Hematopoietic AMPK β1 reduces mouse adipose tissue macrophage inflammation and insulin resistance in obesity

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Individuals who are obese are frequently insulin resistant, putting them at increased risk of developing type 2 diabetes and its associated adverse health conditions. The accumulation in adipose tissue of macrophages in an inflammatory state is a hallmark of obesity-induced insulin resistance. Here, we reveal a role for AMPK β1 in protecting macrophages from inflammation under high lipid exposure. Genetic deletion of the AMPK β1 subunit in mice (referred to herein as β1−/− mice) reduced macrophage AMPK activity, acetyl-CoA carboxylase phosphorylation, and mitochondrial content, resulting in reduced rates of fatty acid oxidation. β1−/− macrophages displayed increased levels of diacylglycerol and markers of inflammation, effects that were reproduced in WT macrophages by inhibiting fatty acid oxidation and, conversely, prevented by pharmacological activation of AMPK β1-containing complexes. The effect of AMPK β1 loss in macrophages was tested in vivo by transplantation of bone marrow from WT or β1−/− mice into WT recipients. When challenged with a high-fat diet, mice that received β1−/− bone marrow displayed enhanced adipose tissue macrophage inflammation and liver insulin resistance compared with animals that received WT bone marrow. Thus, activation of AMPK β1 and increasing fatty acid oxidation in macrophages may represent a new therapeutic approach for the treatment of insulin resistance.

Introduction

Obesity is associated with increased production of inflammatory cytokines, which are important contributing factors to the development of insulin resistance (1) and defects in fatty acid metabolism (2). In obesity, macrophages accumulate in adipose tissue and are in an inflammatory state, and they are the major source of systemic low-grade inflammation (3–5). In mice, this macrophage inflammation is mediated by the activation of the inflammatory serine/threonine kinases inhibitor of κB kinase (IKK) and JNK and is critical for the development of obesity/high-fat diet–induced (HFD-induced) insulin resistance (6, 7).

The M1 activation of macrophages, rendering them inflammatory, is mediated in part by members of the TLR family, which sense not only microbial pathogens but also saturated fatty acids that are commonly elevated in obese humans (8–10). Indeed, mice with hematopoietic deletion of TLR4 are partially protected from developing obesity-related inflammation and insulin resistance (11).

In addition to TLR signaling, the lipid content of macrophages may also be important for regulating inflammation. Total macrophage lipid content is increased in obese rodents fed HFD, and this is associated with M1 activation (12, 13). Furthermore, mice deficient in regulators of fatty acid oxidation and mitochondrial capacity including PPARγ (14, 15), PPARδ (16, 17), and PPARγ coactivator–1β (PGC1β) (18) have an increased propensity for developing lipid-induced inflammation and insulin resistance. Similarly, deletion of the fatty acid–binding protein aP2 or aP2 inhibitor protects mice against the development of obesity-related inflammation, insulin resistance, and atherosclerosis (19, 20). Recent studies in which diacylglycerol (DAG) acyltransferase was overexpressed in hematopoietic cells suggest that the total macrophage lipid content may be less important than the specific lipid species involved and that reductions in DAG may be important for preventing lipid-induced activation of inflammatory signaling (21).

The activation of AMPK acutely increases fatty acid oxidation and suppresses fatty acid synthesis through phosphorylation of acetyl-CoA carboxylase (ACC) (ref. 22; reviewed in ref. 23). AMPK also helps control fatty acid oxidation through regulation of total mitochondrial content (24–26), effects mediated through phosphorylation and deacetylation of PGC-1α (27, 28). In skeletal muscle, the chronic activation of AMPK by cytokines increases mitochondrial content and reduces DAG and inflammatory signaling (29), while the inverse is observed in mice in which AMPK is impaired (2).

In obese humans, adipose tissue macrophage activity is markedly downregulated, and this is associated with adipose tissue inflammation (30). Recent studies using the macrophage-like cell line RAW264.7 and RNAi or adenosine expressing dominant negative and constitutively active AMPK α1 have demonstrated that AMPK activation prevents LPS- and fatty acid–induced production of inflammatory cytokines (31, 32). The mechanisms mediating these antiinflammatory effects are still unclear, but AMPK activation of the Akt/PKB (Akt) and glycogen synthase kinase 3 pathway (31), the inhibition of ROS generation (33), MAPK signaling (33), and activation of sirtuin 1 (SIRT1) (32) have been

