Rictor/mTORC2 Loss in the Myf5 Lineage Reprograms Brown Fat Metabolism and Protects Mice against Obesity and Metabolic Disease

Chien-Min Hung,1 Camila Martinez Calejman,1 Joan Sanchez-Gurmaches,1 Huawei Li,1 Clary B. Clish,2 Simone Hettmer,3,4,5,6,7 Amy J. Wagers,3,4,5,6 and David A. Guertin1,*
1Program in Molecular Medicine, University of Massachusetts Medical School, Worcester, MA 01605, USA
2Broad Institute, Cambridge, MA 02142, USA
3Howard Hughes Medical Institute, USA
4Department of Stem Cell and Regenerative Biology, Harvard Stem Cell Institute, 7 Divinity Avenue, Cambridge, MA 02138, USA
5Joslin Diabetes Center, One Joslin Place, Boston, MA 02215, USA
6Department of Pediatric Oncology, Dana Farber Cancer Institute, Boston, MA 02155, USA
7Division of Pediatric Hematology/Oncology, Children’s Hospital, Boston, MA 02155, USA
*Correspondence: david.guertin@umassmed.edu
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SUMMARY

The in vivo functions of mechanistic target of rapamycin complex 2 (mTORC2) and the signaling mechanisms that control brown adipose tissue (BAT) fuel utilization and activity are not well understood. Here, by conditionally deleting Rictor in the Myf5 lineage, we provide in vivo evidence that mTORC2 is dispensable for skeletal muscle development and regeneration but essential for BAT growth. Furthermore, deleting Rictor in Myf5 precursors shifts BAT metabolism to a more oxidative and less lipogenic state and protects mice from obesity and metabolic disease at thermoneutrality. We additionally find that Rictor is required for brown adipocyte differentiation in vitro and that the mechanism specifically requires AKT1 hydrophobic motif phosphorylation but is independent of pan-AKT signaling and is rescued with BMP7. Our findings provide insights into the signaling circuitry that regulates brown adipocytes and could have important implications for developing therapies aimed at increasing energy expenditure as a means to combat human obesity.

INTRODUCTION

Adipose tissue is essential for many biological processes, and its dysfunction, for example in obesity, is associated with a growing spectrum of human diseases. Thus, understanding the developmental and metabolic regulation of adipose tissue has broad clinical implications. There are two main classifications of adipose tissue: white adipose tissue (WAT) and brown adipose tissue (BAT). WAT is the major energy storage site in the body and has critical endocrine functions (Gesta et al., 2007), whereas BAT dissipates energy as heat in a process called nonshivering thermogenesis (Cannon and Nedergaard, 2004). BAT is particularly important in small rodents and newborn humans to defend against cold exposure, and its functional relevance in adult humans was only recently appreciated (Harms and Seale, 2013; Nedergaard and Cannon, 2010; Tseng et al., 2010). Brown adipocytes are thermogenic because they express uncoupling protein 1 (UCP1), which embeds in the inner mitochondrial membrane and produces heat by uncoupling oxidative metabolism from ATP production. The energy expending properties of brown adipocytes coupled with the observation that human BAT amount inversely correlates with body fat mass is garnering interest in developing strategies to increase brown adipocyte number and/or activity to treat obesity (Harms and Seale, 2013; Nedergaard and Cannon, 2010; Tseng et al., 2010). However, the mechanisms, and in particular the signaling circuitry, by which BAT regulates its energy supply are poorly understood (Townsend and Tseng, 2014). With the obesity pandemic seemingly out of control, and with a desperate need for novel therapeutics, the importance of elucidating mechanisms controlling adipocyte growth and function cannot be overstated.

Studying the in vivo mechanisms of adipose tissue growth has been challenging because adipocyte origins are poorly understood, and consequently few tools are available for genetically targeting adipocyte precursors in vivo (e.g., by Cre-Lox). Lineage tracing studies indicate early mesenchymal precursor cells expressing Myf5 give rise to myocytes, brown adipocytes, and a subset of white adipocytes (Sanchez-Gurmaches and Guertin, 2014; Sanchez-Gurmaches et al., 2012; Seale et al., 2008), and several recent studies have used the Myf5-Cre knockin allele (Tallquist et al., 2000) to study BAT development (Harms et al., 2014; Martinez-Lopez et al., 2013; Ohno et al., 2013; Sanchez-Gurmaches et al., 2012; Schulz et al., 2013). Thus, the multiate potential of Myf5 precursors provides an opportunity to use genetics to distinguish between signaling mechanisms that are required in vivo for the growth of myocytes versus adipocytes.

The mechanistic target of rapamycin (mTOR) kinase is a master regulator of growth that functions in two distinct complexes...
lipid deposition, although a mechanism was not elucidated.During adulthood (defined by the Rictor subunit) (Laplante and Sabatini, 2012). AKT has many effectors including GSK3β, FoxO1/3, and mTORC1 (through TSC2 and PRAS40), and most models indicate mTORC2 is an essential upstream regulator of pan-AKT activity (Laplante and Sabatini, 2012). However, the extent to which this is the case in vivo remains unclear because Rictor-deficient mouse embryo fibroblasts, which lack mTORC2, have seemingly normal GSK3β phosphorylation, mTORC1 activity, and only partially decreased FoxO1/3 phosphorylation (Guertin et al., 2006; Jacinto et al., 2006; Shiota et al., 2006).

Mice lacking Rictor die around embryonic day 10.5 (E10.5) (Guertin et al., 2006; Jacinto et al., 2006; Shiota et al., 2006); therefore, mTORC2 function in vivo is mostly being investigated using floxed Rictor alleles. In adipose tissue, two studies using aP2-cre to delete Rictor reported no effect on individual adipocyte size or overall adipose tissue mass (Cybulski et al., 2009; Kumar et al., 2010). One of the studies finds aP2-cre;Rictorfl/fl mice eventually develop mild glucose intolerance and ectopic lipid deposition, although a mechanism was not elucidated (Kumar et al., 2010). Notably however, the utility of aP2-cre to target adipocytes has recently been questioned (Lee et al., 2013; Mullican et al., 2013; Wang et al., 2013); therefore, the exact function of mTORC2 in adipose tissue remains unclear. Deleting Rictor in skeletal muscle with Hsa-cre or Mck-cre also has no effect on muscle fiber size or overall muscle mass and only minor effects on insulin-mediated glucose metabolism (Bentzinger et al., 2008; Kumar et al., 2008). These relatively mild phenotypes are somewhat surprising considering the importance of AKT signaling in metabolism; however, in both cases (adipose tissue and muscle), the Cre drivers used target mature cells, and thus the in vivo role of mTORC2 in adipose tissue and muscle precursors is unknown.

