a). Macroscopic inspection revealed intense browning of white fat pads of Tg mice (Fig. 1a). Detailed histological analyses showed the presence of multilocular brown or beige fat islets in all types of WAT [i.e. epididymal (ep), inguinal (ing), perimuscular (pm), and retroperitoneal (rp) WAT], whereas the morphology of interscapular BAT was not altered

(Fig. 1a). Western blot, qRT-PCR, and immunofluorescence analyses confirmed elevated LSD1 levels in WAT and BAT of Tg compared to control mice (Fig. 1b, and Fig. 7b-d).

Consistent with the appearance of brown or beige adipocytes in WAT of Tg mice, analyses of transcript and protein levels revealed significantly increased expression of *Prdm16*, *Pgc-1 α* , *Ucp1*, and several genes involved in oxidative metabolism (Fig. 1b,c, and Figs. 7e, and 8). Of note, elevated amounts of LSD1 did not result in altered transcript levels of *Prdm16*, *Pgc-1 α* , *Ucp1*, and oxidative markers in BAT and the metabolically active tissues muscle and liver, thus uncovering selective action of LSD1 in WAT (Fig. 9). Importantly, Tg mice expressing a catalytic inactive mutant of LSD1 (Tg^{Mut}, Fig. 10a)³⁶ show normal appearance of WAT, no signs of browning and unaltered expression of *Prdm16*, *Pgc-1 α* , *Ucp1*, and oxidative markers (Fig. 1c, and Figs. 8 and 10b,c), demonstrating that the demethylase activity is essential for the LSD1-induced phenotype.

Next, we screened WAT of Tg mice for the presence of Myf5, a marker of brown adipocyte precursors²⁰. Since we did not observe Myf5-positive preadipocytes (Fig. 7e), we hypothesised that the islets emerged from a non-Myf5 lineage and thus might represent beige fat cells. Consequently, we compared the expression pattern of beige, brown, and white fat-selective marker genes in Tg and control mice. The expression of beige fat-selective markers was significantly upregulated in white fat pads of Tg mice (Fig. 1b,d, and Figs. 7c and 11), whereas no alterations in the metabolically active tissues BAT, muscle, and liver (Fig. 12), or in WAT of Tg^{Mut} mice (Fig. 1d, and Figs. 10c and 11) were observed. Furthermore, the levels of brown fat-selective, adipogenic, and white fat-selective markers were not altered in WAT of Tg mice (Fig. 1d and Figs. 6c, 13, and 14). Thus, the gene expression profile identifies the LSD1-induced adipocytes as beige fat cells.

Ultrastructure analyses revealed an increased number of hypotrophic lipid droplets (Fig. 1e), as well as dramatically elevated mitochondria size and number (Fig. 1e,f, and Fig. 15a) in beige adipocytes of Tg mice. These findings were corroborated by an increased ratio between mitochondrial *cytochrome C oxidase 2* (*Cox2*) DNA and *nuclear fatty acid synthase* (*Fasn*) DNA (Fig. 15b). In addition, determination of the activities of succinate dehydrogenase (Sdh, mitochondria complex II) and Cox (mitochondria complex IV), two key enzymes of oxidative phosphorylation (OXPHOS), revealed a significantly increased mitochondrial oxidative capacity in WAT of Tg mice (Fig. 1g and Fig. 15c). Together, our observations demonstrate that elevated expression of enzymatically active LSD1 results in the formation of thermogenically active beige fat islets in WAT.

LSD1 Tg mice show limited weight gain and improved glucose tolerance and insulin sensitivity in response to a high-fat diet

To investigate whether the presence of beige fat has physiological consequences, we subjected Tg mice on regular diet (RD) or high-fat diet (HFD) to metabolic analyses. On RD, Tg mice and their control littermates did not display any notable differences in total body weight or in the weight of specific tissues and had a similar food intake (Fig. 16a-c). In contrast, during HFD feeding Tg mice gained significantly less weight (~20 %) than their control littermates (Fig. 16d). Body composition analyses assessed by quantitative Nuclear Magnetic Resonance Spectroscopy (qNMR) after 15 weeks of HFD showed that Tg animals had accumulated less fat, resulting in a higher lean/fat mass ratio compared to control mice (Fig. 16e). These data were corroborated by a decreased epWAT mass (Fig. 16f). In accordance, histological analyses revealed adipocyte hypotrophy as well as the presence of beige fat cells and increased Ucp1 levels in Tg mice (Fig. 16g,h). The limited weight gain of Tg mice was not associated with decreased food intake (Fig. 17a) or altered physical activity (Fig. 17b). However, we observed higher energy expenditure (determined by oxygen consumption, VO_2) in Tg mice (Fig. 17c). CO_2 production (VCO_2) was not altered, resulting in a decreased respiratory quotient (RQ, VCO_2/VO_2 ratio), demonstrating a shift in fuel consumption from carbohydrate to fatty acid usage (Fig. 17d,e). Calorimetric parameters deduced from these analyses indicated that heat production was increased in Tg mice fed a HFD (Fig. 17f). Taken together, these data show that Tg mice are less susceptible to obesity on HFD due to increased energy expenditure.

Diet-induced obesity is frequently associated with glucose intolerance and progressive metabolic dysfunction³⁷. Notably, Tg mice on HFD displayed decreased blood glucose levels (Fig. 17g), associated with improved glucose tolerance relative to control mice (Fig. 17h). Tg mice were also more insulin sensitive, as determined by insulin sensitive test (Fig. 17i), showing that Tg mice are more resistant to HFD-induced type-2 diabetes. These effects were not observed in cohorts on RD (Fig. 17j-l). The blood content in triglycerides, free fatty acids (FFA), and cholesterol was not altered in both RD- and HFD-fed animals (Fig. 17g,j). In summary, these observations demonstrate that increased LSD1 levels results in raised energy expenditure, which counteracts HFD-induced obesity and type-2 diabetes associated dysfunction.

LSD1 levels are regulated by environmental cues

Interestingly, LSD1 protein levels decreased upon HFD in control mice (Fig. 2a), suggesting the existence of regulatory mechanisms controlling physiological amounts of LSD1. Thus, we asked whether other extracellular cues might affect LSD1 levels in wild-type mice. Since cold exposure or treatment of mice with the β 3-adrenergic agonist CL316,243 have previously been shown to promote beige fat formation in WAT^{19,20,32}, we analysed whether protein levels of LSD1 in WAT of mice respond to these stimuli. In both experimental settings, we observed the appearance of multilocular beige adipocytes together with increased LSD1 protein levels in WAT (Fig. 2b-e and Fig. 18a-c), which was not observed in the other metabolically active tissues BAT, muscle, and liver (Fig. 18c). These in vivo data reveal an increase in the amount of LSD1 in WAT as physiological response to environmental challenges such as cold stress or β 3-adrenergic stimulation.

Beige adipogenesis is impaired in *LSD1*^{+/-} mice

Our results suggest that elevated levels of LSD1 initiate a transcriptional cascade that induces the formation of functional beige adipocytes in WAT, which implies that β 3-adrenergic signalling should not efficiently induce beige fat islets in mice lacking or expressing reduced levels of endogenous LSD1. Since ubiquitous *LSD1*-deficient mice die before day E7.5 of embryonic development³⁻⁶, we engineered a conditional *LSD1* allele by flanking exon 1 with loxP sites and deleted *LSD1* by crossing mice harbouring the conditional allele to the well-described *aP2-Cre* deleter strain³⁸, which mediates Cre recombination specifically in WAT and BAT (*LSD1*^{aP2-Cre}, Fig. 19a). Of importance for this study, Cre activity is not restricted to mature adipocytes, but has been observed in white and brown adipocyte precursors³⁹. *LSD1*^{aP2-Cre} mice show a complete absence of white fat pads (Fig. 19b), while BAT is developed, but displays low lipid accumulation (Fig. 19c,d). To demonstrate that the absence of WAT in *LSD1*^{aP2-Cre} mice is due to cell autonomy of LSD1, we crossed mice harbouring the conditional *LSD1* allele to the *Rosa26-CreERT* deleter strain⁴⁰, which allows tamoxifen (Tx)-inducible Cre recombination (*LSD1*^{Rosa26-CreERT}). Adipocyte precursors of the stromal-vascular fraction (SVF) from control and *LSD1*^{Rosa26-CreERT} mice were isolated, treated with Tx for 5 days, and then induced to undergo adipogenesis. As shown in Fig. 19e,f, *LSD1*-deficient cells of the SVF neither expressed markers of mature adipocytes nor accumulated lipid droplets, which is accordance with the absence of WAT in *LSD1*^{aP2-Cre} mice. While the phenotype of these mice requires more detailed future analyses, a likely explanation for the complete absence of WAT in *LSD1*^{aP2-Cre} mice is an essential role of LSD1 in adipocyte differentiation.

Together, our data provide in vivo evidence for an essential and cell autonomous function of LSD1 in the control of white adipogenesis.

However, neither ubiquitous nor adipose-specific *LSD1* knockout mice were suitable models to validate our hypothesis that β 3-adrenergic signalling should not efficiently induce beige fat islets in mice having reduced levels of LSD1. Therefore, we chose heterozygous mice (*LSD1*^{+/-}) (Fig. 20a), in which LSD1 mRNA and protein levels are significantly reduced in WAT and BAT (Fig. 3a-c and Fig. 20b). Compared to control mice, no apparent difference is observed in the morphology of white fat pads of *LSD1*^{+/-} mice (Fig. 3b and Fig. 20c). Transcript levels of the oxidative markers *Cidea*, *Prdm16*, *Pgc-1 α* , and *Ucp1* are significantly reduced in fat pads of *LSD1*^{+/-} mice (Fig. 3c and Fig. 21a), whereas adipogenic and white fat-selective markers are not affected (Fig. 21b,c).

Importantly, treatment of *LSD1*^{+/-} mice with the β 3-selective adrenergic agonist CL316,243 results in fewer clusters of beige fat cells in WAT compared to control mice (Fig. 3b and Fig. 20c). Accordingly, qRT-PCR analyses show that treatment of control mice with CL316,243 significantly increases expression of *Cidea*, *Prdm16*, *Pgc-1 α* , and *Ucp1* as well as that of beige fat-selective markers in WAT, whereas adrenergic induction is impaired in *LSD1*^{+/-} mice (Fig. 3c and Fig. 21a,d). In comparison, expression of white fat-selective and adipogenic markers is not significantly affected (Fig. 21b,c). These in vivo results demonstrate that reduction of LSD1 strongly impedes the efficient induction of the beige fat programme by β 3-adrenergic signalling, thus establishing LSD1 as an important mediator of this pathway.

***LSD1*^{+/-} mice are prone to obesity and type-2 diabetes**

Our data led us to the question whether *LSD1*^{+/-} mice possess decreased metabolic activities compared to control mice and are prone to obesity and type-2 diabetes when challenged with HFD. Upon HFD, *LSD1*^{+/-} mice gained substantially more weight than their age-matched control littermates (Fig. 3d) despite similar food intake (Fig. 22a). Consistent with the reduced LSD1 protein levels, *Ucp1* protein levels were decreased in *LSD1*^{+/-} mice (Fig. 3e). qNMR analyses revealed that the body fat content was 16 % higher in *LSD1*^{+/-} mice than in control littermates (Fig. 22b). In agreement with these results, histological analyses revealed adipocyte hypertrophy (Fig. 3f and Fig. 22c). Increased body fat mass was neither due to altered muscle oxidative capacities as shown by assaying NADH dehydrogenase activity in gastrocnemius muscle nor to decreased mobility (Fig. 22d,e). Energy expenditure assessed by oxygen consumption (VO_2) (Fig. 23a) as well as CO_2 production (VCO_2) (Fig. 23b) was decreased in *LSD1*^{+/-} mice leading to a higher

respiratory quotient (RQ) (Fig. 23c). This reveals a shift in fuel consumption from fatty acid to carbohydrate usage. Calorimetric parameters deduced from these analyses indicated that heat production was lower in *LSD1*^{+/-} mice fed a HFD (Fig. 23d). Blood glucose, triglyceride, and free fatty acid (FFA) levels were higher in *LSD1*^{+/-} than in control mice upon HFD, whereas cholesterol levels were similar (Fig. 23e). Importantly, insulin sensitivity and glucose uptake were significantly reduced in *LSD1*^{+/-} mice (Fig. 3g,h), indicating that *LSD1*^{+/-} mice are prone to type-2 diabetes. Of note, we did not observe such alterations in mice fed a RD (Fig. 23f-h). In summary, the in vivo analyses of *LSD1*^{+/-} mice demonstrate that decreased LSD1 levels lead to altered metabolic capacities resulting in increased susceptibility to obesity and type-2 diabetes.

LSD1 is a cell-autonomous regulator of adipogenesis

To determine whether decreased oxidative capacities observed in WAT of *LSD1*^{+/-} mice are due to cell-autonomous dysfunctions of the fat tissue, we analysed adipocyte precursors from the SVF of *LSD1*^{+/-} and control mice. Upon differentiation, primary adipocytes from *LSD1*^{+/-} mice carried increased lipid content compared to control (Fig. 24a). In accordance with this observation, *LSD1*^{+/-} adipocytes expressed increased levels of general adipogenic and white fat-selective markers (Fig. 24b) and expression of genes involved in thermogenesis, including *Prdm16* and *Ucp1* was reduced in *LSD1*^{+/-} adipocytes (Fig. 24b).

Similarly, to investigate cell autonomy of beige fat formation in Tg mice, adipocyte precursors from the SVF of Tg and control mice were induced to undergo adipogenesis. Tg and control adipocyte cultures expressed equivalent levels of general adipogenic, white fat-selective, and brown fat-selective markers (Fig. 24c). In contrast, elevated levels of LSD1 in primary Tg adipocyte induced expression of genes involved in oxidative metabolism, including *Prdm16*, *Pgc-1α*, and *Ucp1*, and beige fat-selective markers (Fig. 4a). Taken together, these data demonstrate that LSD1 regulates oxidative capacities of adipocytes and beige adipogenesis in a cell-autonomous manner.

To establish a cell culture model for mechanistic studies, we transduced C3H-10T1/2 mouse mesenchymal cells and 3T3-L1 preadipocytes with lentivirus driving constitutive expression of LSD1 (Tg), LSD1 inactive mutant (Tg^{Mut}), or empty control virus (Ctrl) (Fig. 25a,b). Expression levels of genes involved in oxidative metabolism such as *Prdm16*, *Pgc-1α*, and *Ucp1* and of beige fat-selective markers were increased upon differentiation of 3T3-L1(Tg) and C3H-10T1/2(Tg) compared to Ctrl cells (Fig. 4b and Fig. 25b,c). Vice versa, both Tg cell lines showed slightly decreased transcript levels of

white adipocyte-selective markers and similar transcript levels of general adipogenic markers (Fig. 25d,e). In agreement with the in vivo data, oxidative and beige fat-selective markers were not altered in C3H-10T1/2(Tg^{Mut})-derived adipocytes expressing the catalytically inactive LSD1 mutant (Fig. 25b).

Analysis of the oxidative capacities of differentiated 3T3-L1(Tg) and 3T3-L1(Ctrl) cells by staining with the fluorescent dye JC-1 revealed that 3T3-L1(Tg) cells exhibit a significantly increased respiratory activity indicated by red fluorescence (Fig. 4c and Fig. 26a). More intense green fluorescence revealed an augmentation in mitochondrial mass (Fig. 26b). The increased ratio between red and green fluorescence (FL-2/FL-1) in adipocytes derived from 3T3-L1(Tg) cells demonstrated an enhanced mitochondrial activity (Fig. 26c). Thus, consistent with our observations in mice and primary adipocytes from the SVF, increased LSD1 expression suffices to induce the beige fat programme in vitro. Consequently, we used 3T3-L1 and C3H-10T1/2 cells for further mechanistic studies.

To determine whether LSD1 promotes the beige fat programme via commitment of white adipocyte precursors or transdifferentiation of mature adipocytes, we transduced 3T3-L1 cells with lentivirus driving doxycyclin-inducible expression of LSD1 (LSD1^{ind}). LSD1 expression was induced at days 3 or 7 of differentiation. While we observed a strong increase in LSD1 levels upon doxycyclin treatment (Fig. 27a), transcript levels of oxidative markers such as *Prdm16*, *Pgc-1α*, and *Ucp1*, adipogenic, white fat-selective, and beige fat-selective markers (Fig. 27) were not affected by LSD1 induction. These data show that LSD1 does not induce the beige fat programme once adipogenesis has been initiated. Thus, LSD1 appears to act at an early time point by triggering the commitment of adipocyte precursors towards the beige lineage.

LSD1 targets genes that induce the beige fat programme and account for beige adipocyte metabolism

Beige adipogenesis requires induction of adipogenic factors and activation of specific gene sets facilitating thermogenesis and energy consumption. To identify LSD1 direct target genes that mediate induction of the beige fat programme and account for beige adipocyte metabolism, we combined chromatin immunoprecipitation followed by massive parallel sequencing (ChIP-seq) and global transcriptome analysis (RNA-seq) of 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation.

In ChIP-seq analyses, 3024 high-confidence LSD1 peaks [false discovery rate (FDR) less than 1 %] were identified at day 0 in 3T3-L1(Ctrl) cells, with the majority (87 %) located at the promoter (defined as ± 2000 bp around the transcription start site) of 2607

genes (Fig. 5a and Fig. 28a). At day 7, we identified 8303 LSD1 peaks, of which 85 % are located at the promoter of 6904 genes (Fig. 5a and Fig. 28b). In 3T3-L1(Tg) cells, the number of LSD1 peaks at day 0 reached 13997, with 60 % located at the promoter of 8145 genes (Fig. 5b and Fig. 28a), while at day 7, 27221 LSD1 peaks were identified with 43 % located at the promoter of 9840 genes (Fig. 5b and Fig. 28b).

The comparison of genes with LSD1 promoter occupancy in 3T3L1(Ctrl) cells showed that the vast majority [2233 out of 2607 (86 %)] of genes bound at day 0 is still occupied at day 7 (Fig. 5c). On the other hand, 4671 out of 6904 genes (68 %) are associated with LSD1 at day 7 only. Importantly, the comparison with 3T3-L1(Tg) cells revealed that most of the genes occupied in 3T3-L1(Ctrl) cells at day 7 are already associated with LSD1 in 3T3-L1(Tg) cells at day 0 [5689 out of 6904 genes (82 %)] (Fig. 5d). Thus, promoter occupancy by LSD1 in undifferentiated 3T3-L1(Tg) cells at day 0 resembles that in differentiated 3T3-L1(Ctrl) cells at day 7.

Next, we established differential gene expression patterns for 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at days 0 and 7 of differentiation. At day 0, our RNA-seq analyses revealed 1929 genes differentially expressed between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells (Fig. 5e) [p-value < 10^{-5} and logarithm base 2 of fold change (FC) < 0.7 or > 1.4]. Out of these, 1068 genes were found in the intersection between differentially expressed and LSD1-occupied genes in 3T3-L1(Tg) cells at day 0 (Fig. 5e). Pathway analyses for the 1929 differentially expressed and the 1068 genes in the intersection revealed "adipogenesis" as significantly enriched cluster (Fig. 28c). While 3T3-L1(Tg) cells might be committed to become beige adipocytes due to these differentially expressed genes, they are apparently not sufficient to induce adipocyte maturation, for which additional adipogenic stimuli are required.

At day 7, the number of genes differentially expressed between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells increases to 5765 (Fig. 5f). In the intersection between these differentially expressed and LSD1-occupied genes in 3T3-L1(Tg) cells, 4091 genes were found. Importantly, pathway analyses for the 5765 differentially expressed and the 4091 intersection genes unravelled the major metabolic pathways "electron transport chain", "oxidative phosphorylation", "tricarboxylic acid (TCA) cycle", "glycolysis and gluconeogenesis", and "fatty acid beta oxidation" in addition to "adipogenesis" (Fig. 28d,e). Furthermore, the intersection between LSD1 promoter occupancy in 3T3-L1(Ctrl) cells at day 7, 3T3-L1(Tg) cells at day 0, and differentially expressed genes at day 7 revealed that 2406 genes with premature promoter occupancy at day 0 are indeed deregulated in differentiated 3T3-L1(Tg) cells (Fig. 28f). Pathway analyses confirmed that these genes

account for metabolic properties of 3T3-L1(Tg) cells (Fig. 28g). Together, we conclude that increased LSD1 levels result in premature chromatin occupancy, which upon adipogenic stimuli causes deregulated gene expression accounting for differentiation and metabolic properties of beige adipocytes.

5 A detailed inspection of the identified metabolic pathways uncovered that in 3T3-L1(Tg) cells LSD1 occupies and positively regulates the expression of most genes involved in oxidative phosphorylation (84/92 genes), TCA cycle (10/12 genes)⁴¹, fatty acid β -oxidation (3/4 rate limiting Cpt enzymes, and 22/35 genes of β -oxidation), and glycolysis (17/21 genes) (Fig. 29a and Table 1). Consistently, expression of representatives of these
10 pathways is increased in C3H-10T1/2(Tg) and 3T3-L1(Tg) cells and in beige fat of Tg mice in vivo (Figs. 8, 25b,c, and 29b-d).

Next, we asked whether known upstream regulators of the identified metabolic pathways are also targeted by LSD1. A central player in the initiation of signalling events is AMP kinase (Ampk, also referred to as Prka) (schematically depicted in Fig. 30a). Active
15 Ampk phosphorylates *Acaca*, which in turn activates Cpt1, the rate-limiting enzyme of β -oxidation, and positively regulates *Pgc-1 α* expression. *Pgc-1 α* and *Pgc-1 β* act as key regulators of oxidative metabolism, promoting β -oxidation, glycolysis, and TCA cycle. *Pgc-1 α* also serves as a coactivator for Nrf1, a key player in the transcriptional control of nuclear genes required for respiration, mitochondrial DNA transcription and replication via
20 Tfam. Importantly, in 3T3-L1(Tg) cells LSD1 is present at the promoter of ~90 % of Ampk subunits (Table 1), as well as at the promoter of *Acaca*, *Pgc-1 α* , *Pgc-1 β* , *Nrf1*, and *Tfam* (Fig. 30b). In all cases, our RNA-seq results and independent qRT-PCR analyses showed that expression of these genes is increased in 3T3-L1(Tg) compared to 3T3-L1(Ctrl) cells at day 7 (Fig. 4b and Figs. 25c, 30b, and 31a,b,d) as well as in beige fat of Tg mice (Figs.
25 1c, 4a and Figs. 8, 31a,c,d). Furthermore, LSD1 occupies and positively regulates the genes required for uncoupled respiration (*Ucp2* and *Ucp3*) (Fig. 31e), which contributes to increased heat production by mitochondria. Taken together, our ChIP-seq, RNA-seq, and qRT-PCR analyses demonstrate that increased LSD1 levels regulate gene programmes essential for mitochondrial biogenesis and metabolic pathways thereby accounting, at least
30 in part for, the phenotype of 3T3-L1(Tg) cells in vitro and beige adipocytes of Tg mice in vivo.

Table 1. Regulation of metabolic pathways by LSD1. Pathway, total number of genes encoding pathway proteins, promoter occupancy by LSD1 in 3T3-L1(Ctrl) and 3T3-L1(Tg)

cells at day 0, and average logarithmic fold change (FC) of differential gene expression between 3T3-L1(Tg) and 3T3-L1(Ctrl) cells at day 7 of differentiation.

Pathway	Total genes	Gene promoters occupied by LSD1		Average FC day 7
		3T3-L1(Ctrl) cells day 0	3T3-L1(Tg) cells day 0	
Ampk (Prka) sub-units	8	3 (37.5 %)	7 (87.5 %)	2.0
β-oxidation	35	7 (20.0 %)	22 (62.9 %)	2.7
Glycolysis	21	5 (23.8 %)	17 (81.0 %)	2.1
TCA cycle	12	2 (16.7 %)	10 (83.3 %)	2.6
Complex I	41	9 (22.0 %)	38 (92.7 %)	2.9
Complex II	4	1 (25.0 %)	3 (75.0 %)	2.9
Complex III	9	2 (22.2 %)	9 (100. %)	3.3
Complex IV	21	6 (28.6 %)	18 (85.7 %)	2.4
Complex V	17	3 (17.6 %)	16 (94.1 %)	2.4
OXPHOS (Complexes I-V)	92	21 (22.8 %)	84 (91.3 %)	2.7

5 LSD1 regulates mitochondrial functions through Nrf1

To identify transcription factors that cooperate with LSD1 in the control of beige adipogenesis and beige adipocyte metabolism, we performed HOMER motif searches⁴². These analyses revealed that in 3T3-L1(Ctrl) cells at day 7 and in 3T3-L1(Tg) cells at days 0 and 7 promoter occupancy of LSD1 significantly correlates with the presence of binding sites for the transcription factor Nrf1 (Fig. 6a). To investigate whether LSD1 and Nrf1 coordinately control gene expression, we first established by ChIP-seq the genome-wide binding pattern of Nrf1 in 3T3-L1 cells at days 0 and 7 of differentiation. At day 0, we identified 2078 peaks (Fig. 6b), with the majority (67 %) found at the promoter of 1383 genes (Fig. 6c). At day 7, 1629 Nrf1 peaks were observed (Fig. 6b) with 91 % located at the promoter of 1485 genes (Fig. 6c). 914 genes with Nrf1 peaks at the promoter were found in the intersection between days 0 and 7 (Fig. 6c). Whereas only 427 out of 1383 (31 %) gene promoters bound by Nrf1 are cooccupied by LSD1 at day 0 (Fig. 6d), the majority (1178 out of 1485, 79 %) is bound by LSD1 at day 7 (Fig. 6d). The intersection of genes occupied by Nrf1 at days 0 and 7, and LSD1 at day 7 revealed a robust overlap, i.e.