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proposed. Despite the potential importance of macrophage AMPK in regulating inflammatory signaling and lipid metabolism, its role in controlling obesity-related inflammation has not been examined in vivo. In the current study, we provide the first evidence to our knowledge that genetic deletion of the AMPK β1 subunit drastically reduces macrophage AMPK α1 activity, suppressing the expression of mitochondrial enzymes and ACC phosphorylation, which results in increased macrophage lipid accumulation and inflammation. Adoptive transfer of β1−/− bone marrow into WT recipient mice resulted in M1 activation of adipose tissue macrophages, leading to systemic inflammation and the development of whole-body hyperinsulinemia and hyperglycemia due to both hepatic and adipose tissue insulin resistance. These studies demonstrate that hematopoietic AMPK is a critical regulator of obesity-induced inflammation and whole-body glucose homeostasis.
Results

Obese mice have reduced macrophage AMPK T172 phosphorylation. To address whether macrophage AMPK may be important in obesity-related inflammation, we obtained peritoneal derived cells from lean and obese ob/ob mice and used FACS to identify cells that were positive for the macrophage markers F4/80 and CD11b. From this macrophage population, we then measured activating phosphorylation of AMPK using an Alexa Fluor 488–labeled AMPK α T172 antibody. We found that AMPK T172 phosphorylation was reduced by approximately 33% in macrophages from ob/ob mice, and this was associated with a marked increase in macrophage inflammation (Figure 1, A and B).

Deletion of AMPK β1 reduces macrophage AMPK activity and reduces mitochondrial content. AMPK activity is dependent on the expression of an AMPK αβγ heterotrimer in which multiple isoforms of each subunit exist (α1, α2, β1, β2, γ1, γ2, γ3). Bone marrow–derived macrophages (BMDMs) exclusively expressed AMPK α1 and had no detectable α2 protein expression (Figure 1C) or activity (data not shown). AMPK α1 activity and expression were predominately dependent on binding to the β1 subunit, as deletion of β1 resulted in a greater than 85% reduction in AMPK activity and barely detectable AMPK T172 phosphorylation (Figure 1, D and E).

AMPK is an important regulator of fatty acid oxidation, an effects mediated through phosphorylation of its downstream substrate ACC. We found that macrophages exclusively expressed ACC1, in contrast to hepatocytes, which express both ACC1 and ACC2 isoforms (Supplemental Figure 1; supplemental material available online with this article; doi:10.1172/JCI58577DS1) and that consistent with reductions in AMPK activity, the phosphorylation of ACC1 was dramatically reduced in β1–/– macrophages (Figure 1F).

AMPK is also an important regulator of mitochondrial biogenesis. Macrophages from β1–/– mice had no change in the expression of the innate immune receptor Tlr4, but had a greater than 50% reduction in mRNA expression of the mitochondrial encoded Cox2 (Figure 1G). This reduction in mRNA content corresponded to an approximately 50% reduction in protein expression of mitochondrial electron transport chain proteins in macrophages from β1–/– mice relative to WT littermates (Figure 1H). These data dem-
onstrate that the deletion of AMPK β1 reduces macrophage AMPK activity, ACC phosphorylation, and mitochondrial content.

AMPK β1–deficient macrophages are M1 activated and display increased sensitivity to saturated fatty acids. Reduced ACC phosphorylation and mitochondrial content in β1−/− macrophages was associated with reduced rates of fatty acid oxidation (27%, P < 0.05) (Figure 2A) and increased DAG esterification compared with cells from WT mice (Figure 2B). Ceramide levels were not different between genotypes (data not shown). Since DAG activates inflammatory pathways (34), we subsequently examined markers of macrophage polarization and found that β1−/− BMDMs had higher expression of inflammatory cytokines Tnfα, Il6, and Il1β, a difference that was exacerbated by the addition of palmitate (Figure 2, C–E). Great-

![Figure 3](http://www.jci.org) Mitochondrial fatty acid oxidation and β1-specific activation of AMPK suppresses JNK phosphorylation in WT but not β1−/− macrophages. (A) WT and β1−/− BMDMs were treated with 0.5 mM palmitate (0.5 μCi/ml 14C-palmitate) for 4 hours in the presence of A769662 (100 μM), etomoxir (50 μM), and/or rotenone (50 μM) before determination of fatty acid oxidation. (B) BMDMs were incubated as described above with 0.5 mM palmitate and immunoblotted for p-JNK/JNK (T183/Y185) and p-ACC (S79)/ACC as a measure of AMPK activation. Treatment of WT BMDMs with ethidium bromide (Eth Br) (0.4 μg/ml) in the presence or absence of A769662 (100 μM) (C) reduces fatty acid oxidation and increases (D) JNK phosphorylation, blocking the effects of A769662. β1−/− BMDMs were treated with or without dinitrophenol (DNP) (500 μM), and (E) fatty acid oxidation and (F) p-JNK/JNK levels were determined. Data are expressed as mean ± SEM; n = 3–5 from at least 2 independent experiments. *P < 0.05, **P < 0.01, ***P < 0.001 compared with WT; †P < 0.05 compared with WT basal; and ‡P < 0.05 compared with β1−/− basal.