Here, we take advantage of the fact that Myf5-Cre expresses in precursors of muscle and brown adipocytes to investigate the role of Rictor (i.e., mTORC2) and for comparison Raptor (i.e., mTORC1) in muscle and BAT growth. We report that Raptor is essential in the Myf5 lineage for myogenesis, establishing BAT precursors, and viability. In contrast, Rictor is dispensable for myogenesis and viability but essential for normal BAT growth. Moreover, Rictor-deficient BAT is more metabolically active, having elevated mitochondrial activity and decreased lipogenesis. Importantly, deleting Rictor in the Myf5 lineage also augments diet-induced thermogenesis, which protects mice from an obesogenic diet at thermoneutrality. We additionally find that Myf5-lineage white adipocytes require Rictor for normal growth in vivo, suggesting a broader role for mTORC2 in adipose tissue development. Finally, we show that Rictor is also required in vitro for brown adipocyte differentiation, but not for pan-AKT activity, and that this differentiation defect is rescued with BMP7. Collectively, our results provide insight into the regulation of brown adipocytes and implicate Rictor/mTORC2 as a critical signaling node that balances oxidative and lipogenic metabolic states.

RESULTS

Rictor Is Dispensable in the Myf5 Lineage during Embryogenesis

We investigated the role of mTORC1 versus mTORC2 in vivo in fat versus muscle development by generating Myf5-Cre;Raptorfl/fl (RaptorMyf5cKO) and Myf5-Cre;Rictorfl/fl (RictorMyf5cKO) conditional knockout (KO) mice. The RictorMyf5cKO mice are born at the expected Mendelian ratio and show no obvious motor or behavioral defects (data not shown). In contrast, RaptorMyf5cKO mice die perinatally. E16.5 RaptorMyf5cKO embryos are smaller due to a muscle development defect that is not apparent in control or RictorMyf5cKO embryos (Figures S1A–S1D). Transverse sections through the head and neck of RaptorMyf5cKO embryos reveal an underdeveloped tongue and the absence of the masseter, sternohyoid, hyglossus, suprapsinnatus, prevertebral, and trapezius muscles, the later deficiency resulting in hindneck body-wall fragility during specimen preparation (Figures S1A–S1D). Thus, Raptor is essential in the Myf5 lineage for viability and muscle development, whereas Rictor is dispensable for both.

To confirm that Rictor is dispensable for myogenesis, we purified satellite cells (which express Myf5) from RictorMyf5cKO skeletal muscles, confirmed they are deleted for Rictor (Figure S1E), and show they differentiate ex vivo into myosin heavy chain-positive multinucleate myofibers (Figures S1F and S1G). Moreover, deleting Raptor in satellite cells in vivo with Pax7-CreER blocks skeletal muscle repair, whereas deleting Rictor by the same approach does not prevent muscle regeneration following acute injury (Figures S1H and S1I). Thus, Rictor is also dispensable for satellite cell differentiation ex vivo and for adult myogenesis induced by injury.

WATs develop postpartum in mice, but early brown adipocyte precursor cells (bAPCs) are detectable in E16.5 embryos by hematoxylin and eosin (H&E) staining. Qualitatively similar pools of cervical, interscapular, and subscapular bAPCs are detectable in control and RictorMyf5cKO E16.5 embryos (Figures S1A and S1D). In contrast, interscapular and subscapular bAPCs are absent in E16.5 RaptorMyf5cKO embryos (Figures S1A and S1D). Notably, a diminished pool of cervical bAPCs is detectable in the RaptorMyf5cKO embryos consistent with our lineage tracing data showing that only about half of the cervical brown adipocytes arise from Myf5-Cre-expressing precursors (Figure S1D) (Sanchez-Gurmaches and Guertin, 2014). Thus, Raptor, but not Rictor, is also essential in the Myf5 lineage for establishing bAPCs during embryogenesis.

Brown and White Adipose Tissue Growth Requires Rictor

Although RictorMyf5cKO mice show no obvious embryonic phenotypes, they tend to weigh less (not significantly) than controls at postnatal day 1 (P1) (Figure S1J), which reaches significance from 6 to 15 weeks of life (Figure 1A). Individual tissue analysis indicates that the weight difference results from decreased adipose tissue mass. For example, the interscapular BAT (IBAT) in
P1 Rictor<sup>Myf5KO</sup> neonates weighs about 30% less than normal (Figure S1K), and during the first weeks of life, the mutant BAT grows but to a much smaller size, resulting in mutant iBAT and subscapular BAT (sBAT) depots at 6 weeks that weigh about 50% less than controls and are darker (Figure 1B). Adipocytes in the retroperitoneal and anterior subcutaneous WAT depots
(rWAT and asWAT, respectively) are also derived largely from Myf5-Cre-expressing precursors (Sanchez-Gurmaches and Guerin, 2014; Sanchez-Gurmaches et al., 2012), and both of these depots also decrease in mass by approximately 50% in the Rictor\textsuperscript{Myf5cKO} mice (Figure 1C). In contrast, the posterior subcutaneous and perigonadal WAT depots (psWAT and pgWAT, respectively), which are composed of Myf5-negative lineage adipocytes, do not differ in weight (Figure 1C). Skeletal muscles (e.g., triceps, quadriceps, and gastrocnemius) and all other lean tissues examined except the kidneys (which are slightly larger) are of normal size in the KO (Figure 1D). Western analysis for Rictor protein confirms Rictor deletion and reduced AKT-S473 phosphorylation in iBAT and muscle and, to a lesser extent, in rWAT and asWAT, but not in psWAT, pgWAT, or liver (Figure 1E).