736 out of 914 (81 %) genes (Fig. 6e). This finding suggests that LSD1 and Nrf1 coordinately control gene expression during 3T3-L1 cell differentiation. Pathway analyses for this common gene set (736 genes) revealed “electron transport chain” and “oxidative phosphorylation” among the top scoring clusters as exemplified by components of the mitochondrial electron transport chain (Fig. 32). Of note, we also identified the *Nrf1* gene among the prominent LSD1 targets (Fig. 30b). RNA-seq, qRT-PCR, and Western blot analyses showed increased Nrf1 transcript and protein levels in differentiated 3T3-L1(Tg) cells and beige fat of Tg mice (Figs. 31a-c). In contrast, Nrf1 levels were not altered in skeletal muscle and liver of Tg mice (Fig. 33). Short interfering RNA (siRNA)-mediated knockdown of Nrf1 in 3T3-L1(Tg) cells significantly decreased expression of *Prdm16*, *Pgc-1 α* , and *Ucp1*, as well as representative genes of the mitochondrial electron transport chain (Fig. 34). Together, these data suggest that LSD1 promotes mitochondrial respiratory properties of fat cells, at least in part, by induction of and in cooperation with Nrf1.

LSD1 regulates beige adipogenesis through C/ebp β and Ppar γ /Rrx α

HOMER motif searches revealed a significant enrichment of C/ebp β , Ppar γ , and Rrx α binding sites for 3T3-L1(Tg) cells at day 7, whereas for 3T3-L1(Ctrl) cells these binding sites were not identified among the top scoring motifs (Fig. 6a). Since C/ebp β and Ppar γ , in cooperation with *Prdm16* or *Pgc-1 α* , have been shown to promote the browning of fat cells^{16,20}, this observation suggested that in 3T3-L1(Tg) cells LSD1 acts in cooperation with C/ebp β and Ppar γ /Rrx α to regulate early and late phases of beige adipogenesis, respectively. Indeed, previously reported C/ebp β ChIP-seq data⁴³ from 3T3-L1 cells illustrated that at day 0, 729 out of 3285 (22 %) of C/ebp β target genes are cooccupied by LSD1 (Fig. 35a), whereas at day 3, 2034 out of 3287 (62 %) of C/ebp β targets are cooccupied by both proteins (Fig. 6f). Pathway analyses of the common target genes at day 3 of differentiation suggested that LSD1 and C/ebp β control adipogenesis as well as main metabolic pathways (Fig. 35b). As shown by ChIP-seq and RNA-seq analyses, *C/ebp α* , *C/ebp β* , and *C/ebp δ* are direct LSD1 target genes, and LSD1 upregulates expression of *C/ebp α* at day 7, and *C/ebp β* at days 0 and 7 of 3T3-L1 cell differentiation (Fig. 35c). These data were corroborated in both, differentiated 3T3-L1(Tg) cells and beige fat of Tg mice (Fig. 35d-f). In contrast, *C/ebp* transcript levels were neither altered in skeletal muscle nor in liver of Tg mice (Fig. 33). Finally, RNAi-mediated knockdown of *C/ebp β* in 3T3-L1(Tg) cells significantly decreased expression of the beige-selective gene

programme (Fig. 36) demonstrating that C/ebp β , at least in part, mediates LSD1-controlled beige adipogenesis.

C/ebp β and C/ebp δ also promote expression of *Ppar γ* ⁴⁴. Ppar γ /Rxr heterodimers act as a transcriptional activator of numerous adipocyte-specific genes⁴⁵. ChIP-seq analysis of Ppar γ and Rxr α in 3T3-L1 cells⁴⁶ confirmed that at day 0 only a minimal fraction (0.5 %) of LSD1 target genes is cooccupied by Ppar γ /Rxr α (Fig. 37a). However, at day 7, Ppar γ /Rxr α occupy 1831 out of 6904 (27 %) of LSD1 target genes (Fig. 6g). These 1831 common target genes define “adipogenesis” (Fig. 37b) in addition to the main metabolic pathway clusters, as exemplified by representative genes of fatty acid β -oxidation (Fig. 37c), demonstrating that LSD1 in concert with Ppar γ /Rxr α controls late adipogenesis. Furthermore, LSD1 binds to the *Ppar γ* and *Rxr α* gene promoter (Fig. 38a) and induces expression of Ppar γ and Rxr α in 3T3-L1(Tg) cells and beige fat of Tg mice (Fig. 38b-d).

In summary, our data show that LSD1 controls beige adipogenesis by increasing mitochondrial biogenesis and respiration via Nrf1, inducing early adipogenesis through C/ebp β , and enforcing late adipogenesis by Ppar γ /Rxr (Fig. 39).

Methods

Mouse studies

All mice were housed in the pathogen-free barrier facility of the University Medical Center Freiburg in accordance with institutional guidelines and approved by the regional board. Mice were maintained in a temperature- and humidity-controlled animal facility with a 12-hour light/dark cycle, free access to water, and a standard rodent chow (Kliba, breeding, 3807). The high-fat diet (HFD) study was carried out with a chow containing 4.056 kcal/kg (fat: 1.600 kcal/kg and sucrose: 1.600 kcal/kg; Research Diets). HFD was given to mice at 5 weeks of age. Mice were analysed at 25 weeks of age. For cold exposure experiments, mice were maintained at 10 °C with a 12 hour light/dark cycle, free access to water, and a standard rodent chow. Animals were killed by cervical dislocation, tissues were immediately collected, weighted, frozen in liquid nitrogen or processed for further analyses. Nomenclature for dissected adipose depots was used according to Seale et al.¹⁷. Epididymidal WAT (epWAT): prominent bilateral intra-abdominal visceral depots in male mice attached to the epididymis. Inguinal WAT (ingWAT): bilateral superficial inguinal depots between the skin and muscle fascia just anterior to the lower segment of the hind limbs. Perimuscular WAT (pmWAT): depots located on the upper part of the quadriceps muscle. Retroperitoneal WAT (rpWAT): bilateral depots in abdominal cavity behind the

peritoneum on the dorsal side of the kidney. Interscapular BAT (BAT): most prominent depot of brown adipocytes in rodents, found between the scapulae. In vivo experiments including food consumption, serum analysis, glucose tolerance and insulin sensitivity tests, temperature measurements, body lean and fat contents, and energy expenditure were described⁴⁸. CL316,243 (Sigma-Aldrich) was injected intraperitoneally at 1 mg/kg.

Generation of Rosa26-*LSD1* and Rosa26-*LSD1* inactive mutant transgenic mice

To generate transgenic (Tg) mice or inactive mutant transgenic (Tg^{Mut}) mice, the complete human wild type or K661A/W751A/Y761S mutated *LSD1* cDNA was cloned 3' to the Rosa26 promoter/enhancer (Figs. 7a and 10a, respectively). Tg and Tg^{Mut} mice were generated by pronuclear injection into fertilized FVB oocytes. For analyses wild-type littermates were used as controls. Mice were genotyped by PCR amplification of genomic DNA extracted from tail biopsies using the DirectPCR extraction kit (Viagen) with primers for detection of the transgene Rosa26-*LSD1* or Rosa26-*LSD1*^{Mut} (Table 2).

Table 2 Primers used for genotyping

Gene	Sense	Primer 5'-3'
Rosa26- <i>LSD1</i>	fw	AATGCCTTCGAATTCAGCAC
Rosa26- <i>LSD1</i>	rev	CCTTGTCATCGTCGTCCTTG
Rosa26- <i>LSD1</i> ^{Mut}	fw	TCTTCTTTGCGGGAGAACAT
Rosa26- <i>LSD1</i> ^{Mut}	rev	CGCCTCTAGCTCACATGCTT
<i>LSD1</i> WT/L2	fw	CCTCAGTAGGCCTGGTTTGT
<i>LSD1</i> WT/L2	rev	TTGGTTTTGGTTGACCCTTC
<i>LSD1</i> L-	fw	CCGTGGAAATTCGTGCACTC
<i>LSD1</i> L-	rev	GCAGGCGGTTTGAAATGTATTC
<i>Cre</i>	fw	TTCCCGCAGAACCTGAAGATGTTCG
<i>Cre</i>	rev	GGGTGTTATAAGCAATCCCCAGAAATGC

Generation of conditional *LSD1* mice

The targeting strategy for the conditional deletion of the first exon of *LSD1* (*LSD1*^{tm1Schüle}) is available upon request. To delete *LSD1*, conditional *LSD1* mice were crossed to either Rosa26-*Cre*^(Tg/0) transgenic mice that ubiquitously express the Cre recombinase⁴⁹ (Fig. 20a), aP2-*Cre* mice³⁸ to selectively ablate *LSD1* in adipose tissue, or Rosa26-

CreERT^(Tg/0) transgenic mice, which mediates tamoxifen-inducible Cre recombination (*LSD1*^{Rosa26-CreERT})⁴⁰. Mice were maintained on a mixed C57/Bl6NCrl;129S2/Sv background. Homozygous conditional mice were used as controls. Mice were genotyped with primers for detection of the conditional *LSD1* and the deleted alleles (Table 2).

5

Analysis of mitochondrial activity

Tissues obtained from mice were immediately frozen in liquid nitrogen. The activities of the respiratory chain enzyme complex II (Sdh) and complex IV (Cox) were determined as described⁵⁰.

10

Food consumption

Mice were individually housed. Food pellets (150 g) were delivered and weighed after 1 week. Weekly food consumption was calculated by subtracting the final from the initial pellet weight.

15

Serum analysis

Blood was collected from retro orbital sinus after a 6 hr fast that started at the beginning of the light cycle. Serum glucose, cholesterol, triglyceride, and free fatty acid levels were analysed as described⁵¹.

20

Glucose tolerance and insulin sensitivity tests

Intraperitoneal glucose tolerance test (IPGTT) and insulin sensitivity test (IPIST) were performed with mice fed a RD or a HFD after 6 h or 16 h of fasting, respectively. For IPGTT, following measurement of the basal glucose level (time 0), mice were intraperitoneally injected with 20 % glucose in sterile saline solution (0.9 % NaCl) at a dose of 2 g glucose/kg body weight. Blood was collected from the tail vein after 15, 30, 45, 60, 90, and 120 min for glucose determination. For IPIST, mice were intraperitoneally injected with porcine insulin (0.5 U/kg; Sigma). Blood was collected at 15, 30, 60, and 90 min.

25

Body lean and fat content

Body lean and fat content were recorded in anaesthetized mice by quantitative nuclear magnetic resonance (qNMR, PIXIMUS, GE Medical Systems) according to the manufacturer's instructions.

30

Energy expenditure

Total activity, oxygen consumption (O_2) and carbon dioxide (CO_2) production were measured with a LabMaster (TSE systems) at 26 min intervals for 24 h. VO_2 and VCO_2 values were normalized to body mass. The respiratory quotient (RQ) corresponds to VCO_2/VO_2 . Heat (Cal/h) was calculated using the formula: Heat (H) = (Caloric Value x VO_2 x 0.001) / body weight x 0.75; (Caloric Value = $3.815 + 1.232 \times RQ$). Body temperature was measured with a rectal probe linked to a digital thermometer (Bioseb).

Histological and immunofluorescence analysis

Tissues were fixed in 10 % buffered formalin and embedded in paraffin. For immunofluorescence analyses, 5 μ m paraffin sections were deparaffinised, rehydrated, boiled in antigen unmasking solution (Vector laboratories, H-3300) for 10 min, cooled to room temperature, washed 3 times with PBS, 0.1 % Triton-X100 for 5 min, incubated for 1 h in 5 % FBS (Gibco, 10270-106) in PBS, 0.1 % Triton-X100, followed by overnight incubation at 4°C with anti-LSD1¹ (1/1000), anti-Myf5 (Santa Cruz, C-20, sc-302, 1/500), anti-Prdm16 (abcam, ab118573, 1/500), or anti-Ucp1 (abcam, ab10983, 1/200) antibody. Slides were then incubated with secondary antibody conjugated to Alexa546 (Invitrogen, 1/400) and mounted in aqueous medium (Fluoromount-G, SouthernBiotech, 0100-01) with DAPI (Sigma, D-9542, 1/1000). Between each step, sections were washed with PBS, 0.1 % Triton-X100.

For NADH-tetrazolium reductase activity staining, 10 μ m cryosections were incubated in 0.2 M Tris-HCl pH 7.4, containing 1.5 mM NADH (Roche) and 1.5 mM nitrobluetetrazolium (Sigma) for 15 min at 55°C, dehydrated, and mounted⁵².

For ultrastructural analyses samples were fixed by immersion in 2.5 % glutaraldehyde and 2.5 % paraformaldehyde in cacodylate buffer (0.1 M, pH 7.4), washed in cacodylate buffer for 30 min and kept at 4 °C. Post-fixation was performed with 1 % osmium tetroxide in 0.1 M cacodylate buffer for 1 h at 4 °C and dehydration through graded alcohol (50, 70, 90 and 100 %) and propylene oxide for 30 min each. Samples were embedded in Epon 812. Ultrathin sections were cut at 70 nm and contrasted with uranyl acetate and lead citrate and examined at 70 kV with a Morgagni 268D electron microscope. Images were captured digitally by a Mega View III camera (Soft Imaging System). Mitochondria number and cross section areas were determined with the Image J software (NIH).

RNA preparation and analysis

RNA was isolated with TRIzol Reagent (Invitrogen). Two micrograms of RNA were converted to cDNA with SuperScript II reverse transcriptase (Invitrogen) and polyT oligonucleotides according to the supplier's protocol. Quantitative RT-PCR was performed using the Abgene SYBR Green PCR kit (Invitrogen) according to the supplier's protocol. Data were analysed using the standard curve method⁵³. *36b4*, *Hprt*, *Tbp*, or β -actin were used for normalization. Primer sequences are given in Table 3.

RNA sequencing (RNA-seq)

RNA samples were sequenced by the standard Illumina protocol to create raw sequence files (.fastq files). We aligned these reads to the mm10 build of the mouse genome using TopHat version 2⁵⁴. The aligned reads were counted with the homer software (analyze RNA) and DEG's were identified using EdgeR⁵⁵ and DESeq version 1.8.3⁵⁶.

Protein preparation, Western blot analysis, and coimmunoprecipitation assays

Experiments were performed as described¹. Fat tissues were grounded in RIPA buffer [50 mM Tris pH 7.5, 1 % NP40, 0.5 % sodium deoxycholate, 0.1 % SDS, 150 mM NaCl, 5 mM EDTA, and protease inhibitor cocktail (45 µg/ml, Roche, 11 873 580 001)] at 4 °C. Homogenates were separated in 10 % polyacrylamide gels and blotted to Hybond nitrocellulose membranes (GE Healthcare). Membranes were decorated using following antibodies: anti-LSD1¹ (1/1000), anti-Prdm16 (abcam, ab118573, 1/500), anti-Pgc-1 (Santa-Cruz, H300, sc-13067, 1/1000), anti-Nrf1 (abcam, ab55744, 1/1000), anti-Ucp1 (abcam, ab10983, 1/1000), anti-Klhl13 (Santa-Cruz, H-286, sc-99119, 1/500), Fabp4 (Santa-Cruz, sc-18661, 1/2000), anti-Flag (Sigma, F3165, 1/500), anti-Ear2 (Proteintech, 60117-2-Ig, 1/400), anti-C/ebpβ (Santa-Cruz, sc-746, 1/500), anti-Ppary (AbD Serotec, AHP1461, 1/500), anti-Rxrα (Santa-Cruz, sc-553, 1/500), anti-β-Tubulin (Sigma, T6074, 1/10000), or anti-β-Actin (Sigma, A1978, 1/10000). Secondary antibodies conjugated to horseradish peroxidase (GE Healthcare) were detected using an enhanced chemiluminescence detection system (GE Healthcare). Protein levels were quantified using the Chemi Capt software (Pepqlab).

ChIP sequencing (ChIP-seq)

Chromatin immunoprecipitation experiments were performed using anti-LSD1 (20752, Schüle laboratory) or anti-Nrf1 (abcam, ab55744, lot GR 95770-1) antibodies, on protein A-Sepharose 4B (GE Healthcare) essentially as described⁵⁷. Libraries were prepared from

immunoprecipitated DNA according to standard methods. ChIP-seq libraries were sequenced using a HiSeq 2000 (Illumina) and mapped to the mm10 reference genome using bowtie 2⁵⁸. Data were further analysed using the peak finding algorithm MACS 1.41⁵⁹ using input as control. All peaks with FDR greater than 1 % were excluded from further analysis. The uniquely mapped reads were used to generate the genome-wide intensity profiles, which were visualized using the IGV genome browser⁶⁰. HOMER⁴² was used to annotate peaks, to calculate overlaps between different peak files, and for motif searches. The genomic features (promoter, exon, intron, 3' UTR, and intergenic regions) were defined and calculated using Refseq and HOMER. Genes annotated by HOMER were further used for a pathway analysis⁴². Previously reported ChIP-seq results for C/ebp β (GSE27826)⁴³, Ppar γ , and Rxr α (GSE13511)⁴⁶ were used for analysis.

Quantification of mitochondrial and nuclear DNA

Fat pads were digested overnight with Proteinase K and DNA was extracted with phenol-chloroform. Mitochondrial and nuclear DNA was amplified by quantitative PCR using Cox2 and *Fasn* primers (Table 3), respectively.

Plasmids

The following plasmids were used: pLenti4_Flag_HA_Puro, pLenti4_Flag_HA_Puro_LSD1, pRTS_Puro_GW, pRTS_Puro_GW-Flag_LSD1, pRTS_Puro_GW-Flag_LSD1-K661A-W751A-Y761S, pSlik-Neo, and pSlik-Neo_Flag_HA_LSD1. Plasmids were obtained by Gateway LRII cloning in pLenti4 vector (Invitrogen) or in a puromycin-selectable and doxycycline-inducible pRTS plasmid⁶¹ modified to contain a Gateway cassette, V5, and His tags. Cloning details can be obtained upon request.

Cell culture

Primary white fat stromal vascular and mature fat cells were fractionated according to published methods^{62,63}. Primary SV cells were cultured in DMEM/F12 containing 10% fetal bovine serum (FBS). For induction of CreERT recombinase, primary cells were treated with 4-hydroxy-tamoxifen (Sigma) at 0.2 μ M. Mouse 3T3-L1 and C3H-10T1/2 preadipocytes were maintained in Dulbecco's modified Eagle's medium (DMEM) or Eagle's minimal essential medium (EMEM), respectively, supplemented with 10 % FBS and glutamine. Differentiation of primary SV cells, 3T3-L1, and C3H-10T1/2 was induced by treatment of confluent cells (designated day 0) with an adipogenic mixture consisting of 10 μ g/ml insulin (Gibco), 1 μ M dexamethasone (Calbiochem), 10 μ M rosiglitazone

(Cayman) and 500 μ M isobutylmethylxanthine (Serva) in the presence of 10 % FBS. The differentiation medium was replaced 3 days later (day 3) with medium supplemented with 10 % FBS and 10 μ g/ml insulin for 2 days. Subsequently, the cells were cultured in the same medium for 2 more days (day 7). For the determination of mitochondrial metabolism

5 3T3-L1 cells were stained with fluorescent dye JC-1 (Invitrogen) followed by flow cytometric analysis. Following trypsin treatment, cells were exposed to 20 μ g/ml of JC-1 in culture medium for 15 min at 37 °C and suspended in PBS for fluorescence-activated cell sorting (FACS) analysis. Green and red fluorescent signals corresponding to mitochondrial mass (FL-1) and mitochondrial membrane potential (FL-2), respectively, were detected

10 using a FACS Canto cytometer (Becton Dickinson). 293FT cells were cultured in DMEM supplemented with 10 % FBS, non-essential amino-acids (Gibco) and glutamine (Gibco). Viral production was performed as described¹. 3T3-L1 cells were infected with pLenti4_Flag_HA_Puro, pLenti4_Flag_HA_Puro_LSD1, pSlik-Neo, or pSlik-Neo_Flag_HA_LSD1 virus and subsequently selected in medium containing 1 μ M puromycin (Sigma).

15 Stable transfection of C3H-10T1/2 with pRTS_Puro_GW, pRTS_Puro_GW-Flag_LSD1, or pRTS_Puro_GW-Flag_LSD1-K661A-W751A-Y761S was carried out in 6-well plates. Briefly, at 50-70 % confluence cell medium was changed for growth medium (DMEM, 10 % FBS, non-essential amino-acids and glutamine) for 3 h. Cells were then transfected with Eugene HD (Roche) and 750 ng of DNA in growth medium without FBS for 5 h at 37 °C.

20 FBS was then adjusted at 10 % and cells were selected using 0.5 μ M puromycin (Sigma). 3T3-L1 cells were transfected with 1 μ M siRNA against Nrf1 or unrelated control (Invitrogen) using DharmaFECT 1 (Thermo Scientific) according to the manufacturer's instructions. siRNA oligonucleotide sequences were as follows:

Nrf1 siRNA sense: 5'-UAUGGUAGCCAUGUGUUCAGUUUGG-3'

25 Control-Nrf1 siRNA sense: 5'-UAUUUGGAUGUACCUGUGGACUUGG-3'

C/ebp β siRNA sense: 5'-CCAAGAUGCGCAACCUGGAGACGCA-3'

Control-C/ebp β siRNA sense: 5'-CCAGUACGCCAAGUCGAGCAAGGCA-3'

Data analysis

30 Data are represented as mean + standard error of the mean (SEM). Significance (except Fig. 6a) was calculated by a two-tailed Student's t test.

Table 3. Primers used for qPCR analyses

Gene	Sense	Primer 5'-3'
Tbp	fw	GAAGCTGCGGTACAATCCAG
Tbp	rev	CCCCTTGTAACCTTCACCAAT
36B4	fw	GCGTCTGGCATTGTCTGT
36B4	rev	GCAAATGCAGATGGATCAGCC
Hprt	fw	AGGGCATATCCAACAACAACTT
Hprt	rev	GTTAAGCAGTACAGCCCCAA
Prdm16	fw	CCCCAACGCTCTCGGATCC
Prdm16	rev	CCGAAGCAGCGTTGCACAG
Pgc-1 α	fw	AAGTGTGGAACCTCTTGGAAGT
Pgc-1 α	rev	GGGTATCTTGGTTGGCTTTATG
Ucp1	fw	TGGCAAAAACAGAAGGATT
Ucp1	rev	CGAGTCGCAGAAAAGAAGC
Cidea	fw	TGCTCTCTGTATCGCCAGT
Cidea	rev	GCCGTGTTAAGGAATCTGCTG
Acads	fw	TCGCTGGTCCCTTCGTAGAT
Acads	rev	TGGGATGGGCTTCAAAATAG
Hadhb	fw	TTCCCAACTGCACTCTGCCCA
Hadhb	rev	AGCAGAAATGGAATGCGGACCCC
Fabp3	fw	TGACGCTGGACGGAGGCAAAAC
Fabp3	rev	GACGGAGCAGCCAGGTCACG
Ucp2	fw	ACCAAGGGCTCAGAGCATGCA
Ucp2	rev	AGGTCACAGCTCAGCACAGT
Ucp3	fw	ACTCCAGCGTCGCCATCAGGATTCT
Ucp3	rev	TAAACAGGAGAGACTTCAGCAACTT
Cpt1b	fw	CAGCTGGCTGGTTGTGTCA
Cpt1b	rev	TTGTGGAAGAAGAAAATGC
Acaca	fw	GGGCTGCTAAGGTGGAAGTA
Acaca	rev	AAGTTGAGGAAGATGTGGTT
Cox8b	fw	GAACCATGAAGCCAACGACT
Cox8b	rev	GCGAAGTTCACAGTGGTTC
Ear2	fw	CCTGTAAACCCAGAACTCCA
Ear2	rev	CAGATGAGCAAGGTGCAAA
Klh13	fw	AGAATTGGTTGCTGCAATACTCC
Klh13	rev	AAGGCACAGTTTCAAGTGCTG
Tbx1	fw	GGCAGGCAGACGAATGTTC
Tbx1	rev	TTGTCATCTACGGGCACAAAG
Slc27a1	fw	CTGGGACTTCCGTGGACCT
Slc27a1	rev	TCTTGACAGACGATACGCAGAA
Tmem26	fw	ACCCTGTCATCCACAGAG
Tmem26	rev	TGTTTGGTGGAGTCTTAAGGTC
Sp100	fw	TGATGGAGGGAACCCAACTC
Sp100	rev	CTTCCTTGAGAATAGCTGGCAC
Cd137	fw	CGTGCAAGAATCCTGTGATAAC
Cd137	rev	GTCCACCTATGCTGGAGAAGG
Cd40	fw	TTGTTGACAGCGGTCCATCTA
Cd40	rev	CCATCGTGGAGGTACTGTTTG
Eva1	fw	CCACTTCTCTGAGTTACAGC
Eva1	rev	GCATTTTAAACCGAACATCTGTCC
Fbxo31	fw	AAACTGCTTCACCGATACAGAC
Fbxo31	rev	ACCACGACGTTTCAGCAATCC
Hspb7	fw	GAGCATGTTTTAGACGACTTTG
Hspb7	rev	CCGAGGGTCTTGATGTTTCCTT
Ebf3	fw	CGAAAGGACCGCTTTTGTTG
Ebf3	rev	AGTGAATGCCGTTGTTGGTTT
Oplah	fw	CTTCACGCACGTCTCTCTTGT
Oplah	rev	GCATCTGCACAGGCCGTAT
Pdk4	fw	CAAGGAGATCTGAATCTCTA
Pdk4	rev	GATAATGTTTGAAGGCTGAC
Acot2	fw	ATGGTGGCTCGTCTTTCG
Acot2	rev	GAGCGGCGGAGGTACAAAC
Slc29a1	fw	CACCAGCCTCAGGACAGGTAT
Slc29a1	rev	GTCCAGGCGGTTTGTGAAA
Fabp4	fw	AGGGCAATGAGGTCACATCC
Fabp4	rev	GCATCTCGTTATCCGAGTACCAG
Adipoq	fw	GCACTGGCAAGTTCTACTGCAA
Adipoq	rev	GTAGGTGAAGAGAACGGCCTTGT
Tnfa	fw	TCGTAGCAAACCAAGTGT
Tnfa	rev	AGATAGCAAATCGGCTGACG
Agt	fw	GCACCCTGGTCTCTTCTACC
Agt	rev	TGTGTCCATCTAGTCGGGAGG
Lep	fw	CCTGCTCCAGCAGCTGCAAG
Lep	rev	ACCGACACAGGGGTCTCCAGC
Retn	fw	CTGTCCAGTCTATCCTTGAC
Retn	rev	CAGAAGGCACAGCAGTCTTGA
Ppar γ	fw	GAAAGACAACGGACAAATCACC
Ppar γ	rev	GGGGGTGATATGTTTGAAGTTG
Ndufa6	fw	GTCACAGACCCAGAGTGGT
Ndufa6	rev	TAACATGCACCTTCCATCA
Sdh α	fw	ACACAGACCTGGTGGAGACC
Sdh α	rev	GGATGGGCTTGGAGTAATCA
Uqcrc1	fw	GACAACGTGACCCCTCCAAGT
Uqcrc1	rev	ACTGGTACATAGGCGCATCC
Cox6a1	fw	TGCTCAACGTGTTCTCAAG
Cox6a1	rev	TAAGGGTCCAAAACAGTGC
Atp5b	fw	GAGGGATTACCACCATCCT
Atp5b	rev	CATGATTCTGCCCAAGGTCT
Nrf1	fw	TGGAGTCCAAGATGCTAATG
Nrf1	rev	AGAGCTCCATGCTACTGTTT
Tfam	fw	AGGCCCCGCAGAGACGGTTAA
Tfam	rev	CCTGAGCCGAATCATCTTTGCC
Cs	fw	CAGCTACAGAAGGAAGTTGG
Cs	rev	AGGAATAGCGAGGGTCAGTC
Gapdh	fw	TGCCAAGTATGATGACATCAAGAAG
Gapdh	rev	GGTCCTCAGTGTAGCCCAAGAT
mhLSD1	fw	GTGTTCTGGGACCCAAGTGT
mhLSD1	rev	TAATGCCAGCAGCTTCTCCT
hLSD1	fw	GCTCGGGGCTCTTATTCCTA
hLSD1	rev	ATGTTCTCCCGCAAAGAAGA
Cox2	fw	CAGTCCCTCCCTAGGACTT
Cox2	rev	TTTCAGAGCATTGCCATAGAA
Fasn	fw	AGGATATGGAGAGGGCTGGT
Fasn	rev	ACCCAAGCATCATTTTCGTC
C/ebp α	fw	TTACAACAGGCCAGGTTTCC
C/ebp α	rev	CTCTGGGATGGATCGATTGT
C/ebp β	fw	CAAGCTGAGCGACGAGTACA
C/ebp β	rev	AGCTGCTCCACCTTCTTCTG
C/ebp δ	fw	AGAAGCTGGTGGAGTTGTCTG
C/ebp δ	rev	CGCAGGTCCCAAAGAACTA
Rxra	fw	GTCGAGCCCAAGACTGAGAC
Rxra	rev	TCTAGGGGCAGCTCAGAAAA
β -Actin	fw	CCCTGTATGGCTCTGGTCTGT
β -Actin	rev	ATGGCGTGAGGGAGAGCAT