For expression of total JNK, duplicate gels were used.

er classical activation of β1−/− BMDMs was also evident, as there was an increase in the iNos to arginase-1 (Arg1) expression ratio (Figure 2F). Consistent with these changes in gene expression, we found that JNK phosphorylation was increased in β1−/− BMDMs, an effect that became greater following palmitate treatment (Figure 2G). Importantly, these changes in JNK phosphorylation and mRNA transcripts, suggestive of increased M1 activation, were also reflected by alterations in cytokine secretion; as β1−/− BMDMs had a 56% reduction in the antiinflammatory cytokine IL-10 and 46% and 61% increases in TNF-α and IL-6, respectively (Supplemental Table 1). These inflammatory effects were not specific to palmitate, as similar observations were also made with the saturated fatty acid stearate (Supplemental Figure 2).
To examine whether AMPK β1 deficiency altered sensitivity to other M1 or M2 stimulants, we incubated cells with LPS and IL-4, respectively. In contrast to the effects of saturated fatty acids, both LPS and IL-4 exerted effects on inflammatory markers, largely independent of AMPK β1 deficiency (Supplemental Figure 3, A and B). To investigate the reason for the differential response between the M1 stimulants palmitate and LPS, we examined their effects on AMPK expression and activity and found that similar to our previous findings in muscle (35), palmitate concentrations that induce macrophage inflammation acutely activated AMPK in WT but not β1–/– macrophages, without altering AMPK α expression (Figure 2H). In contrast, but in agreement with previous reports (31, 32), LPS was found to suppress AMPK activity largely due to a reduction in AMPK α expression (Figure 2I). These data suggest that “feed-forward” activation of AMPK resulting in increases in fatty acid oxidation is important for buffering against palmitate-induced inflammation, but in obesity, increases in LPS (36) and subsequent degradation of AMPK α likely contribute to the observed decrease in macrophage AMPK activity.

AMPK β1 regulation of fatty acid oxidation is essential for inhibiting lipid-induced macrophage inflammation. To address the hypothesis that activation of fatty acid oxidation was central to buffering against lipid-induced inflammation, we performed a series of experiments in WT and β1–/– macrophages in which we pharmacologically activated AMPK using the small molecule, β1-specific activator A769662 (37, 38), while inhibiting fatty acid oxidation using inhibitors of either CPT-1 (etomoxir) or mitochondrial complex–1 (rotenone). Following the various treatments, the activating phosphorylation of JNK was used as an assay to assess macrophage inflammation (7), while the phosphorylation of ACC was used as a surrogate measure of AMPK activity (38). We found that A769662 selectively and dose-dependently increased ACC phosphorylation in WT but not β1–/– BMDMs (Supplemental Figure 4A). The activation of β1 resulted in a significant increase in fatty acid oxidation (Figure 3A) and, importantly, reduced JNK activation (Figure 3B) in WT but not β1–/– cells. Both etomoxir and rotenone decreased rates of fatty acid oxidation (Figure 3A) and subsequently increased JNK phosphorylation (Figure 3B), but importantly, this affect could not be reversed, despite activation of AMPK.

Interestingly, basal differences in fatty acid oxidation between genotypes were preserved in the presence of etomoxir and rotenone, suggesting that the primary cause of the reduced fatty acid oxidation in β1–/– BMDMs was due to a lower mitochondrial content.
and not an increase in malonyl-CoA inhibition of CPT-1. Therefore, we also depleted mitochondrial DNA from WT macrophages using ethidium bromide. In agreement with previous reports (39, 40), ethidium bromide treatment inhibited mitochondrial (Cox2) but not nuclear encoded DNA (Cs, Bhad) (Supplemental Figure 4B), reducing the expression of complex I, complex II, and complex IV by approximately 40% (Supplemental Figure 4C). Consistent with findings from β1⁻/⁻ macrophages, we found that lower levels of mitochondria led to reductions in fatty acid oxidation (Figure 3C) and dramatically increased the phosphorylation of JNK (Figure 3D). Treatment of mitochondrial depleted macrophages with A769662 had no effect on fatty acid oxidation and was unable to prevent palmitate-induced JNK phosphorylation (Figure 3, C and D). Last, we attempted to rescue the inflamed phenotype