From 6 weeks to 6 months, the mutant iBAT and sBAT show no additional growth increase, whereas asWAT and rWAT grow to about half (asWAT) or one-third (rWAT) the size of their anatomically matched control tissues (Figure 1F). In contrast, Rictor\textsuperscript{Myf5cKO} psWAT, pgWAT, muscles, and liver grow to their normal size in the same time frame (Figure 1F). Thus, Rictor\textsuperscript{Myf5cKO} mice can grow small BAT tissues in the first weeks of life; however, as Rictor\textsuperscript{Myf5cKO} mice age, the iBAT and sBAT maintain their weight, whereas asWAT and rWAT grow at a reduced rate. Collectively, these results indicate Rictor is essential in the Myf5 lineage for adipose tissue growth, but not for skeletal muscle growth.

Brown Adipocytes Lacking Rictor Are Smaller
To better define the BAT growth defect, we histologically examined iBAT in control and Rictor\textsuperscript{Myf5cKO} mice. At E18.5, there is no qualitative difference between control and Rictor\textsuperscript{Myf5cKO} bAPCs pools (Figure 2A). In P1 neonates, however, lipids begin accumulating in control BAT, but not in the Rictor\textsuperscript{Myf5cKO} BAT (Figure 2A). From P1 to 6 months, lipid droplets grow in size in control BAT but remain small in the Rictor\textsuperscript{Myf5cKO} BAT (Figure 2A), resulting in smaller cells measured by the increase in nuclei per mm\textsuperscript{2} (Figure S2A). Total genomic DNA content is also lower in the Rictor\textsuperscript{Myf5cKO} BAT, indicating additional hypoplasia (Figure S2B). In contrast, Rictor\textsuperscript{Myf5cKO} skeletal muscle fibers appear histologically identical to control fibers (Figure S2C).

Myf5-Lineage White Adipocytes Lacking Rictor Are Also Small and Multilocal
Compared to controls, many adipocytes in the Rictor\textsuperscript{Myf5cKO} rWAT and asWAT are also smaller and multilocal (Figure 2B), but the pattern is heterogeneous in that several large unilocular white adipocytes are also detectable. The psWAT and pgWAT adipocytes appear unchanged in the KO (Figure S2C). The adipocyte precursor pools in rWAT and asWAT are a mix of Myf5-Cre-lineage-positive and negative precursors (Sanchez-Gurmaches et al., 2012). Therefore, we reasoned that the size heterogeneity in Rictor\textsuperscript{Myf5cKO} rWAT and asWAT could reflect a mosaic of Myf5-lineage-negative (i.e., undeleted) and Myf5-lineage-positive (i.e., Rictor KO) cells. To test this, we incorporated the Rosa26:\textit{mTmG} reporter (Muzumdar et al., 2007) into control and Rictor\textsuperscript{Myf5cKO} mice to irreversibly label Cre-expressing cells and their lineages with membrane-targeted enhanced GFP (mGFP); all other (Cre\textsuperscript{mGFP}) cells and their descendants are labeled with membrane-targeted tdTomato fluorescent protein (mTFP). The result is unequivocal; only the small adipocytes are mGFP\textsuperscript{+} in Rictor\textsuperscript{Myf5cKO} rWAT and asWAT, whereas all the large unilocular adipocytes are mTFP\textsuperscript{+} (Figure 2C). As expected, in both the control and Rictor\textsuperscript{Myf5cKO} mice, the iBAT adipocytes are mGFP\textsuperscript{+} and the psWAT and pgWAT adipocytes are mTFP\textsuperscript{+} (Figure S2D). We also detect a slight increase in UCP1 staining in the Rictor\textsuperscript{Myf5cKO} adipocytes, suggesting the cells might have brown-adipocyte-like characteristics (Figure S2E) (not shown). These data confirm that the heterogeneous small-cell phenotype results from cell-autonomous Rictor deletion in the Myf5-lineage white adipocytes.

Lipogenesis Is Decreased in Rictor-Deficient BAT
We hypothesized that the paucity of lipid and marked color difference between control and Rictor\textsuperscript{Myf5cKO} BAT indicates a shift from a lipogenic to oxidative state. To test this, we first examined AKT signaling in BAT, which positively regulates lipogenesis. In vivo AKT-T308 phosphorylation is intact in both fasted/refed and insulin-stimulated Rictor\textsuperscript{Myf5cKO} BAT despite ablation of pAKT S473 and pAKT T450 (which is also mTORC2 dependent) (Figures 3A and S3A), consistent with the ability of T-loop (T308) and hydrophobic motif (S473) phosphorylation to be regulated independently (Pearce et al., 2010). Surprisingly, phosphorylation of the AKT substrates FoxO1/3, GSK3\textbeta, TSC2, PRAS40, and AS160 is normal in Rictor\textsuperscript{Myf5cKO} BAT (Figure 3A), indicating Rictor is not essential in BAT for pan-AKT signaling. Rictor loss in BAT also does not affect phosphorylation of the SGK substrate NDRG1 (Figure 3A), indicating mTORC2 is not essential for SGK signaling to NDRG1 in BAT or that a compensatory pathway exists.

Next, we examined whether deleting Rictor in the Myf5 lineage affects BAT differentiation markers. In P1 neonates, Prdm16, C/ebp\textalpha, and C/ebp\textbeta expression do not differ between controls and KOs, whereas Pr\textbeta and Ucp1 levels slightly decrease (Figure 3B), indicating a possible delay in BAT maturation in the KOs. However, by 6 weeks, Pr\textbeta, Prdm16, and C/ebp\textalpha express at control levels, whereas C/ebp\beta, Ucp1, and Dio2 express at significantly higher-than-control levels (Figure 3B). The mature adipocyte markers Cidea and aP2 are unchanged between control and KO both at P1 and 6 weeks (Figure 3B). Consistent with the gene expression data, PPAR\gamma, UCP1, and insulin receptor beta (IR\beta) proteins also express at near-control levels in Rictor\textsuperscript{Myf5cKO} BAT (Figure 3A). Thus, terminal differentiation per se (i.e., PPAR\gamma, UCP1, and IR\beta induction) occurs in vivo in Rictor\textsuperscript{Myf5cKO} brown adipocytes.