References

1. Metzger, E., *et al.* LSD1 demethylates repressive histone marks to promote androgen-receptor-dependent transcription. *Nature* **437**, 436-439 (2005).
2. Shi, Y., *et al.* Histone demethylation mediated by the nuclear amine oxidase homolog LSD1. *Cell* **119**, 941-953 (2004).
3. Wang, J., *et al.* The lysine demethylase LSD1 (KDM1) is required for maintenance of global DNA methylation. *Nat Genet* **41**, 125-129 (2009).
4. Wang, J., *et al.* Opposing LSD1 complexes function in developmental gene activation and repression programmes. *Nature* **446**, 882-887 (2007).
5. Foster, C.T., *et al.* Lysine-specific demethylase 1 regulates the embryonic transcriptome and CoREST stability. *Mol Cell Biol* **30**, 4851-4863 (2010).
6. Macfarlan, T.S., *et al.* Endogenous retroviruses and neighboring genes are coordinately repressed by LSD1/KDM1A. *Genes Dev* **25**, 594-607 (2011).
7. Chen, Y., Jie, W., Yan, W., Zhou, K. & Xiao, Y. Lysine-specific histone demethylase 1 (LSD1): A potential molecular target for tumor therapy. *Crit Rev Eukaryot Gene Expr* **22**, 53-59 (2012).
8. Wang, Y., *et al.* LSD1 is a subunit of the NuRD complex and targets the metastasis programs in breast cancer. *Cell* **138**, 660-672 (2009).
9. Musri, M.M., *et al.* Histone demethylase LSD1 regulates adipogenesis. *J Biol Chem* **285**, 30034-30041 (2010).
10. Hino, S., *et al.* FAD-dependent lysine-specific demethylase-1 regulates cellular energy expenditure. *Nat Commun* **3**, 758 (2012).
11. Langin, D. Recruitment of brown fat and conversion of white into brown adipocytes: strategies to fight the metabolic complications of obesity? *Biochim Biophys Acta* **1801**, 372-376 (2010).
12. Matthias, A., Jacobsson, A., Cannon, B. & Nedergaard, J. The bioenergetics of brown fat mitochondria from UCP1-ablated mice. Ucp1 is not involved in fatty acid-induced de-energization ("uncoupling"). *J Biol Chem* **274**, 28150-28160 (1999).
13. Monemdjou, S., Kozak, L.P. & Harper, M.E. Mitochondrial proton leak in brown adipose tissue mitochondria of Ucp1-deficient mice is GDP insensitive. *Am J Physiol* **276**, E1073-1082 (1999).
14. Himms-Hagen, J. Brown adipose tissue thermogenesis: interdisciplinary studies. *FASEB J* **4**, 2890-2898 (1990).
15. Fisher, F.M., *et al.* FGF21 regulates PGC-1 α and browning of white adipose tissues in adaptive thermogenesis. *Genes Dev* **26**, 271-281 (2012).

16. Kajimura, S., Seale, P. & Spiegelman, B.M. Transcriptional control of brown fat development. *Cell Metab* **11**, 257-262 (2010).
17. Seale, P., *et al.* Prdm16 determines the thermogenic program of subcutaneous white adipose tissue in mice. *J Clin Invest* **121**, 96-105 (2011).
- 5 18. Petrovic, N., *et al.* Chronic peroxisome proliferator-activated receptor gamma (PPARgamma) activation of epididymally derived white adipocyte cultures reveals a population of thermogenically competent, UCP1-containing adipocytes molecularly distinct from classic brown adipocytes. *J Biol Chem* **285**, 7153-7164 (2010).
- 10 19. Wu, J., *et al.* Beige adipocytes are a distinct type of thermogenic fat cell in mouse and human. *Cell* **150**, 366-376 (2012).
20. Seale, P., *et al.* PRDM16 controls a brown fat/skeletal muscle switch. *Nature* **454**, 961-967 (2008).
21. Cristancho, A.G. & Lazar, M.A. Forming functional fat: a growing understanding of adipocyte differentiation. *Nat Rev Mol Cell Biol* **12**, 722-734 (2011).
- 15 22. Stephens, J.M. The fat controller: adipocyte development. *PLoS Biol* **10**, e1001436 (2012).
23. Wu, J., Cohen, P. & Spiegelman, B.M. Adaptive thermogenesis in adipocytes: is beige the new brown? *Genes Dev* **27**, 234-250 (2013).
- 20 24. Mazzucotelli, A., *et al.* The transcriptional coactivator peroxisome proliferator activated receptor (PPAR)gamma coactivator-1 alpha and the nuclear receptor PPAR alpha control the expression of glycerol kinase and metabolism genes independently of PPAR gamma activation in human white adipocytes. *Diabetes* **56**, 2467-2475 (2007).
- 25 25. Tiraby, C., *et al.* Acquirement of brown fat cell features by human white adipocytes. *J Biol Chem* **278**, 33370-33376 (2003).
26. Puigserver, P., *et al.* A cold-inducible coactivator of nuclear receptors linked to adaptive thermogenesis. *Cell* **92**, 829-839 (1998).
27. Scarpulla, R.C. Transcriptional paradigms in mammalian mitochondrial biogenesis and function. *Physiol Rev* **88**, 611-638 (2008).
- 30 28. Puigserver, P. & Spiegelman, B.M. Peroxisome proliferator-activated receptor-gamma coactivator 1 alpha (PGC-1 alpha): transcriptional coactivator and metabolic regulator. *Endocr Rev* **24**, 78-90 (2003).
29. Wu, Z., *et al.* Mechanisms controlling mitochondrial biogenesis and respiration through the thermogenic coactivator PGC-1. *Cell* **98**, 115-124 (1999).
- 35

30. Koh, E.H., *et al.* Essential role of mitochondrial function in adiponectin synthesis in adipocytes. *Diabetes* **56**, 2973-2981 (2007).
31. Auffret, J., *et al.* Beige differentiation of adipose depots in mice lacking prolactin receptor protects against high-fat-diet-induced obesity. *FASEB J* **26**, 3728-3737 (2012).
- 5 32. Vegiopoulos, A., *et al.* Cyclooxygenase-2 controls energy homeostasis in mice by de novo recruitment of brown adipocytes. *Science* **328**, 1158-1161 (2010).
33. Yadav, H., *et al.* Protection from obesity and diabetes by blockade of TGF-beta/Smad3 signaling. *Cell Metab* **14**, 67-79 (2011).
- 10 34. Beranger, G.E., *et al.* In vitro brown and "brite"/"beige" adipogenesis: Human cellular models and molecular aspects. *Biochim Biophys Acta* (2012).
35. Gesta, S., Tseng, Y.H. & Kahn, C.R. Developmental origin of fat: tracking obesity to its source. *Cell* **131**, 242-256 (2007).
36. Metzger, E., *et al.* Phosphorylation of histone H3T6 by PKCbeta(I) controls demethylation at histone H3K4. *Nature* **464**, 792-796 (2010).
- 15 37. Rosen, E.D. & Spiegelman, B.M. Adipocytes as regulators of energy balance and glucose homeostasis. *Nature* **444**, 847-853 (2006).
38. He, W., *et al.* Adipose-specific peroxisome proliferator-activated receptor gamma knockout causes insulin resistance in fat and liver but not in muscle. *Proc Natl Acad Sci U S A* **100**, 15712-15717 (2003).
- 20 39. Shan, T., Liu, W. & Kuang, S. Fatty acid binding protein 4 expression marks a population of adipocyte progenitors in white and brown adipose tissues. *FASEB J* **27**, 277-287 (2013).
40. Vooijs, M., Jonkers, J. & Berns, A. A highly efficient ligand-regulated Cre recombinase mouse line shows that LoxP recombination is position dependent. *EMBO Rep* **2**, 292-297 (2001).
- 25 41. Kanehisa, M., Goto, S., Sato, Y., Furumichi, M. & Tanabe, M. KEGG for integration and interpretation of large-scale molecular data sets. *Nucleic Acids Res* **40**, D109-114 (2012).
- 30 42. Heinz, S., *et al.* Simple combinations of lineage-determining transcription factors prime cis-regulatory elements required for macrophage and B cell identities. *Mol Cell* **38**, 576-589 (2010).
43. Siersbaek, R., *et al.* Extensive chromatin remodelling and establishment of transcription factor 'hotspots' during early adipogenesis. *EMBO J* **30**, 1459-1472 (2011).
- 35

44. Farmer, S.R. Regulation of PPARgamma activity during adipogenesis. *Int J Obes (Lond)* **29 Suppl 1**, S13-16 (2005).
45. Koppen, A. & Kalkhoven, E. Brown vs white adipocytes: the PPARgamma coregulator story. *FEBS Lett* **584**, 3250-3259 (2010).
- 5 46. Nielsen, R., *et al.* Genome-wide profiling of PPARgamma:RXR and RNA polymerase II occupancy reveals temporal activation of distinct metabolic pathways and changes in RXR dimer composition during adipogenesis. *Genes Dev* **22**, 2953-2967 (2008).
47. Kajimura, S., *et al.* Initiation of myoblast to brown fat switch by a PRDM16-C/EBP-
10 beta transcriptional complex. *Nature* **460**, 1154-1158 (2009).
48. Duteil, D., *et al.* The transcriptional coregulators TIF2 and SRC-1 regulate energy homeostasis by modulating mitochondrial respiration in skeletal muscles. *Cell Metab* **12**, 496-508 (2010).
49. Schwenk, F., Baron, U. & Rajewsky, K. A cre-transgenic mouse strain for the
15 ubiquitous deletion of loxP-flanked gene segments including deletion in germ cells. *Nucleic Acids Res* **23**, 5080-5081 (1995).
50. Puccio, H., *et al.* Mouse models for Friedreich ataxia exhibit cardiomyopathy, sensory nerve defect and Fe-S enzyme deficiency followed by intramitochondrial iron deposits. *Nat Genet* **27**, 181-186 (2001).
- 20 51. Picard, F., *et al.* SRC-1 and TIF2 control energy balance between white and brown adipose tissues. *Cell* **111**, 931-941 (2002).
52. Hamalainen, N. & Pette, D. The histochemical profiles of fast fiber types IIB, IID, and IIA in skeletal muscles of mouse, rat, and rabbit. *J Histochem Cytochem* **41**, 733-743 (1993).
- 25 53. Bookout, A.L., Cummins, C.L., Mangelsdorf, D.J., Pesola, J.M. & Kramer, M.F. High-throughput real-time quantitative reverse transcription PCR. *Curr Protoc Mol Biol* **Chapter 15**, Unit 15 18 (2006).
54. Trapnell, C., *et al.* Differential gene and transcript expression analysis of RNA-seq experiments with TopHat and Cufflinks. *Nat Protoc* **7**, 562-578 (2012).
- 30 55. Robinson, M.D. & Smyth, G.K. Small-sample estimation of negative binomial dispersion, with applications to SAGE data. *Biostatistics* **9**, 321-332 (2008).
56. Anders, S. & Huber, W. Differential expression analysis for sequence count data. *Genome Biol* **11**, R106 (2010).
57. Metzger, E., *et al.* Phosphorylation of histone H3 at threonine 11 establishes a
35 novel chromatin mark for transcriptional regulation. *Nat Cell Biol* **10**, 53-60 (2008).

58. Langmead, B., Trapnell, C., Pop, M. & Salzberg, S.L. Ultrafast and memory-efficient alignment of short DNA sequences to the human genome. *Genome Biol* **10**, R25 (2009).
59. Zhang, Y., *et al.* Model-based analysis of ChIP-Seq (MACS). *Genome Biol* **9**, R137 (2008).
5
60. Thorvaldsdottir, H., Robinson, J.T. & Mesirov, J.P. Integrative Genomics Viewer (IGV): high-performance genomics data visualization and exploration. *Brief Bioinform* (2012).
61. Hölzel, M., *et al.* Rapid conditional knock-down-knock-in system for mammalian cells. *Nucleic Acids Res* **35**, e17 (2007).
10
62. Rodbell, M. Metabolism of Isolated Fat Cells. I. Effects of Hormones on Glucose Metabolism and Lipolysis. *J Biol Chem* **239**, 375-380 (1964).
63. Soukas, A., Socci, N.D., Saatkamp, B.D., Novelli, S. & Friedman, J.M. Distinct transcriptional profiles of adipogenesis in vivo and in vitro. *J Biol Chem* **276**, 34167-34174 (2001).
15
64. Hood, D.A., Irrcher, I., Ljubcic, V. & Joseph, A.M. Coordination of metabolic plasticity in skeletal muscle. *J Exp Biol* **209**, 2265-2275 (2006).

Claims

1. The use of a modified non-human animal as an animal model for obesity or obesity-related disorders, wherein the amount of Lysine-specific Demethylase 1 (LSD1) in at least one tissue or at least one cell type of said animal is reduced, wherein the modified non-human animal preferably is a genetically modified non-human animal.
2. The use of claim 1, wherein the genetically modified non-human animal has a nucleic acid inserted in its genome, wherein the presence of the inserted nucleic acid in the genome of the animal results in reduced expression of LSD1.
3. The use of claim 1 or 2, wherein said genetic modification is a disruption of an allele of the endogenous gene encoding LSD1.
4. The use of any one of the preceding claims, wherein said animal is a non-human transgenic animal which is heterozygous for the disruption of the gene encoding LSD1.
5. The use of any one of the preceding claims, wherein the amount of LSD1 is reduced in tissue of said animal, preferably in adipose, liver or muscle of said animal.
6. The use of any one of the preceding claims, wherein said animal develops obesity after high fat diet.
7. The use of any one of the preceding claims, wherein said animal has at least one symptom of type 2 diabetes.
8. The use of any one of the preceding claims, wherein the animal is a rodent, preferably a mouse.
9. A method for identifying a compound useful in the treatment and/or prevention of obesity or an obesity-related disorder, comprising (a) administering a test compound to a transgenic animal as defined in any one of claims 1 to 8, and (b) determining the effect of the test compound on the initiation, maintenance, or progression of at least one obesity-related parameter in said transgenic animal, thereby identifying a compound that inhibits obesity or an obesity-related disorder.

10. The method of claim 9, wherein said obesity-related parameter is selected from the group consisting of the mass of white adipose tissue, the total mass of adipose tissue, glucose intolerance, and expression of a adipose tissue differentiation marker.

5 11. A compound for use in the treatment and/or prevention of obesity or an obesity-related disorder, wherein said compound is capable of modulating LSD1 protein, the LSD1 gene or a target gene of LSD1.

10 12. The compound for use according to claim 11, wherein the target gene of Lsd1 is selected from the group consisting of *Nrf1*, *Prdm16* and *Pgc-1 α* .

13. A method for identifying a compound useful in the treatment and/or prevention of obesity or an obesity-related disorder, comprising (i) contacting a cell with a test compound; (ii) determining expression level of the LSD1 gene and/or of a target gene of
15 LSD1; and (iii) selecting the compound if the test compound is capable of increasing the expression of the LSD1 gene and/or of the target gene of LSD1, as compared to a control cell which has not been contacted with the test compound.

20 14. The method of claim 13, wherein the cell is an adipocyte or a preadipocyte, preferably a mouse 3T3-L1 cell, a 3T3-F442 cell or a 10T1/2 cell.

15. The use according to any one of claims 1 to 8, the method of claim 9 or 10, the compound for use according to claim 11 or 12, or the method of claim 13 or 14, wherein said obesity-related disorder is selected from the group consisting of insulin resistance,
25 type II diabetes, hyperuricemia, fatty liver, non-alcoholic fatty liver disease, polycystic ovarian syndrome, acanthosis nigricans, hyperphagia, endocrine abnormalities, triglyceride storage disease, Bardet-Biedl syndrome, and Lawrence-Moon syndrome.

16. The use of a non-human transgenic animal whose genome comprises a stably
30 integrated transgenic nucleotide sequence encoding Lysine-specific Demethylase 1 (LSD1) operably linked to a promoter for studying metabolism and/or as an animal model for metabolic disorders.

17. The use of claim 16, wherein said LSD1 is human LSD1.

18. The use of claim 16 or 17, wherein said LSD1 comprises at least amino acids 2 to 852 of the amino acid sequence as shown in SEQ ID NO:3.

19. The use according to any one of claims 16 to 18, wherein said transgenic nucleotide sequence comprises nucleotides 4 to 2556 of the nucleotide sequence as shown in SEQ ID NO:1.

20. The use according to any one of claims 16 to 19, wherein said LSD1 is overexpressed in the transgenic animal.

21. The use of claim 20, wherein said overexpression is present at least in white adipose tissue.

22. The use according to any one of claims 16 to 21, wherein said promoter is a Rosa26 promoter.

23. The use according to any one of claims 16 to 22, wherein said animal has a reduced weight relative to a wild type mouse.

24. The use according to any one of claims 16 to 23, which is a rodent, preferably a mouse.

25. A use according to any one of claims 16 to 24, wherein said animal does not comprise other transgenic nucleotide sequences.

26. A method for identifying a compound useful in the treatment and/or prevention of a metabolic disorder, comprising (a) administering a test compound to a transgenic animal as defined in any one of claims 16 to 25 and (b) determining the effect of the test compound on the initiation, maintenance, or progression of at least one metabolic parameter in said transgenic animal, thereby identifying a compound that inhibits the metabolic disorder, wherein said metabolic parameter is selected from the group consisting of the mass of white adipose tissue, the total mass of adipose tissue, glucose intolerance, expression of a adipose tissue differentiation marker.

27. A method according to claim 26, wherein said test compound is selected from the group consisting of LSD1 inhibitors or LSD1 modulators, modulators of androgen receptor, modulators of p53, and modulators of Rb.

5 28. A LSD1 inhibitor or LSD1 modulator for use in the treatment and/or prevention of a metabolic disorder.

29. The LSD1 inhibitor or LSD1 modulator of claim 28, which is siRNA capable of inhibiting expression of the LSD1 gene.

10

30. The use according to any one of claims 16 to 25, the method of item 26 or 27, or the LSD1 inhibitor for use according to claim 28 or 29, wherein said metabolic disorder is selected from the group consisting of eating disorders, body weight disorders, cachexia, anorexia, sarcopenia and wasting syndrome or disease.