Figure 5
Hematopoietic deletion of AMPK β1 results in macrophage recruitment and inflammatory activation of adipose tissue macrophages. (A) PCR genotyping of genomic DNA from liver, white adipose tissue (WAT), and skeletal muscle (Sk mus), with WT- or β1-specific primers. (B) mRNA expression of macrophage markers Emr1 (F4/80) and Cd68 in WAT and liver of HFD-fed WT⁰⁰ and β1⁻⁻ mice (dotted line indicates expression in chow-fed WT⁰⁰ mice). Immunochemical staining and quantification of F4/80 in (C) WAT and (D) liver (original magnification, ×200). Adipose tissue macrophage (ATM) mRNA expression of (E) Arg1 and iNos, (F) Itgax (Cd11c), (G) inflammatory cytokines Ccl2, Tnfa, Il6, Il1b, and Il10, and (H) markers of mitochondrial density Pgc1a, Cs, and Hadh. (I) Correlation analysis between expression of Cs and Arg1. All data presented are mean ± SEM; n = 8–10. *P < 0.05, **P < 0.01 compared with WT⁰⁰, within dietary treatment, where the relative expression was normalized to Actb.
of β1−/− macrophages by increasing fatty acid oxidation using the mitochondrial uncoupler dinitrophenol and found that increased rates of fatty acid oxidation (Figure 3E) led to marked reductions in JNK phosphorylation (Figure 3F). Taken together, these data demonstrate that AMPK β1 is required to prevent lipid-induced inflammation through the activation of fatty acid oxidation.

Hematopoietic deletion of AMPK β1 causes adipose tissue and hepatic insulin resistance. WT(BMT) and β1−/−BMT mice were fed a chow diet or HFD for 22 weeks, and (A) fed blood glucose and (B) serum insulin levels were determined. (C) WT(BMT) and β1−/−BMT mice fed HFD were fasted for 6 hours and insulin tolerance tests performed after intraperitoneal injection of 0.7 U/kg insulin (right: AUC calculated as mM*min). Hyperinsulinemic-euglycemic clamps were performed in WT(BMT) and β1−/−BMT fed HFD, and (D) post-clamp serum NEFA and (E) adipose tissue Akt (pS473) phosphorylation were determined. (F) Hepatic glucose output and (G) percent suppression of hepatic glucose production were measured, and livers were collected after the clamp for analysis of (H) phosphorylated Akt (S473) and (I) mRNA expression of gluconeogenic enzymes G6pc and Pck1. All data presented are mean ± SEM; n = 8–10. *P < 0.05 compared with WT(BMT) within dietary treatment, where relative expression was normalized to Actb. For expression of total Akt, duplicate gels were used.
hematopoietic cell growth and proliferation (41–43). Consistent with these reports, there were no differences in T cell, B cell, or macrophage numbers in the bone marrow, spleen, or thymus of WT and β1−/− mice (data not shown). Since the activation of T cells has been shown to play an important role in regulating obesity-induced inflammation and insulin sensitivity (44–46), we also measured markers of T cell activation. There were no differences in the percentage of CD3⁺/CD4⁺ cells or in Foxp3 expression between

Figure 7
Increased hepatic inflammation due to β1 deletion in macrophages leads to hepatic insulin resistance. (A) mRNA expression inflammatory cytokine production in liver tissue from WT and β1−/− mice on chow and HFD: Il1b, Tnfa, Il6, and iNos. (B) Antinflammatory marker expression in WT and β1−/− mice: Arg1 and Il10. (C) Immunoblotting for phosphorylated JNK (T183/Y185) and total JNK between genotypes fed HFD. (D) Liver triglyceride (TG) levels in WT and β1−/− mice fed chow or HFD. Primary hepatocytes were incubated with conditioned medium from 0.5 mM palmitate–treated WT and β1−/− BMDMs for 4 hours (as described in Methods). (E) The mRNA expression of markers of hepatocyte inflammation Kc and iNos and (F) the mRNA expression of gluconeogenic genes following 4 hours treatment with 10 nM insulin. All data shown are mean ± SEM; n = 8–10 for animal experiments. In vitro work was performed in triplicate from at least 2 livers. *P < 0.05, **P < 0.01 compared with WT, within treatment group; #P < 0.05 between basal and insulin treatment within genotype, where expression was normalized to Actb. For expression of total JNK, duplicate gels were used. ND, not detected.
genotypes, and while the HFD increased T cell infiltration into adipose tissue and liver, there was no difference between genotypes (Supplemental Figure 5, A–D).