Next, we examined lipogenesis genes. In P1 Rictor\textsuperscript{Myf5cKO} BAT, acetyl-coA carboxylase (Acc), fatty acid synthase (Fasn), and fatty acid elongase 6 (Elov6) decrease expression by 40%, 40%, and 25%, respectively (Figure 3C). By 6 weeks, expression of ATP citrate lyase (Acly) in addition to Acc, Fasn, and Elov6 is reduced by 90%, 75%, 80%, and 40%, respectively (Figure 3C), which we confirmed by western blot for ACly and ACC (Figure 3A). In addition, stearoyl-CoA desaturase (Scd1) decreases expression by 45% in 6-week Rictor\textsuperscript{Myf5cKO} BAT (Figure 3C). The SREBP1c and ChREBP transcription factors regulate lipogenesis gene expression (Czech et al., 2013; Filhoulaud et al., 2013). In both P1 and 6-week Rictor\textsuperscript{Myf5cKO} BAT, the mRNA
expression of SREBP1c (Srebf1c), which is induced by insulin, and CHREBP (a and b isoforms), which is induced by glucose, is similar (Figure 3D). However, there is a marked decrease in the amount nuclear SREBP1c (nSREBP1c), the transcriptionally active SREBP1c cleavage product, in Rictor-deficient BAT (Figure 3A) consistent with the decrease in lipogenic gene expression. The levels of insig1, another nSREBP1c target gene and negative regulator of SREBP1c processing, also decreases (Figure 3C). The mRNA expression of SREBP2 (which regulates cholesterol biosynthesis) slightly decreases in RictorMyf5cKO
BAT at 6 weeks, but the SREBP2 target genes HMG-CoA synthase (Hmg-cs) and HMG-CoA reductase (Hmg-cr) express at similar levels in control and KO BAT (Figure 3D), and nuclear SREBP2 (nSREBP2) accumulates possibly to higher levels in the KO BAT (Figure 3A). We find no difference in AMPK or hormone-sensitive lipase phosphorylation between control and RictorMyf5cKO BAT (Figures 3A and S3A). Together, these results indicate that despite having seemingly normal AKT signaling, de novo lipogenesis is reduced in RictorMyf5cKO BAT.

Mitochondrial Activity Is Elevated in Rictor-Deficient BAT

To further examine the metabolic state of RictorMyf5cKO BAT, we examined mitochondrial activity. In P1 neonate RictorMyf5cKO BAT, Pgc1a expresses normally, whereas expression of mitochondrial transcription factor A (Tfam), which regulates mtDNA replication, and carnitine palmitoyltransferase 1B (Cpt1b), which encodes the rate-limiting enzyme in β-oxidation, slightly decreases (Figure 4A). In contrast, Pgc1a, Tfam, and Cpt1b in addition to Ucp1 express at higher levels in the BAT of 6-week-old RictorMyf5cKO mice (Figures 4A and 3B), suggesting BAT mitochondrial activity progressively increases or is maintained at a higher level in RictorMyf5cKO mice as they age.

To explore this in more detail, we used quantitative RT-PCR (qRT-PCR) arrays to broadly measure mitochondrial gene expression in the 6-week-old BAT. Using arrays for functional genes involved in mitochondrial molecular transport and biogenesis, we detect increases in several genes indicative of increased mitochondrial activity (Figure 4B). Furthermore, the mitochondrial citrate and malate transporters Slc25a1 and Slc25a10

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### Figure 3. Rictor-Deficient Brown Adipocytes Have a Lipid Metabolism Defect

(A) Western blots total and phosphoproteins using 6-week iBAT lysates. Mice were fasted overnight and refed for 45 min prior to preparing lysates. (B–D) qRT-PCR of the indicated genes in P1 (n = 6) and 6-week (n = 8) iBAT (mean ± SEM; t test; *p < 0.05, **p < 0.01)

See also Figure S3.
respectively—both of which function in fatty acid biosynthesis, the former also being an SREBP1c target gene (Infantino et al., 2007; Mizuarai et al., 2005)—significantly decrease expression in the mutant BAT. Using mitochondrial energy metabolism gene arrays, we found 58 additional genes involved in respiration (OXPHOS) are elevated in RictorMyf5cKO BAT (Figure S4A), suggesting an increase in mitochondrial mass, which we confirmed by Cox IV immunofluorescence (Figure 4C). Transmission electron microscopy (TEM) reveals individual mitochondria in the mutant BAT are larger and have more disorganized cristae (Figure 4D). To directly confirm elevated mitochondrial activity, we measured BAT oxygen consumption rate (OCR) in a Seahorse Flux Analyzer and determined that basal and pyruvate-stimulated OCRs are elevated by around 18% in RictorMyf5cKO BAT (Figure 4E). We did not detect a significant increase in overall oxygen consumption when RictorMyf5cKO mice were placed in metabolic cages at 22°C, except when normalized for body weight (Figure S4B). Notably, however, mice are under thermal stress at this temperature, which can mask effects on BAT activity (Feldmann et al., 2009).

Figure 4. Mitochondrial Activity Is Elevated in Rictor-Deficient BAT
(A) qRT-PCR of mitochondrial genes in P1 (n = 6) and 6-week iBAT (n = 8) (mean ± SEM; t test; *p < 0.05, **p < 0.01)
(B) Differentially expressed genes using mitochondrial qRT-PCR arrays (n = 4; t test; p < 0.05)
(C) Representative immunofluorescence images of Cox IV staining in 6-week iBAT (n = 3).
(D) Representative TEM images of 6-week iBAT (left) and mitochondria size (right) (n = 3; mean ± SEM; t test; ***p < 0.001)
(E) Oxygen consumption of iBAT using a Seahorse Flux Analyzer (12 weeks, n = 5; normalized to DNA content; mean ± SEM; t test; *p < 0.05)
(F) qRT-PCR of Ucp1 mRNA in iBAT with or without cold exposure (left) (n = 3 for 22°C; n = 4 for 4°C; mean ± SEM; two-way ANOVA; ***p < 0.001) and rectal temperature in acute cold challenge (right) (n = 4; mean ± SEM; t test; no significant difference).
See also Figure S4.
Interestingly, we also detect an approximate 2-fold increase in basal glucose uptake in Rictor<sup>Myric KO</sup> BAT measured by <sup>18</sup>FDG positron emission tomography computed tomography scanning (Figure 4C) and an increase in lipoprotein lipase (LpL) expression (Figure 3C), suggesting that Rictor<sup>Myric KO</sup> BAT may consume more nutrients than age-matched control BAT. Small-metabolite profiling reveals that Rictor<sup>Myric KO</sup> BAT also has elevated levels of inosine monophosphate (IMP) (Figure 4D), a deamination product of AMP, the accumulation of which suggests increased uncoupling (Balcke et al., 2011). In an acute cold challenge, Rictor-deficient BAT also induces Ucp1 expression significantly more than control BAT and the mutants have no difficulty maintaining body temperature, although body temperature regulation in an acute cold challenge is largely a function of muscle (Figure 4F). Finally, we see no compensatory “browning” in the psWAT as would be expected if Rictor<sup>Myric KO</sup> BAT were dysfunctional (Figures S2C and S2D) (Schulz et al., 2013). These results are consistent with Rictor loss in BAT shifting metabolism to a more oxidative and less lipogenic state.