15

Figure 1

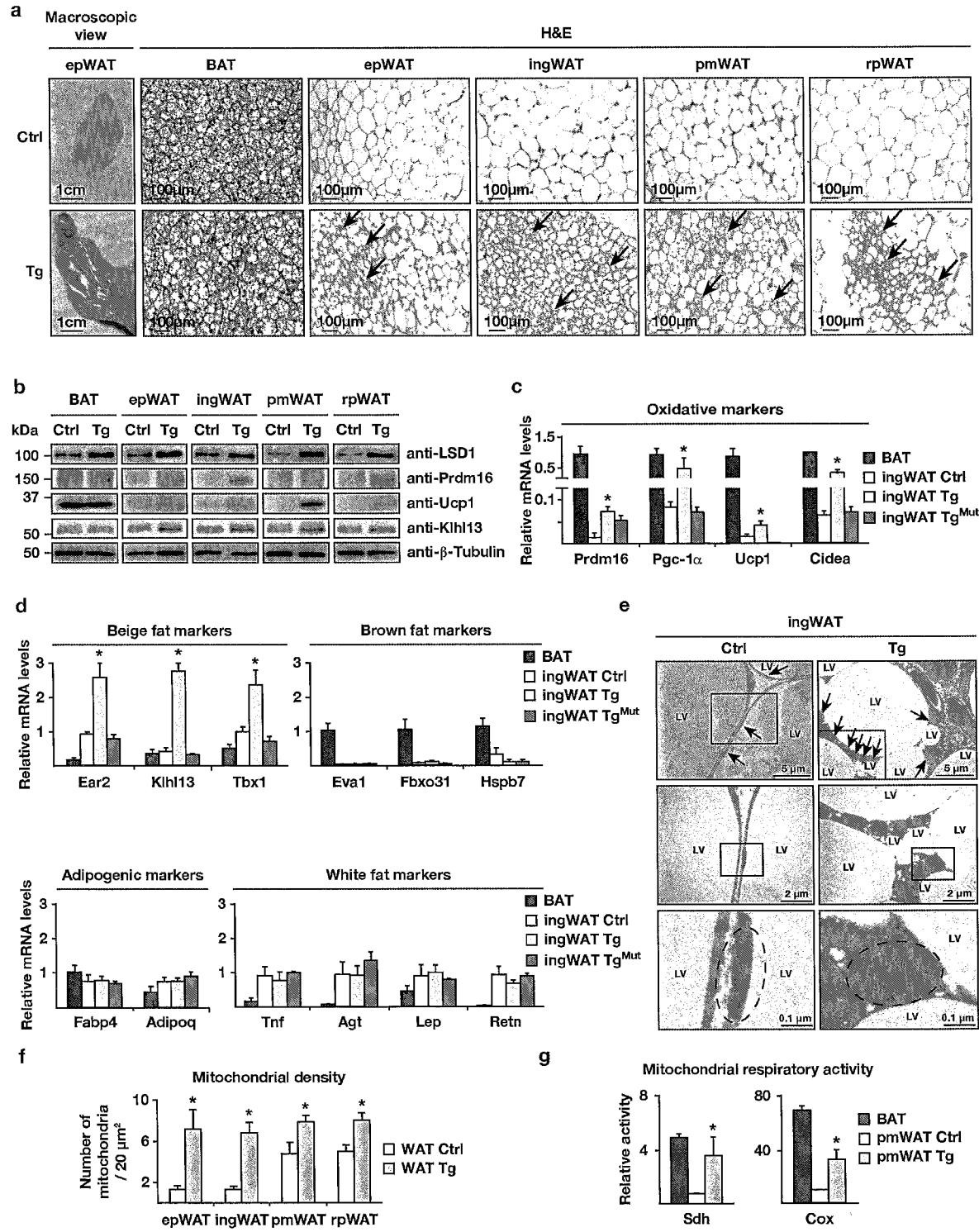


Figure 2

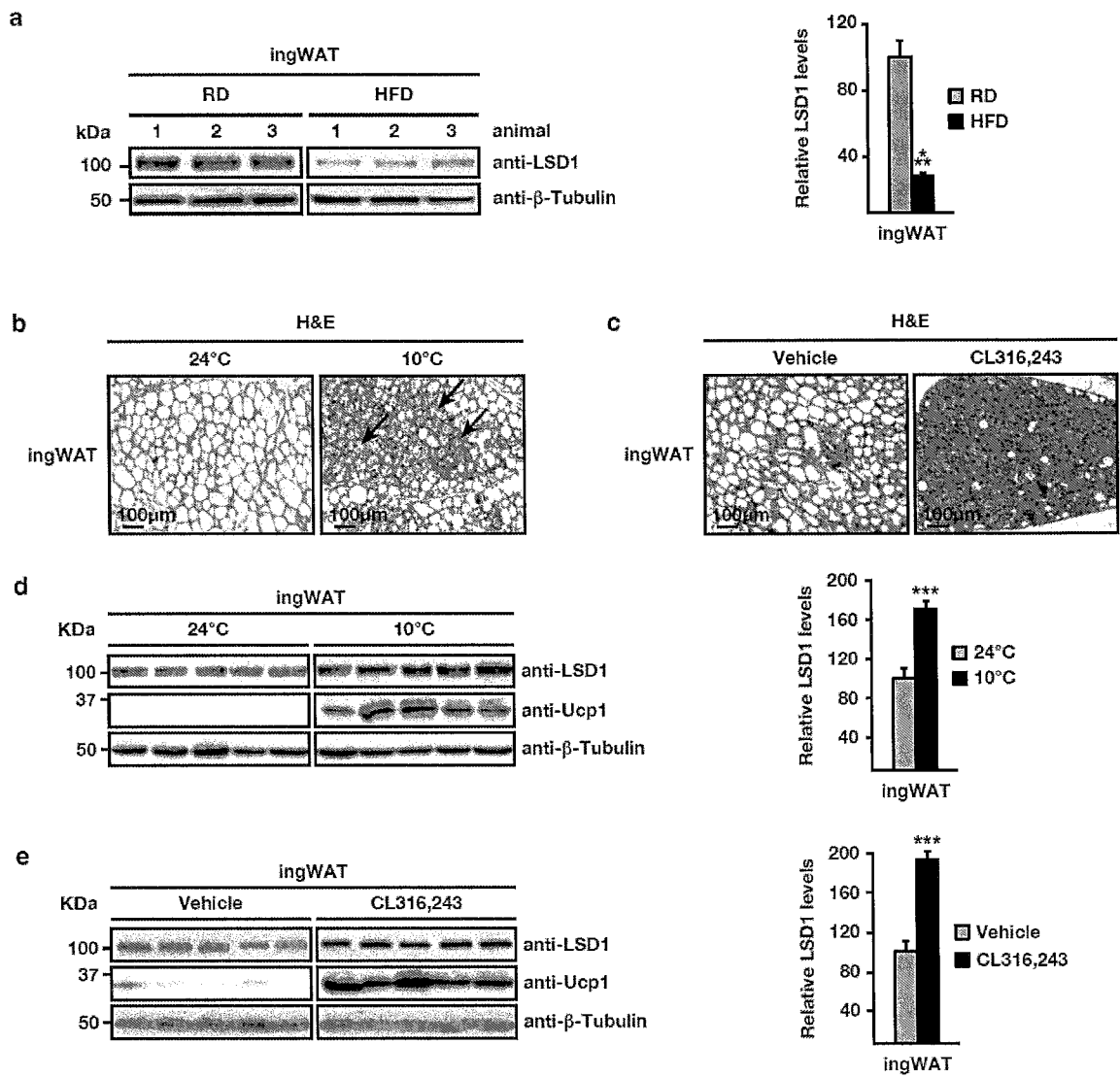


Figure 3

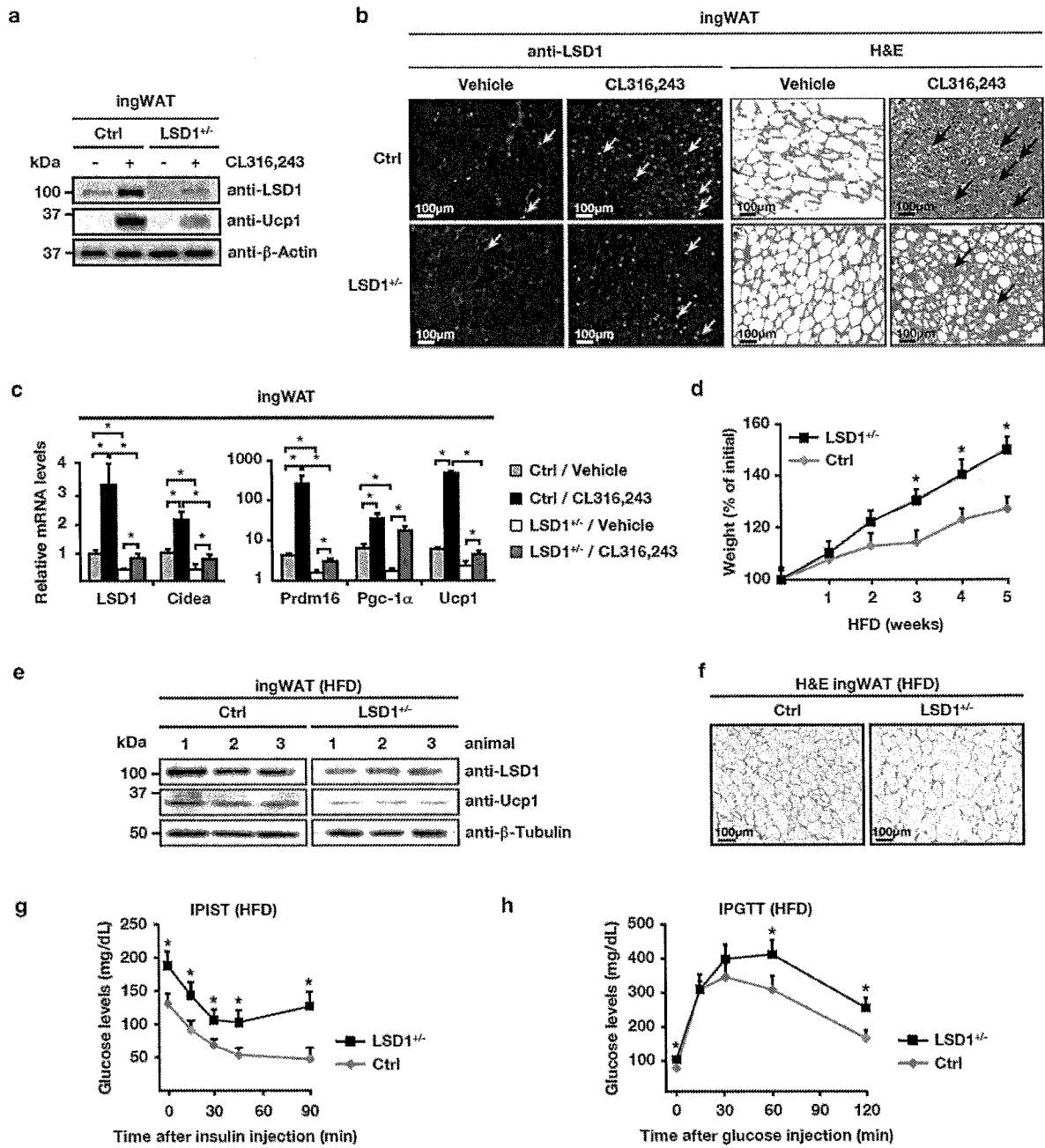


Figure 4

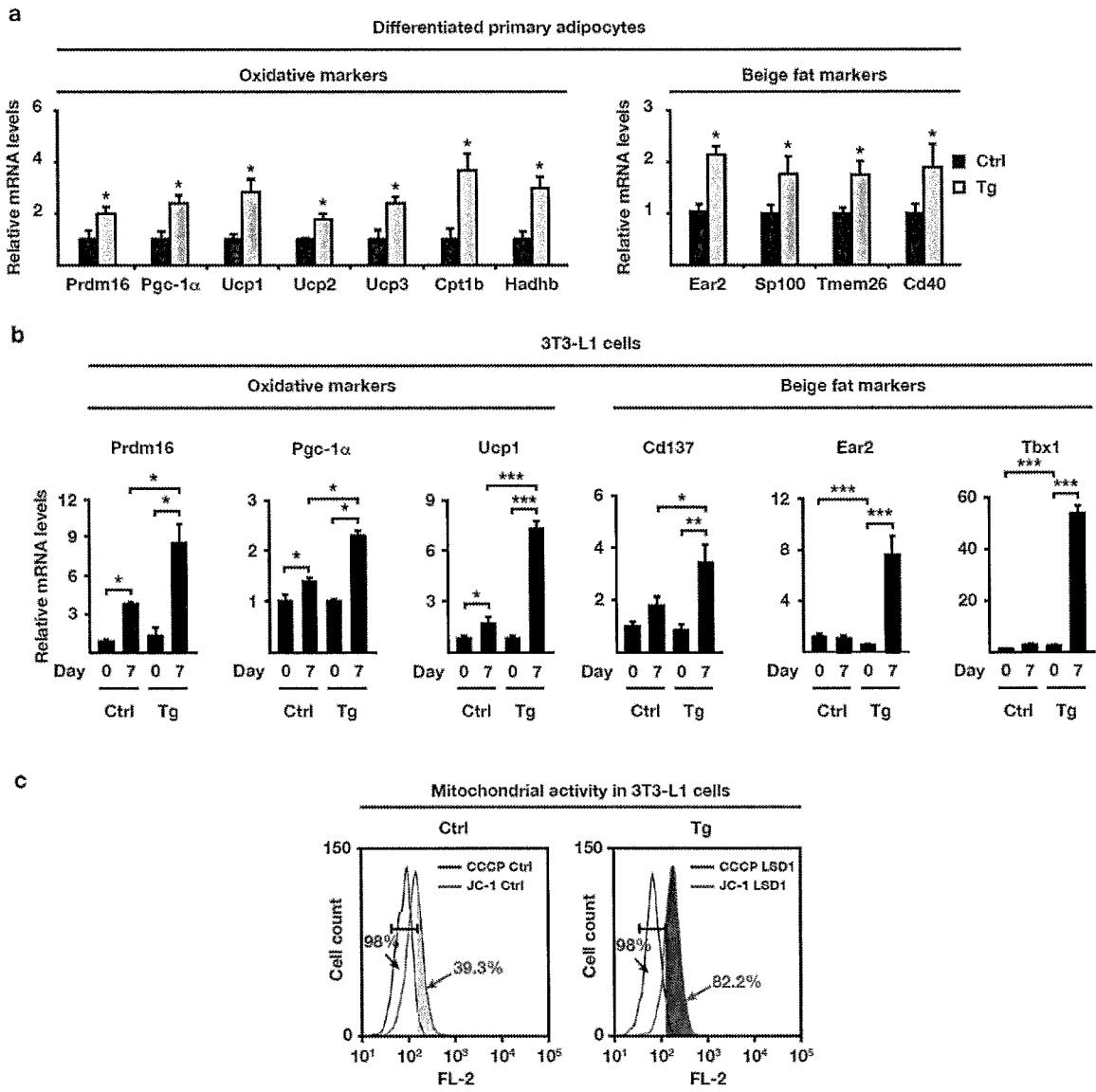


Figure 5

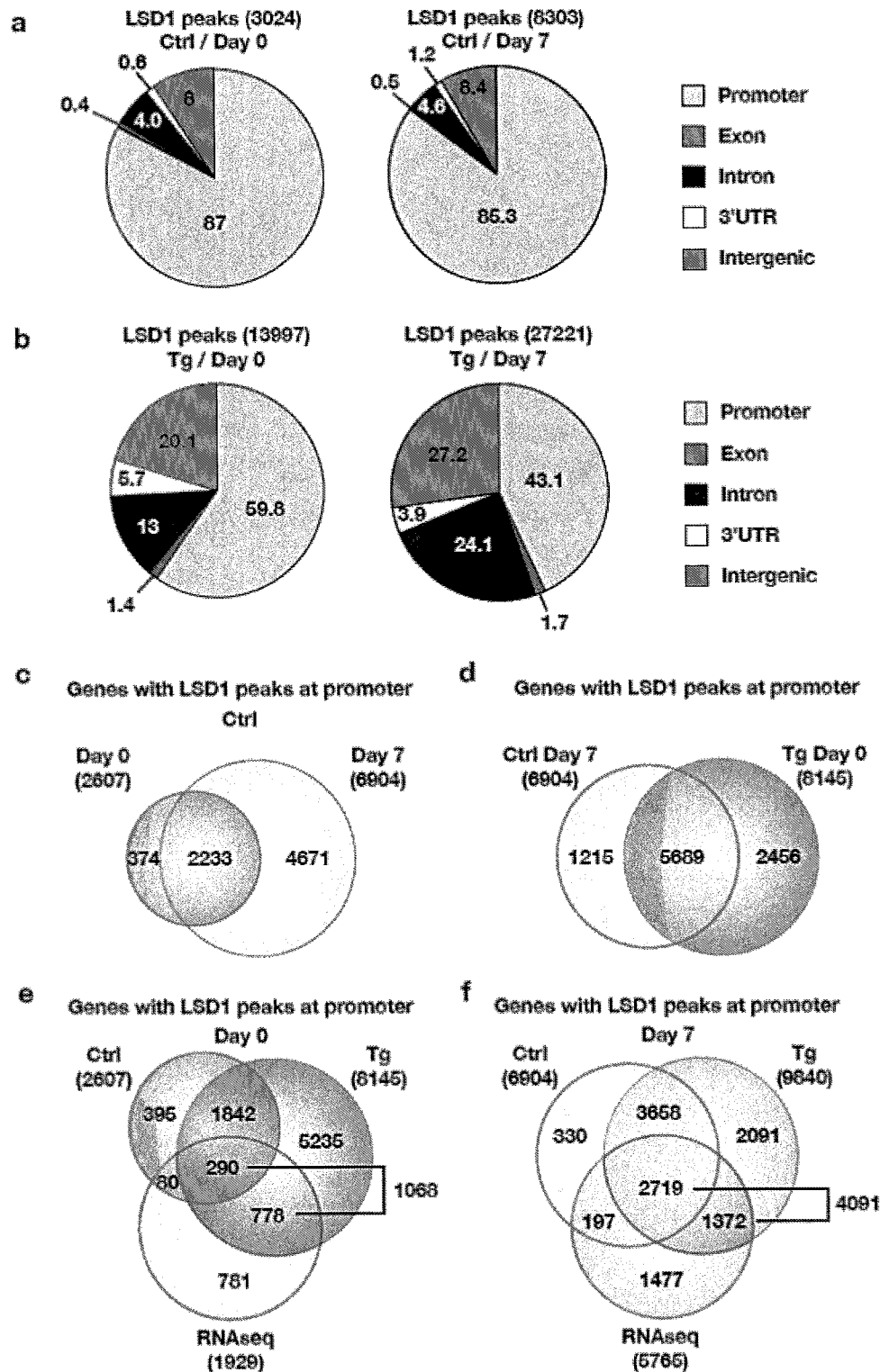


Figure 6

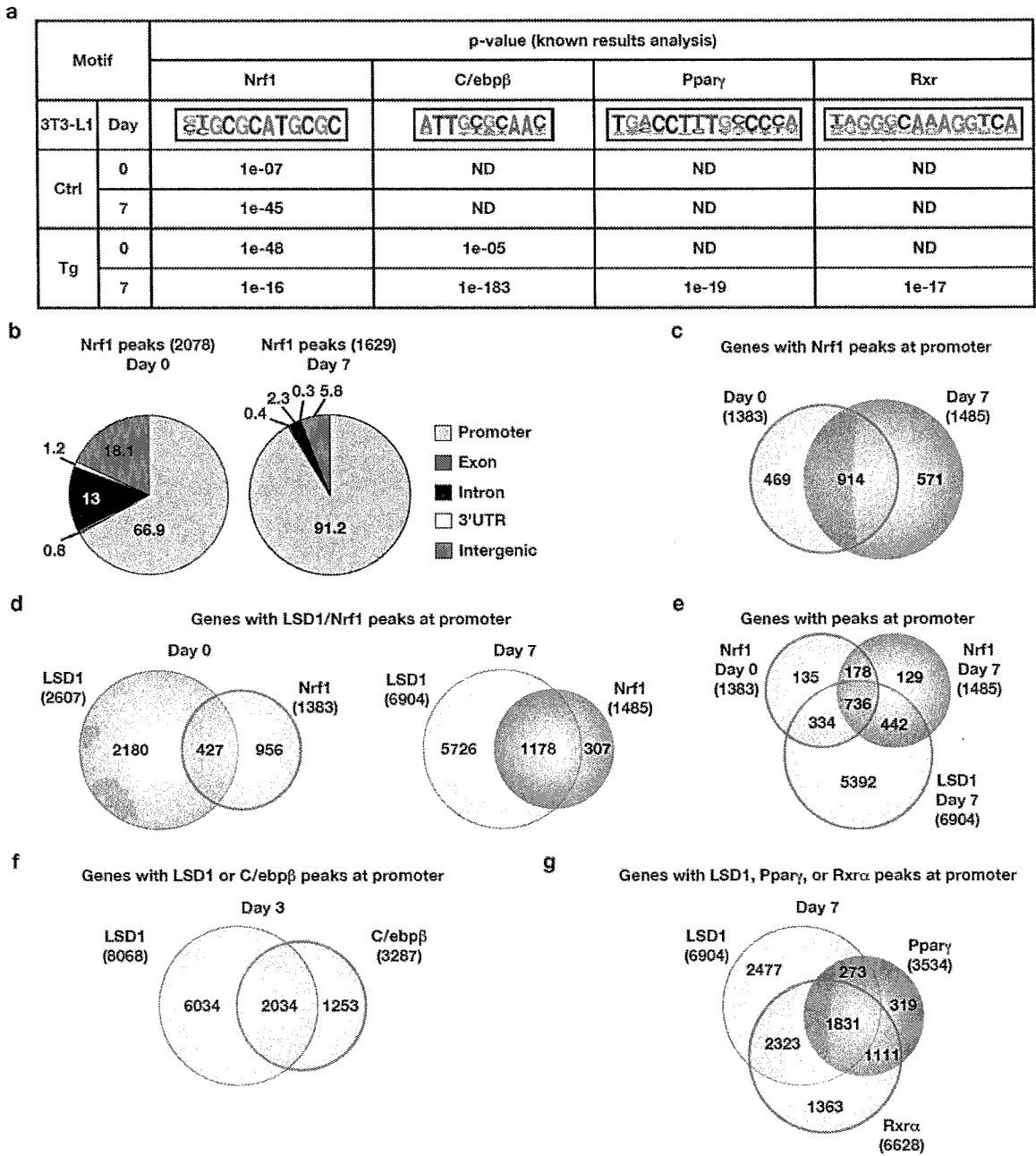


Figure 7

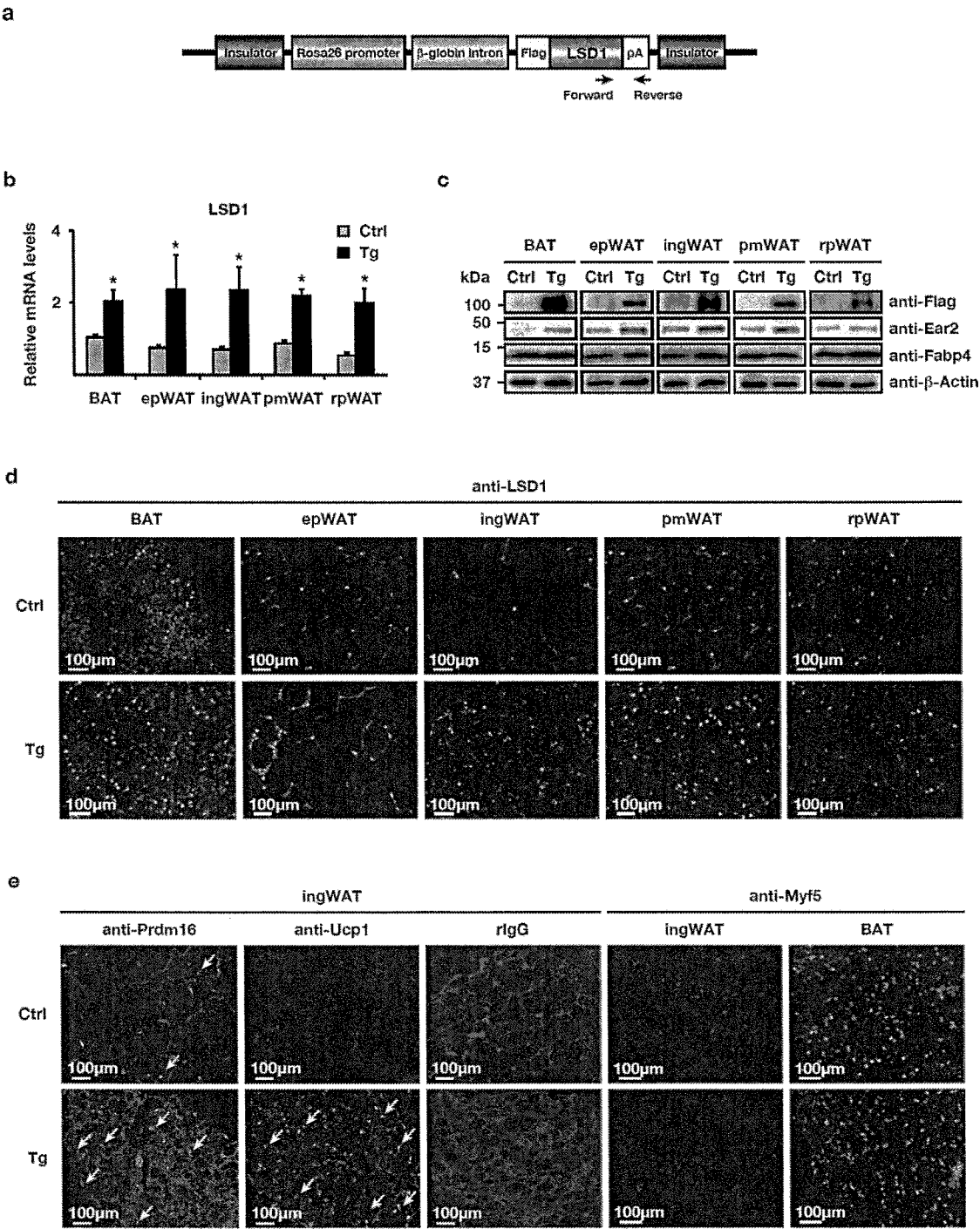


Figure 8