We found that on the control chow diet, there was no difference in body mass (Figure 4B) or adiposity (Figure 4C) between WTβ1−/−BMT and β1−/−BMT mice, and while the HFD increased both body mass and adiposity, there were no discernible differences between genotypes. There were no detectable differences in serum cytokines in chow-fed mice. However, despite similar body mass and adiposity, levels of serum monocyte chemoattractant protein–1 (MCP-1) and TNF-α were higher in HFD-fed β1−/−BMT mice (Figure 4D). Consistent with known effects of TNF-α on the adipokines leptin (47, 48) and adiponectin (49), we found that HFD-fed β1−/−BMT mice had increased leptin and reduced adiponectin levels (Figure 4E). Systemic inflammation leads to hypothalamic leptin resistance (50–52), and consistent with the increase in circulating TNF-α, we found that HFD-fed β1−/−BMT mice had increased food intake and hypothalamic expression of the orexigenic peptide Npy (Supplemental Figure 6, A and B). However, increases in energy intake of HFD-fed β1−/−BMT mice appeared to be offset by a corresponding increase in activity levels, particularly at the onset of feeding (Supplemental Figure 6C).

Hematopoietic deletion of AMPK β1 results in the infiltration of liver and adipose tissue with macrophages. In obesity, BMDMs accumulate within white adipose tissue and liver (Kupffer cells). We detected substantial infiltration of β1−/− bone marrow–derived cells into liver and white adipose tissue, but not skeletal muscle, of β1−/−BMT mice (Figure 5A). We subsequently examined the macrophage content of liver and white adipose tissue using quantitative RT-PCR (qRT-PCR) (Emr1 [F4/80] and Cd68) or histological staining (F4/80). On the control chow diet, there were modest increases in Cd68 but not Emr1 expression in the adipose tissue and liver (Supplemental Figure 7, A and B). However, when fed HFD, β1−/−BMT mice had greater expression of Emr1 and Cd68 in both adipose tissue and liver (Figure 5B). Consistent with the increase in mRNA transcripts, immunohistochemical staining of F4/80 was greater in adipose tissue (Figure 5C) and liver (Figure 5D) of HFD-fed β1−/−BMT mice, indicating increased macrophage infiltration.

Hematopoietic deletion of AMPK β1 results in the inflamed adipose tissue macrophages. We subsequently examined the inflammatory profile of adipose tissue macrophages and found that adipose tissue macrophages from HFD-fed β1−/−BMT mice had lower expression of Arg1 and increased iNos (Figure 5E) and Itgax (Cd11c) expression (Figure 5F), indicating that the deletion of AMPK β1 promoted macrophage M1 activation. Consistent with this activation state, adipose tissue macrophages from β1−/−BMT mice on a chow diet tended to have increased inflammatory cytokine expression (Tnfα, Il6, Ccl2, B1b) and lower expression levels of antinflammatory Il10, a difference that became much more dramatic when mice were fed HFD (Figure 5G). We also observed that increases in inflammation were associated with reduced expression of mitochondrial markers such as Cs and Hadhb (Figure 5, H and I), a finding consistent with our observations in vitro. These data demonstrate that deletion of AMPK β1 from macrophages results in a shift toward inflammatory, M1-activated adipose tissue macrophages.

Hematopoietic deletion of AMPK β1 results in hepatic insulin resistance. We next examined glucose homeostasis and insulin sensitivity and found that on the control chow diet, overnight fasted (data not shown) and fed glucose (Figure 6A) and insulin levels (Figure 6B) were not different between WTβ1−/−BMT and β1−/−BMT mice. When challenged with HFD, β1−/−BMT mice had significantly elevated serum glucose and insulin levels (Figure 6, A and B). Consistent with the insulin and glucose levels, we found that chow-fed β1−/−BMT mice had normal insulin sensitivity following a bolus of insulin (Supplemental Figure 8), while β1−/−BMT mice fed HFD became refractory to the suppressive effects of insulin on blood glucose compared with WTβ1−/−BMT controls (Figure 6C). To assess whether increased insulin resistance in HFD fed β1−/−BMT mice was due to peripheral or hepatic insulin resistance, we conducted hyperinsulinemic-euglycemic clamps. We did not clamp chow-fed mice, as there was no sign of insulin resistance. Blood glucose at the start of the clamp and basal glucose turnover were similar in WTβ1−/−BMT and β1−/−BMT mice (data not shown). Insulin-stimulated glucose disposal rate (data not shown) was not different between genotypes, despite higher levels of non-esterified fatty acids (NEFAs) and reduced Akt phosphorylation in adipose tissue, indicating the presence of adipose tissue insulin resistance (Figure 6, D and E). There was no difference in skeletal muscle Akt phosphorylation between HFD-fed WT and β1−/−BMT mice, suggesting that skeletal muscle did not develop insulin resistance (data not shown). HFD-fed β1−/−BMT mice had increased hepatic glucose output (Figure 6F) and a blunted suppression of hepatic glucose production (Figure 6G), indicating hepatic insulin resistance. Consistent with this, we found that at the completion of the clamp, liver Akt phosphorylation was lower (Figure 6H), while the expression of the glucogenic genes G6pc and Pck1 was elevated in β1−/−BMT mice (Figure 6I). Thus, β1−/−BMT mice developed exaggerated adipose tissue and liver insulin resistance compared with WTβ1−/−BMT mice when fed HFD.