**Brown Preadipocytes Require Rictor to Differentiate In Vitro**

To examine if brown adipocyte differentiation also requires Rictor in vitro, we generated brown adipocyte precursor cells (bAPCs) harboring an inducible KO system (i.e., Rictor<sup>KO</sup>) in which Rictor deletion is triggered by 4-hydroxytamoxifen (4-OHT) (Figure S5A). Compared to isogenic controls, inducibly deleting Rictor rapidly and robustly depletes Rictor protein and AKT-S473 phosphorylation and, consistent with our in vivo data, leaves AKT-T308 phosphorylation intact (Figure S5B). Also consistent with the in vivo results, both basal and insulin-stimulated phosphorylation of FoxO1/3, GSK3β, TSC2, and PRAS40 are normal in Rictor<sup>KO</sup> bAPCs (Figure S5A). S6K1 phosphorylation is also unaffected (Figure S5A). Contrary to the in vivo results, acute Rictor loss in vitro decreases NDRG1 phosphorylation (Figure S5A). This indicates Rictor is required in cultured bAPCs for SGK activity to NDRG1, but not for pan-AKT or mTORC1 activity.

To our surprise, Rictor<sup>KO</sup> bAPCs are completely incapable of synthesizing lipid droplets when induced to differentiate (Figure 5B). This is surprising, because Rictor<sup>KO</sup> cells maintain normal levels of pAKT-T308, pGSK3β-S9, and pS6K1-T389 (i.e., PDK1, AKT, and mTORC1 activity, respectively) throughout the differentiation protocol (Figure 5C). The differentiation block occurs early as Rictor<sup>KO</sup> bAPCs fail to induce C/ebpα, Ppara, Pdmd16, Pgc1α, Srebf1c, Ucp1, and Glut4 (Figures 5D and S5C). The expression of C/ebpβ and C/ebpδ on the other hand is induced normally and slightly higher (respectively) in the Rictor<sup>KO</sup> bAPCs at differentiation day 6 (Figure 5D). Consistent with the gene expression data, PPARγ, IRβ, UCP1, nSREBP1c, ACC, and ACLY levels fail to increase during differentiation in Rictor<sup>KO</sup> bAPCs (Figure 5E). Notably, 4-OHT or CreER activation alone (i.e., in the absence of Rictor floxed alleles) has no effect on differentiation (not shown). Moreover, bAPCs prepared from P1 Rictor<sup>Myric KO</sup> neonates also fail to differentiate, indicating that the ex vivo differentiation block is not unique to using the inducible KO system (Figure S5D). Importantly, expressing recombinant PPARγ in Rictor<sup>KO</sup> bAPCs rescues IRβ, UCP1, and nSREBP1c expression (Figure 5F) and lipid droplet production (Figure 5G), indicating Rictor promotes differentiation at least in part by facilitating PPARγ induction.

**Insulin receptor substrate 1 (irs1) and Irs3 KO bAPCs also fail to induce PPARγ ex vivo** (Fasshauer et al., 2001). It was later shown that Irs1/3 KO bAPCs are unable to differentiate because they express high levels of Pref-1, Wnt10a, and Necdin, which encode adipogenesis inhibitors (Tseng et al., 2005). In contrast, Rictor-deficient bAPCs express normal levels of Pref-1, Wnt10a, and Necdin in culture, and during differentiation, Necdin and Pref-1 increase, but only late in the differentiation protocol (Figure S5C). Thus, the mechanism by which deleting Rictor inhibits brown adipocyte differentiation differs from that of deleting Irs1/3.

**AKT1 Functions Downstream of Rictor in Brown Adipocyte Differentiation**

To further explore the mechanism by which Rictor regulates differentiation, we next asked whether an AKT or SGK pathway is required downstream of Rictor. To this end, we generated Rictor<sup>KO</sup> bAPCs that express hemagglutinin (HA)-SGK1, HA-AKT1, and HA-AKT2 or their phosphomimetic counterparts HA-SGK1, HA-AKT1-S473D, and HA-AKT2-S474D in which a phosphomimetic residue was placed at the mTORC2 hydrophobic motif site, confirmed they were functional (Figure S6A), and asked whether any of these constructs rescue differentiation. Only HA-AKT1-S473D efficiently rescues lipid biosynthesis (Figure 6A). HA-AKT1-S473D-expressing Rictor<sup>KO</sup> bAPCs also induce PPARγ and restore IRβ, UCP1, nSREBP1c, ACLY, and ACC expression (Figure 6B). Thus, Rictor promotes differentiation as part of mTORC2 through an AKT pathway.

Our rescue experiments point to AKT1 as the isoform driving bAPC differentiation in vitro. Consistent, AKT1 is highly expressed in undifferentiated precursors and decreases expression during differentiation, whereas AKT2 expression increases during differentiation (Figure S6B). To further examine the role of AKT1 and AKT2 in bAPC differentiation, we generated bAPC lines that specifically lack either AKT1 or AKT2 and determined their in vitro differentiation capacity. Consistent with AKT1, but not AKT2, being required for differentiation, AKT1-deficient bAPCs cannot efficiently synthesize lipid droplets (Figure 6C) or upregulate PPARγ, IRβ, or UCP1 when induced to differentiate (Figure 6D). In contrast, AKT2-deficient bAPCs induce PPARγ, IRβ, and UCP1 normally (Figures 6C and 6D), indicating that AKT1 is indeed the isoform required downstream of Rictor/mTORC2 for brown adipocyte differentiation. Interestingly, we noticed in our in vitro differentiation assays that although the AKT2-deficient cells differentiate, they fail to induce nSREBP1c, that ACLY and ACC express at low levels, and that lipid droplet content is reduced (Figures 6C and 6D). This suggests that although AKT2 is not essential for differentiation, it is important downstream of Rictor/mTORC2 for lipid metabolism. Indeed, when we immunoprecipitate AKT1 or AKT2 from undifferentiated bAPCs, most of the AKT phosphorylation is on AKT1, while in vivo the bulk of AKT phosphorylation shifts to AKT2 (Figures S6C and S6D). Thus, although the inability of Rictor<sup>KO</sup> bAPCs to differentiate in culture reflects
an AKT1 deficiency, the in vivo metabolic phenotype appears to reflect an AKT2 deficiency.