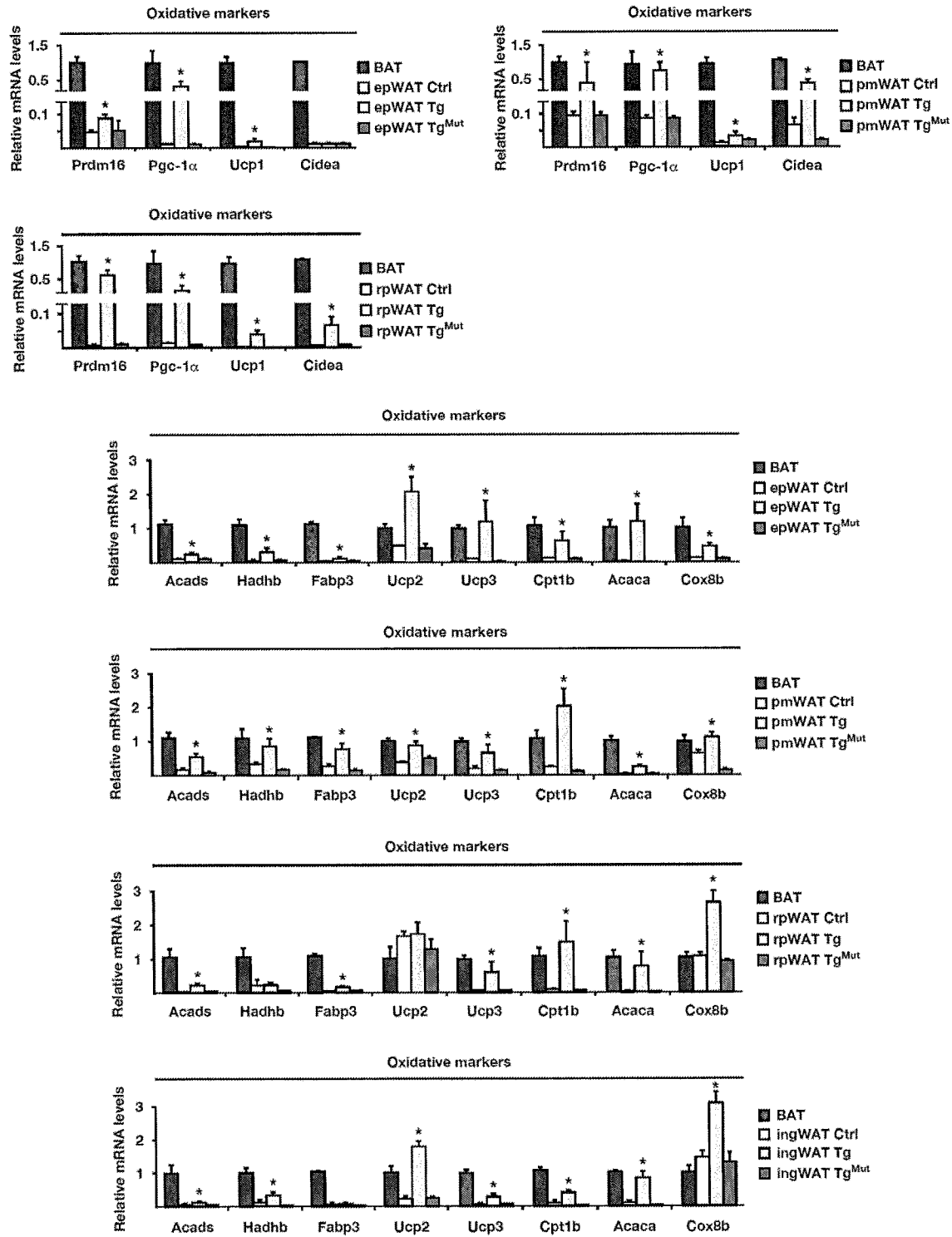


Figure 9

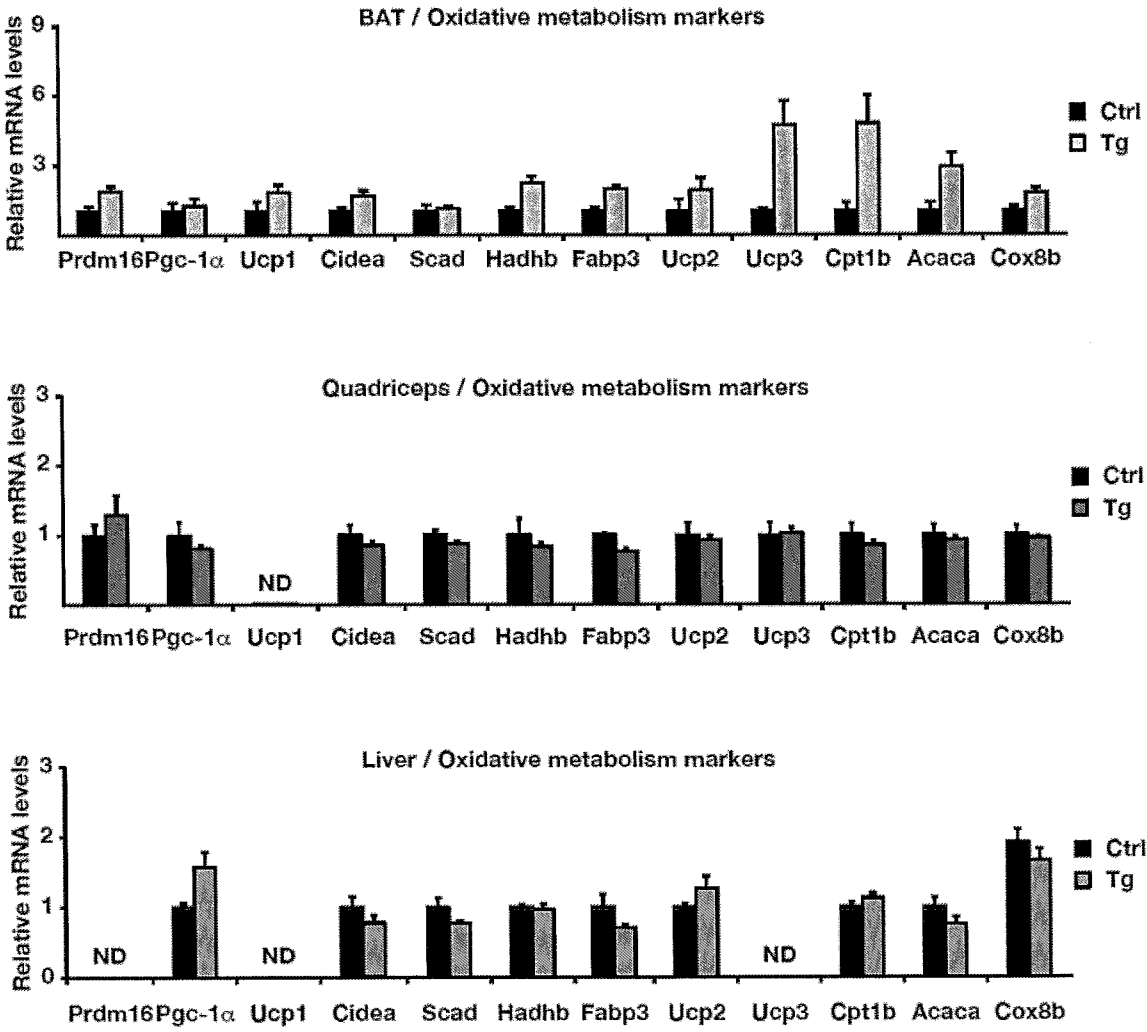


Figure 10

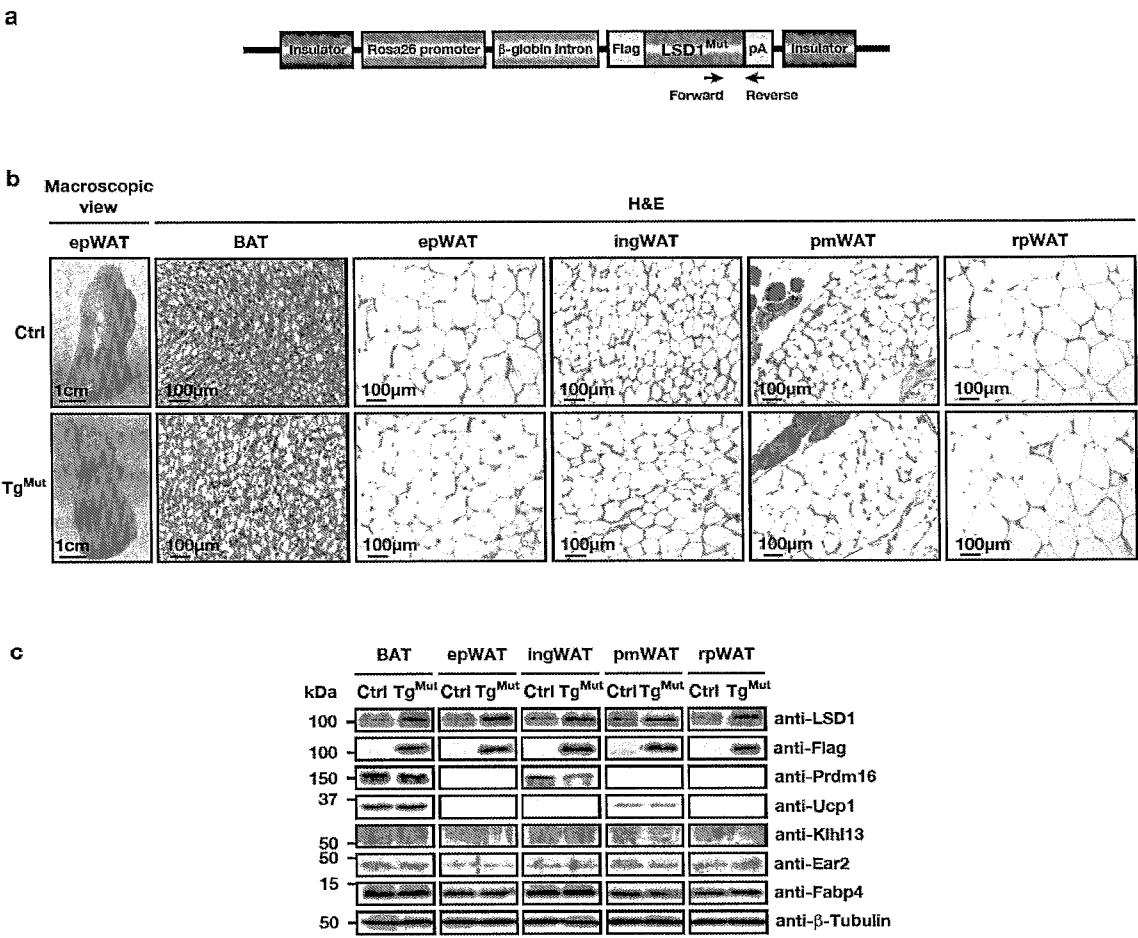


Figure 11

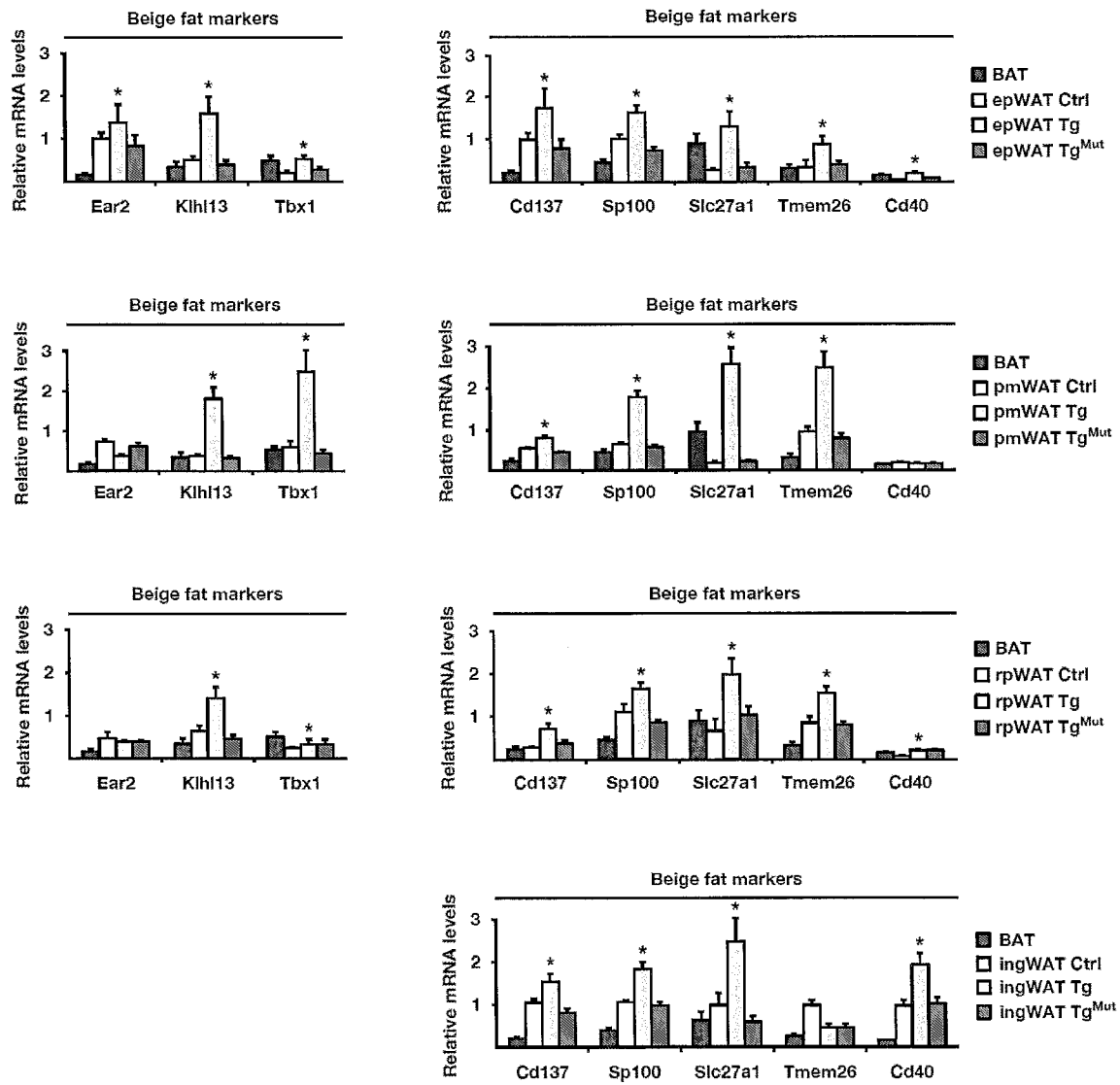


Figure 12

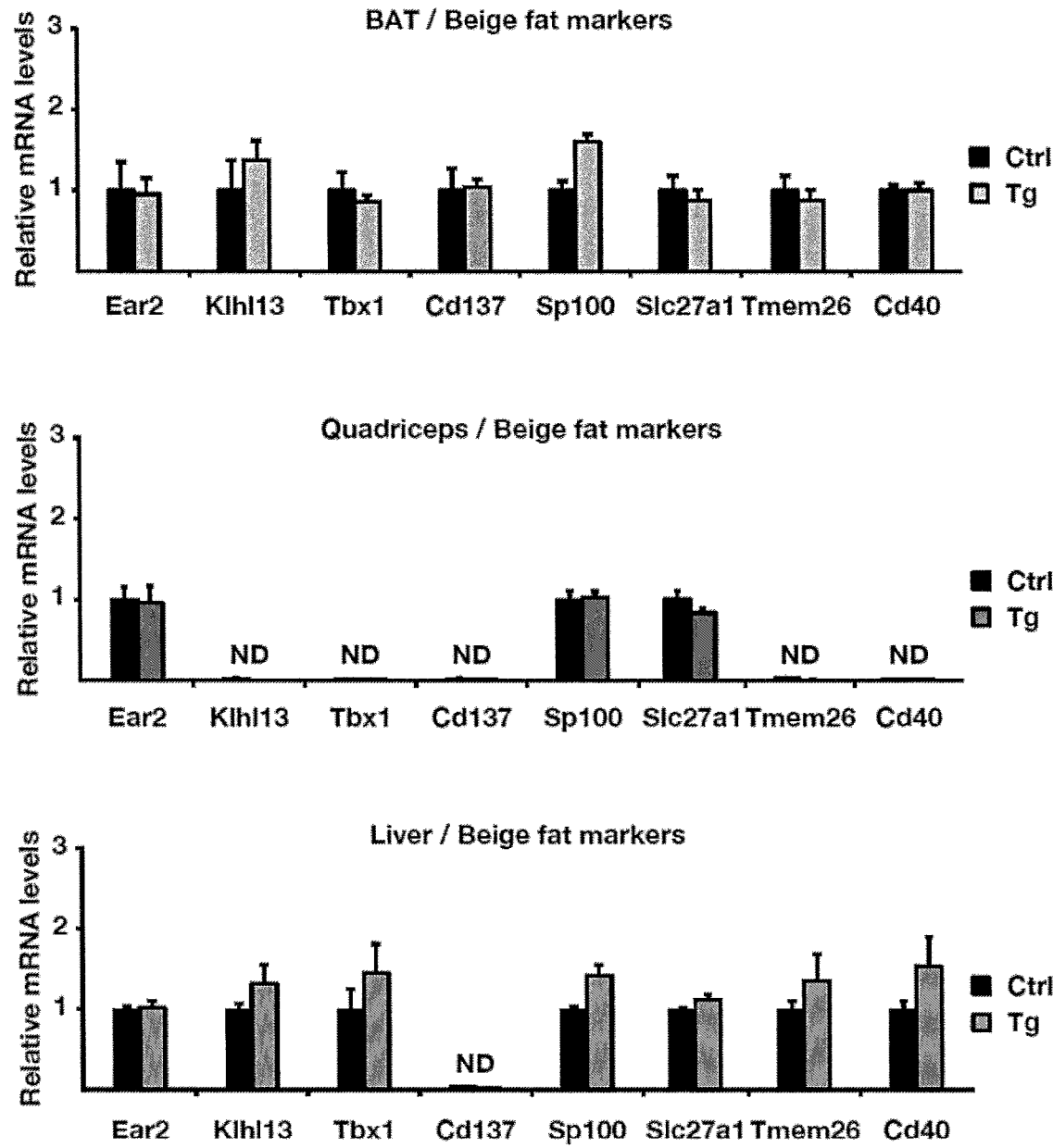


Figure 13

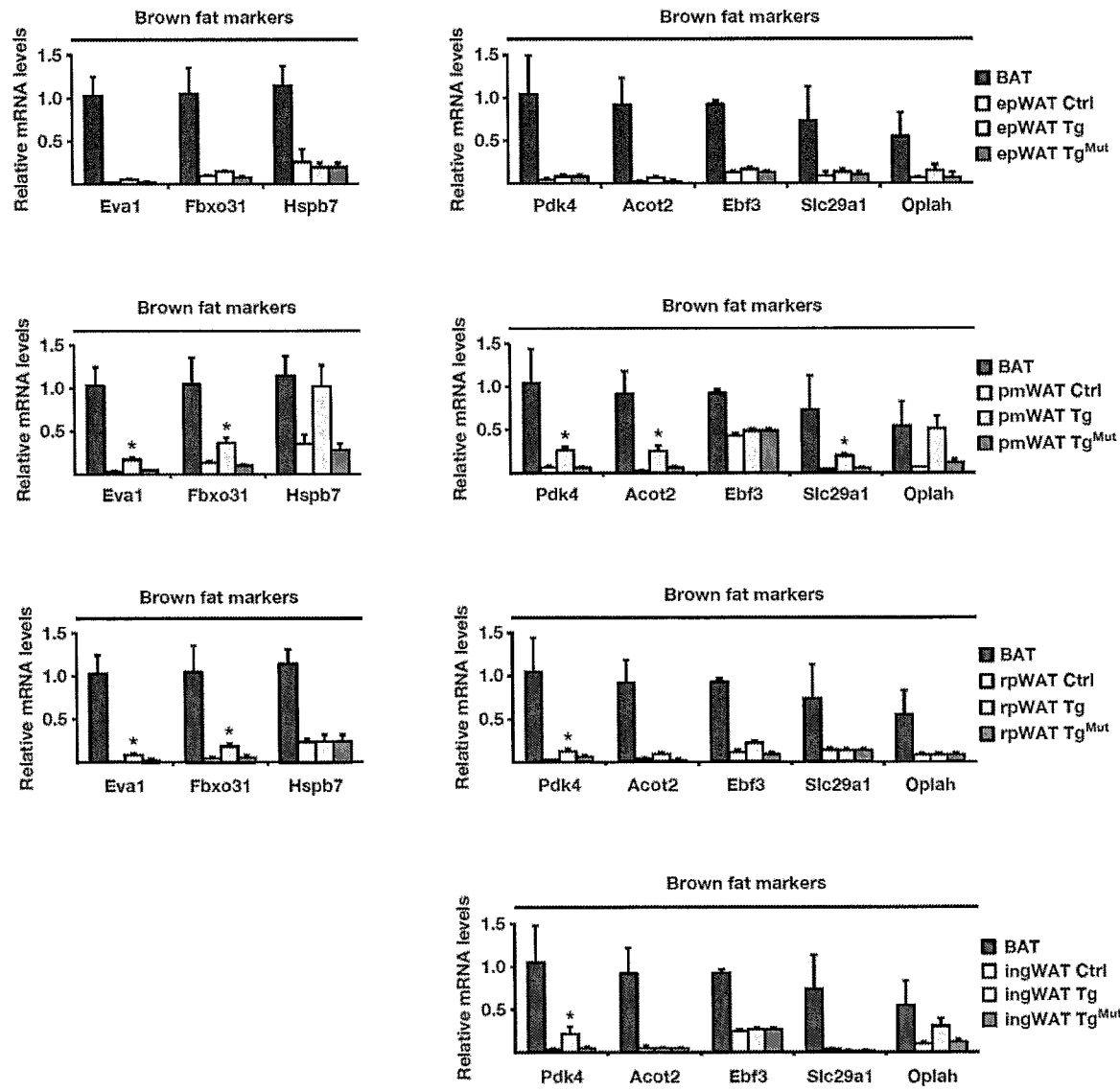


Figure 14

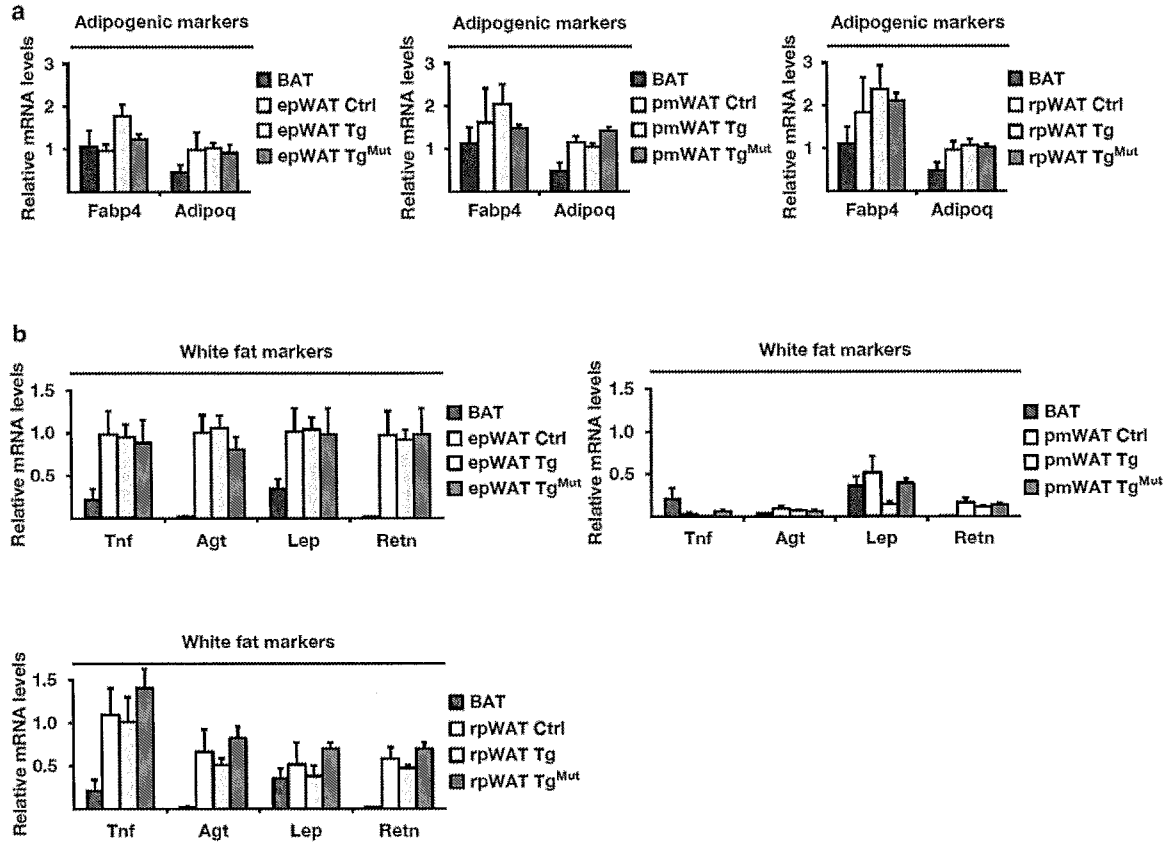
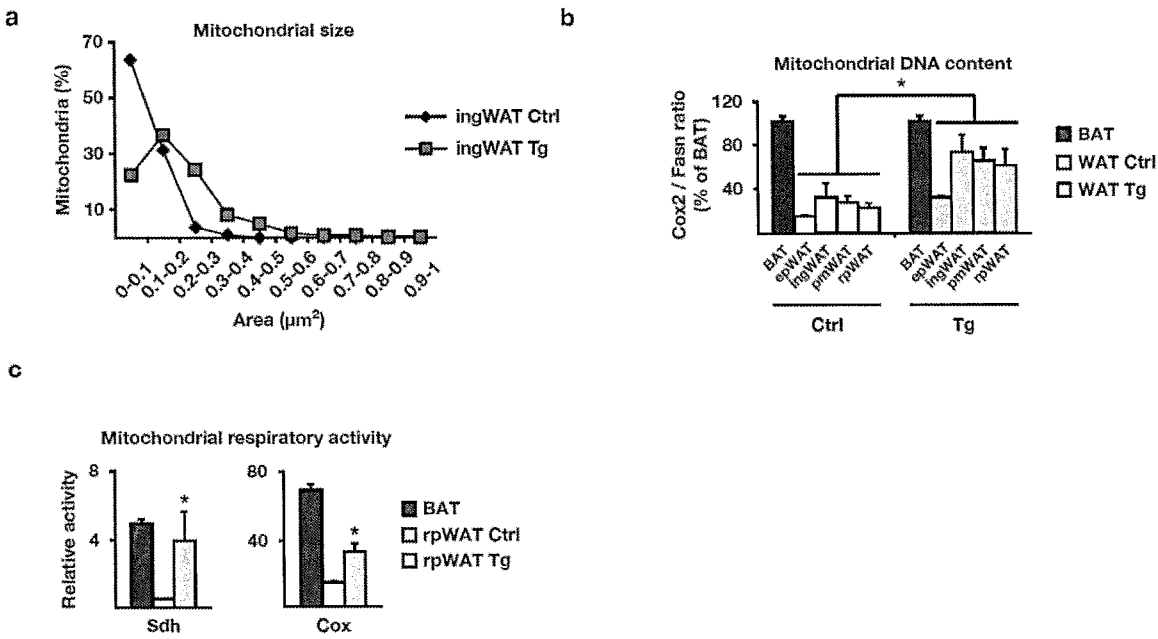