Increased hepatic inflammation due to β1 deletion in macrophages leads to hepatic insulin resistance. In agreement with the observed increase in macrophage infiltration into the liver of β1−/−BMT mice (Figure 5, A, B, and D), we found that there was also a marked increase in the expression of inflammatory cytokines Tnfα, Il6, Il1b, and iNos and decreased expression of Arg1 and Il10 (Figure 7, A and B). This increase in inflammatory gene expression was accompanied by a 20% increase in liver IL-1β protein in HFD-fed β1−/−BMT mice compared with WTβ1−/−BMT mice (Supplemental Table 2). Increased liver inflammation in HFD-fed β1−/−BMT mice was associated with increased JNK phosphorylation (Figure 7C). Since inflammation could have been due to high levels of lipid, we measured liver triglycerides and found that while the HFD increased levels, there was no difference between WTβ1−/−BMT and β1−/−BMT mice (Figure 7D). To determine whether the exacerbation of hepatic insulin resistance in β1−/−BMT mice could be attributed to increased inflammation in β1−/− macrophages, we treated WT primary hepatocytes with medium that had been conditioned from palmitate-treated WT and β1−/− BMDMs. We found that media from β1−/− BMDMs caused greater hepatic inflammation, as indicated by increased expression of Kc (a murine IL-8 homolog) and iNos (Figure 7E), and importantly, this was associated with an impaired ability of insulin to suppress Pck1 and G6pc expression in hepatocytes (Figure 7F). These findings, which paralleled those observed in vivo, support a critical role for macrophage AMPK β1 in the regulation of liver inflammation and insulin sensitivity.

Discussion

Resident macrophages in lean adipose tissue are characterized by a program of gene expression that is directed toward limiting local inflammatory responses and promoting tissue repair. These alternative, or M2, macrophages are characterized by high levels of arginase and low levels of iNos, which facilitates the production of collagen

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and secretion of antiinflammatory cytokines, such as IL-10 (12, 13). We detected lower levels of AMPK activity in inflamed macrophages from obese mice. Similarly, reducing AMPK activation through genetic deletion of the β1 subunit resulted in lower levels of Arg1 and higher levels of iNos, Il1b, and Tnfα, an M1 inflamed phenotype that was further exacerbated by treatment with palmitate. Importantly, we expand on these in vitro findings by showing that this M1-activated phenotype is also observed in vivo, in adipose tissue macrophages from obese β1−/−BMT mice. These findings demonstrate that even within the diverse metabolic milieu that defines the adipose tissue macrophage, AMPK activity is essential for regulating M1/M2 polarization. Notably, although no differences were observed in markers of T-cell activation/infiltration, it remains possible that hematopoietic deletion of AMPK β1 may have affected other cell lineages to influence the onset and severity of macrophage inflammation.

Our finding that β1 deficiency resulted in a greatly enhanced inflammatory phenotype in response to palmitate or HFD challenge led us to the hypothesis that AMPK regulation of lipid metabolism may be important for controlling macrophage inflammation. We subsequently found that palmitate acutely increases AMPK activity and ACC phosphorylation in macrophages from WT mice and that deletion of β1 reduces mitochondrial content and prevented phosphorylation of ACC. This resulted in reduced rates of fatty acid oxidation and increased accumulation of macrophage DAG. In agreement with recent findings showing a role for DAG in regulating macrophage inflammation (21), we show that β1−/− macrophages had much greater activation of JNK and increased expression and secretion of inflammatory cytokines both in vitro and in vivo. We subsequently established that the control of mitochondrial fatty acid oxidation is a critical factor for controlling inflammatory activation. Importantly, the activation of AMPK β1–containing complexes in the absence of increases in fatty acid oxidation is unable to prevent lipid-induced inflammation. Since the activation of SIRT1 has been shown to require AMPK-dependent increases in fatty acid oxidation (28), our findings are consistent with recent reports showing that activation of AMPK inhibits inflammation via a SIRT1-dependent pathway (32) and that polarization of M1 macrophages in adipose tissue is associated with increased lipid accumulation (53). Taken together, these data demonstrate that pharmacological activation of AMPK β1–containing complexes prevents lipid-induced inflammation and that the activation of fatty acid oxidation is required for this effect.