**BMP7 Rescues Brown Adipocyte Differentiation in the Absence of Rictor**

In vitro RictorKO bAPCs cannot differentiate (i.e., induce PPARγ and UCP1), but in vivo, PPARγ and UCP1-positive Rictor-deficient BAT develops. One possible explanation for this paradox is that in vivo there are developmental signals present that are missing from the artificial in vitro differentiation assay. The signals that drive brown adipocyte differentiation in vivo are poorly understood. One proposed inducer of brown adipocyte differentiation is the transforming growth factor-β superfamily member BMP7 (Schulz and Tseng, 2013; Tseng et al., 2008). When given to control or RictorKO bAPCs, BMP7 does not induce AKT phosphorylation (Figure S6E). However, when supplemented into the differentiation cocktail, BMP7 restores to RictorKO bAPCs their ability to synthesize lipid droplets (Figure 5E) and express PPARγ, IRβ, UCP1, and to a lesser extent nSREBP1c, ACLY, and ACC (Figure 5F). This is consistent with the in vitro differentiation assay lacking signaling molecules present in vivo and suggests BMP7 and mTORC2-AKT1 signaling converge during brown adipocyte differentiation. A model depicting the role mTORC2-AKT signaling in vitro in brown adipocyte differentiation is shown in Figure 6G.

**RictorMyf5cKO Mice Are Less Susceptible to Obesity and Metabolic Disease at Thermoneutrality**

The higher metabolic activity of Rictor-deficient BAT led us to wonder whether RictorMyf5cKO mice are resistant to obesity. Chronic consumption of a high-fat diet (HFD) triggers a phenomenon in mice called diet-induced thermogenesis, which requires UCP1 and counteracts obesity (Cannon and Nedergaard, 2010; Feldmann et al., 2009). Because BAT activity is masked by chronic thermal stress at 22°C, we conducted the following studies at thermoneutrality (30°C for mice), which exempts mice from thermal stress (Feldmann et al., 2009). When eating a normal chow diet, control and RictorMyf5cKO mice gain equal weight (Figure 7A) and consume the same total energy (Figure 7B) over 12 weeks. In contrast, when eating an HFD, control mice gain 14.67 ± 1.05 g whereas RictorMyf5cKO mice gain 10.57 ± 1.18 g (Figure 7A), despite both groups consuming the same energy (Figure 7B). Thus, controls gain 64% more weight when eating an HFD versus chow compared to RictorMyf5cKO mice. This suggests RictorMyf5cKO mice living at thermoneutrality and eating an HFD are less metabolically efficient than controls, which is indeed the case (Figure 7C).

The resistance to weight gain in the HFD-fed RictorMyf5cKO cohort is partly due to reduced growth of adipose tissue. For example, the pgWAT gains significantly less mass in the HFD-fed RictorMyf5cKO cohort than in HFD-fed controls (Figure 7D). Liver and heart also grow larger in controls eating HFD compared to chow, whereas liver and heart grow to the same mass in the RictorMyf5cKO cohorts regardless of diet (Figures 7D and S7A). Diet has no effect on other lean tissues in either the controls or RictorMyf5cKO cohorts (Figures 7D and S7A). That pgWAT grows less in HFD-fed RictorMyf5cKO mice compared to HFD-fed controls indicates systemic protection against obesity is occurring because Myf5-Cre does not target pgWAT (Figures 1F and S2C). The reduction in pgWAT mass is due in part to smaller adipocyte size (Figure 7E); the livers of RictorMyf5cKO mice also resist hepatic steatosis (Figure 7E), and the HFD-fed RictorMyf5cKO mice perform better in a glucose tolerance test (Figure S7B).

In chow-fed cohorts, histology reveals that control BAT adopts a more ‘‘white adipocyte-like’’ appearance (Figure 7E). In contrast, the BAT in chow-fed RictorMyf5cKO mice resists the whitening effects of living at thermoneutrality and maintains a more ‘‘brown-adipocyte-like’’ appearance (Figure 7E). The resistance of RictorMyf5cKO BAT to whitening is reflected in the gene expression signature; for example, when normalized to BAT gene expression at 22°C, the shift to thermoneutrality decreases the expression of BAT-selective genes (Pdm16, Sgk2, cideb, and cyp2b10) and increases the expression of WAT-selective genes (Opt1, Retn, Trim14, and Nnmt) (Harms et al., 2014) to a greater extent in control BAT than in RictorMyf5cKO BAT, which maintains a more BAT-like identity (Figure S7C).

In HFD-fed cohorts, histology reveals a large number of multilocular adipocytes in control BAT (Figure 7F) that are not apparent in chow-fed controls (Figure 7E), suggesting diet-induced thermogenesis. This is reflected in the gene expression data as Prdm16 increases in control BAT in HFD-fed mice compared to chow-fed mice (Figure 7G), whereas the WAT-specific genes Retn, Trim14, and Nnmt decrease (Figure 7G). Consistently, BAT functional genes (Ucp1, Pgc1α, Cpt1β, and Dio2) are induced to a greater extent in HFD-fed RictorMyf5cKO mice (Figure 7H), which also maintain low Acly, Acc, and Fasn expression (Figure S7D). Importantly, UCP1 protein levels are higher in the BAT of RictorMyf5cKO mice eating an
HFD (Figure 7I). Notably, after 20 weeks of eating an HFD, the control BAT reverts to a more white-adipocyte-like histology; however, BAT character is preserved in Rictor<sup>Myf5cKO</sup> mice (Figure S7E). Collectively, these results suggest that inhibiting mTORC2 in BAT increases diet-induced thermogenesis and, consequently, Rictor<sup>Myf5cKO</sup> mice living without thermal stress and consuming an obesogenic diet are less susceptible to developing obesity and metabolic disease.