Figure 15



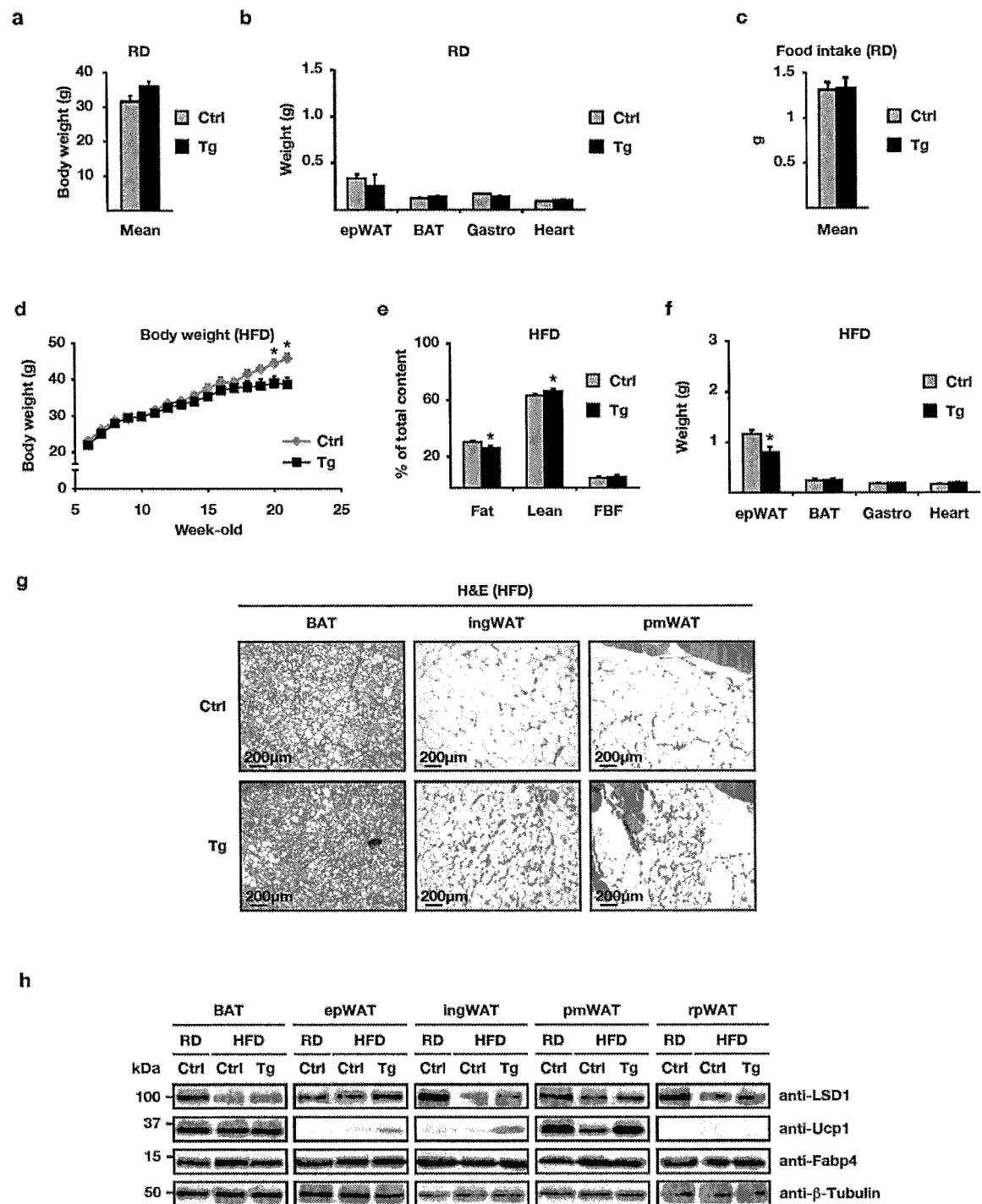


Figure 17

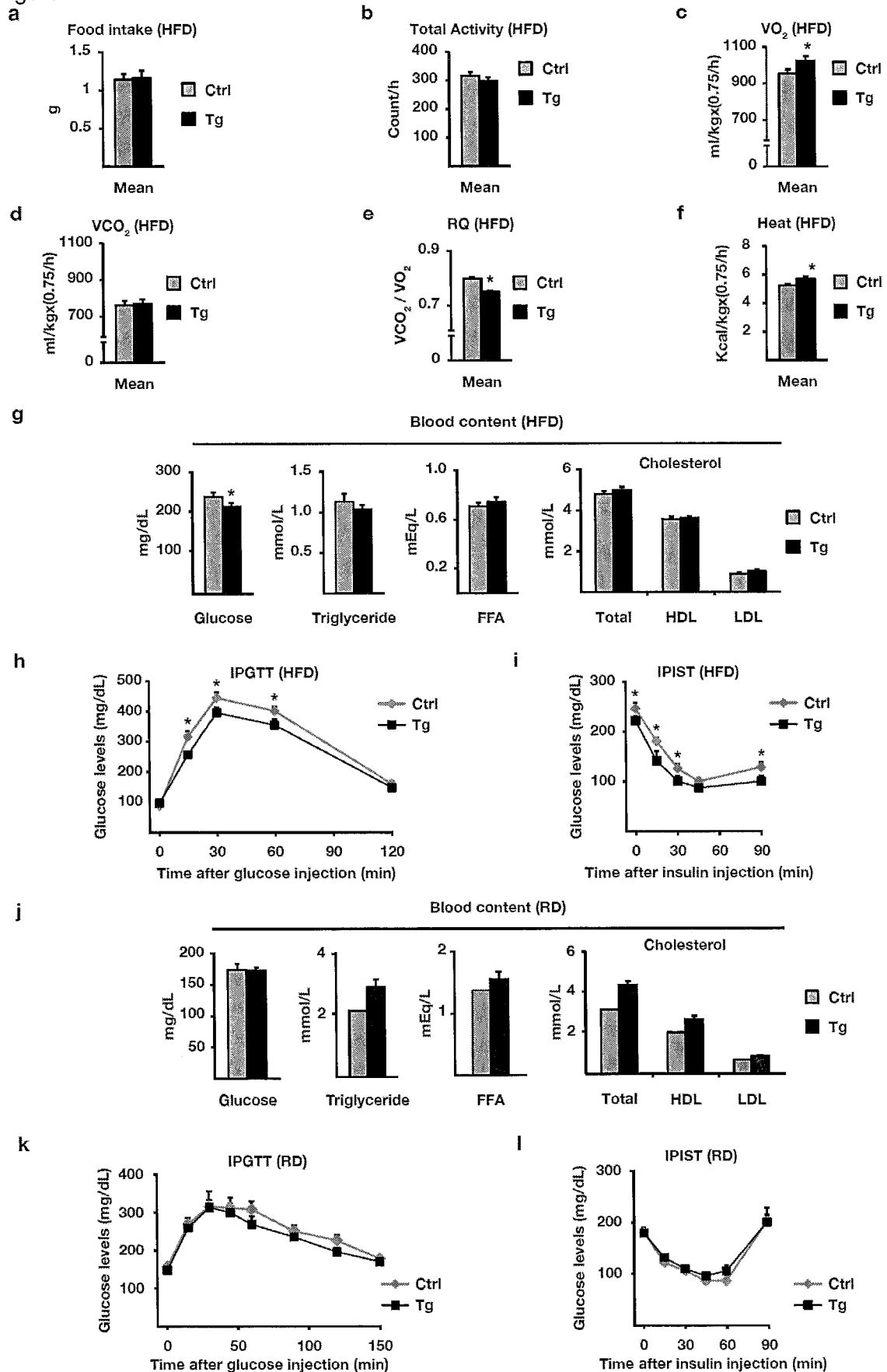


Figure 19

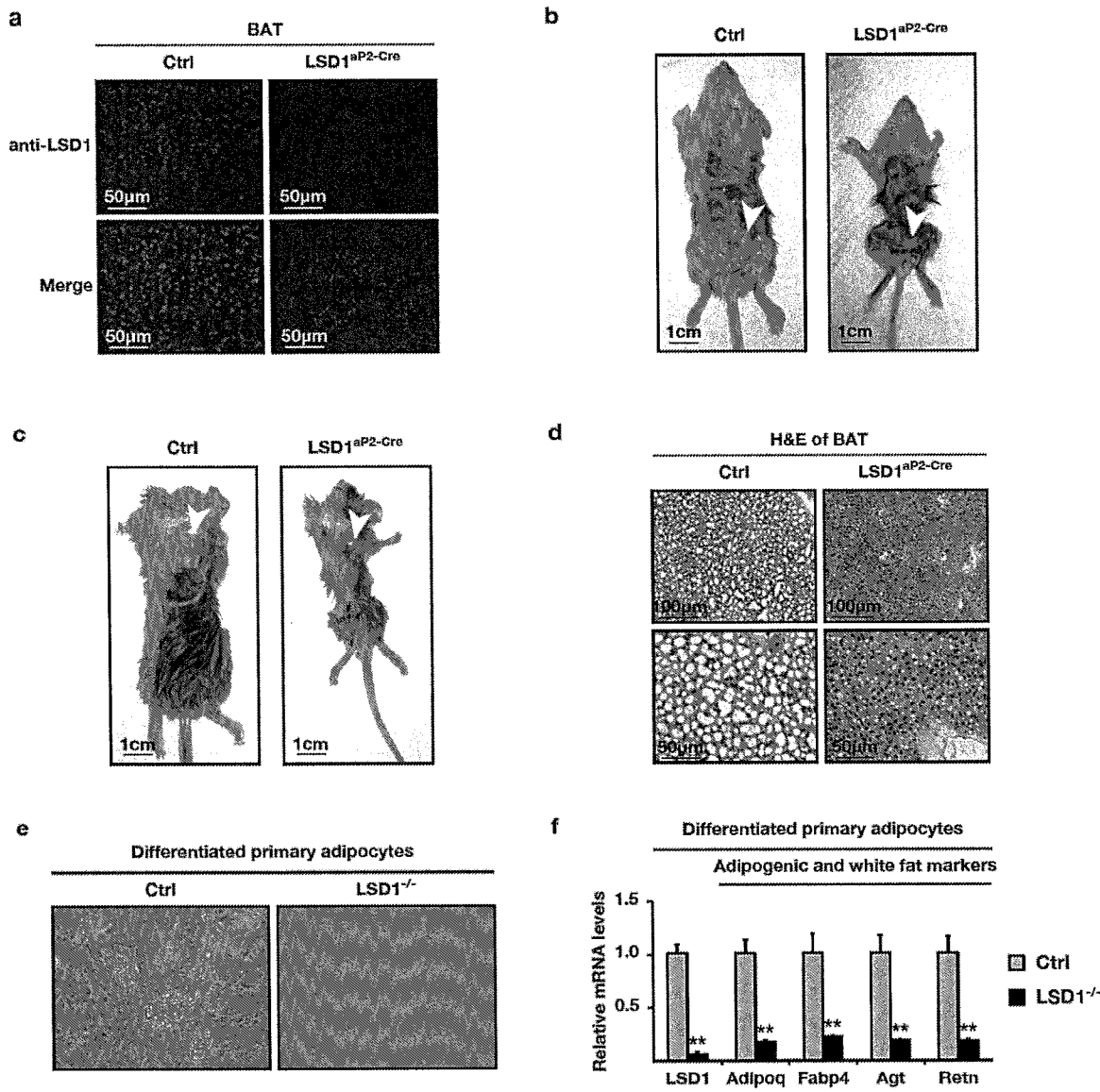


Figure 20

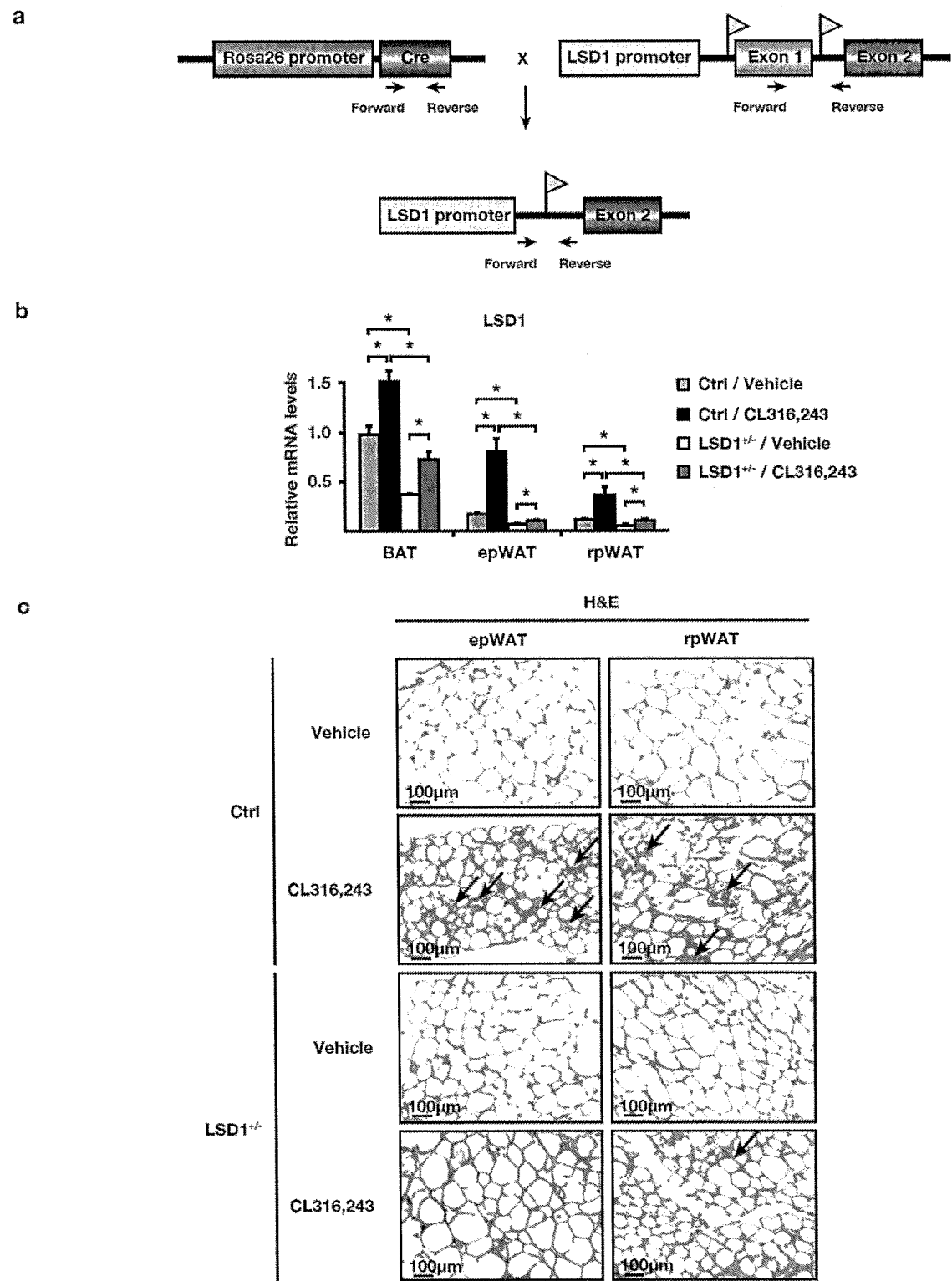


Figure 21

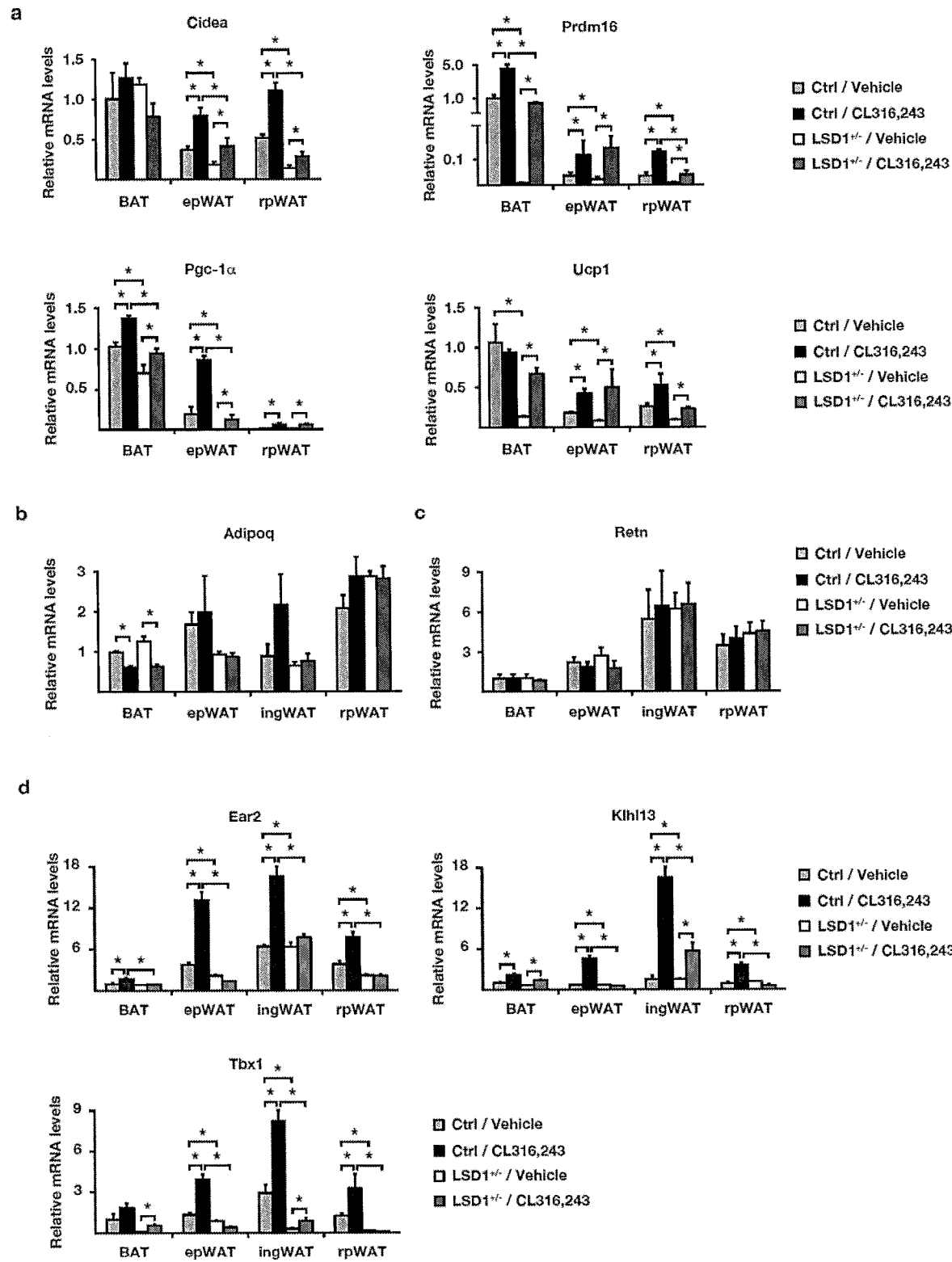


Figure 22

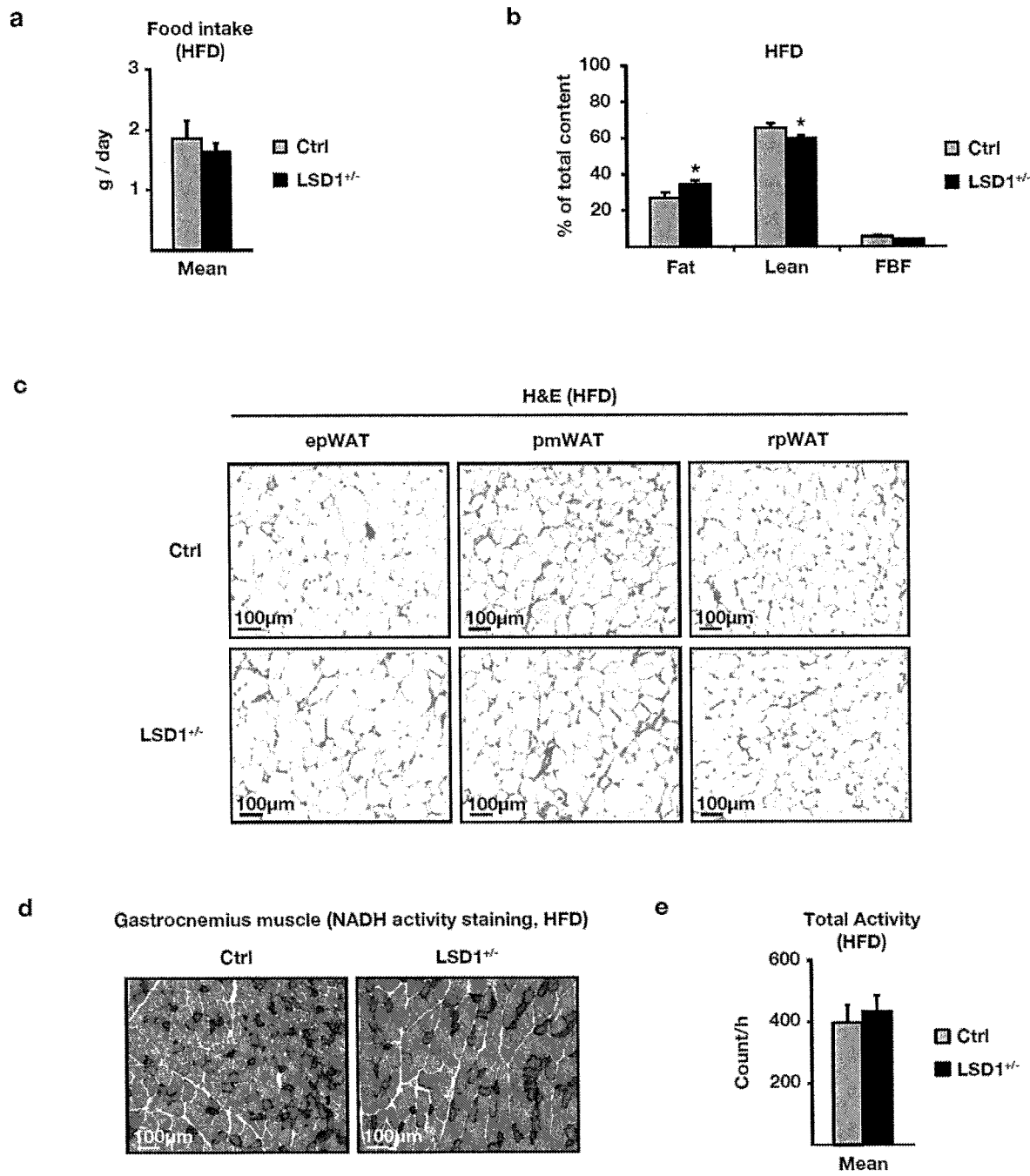


Figure 23

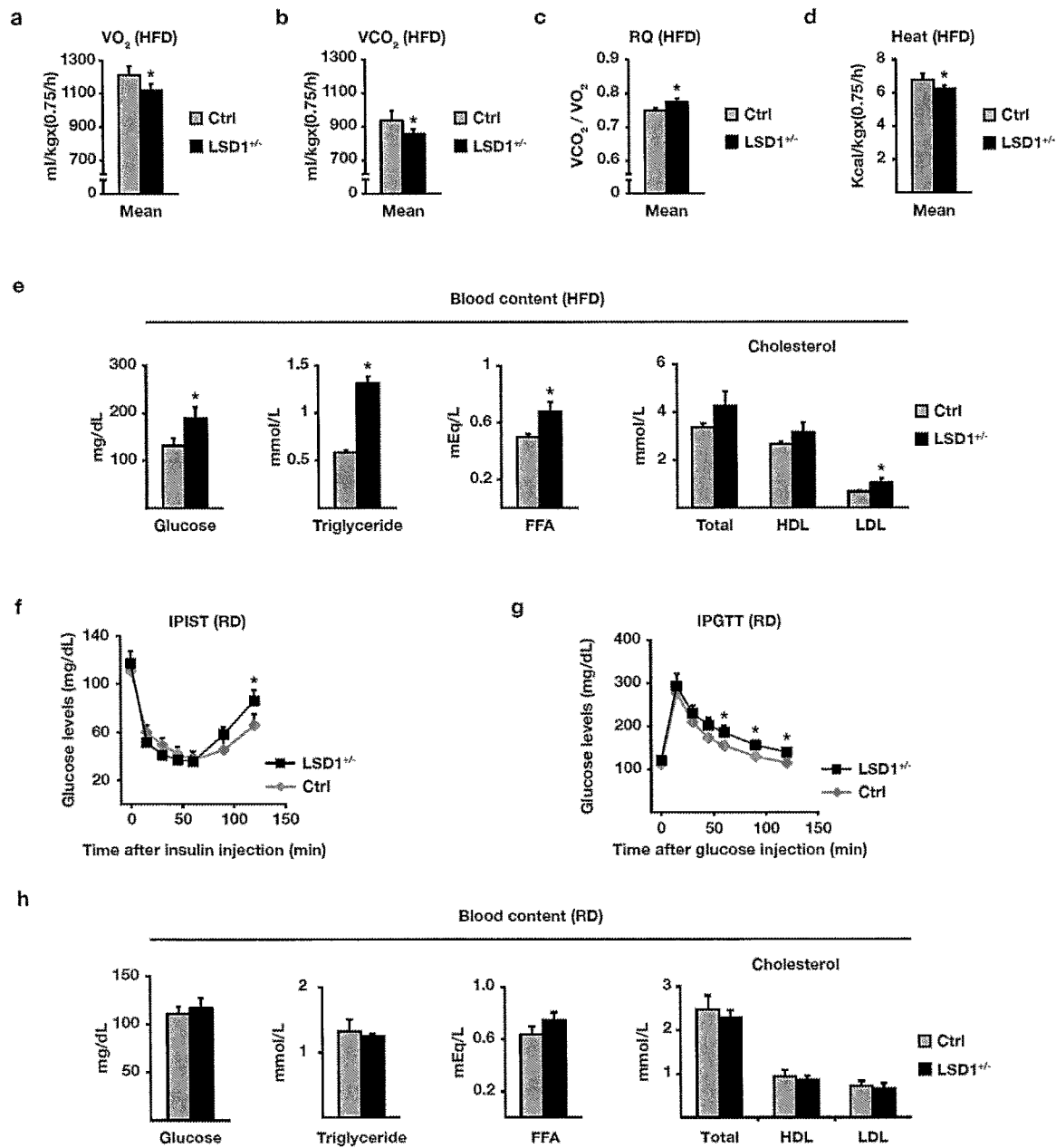