Consistent with the increased inflammation in HFD-fed β1−/−BMT mice, we found that these mice developed more pronounced hyperglycemia and hyperinsulinemia than HFD-fed WT BMT littermates. Subsequent studies using hyperinsulinemic-euglycemic clamps demonstrated the presence of both adipose tissue and hepatic insulin resistance. Given that the hematopoietic deletion of β1 may have affected multiple cell types, including T cells, that are important for regulating insulin sensitivity in obesity (44–46), we subsequently conducted conditioned medium experiments with BMDMs. We found that increased cytokine secretion from palmitate-treated β1−/− BMDMs induced greater hepatic inflammation and insulin resistance than medium from WT cells, thus supporting a critical role for macrophage AMPK B1 in regulating hepatic insulin sensitivity. However, future studies are needed to investigate the role of AMPK β1 in Kupffer cells.

We did not observe any differences in the glucose disposal rate in β1−/−BMT mice during the hyperinsulinemic-euglycemic clamp, despite evidence of adipose tissue insulin resistance, as demonstrated by higher levels of circulating NEFA and reduced adipose tissue Akt phosphorylation. These data suggest that skeletal muscle, which accounts for approximately 80% of glucose disposal during the clamp, did not develop insulin resistance. This may have been related to the lack of infiltration of bone marrow–derived cells into this tissue and is consistent with other models of hematopoietic or myeloid specific disruptions in inflammatory signaling that failed to detect any changes in skeletal muscle insulin sensitivity (11, 16, 17).

Loss of whole-body AMPK β1 protects against HFD-induced obesity, liver lipid accumulation, and insulin resistance (54). This protection against obesity and insulin resistance was attributed to lower hypothalamic AMPK, which resulted in reduced food intake and hence body mass/adiposity (54). In contrast, we show that β1−/−BMT mice develop greater HFD-induced hepatic insulin resistance than WT BMT controls. Since adipose tissue cell size appears to be the primary factor dictating macrophage recruitment and adipose tissue inflammation (55, 56) and mice lacking whole-body AMPK β1 do not develop obesity, this may be a likely explanation for the disparity between mice with hematopoietic compared with global deletion of β1.

In summary, our results demonstrate that macrophage AMPK β1 is critical in regulating mitochondrial capacity and that the activation of fatty acid oxidation is essential for limiting inflammation in response to saturated fatty acids. We find that in lean mice, hematopoietic deletion of AMPK β1 appears to have a relatively modest impact on adipose tissue macrophage inflammation. However, when mice are made obese and there is a dramatic need to buffer against lipids, AMPK is essential for controlling adipose tissue macrophage inflammation and in turn insulin sensitivity. Thus, macrophage AMPK may be the first line of defense to prevent the deleterious effects of nutrient overload during obesity. This raises the exciting possibility that the insulin-sensitizing effects of agents such as metformin, rosiglitazone, and exercise — all of which have been shown to reduce inflammation (14, 57–59) and activate AMPK (60–65) — may be mediated in part by activation of AMPK in macrophages; however, to our knowledge, this has yet to be investigated. These studies also suggest that the recently developed thienopyridone class of AMPK β1–specific activators, in addition to preventing insulin resistance (37, 38), may be effective in treating other inflammatory diseases such as atherosclerosis and rheumatoid arthritis.

Methods

Animals. All mice used in the study were males, housed in specific pathogen-free micro-isolators and maintained on a 12-hour light/12-hour dark cycle with lights on at 0700. The generation and characterization of β1−/− mice has been described previously (54, 66). For bone marrow transplantation experiments, whole bone marrow from WT and β1−/− mice was prepared by flushing the marrow cavities of the long bones with sterile saline. 5 × 10⁶ cells were injected retro-orbitally into lethally irradiated (11 Gy) WT recipient mice (Animal Resources Centre). After a 6-week recovery period, mice were placed on a standard mouse chow diet (12% kcal fat, Barastoc, Ridley Agriproducts) or HFD (45% kcal fat, diet SF-01-028, Specialty Feeds) for 22 weeks. Insulin tolerance tests were performed after 16 weeks of feeding as described previously (67). For serum insulin and cytokine measurements, fasting and fed blood samples were collected by retro-orbital bleed between weeks 16 and 18 using a non-heparinized capillary tube, and insulin, adiponecin, and leptin were measured as described previously (29). Serum cytokines (MCP-1, TNF-α, and IL-6) were measured using a multiplexed bead–based immunoassay (BD Biosciences) following
the manufacturer’s instructions. Hyperinsulinemic-euglycemic clamps were performed on conscious mice after 22 weeks of feeding as previously described (54, 67). After the hyperinsulinemic-euglycemic clamp, adipose tissue macrophages were isolated from epididymal adipose tissue following collagenase digestion (Liberase enzyme; Roche) and isolated using a Mouse CD11b Positive Selection Kit (STEMCELL Technologies). Cells were then lysed in TRizol reagent (Invitrogen), and RNA was extracted for qRT-PCR as described previously (29). Immunoblotting of tissues was performed using antibodies and procedures as described (29, 68).