**DISCUSSION**

Transcriptional regulation of BAT development has been extensively described (Kajimura et al., 2010), whereas less is known about the signaling mechanisms that regulate BAT. The control of brown fat fuel utilization is also incompletely understood (Townsend and Tseng, 2014). Previous studies reported that conditionally deleting Rictor in WAT and BAT or skeletal muscle has no affect on WAT or BAT mass or individual adipocyte or myocyte size (Bentzinger et al., 2008; Cybulski et al., 2009; Kumar et al., 2008, 2010). However, these studies used Cre drivers that reportedly delete Rictor in mature cells, which led us to hypothesize that Rictor/mTORC2 may be more important for BAT/WAT and/or muscle development. By conditionally deleting Rictor in Myf5 precursors, we discovered that Rictor is not essential in vivo for muscle development or regeneration. In contrast, Myf5-lineage brown and white adipocytes lacking Rictor are reduced in size. Furthermore, Rictor-deficient BAT undergoes a metabolic shift to a more oxidative and less lipogenic metabolic despite having seemingly normal pan-AKT signaling. Importantly, at thermoneutrality, this protects mice against an obesogenic diet. These findings implicate Rictor/mTORC2 as an essential signaling node in BAT that regulates the balance of energy utilization.

We also report that in vitro brown adipocyte differentiation requires Rictor/mTORC2. Mechanistically, Rictor/mTORC2 promotes Ppar<sub>γ</sub> induction through AKT1 independently of pan-AKT signaling and mTORC1 activity. In vivo, however, brown adipocytes differentiate in Rictor<sup>Myf5cKO</sup> mice despite lacking Rictor expression. We hypothesize that this paradox indicates that the artificial in vitro culture conditions lack important signals present in vivo that overcome this deficiency. Supporting this notion, supplementing the differentiation assay with BMP7, a proposed in vivo inducer of brown adipocyte differentiation and thermogenesis (Schulz and Tseng, 2013; Tseng et al., 2008), rescues differentiation in the absence of Rictor. Notably, we do detect low Ppar<sub>γ</sub> expression in Rictor<sup>Myf5cKO</sup> P1 BAT, which may reflect the role of Rictor/mTORC2 in early brown adipocyte differentiation and explain the mutant BAT hypoplasia. Exactly how Rictor/mTORC2 and BMP7 signaling might converge on PPAR<sub>γ</sub> is not yet clear. We also show that during brown adipocyte differentiation, the major AKT isoform switches from AKT1 to AKT2; thus, although Rictor/mTORC2 may regulate differentiation through an AKT1 pathway that can be bypassed in vivo, its role in BAT metabolism is likely mediated through an AKT2 pathway that cannot be compensated for. Consistent with this idea, whole-body Akt2 KO mice among many other phenotypes have smaller BATs (Cho et al., 2001; Garofalo et al., 2003).

Why does deleting Rictor in BAT cause a metabolic shift? One possibility is that forkhead box O (FOXO) transcription factors are more active in Rictor-deficient brown adipocytes. FOXOs are regulated by multiple signals and function as cellular homeostasis regulators under stressful conditions (Eijkelenboom and Burgering, 2013). Fox01 and Fox03 are AKT substrates that are partially dephosphorylated in some Rictor-deficient cells (Guertin et al., 2006, 2009; Hagiwara et al., 2012; Jacinto et al., 2006; Yuan et al., 2012). When dephosphorylated, Fox01/3 translocate to the nucleus, where they affect metabolism, survival, and cell-cycle genes and the activity of transcriptional regulators (including PPAR<sub>γ</sub> and C/EBP<sub>a</sub>) (Eijkelenboom and Burgering, 2013). However, Fox01/3 phosphorylation is not affected in Rictor-deficient BAT; thus, if the metabolic shift is driven by Fox01/3, it may be through an alternative mechanism such as acetylation ( Banks et al., 2011; Masui et al., 2013). Another possibility is that FoxC2 mediates the metabolic shift (Cederberg et al., 2001; Yao et al., 2013); however, we do not observe any change in FoxC2 expression in Rictor-deficient preadipocytes (not shown), nor do we see effects on the FoxC2 targets Cebpa or Wnt10b during differentiation (Gerin et al., 2009). The shift could also be mediated through unidentified AKT substrates that uniquely require hydrophilic motif phosphorylation. This is an important ongoing area of investigation.

Consistent with the Myf5 lineage giving rise to a subset of white adipocytes, we also uncovered an essential role for Rictor/mTORC2 in white adipocyte growth in vivo. This confirms our previous discovery that some white adipocytes arise from Myf5-Cre expressing precursors (Sanchez-Gurmaches and Guertin, 2014; Sanchez-Gurmaches et al., 2012). However, because in the Rictor<sup>Myf5cKO</sup> mice the Rictor-deficient white adipocytes are interspersed heterogeneously with nondeleted adipocytes within the same depot, we could not perform the appropriate whole-tissue biochemical studies using Rictor-deficient WAT. We did, however, determine that Rictor<sup>KO</sup> white adipocyte precursors purified from the stromal vascular fraction of psWAT (which are not Myf5-lineage derived) are also defective at differentiating in vitro (not shown), indicating Rictor also has a...
cell-autonomous role in white adipocyte differentiation that is not dependent upon being Myf5-lineage derived. To determine the in vivo relevance of these findings, we will need to identify Cre drivers that express uniformly and specifically in white adipocyte precursors; however, the origins of adipocytes are just beginning to be revealed, and appropriate tools are not yet available for this line of investigation.

Is Rictor/mTORC2 a master regulator of lipid metabolism? Recent studies of liver collectively report that deleting hepatic Rictor results in a complex phenotype including increased gluconeogenesis, decreased glycolysis, and impaired lipogenesis (Hagiwara et al., 2012; Lamming et al., 2012; Yuan et al., 2012). Two studies find that hepatic Rictor loss also decreases SREBP1c activity; however, one study suggests AKT2 mediates this function (Hagiwara et al., 2012), whereas the other proposes an AKT-independent pathway (Yuan et al., 2012). These two studies are also inconsistent with respect to how Rictor loss affects AKT signaling, and thus the role of hepatic Rictor/mTORC2 is currently controversial. Nevertheless, the glucose uptake and glycolysis defect is reportedly independent of the lipogenesis defect, because restoring glucose flux in Rictor-KO hepatocytes did not rescue lipogenesis (Hagiwara et al., 2012). This study also reports that fatty acid oxidation genes are elevated in Rictor-deficient hepatocytes (Hagiwara et al., 2012). Thus, Rictor/mTORC2 may have a broad role in establishing a prolipogenic metabolic state. Going forward, it is important to determine if Rictor/mTORC2 regulates de novo lipogenesis and β-oxidation by a common or coordinate set of mechanisms or whether one metabolic deficiency is indirectly driving the other. Notably, we detect a decrease in lipogenesis gene expression in P1 BAT lacking Rictor, but the increase in fatty acid oxidation gene expression we first detect in 6-week mutant BAT. Thus, mitochondrial activity may progressively increase in the Rictor-deficient BAT and be secondary to a lipogenesis defect. Regardless, our findings support the idea that targeting lipogenesis and/or β-oxidation pathways in adipocytes could be one approach to treating obesity and diabetes.