Figure 24

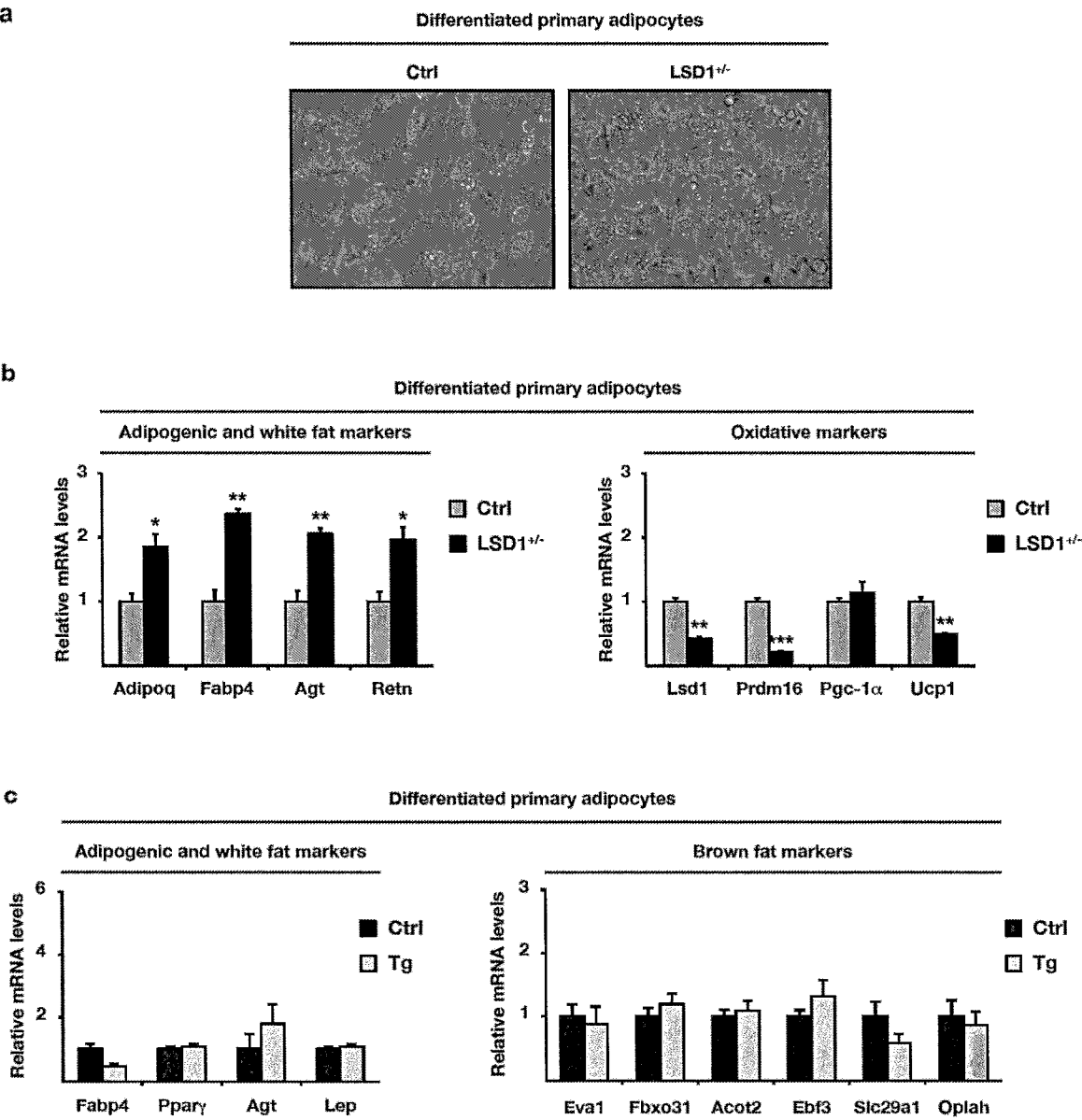


Figure 25

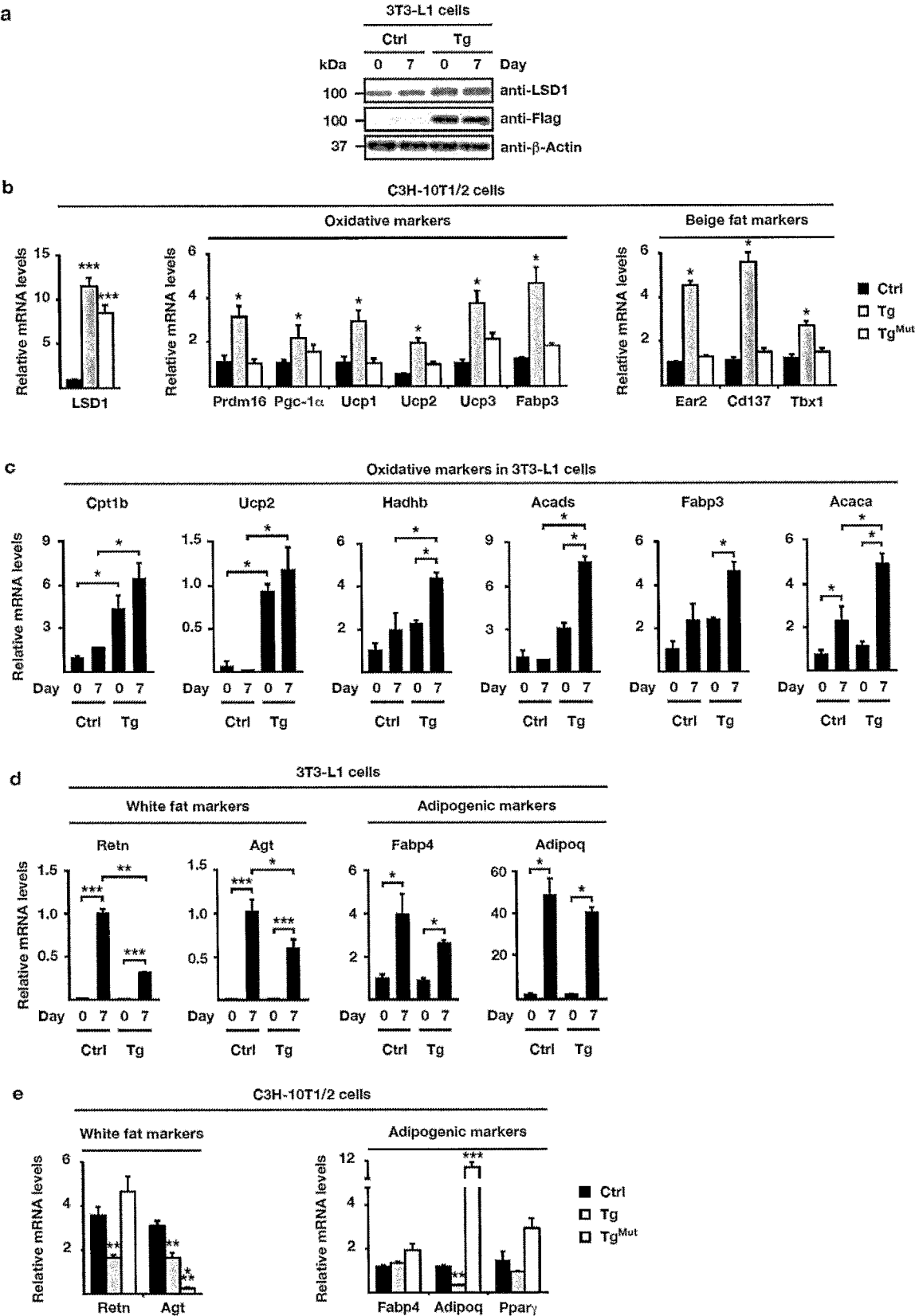


Figure 26

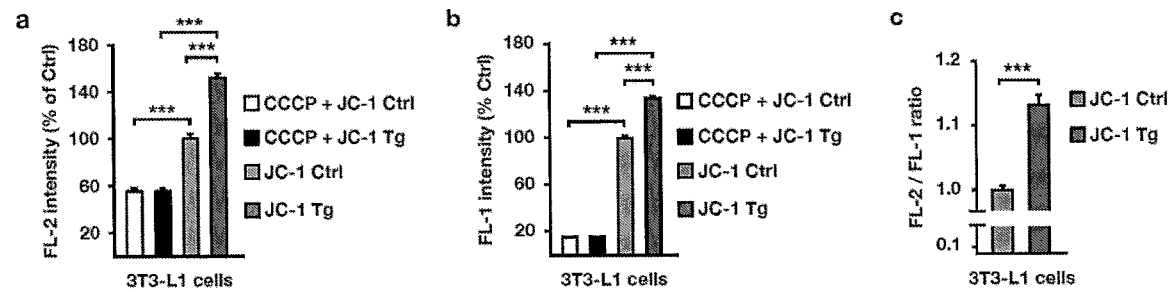
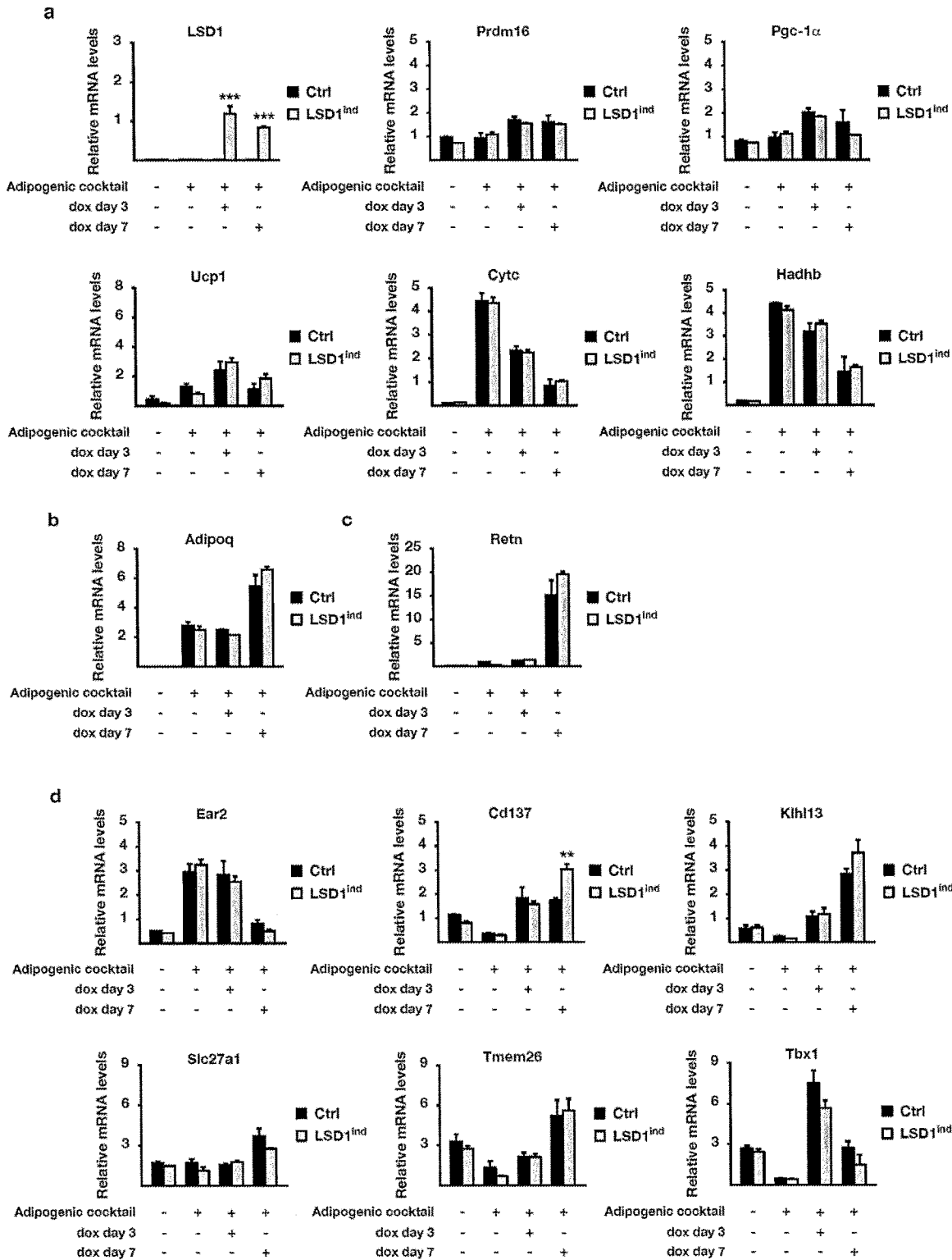


Figure 27



Figur 28

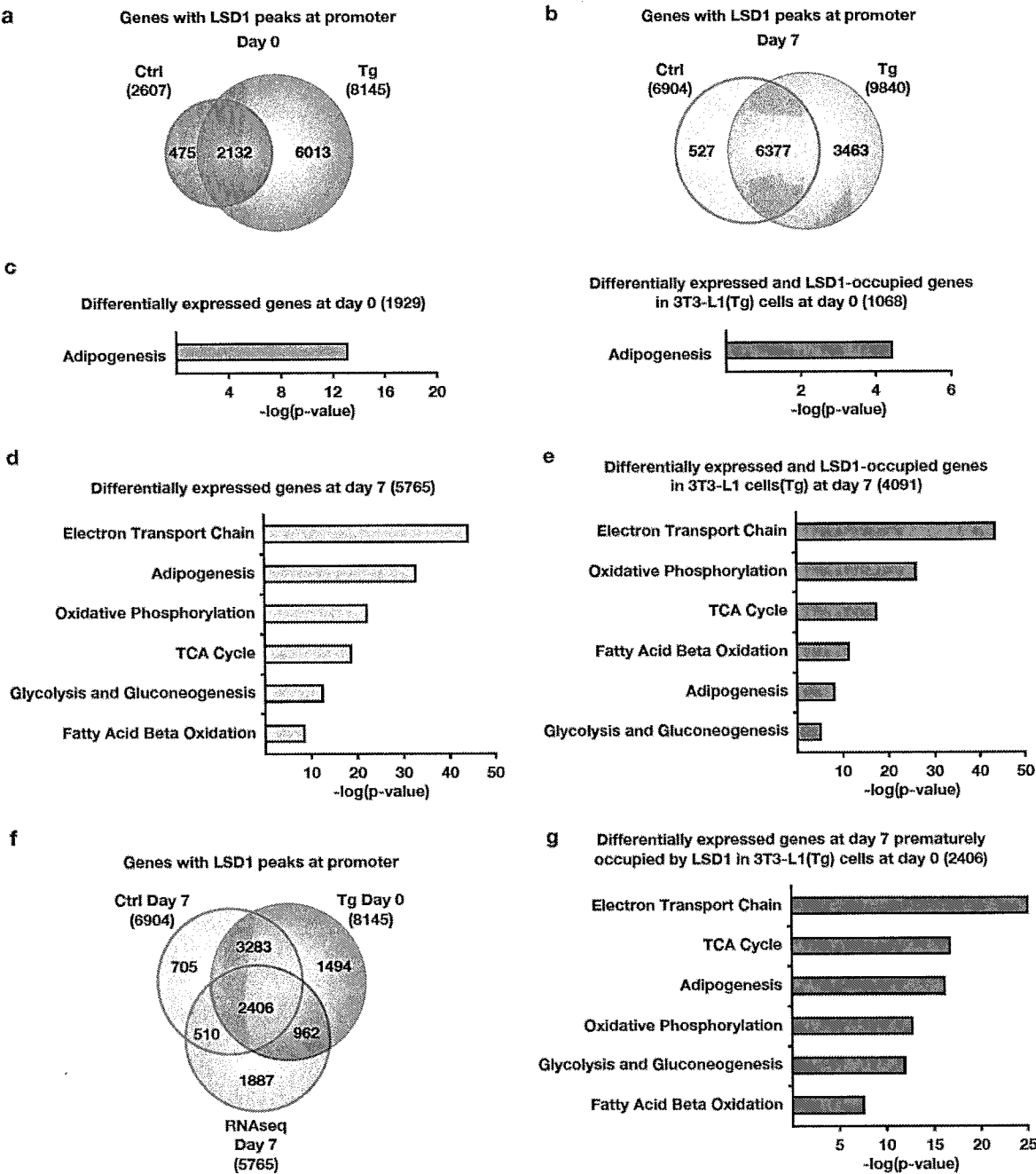
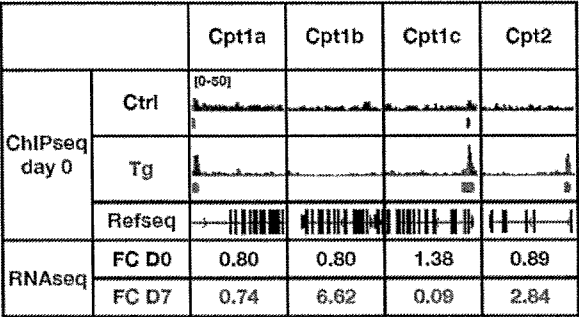
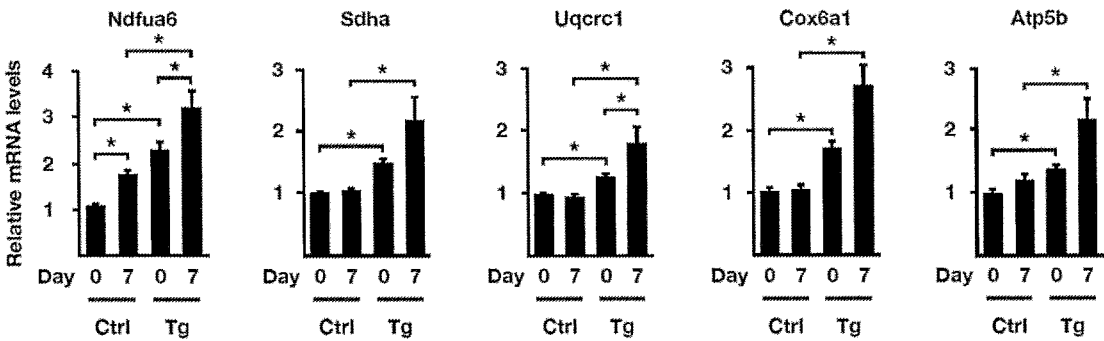