One prediction is that increasing BAT energy expenditure could have antiobesity therapeutic potential (Tseng et al., 2010). To achieve this goal, a deeper understanding of how BAT utilizes fuel is required (Townsend and Tseng, 2014). An important finding in our study is that RictorMyf5cKO mice living at thermoneutrality, when challenged with an obesogenic diet, induce higher levels of UCP1 and are more resistant to developing obesity and metabolic disease compared to HFD-fed controls. This suggests that inhibiting mTORC2 in BAT augments diet-induced thermogenesis (Cannon and Nedergaard, 2010; Feldmann et al., 2009), although we cannot yet rule out that Rictor loss in other Myf5-lineage tissues might also contribute to this phenotype. It is currently being debated whether humans have classic brown adipocytes or a potential third class of adipocyte called a brite/beige adipocyte (Nedergaard and Cannon, 2013). Recent work indicates that in the neck, deep fat is similar to rodent BAT and expresses high levels of UCP1, whereas more superficial fat expresses lower UCP1 levels and has more brite/beige characteristics (Cypess et al., 2013). Notably, humans typically adjust temperature to be around thermoneutrality (Cannon and Nedergaard, 2010), and the BAT of mice living at thermoneutrality appears more “white-fat like,” or perhaps more “brite/beige-fat” like (Figure 7). Thus, it seems likely that humans possess classic brown fat and that studies of brown fat in mice will provide important insights into human BAT regulation. Continued elucidation of mTORC2 pathways in BAT bioenergetics could therefore lead to novel antiobesity therapies that target cellular energy expenditure.

**EXPERIMENTAL PROCEDURES**

**Gene Expression**

Total RNA was isolated using Qiazol (Invitrogen) and an RNeasy kit (Invitrogen). Equal amounts of RNA were retrotranscribed to cDNA using a high-capacity cDNA reverse transcription kit (Applied Biosystems). Tbp expression was used as a normalization gene. A different set of iBAT samples was used in RT-PCR arrays (QIAGEN) according to the manufacturer’s instruction. See also Supplemental Experimental Procedures.

**In Vitro Differentiation**

Primary brown adipocyte precursor (bAPC) cells were isolated from P1 neonates and immortalized with pBabe-SV40 large T antigen. To induce Rictor deletion, ubc-creERT2;Rictor−/− cells were treated on 3 consecutive days with 1 μM 4-OHT. bAPCs were seeded at 4 × 10^3 cells/ml and allowed reach confluence over 3 days in medium containing 20 nM insulin and 1 nM T3 (differentiation medium). On day 4, cells were induced with 20 nM insulin, 1nM T3, 0.125 mM indomethacin, 2 μg/ml dexamethasone, and 0.5 mM 3-isobutyl-1-methylxanthine. Two days later, the induction medium was replaced with fresh

**Figure 7. RictorMyf5cKO Mice Exempt from Thermal Stress and Consuming a High-Fat Diet Are Resistant to Obesity and Metabolic Disease**

(A) Weight gain of control and RictorMyf5cKO mice during 12-weeks of normal chow (chow) or high-fat diet (HFD) (n = 8 control and n = 12 for KO in chow; n = 10 for both genotypes on an HFD; mean ± SEM; t test; *p < 0.05). Control mice initially weighed 21.63 ± 0.812 g in the chow group and 21.24 ± 0.621 in the HFD group. The RictorMyf5cKO mice initially weighed 19.42 ± 0.306 g in the chow group and 19.32 ± 0.348 in the HFD group.

(B) Total energy intake (MJ) during the feeding regimen in (A). Control mice consumed 3.75 ± 0.56 g of chow and 2.81 ± 0.12 g of HFD; RictorMyf5cKO mice consumed 3.85 ± 0.24 g of chow and 2.95 ± 0.35 g of HFD.

(C) Metabolic efficiency determined as the amount of body weight increase (g) per MJ food consumed (n = 8 control and n = 12 KO in chow; n = 10 for both genotypes on an HFD; mean ± SEM; t test; *p < 0.05). Control mice consumed 3.85 ± 0.24 g of chow and 2.95 ± 0.35 g of HFD.

(D) Mass (mg) of the indicated tissues collected from control and KO mice after 12 weeks on chow or an HFD (n = 8 control and n = 12 KO on chow; n = 10 for both genotypes on HFD; mean ± SEM; two-way ANOVA; *p < 0.05, ***p < 0.001).

(E and F) H&E staining of iBAT and pgWAT and oil red O staining of livers after 12 weeks of eating chow (E) or HFD (F).

(G) qRT-PCR of the indicated brown and white fat genes in iBAT from chow- or HFD-mice (n = 8 control and n = 12 KO on chow; n = 10 for both genotypes on HFD; mean ± SEM; two-way ANOVA; *p < 0.05, **p < 0.01, ***p < 0.001; # indicates significant difference over the control chow group).

(H) qRT-PCR of the indicated metabolic genes in iBAT from chow- or HFD-mice (n = 8 control and n = 12 KO in chow; n = 10 for both genotypes in HFD; mean ± SEM; two-way ANOVA; *p < 0.05, **p < 0.01, ***p < 0.001; # indicates a significant difference over the control chow group).

(i) Western immunoblots of iBAT lysates. See also Figure S7.

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dissociation of the glucose and lipid regulatory functions of FoxO1 by targeted mTORC2 is required for signaling to Akt-FOXO and PKCalpha, but not S6K1. Dev. Cell 21, 242–256.


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