Figure 29

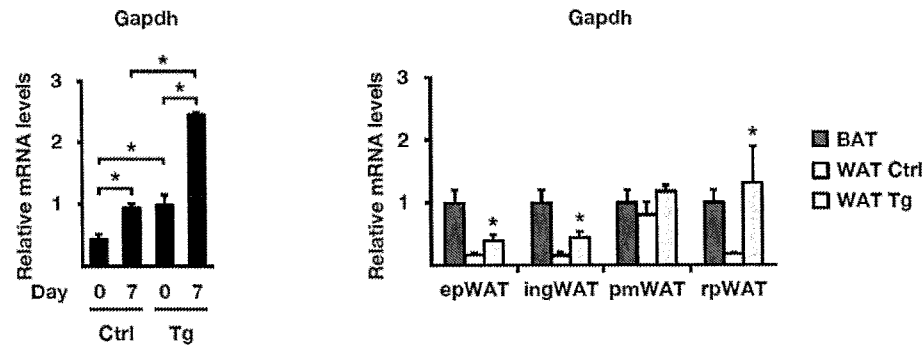
a



b



c



d

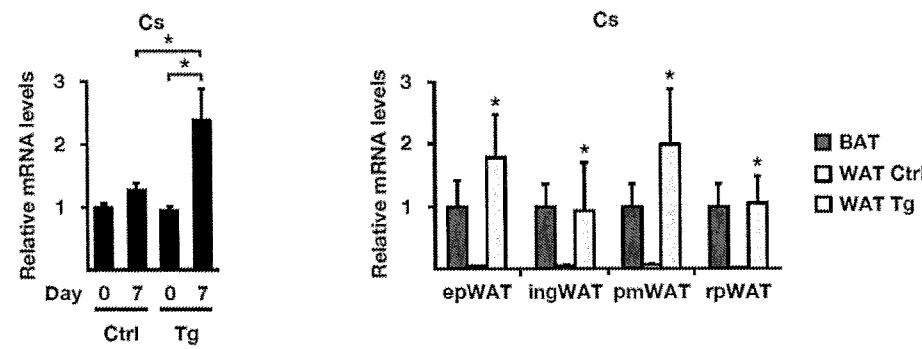


Figure 30

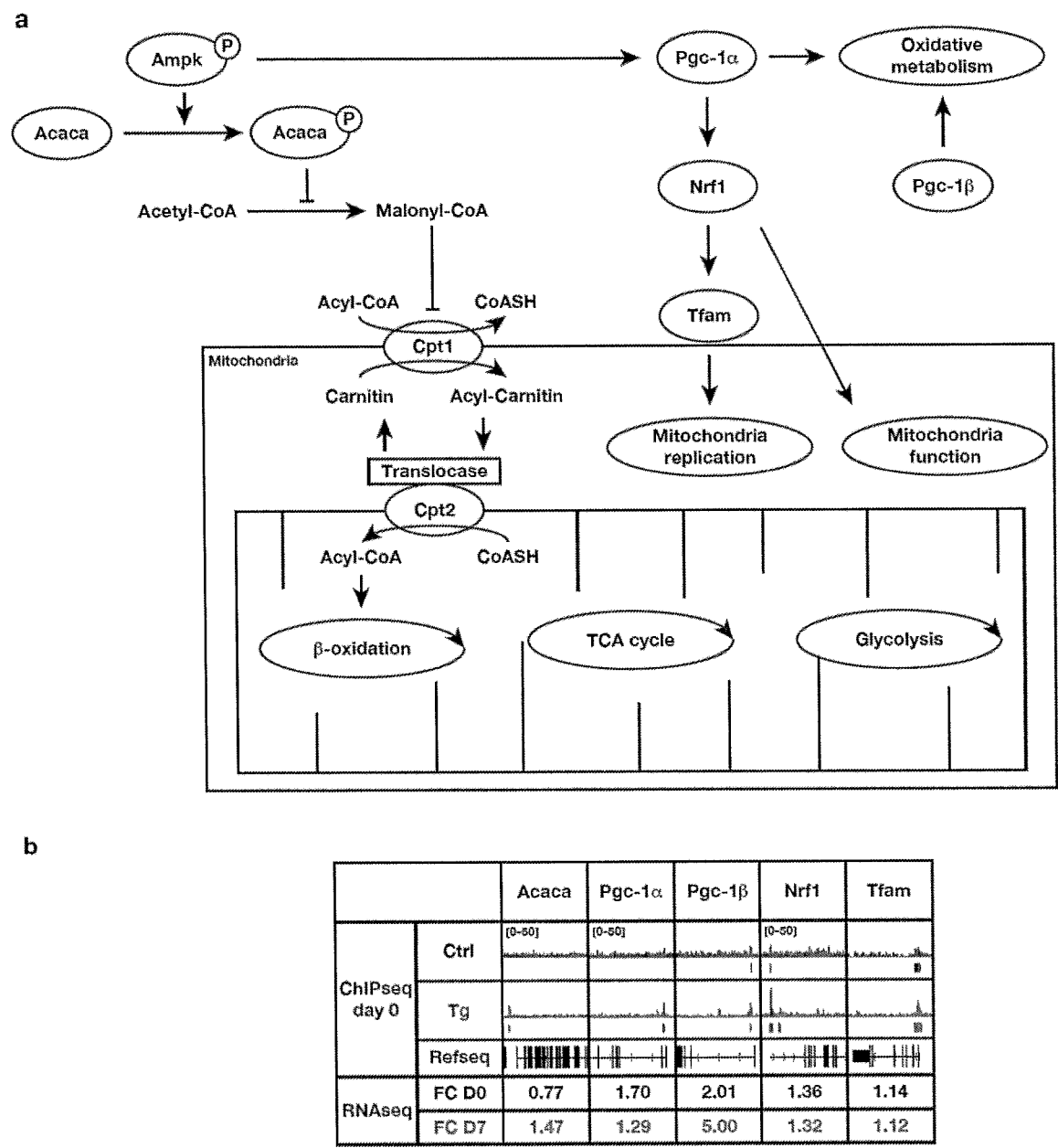


Figure 31

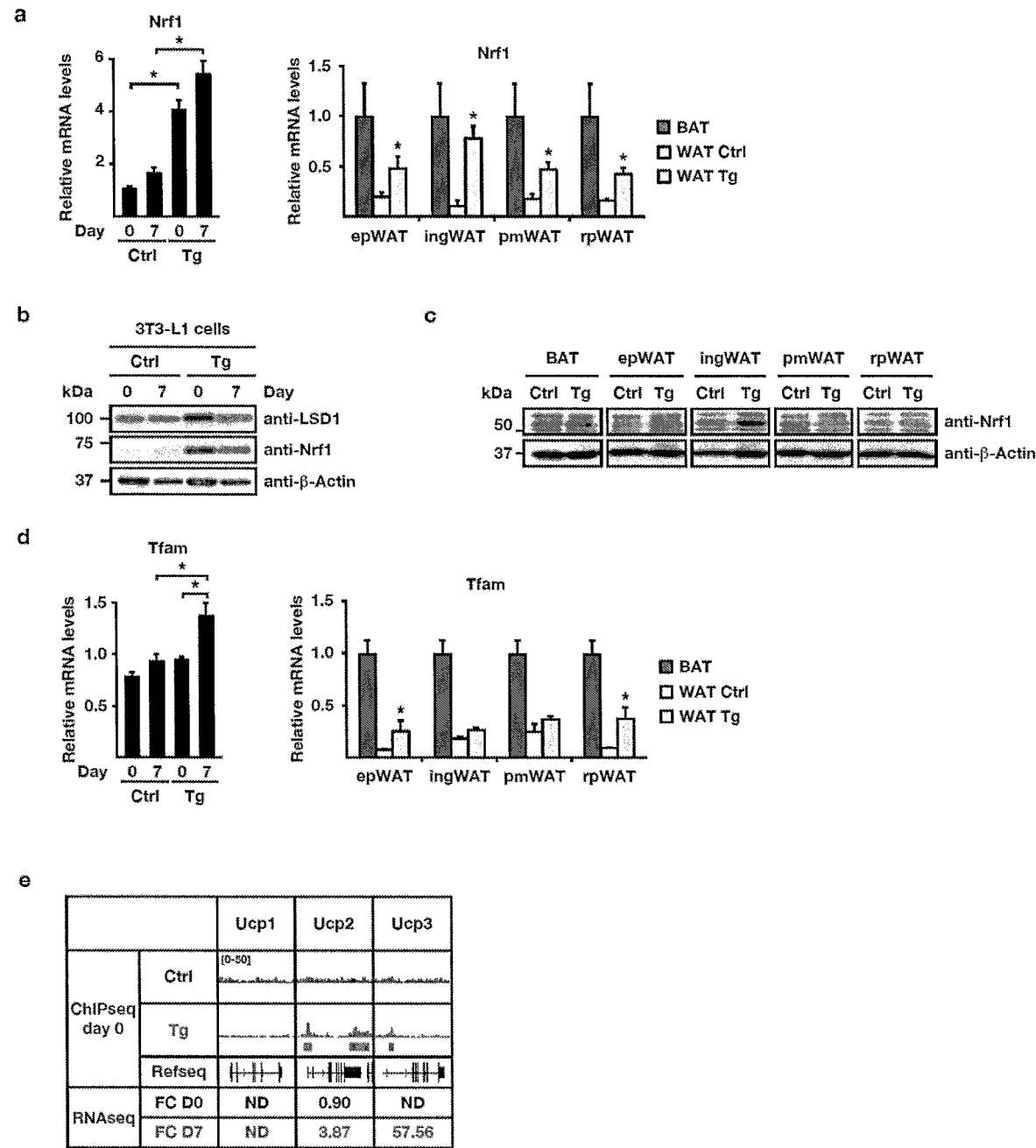


Figure 32

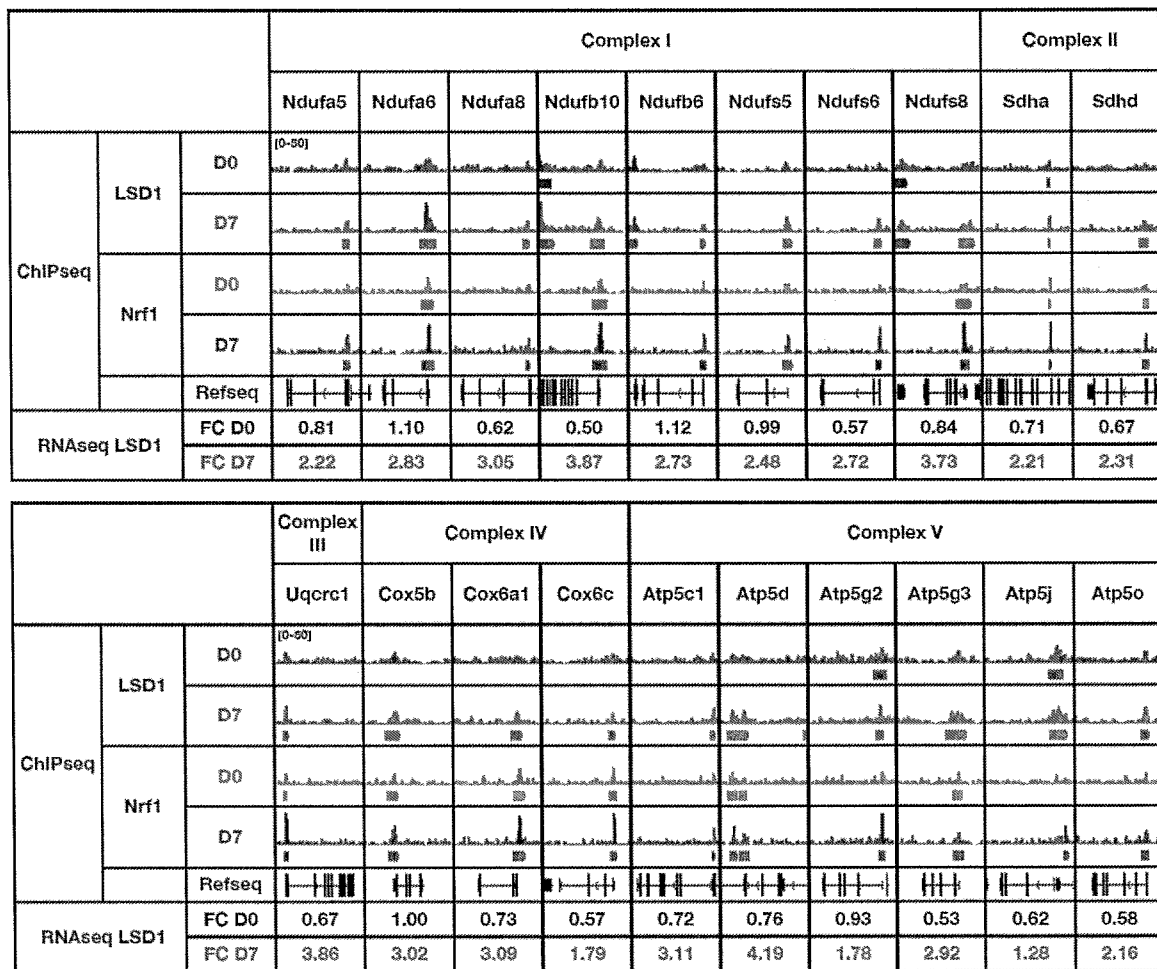


Figure 33

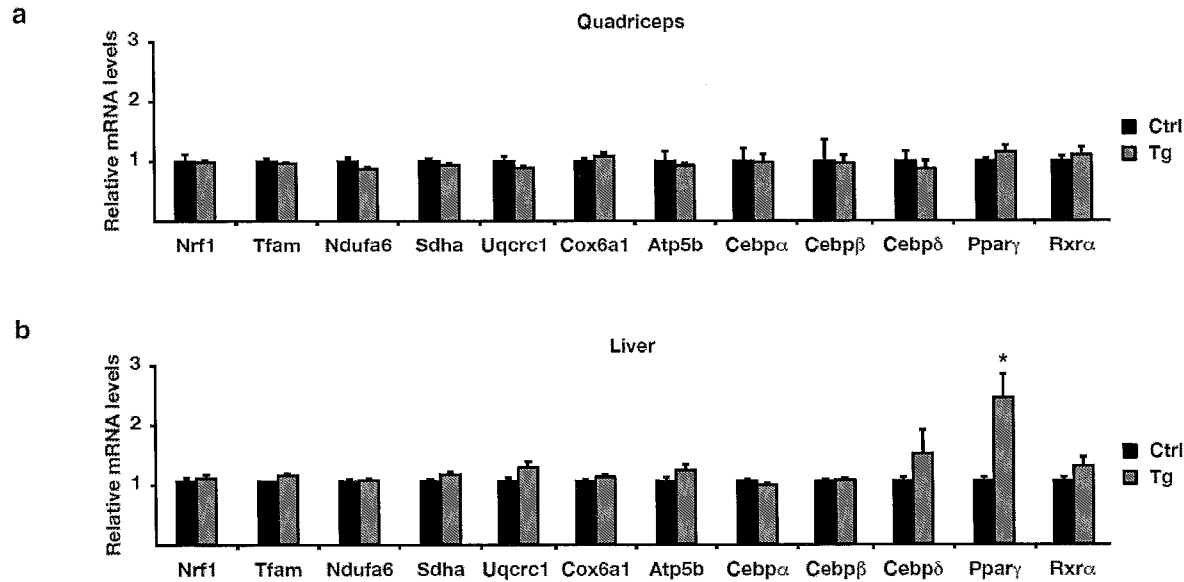


Figure 34

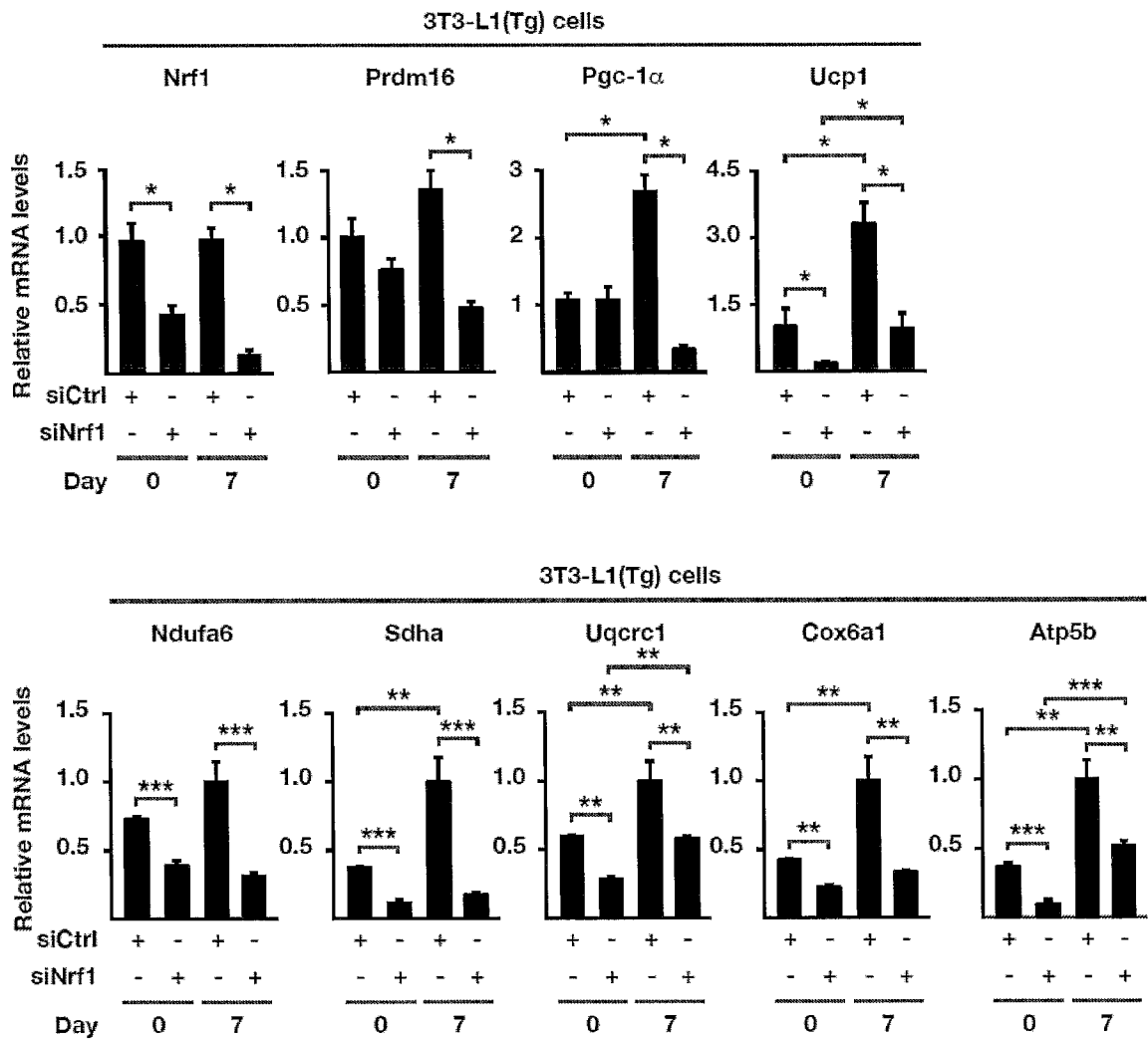
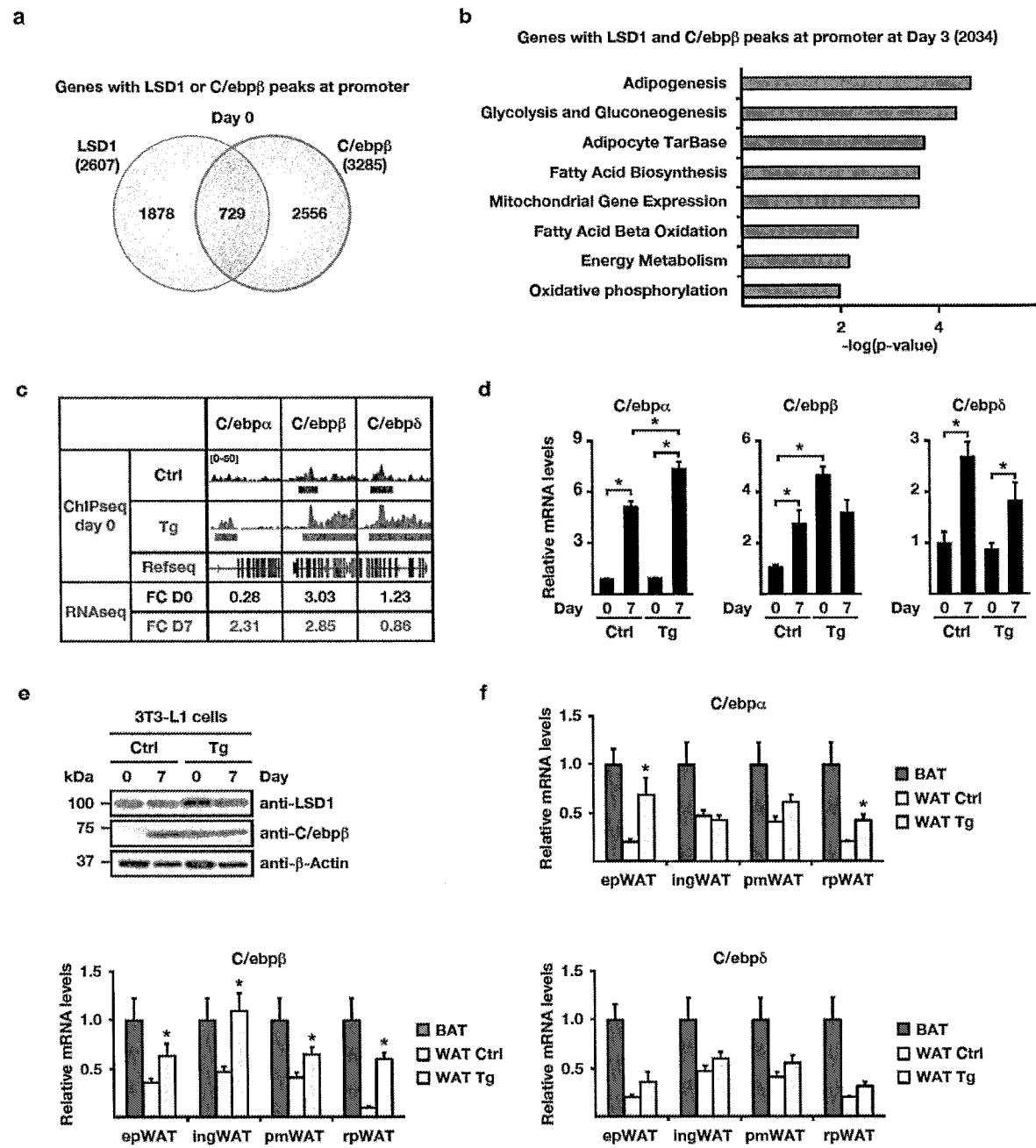


Figure 35



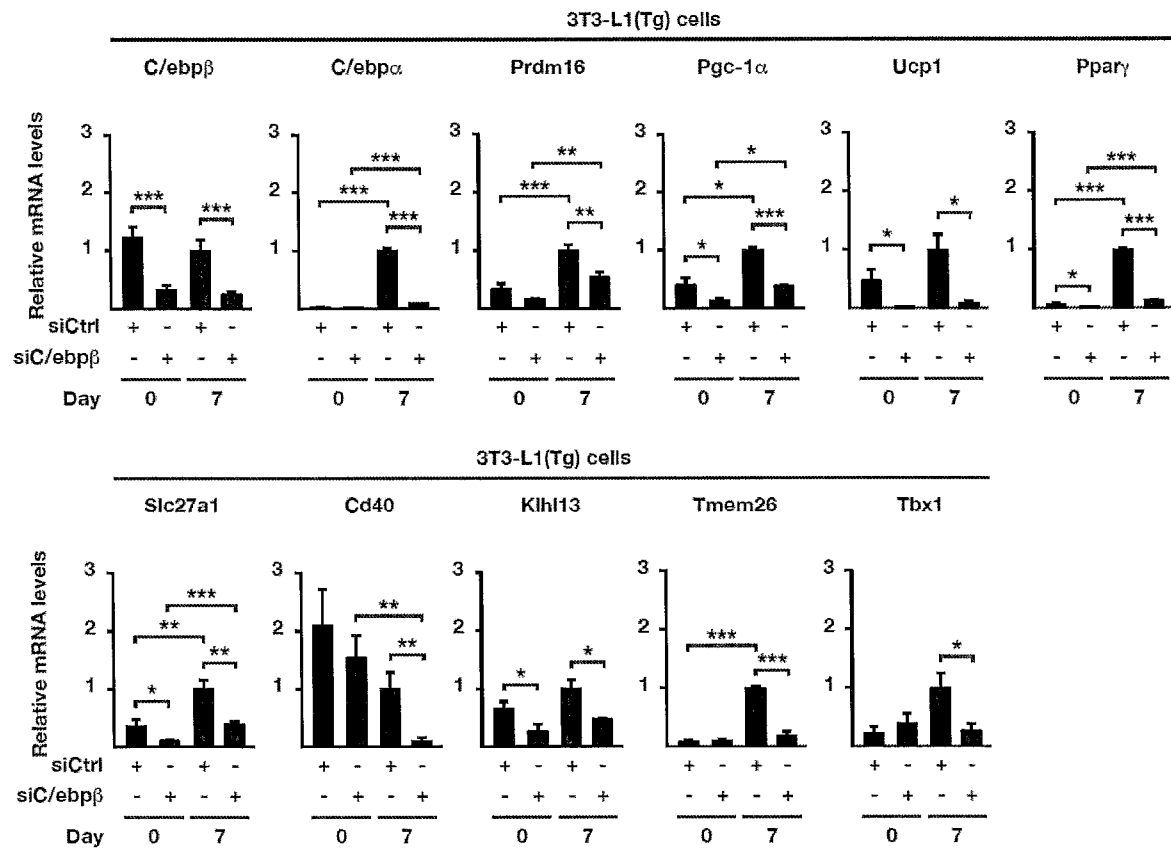


Figure 37

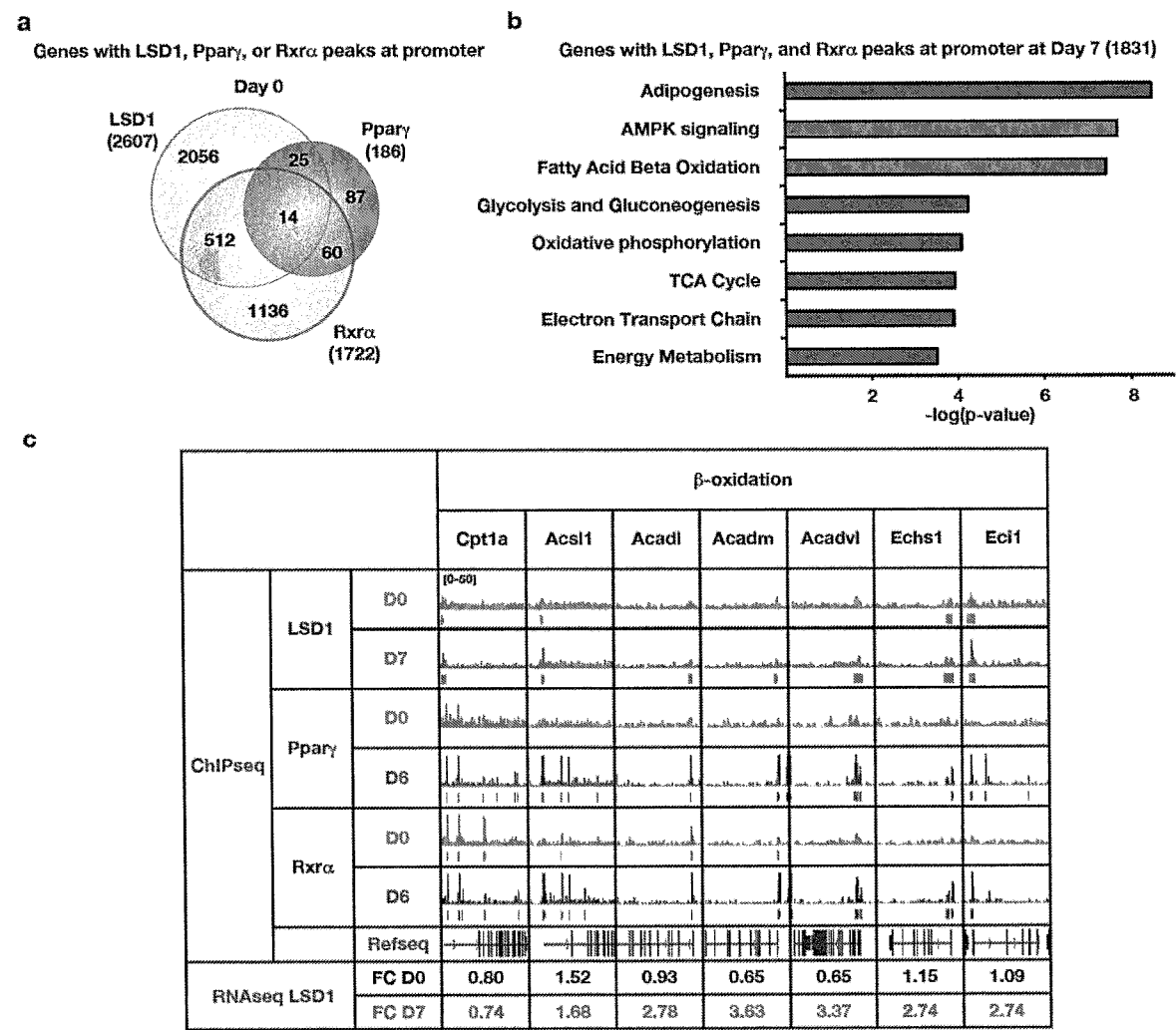


Figure 38

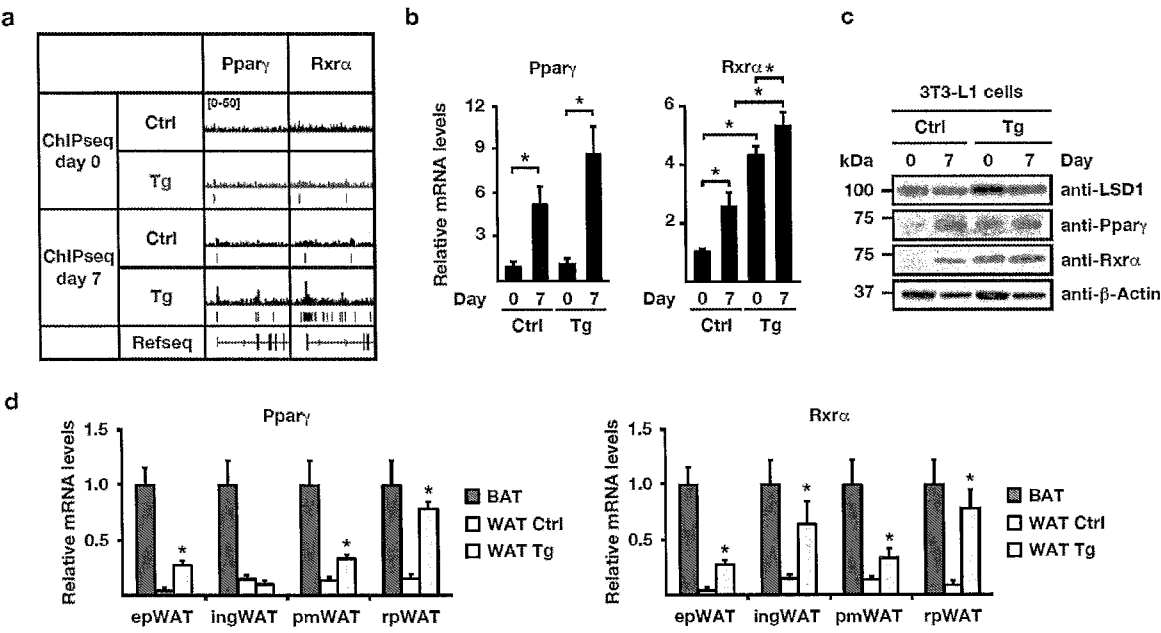


Figure 39

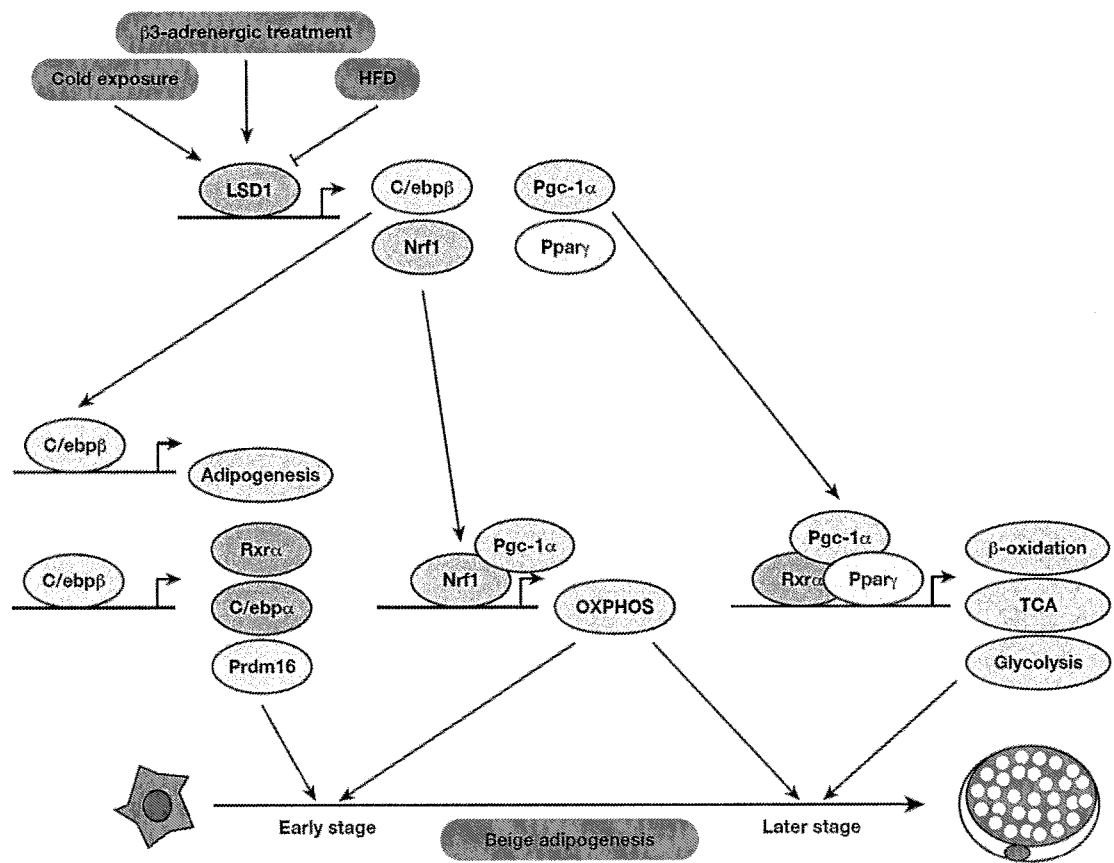


Figure 40

			Beige adipogenesis inducers					
			Ncoa1	Fndc5	Fgf21	Opa3	Klf11	Klf15
ChIPseq	Ctrl	D0	[0-50] 					
		D7						
	Tg	D0						
		D7						
	Refseq							
RNAseq LSD1		FC D0	1.23	ND	33.99	0.95	0.99	2.68
		FC D7	2.53	5.05	335.12	2.03	1.92	5.94