CT scanning. Adiposity was determined using CT scanning after 20 weeks of feeding as described previously (69). Briefly, mice were anesthetized with isoflurane gas, and images were acquired on an X-SPECT (Gamma Medica) within the McMaster Centre for Pre-Clinical and Translational Imaging. A water-filled tube was included with each scan as a calibrator for Hounsfield units (HU). CT images were analyzed using Amira software (version 5.2.2; Visage Imaging), and the whole-body adipose volume was segmented using a computer-assisted application selecting a range of volume from −450 to −125 HU. To facilitate use of volume segmentation tools, digital Gaussian filtering (kernel 3, sigma value 0.67) was employed to smooth the three-dimensional, HU-calibrated CT images. Density histograms of the volume within the selected range (−450 to −125 HU) were generated, and the total volume of adipose tissue was calculated by summation of the total density.

Immunohistochemistry. Paraffin-embedded epididymal fat and liver were sectioned, dewaxed, and rehydrated prior to antigen retrieval by boiling in 10 mM sodium citrate buffer (pH 6.5). Endogenous peroxidase was quenched by treatment with 3% H2O2 in PBS. Tissue sections were blocked with 5% normal rabbit serum for 40 minutes, followed by blocking of endogenous biotin and avidin binding sites using the Biotin/Avidin blocking kit form Vector Laboratories. Sections were incubated for 2 hours with 10 μg/ml rat anti-mouse F4/80 antibody (AbD Serotec). Biotin-conjugated secondary anti-rat antibody was applied for 1 hour, followed by 30 minutes incubation with Vectastain ABC solution (Vector Laboratories). The sections were developed using the DAB substrate kit (Vector Laboratories) and counterstained with Mayer’s hematoxylin. The total number of nuclei and the number of nuclei of F4/80-positive cells were counted in a total of 12–14 different x20 fields from three different sections for each genotype. The percentage of F4/80-positive cells for each sample was calculated as the number of nuclei of F4/80-expressing cells divided by the total number of nuclei per sample. Liver F4/80 staining was quantified using ImageJ (http://rsweb.nih.gov/ij/) and the color segmentation plug-in.

Cell culture. WT and β1 −/− bone marrow was isolated from the femur and tibia of 10- to 12-week-old mice as described previously (56). For palmitate treatments, day-8 BMDMs were serum starved 3–4 hours before incubation with the indicated palmitate concentrations at the indicated times, conjugated to 2% (w/v) fatty acid–free and low endotoxin BSA (Sigma-Aldrich). BMDMs were pretreated with 50 μM etomoxir (Sigma-Aldrich), 50 μM rotenone (Sigma-Aldrich), 500 μM dinitrophenol (Sigma-Aldrich), or A769662 (Ascent Scientific) for 2 hours before the addition of assay medium containing palmitate. Compounds were subsequently replenished into the medium and kept present throughout the incubation period with palmitate. Mitochondria were depleted from WT BMDMs by treatment with 0.4 μg/ml ethidium bromide (Bio-Rad) for 48 hours prior to experiments and replenished throughout the experimental incubations with palmitate. To examine fatty acid oxidation and incorporation into lipid pools, BMDMs were incubated with [1-14C] palmitic acid (0.5 μCi/ml) (Amersham Biosciences) and 0.2 mM unlabeled palmitate for 4 hours as described previously (70). For gene expression analysis, cells were left untreated or incubated with 0.5 mM palmitate for 6 or 24 hours and subsequently lysed in TRizol reagent (Invitrogen), and RNA was extracted for qRT-PCR as described previously (35). Immunoblotting and AMPK α1 activity assays of cellular lysates were performed using antibodies and procedures as previously described (29, 68). BMDM supernatants were analyzed for the presence of cytokines (IL-1β, IL-6, TNF-α) after overnight incubation of cells with 0.5 mM palmitate using a multiplexed bead-based immunoassay (Mouse Inflammation Kit) from BD Biosciences.

Isolation and preparation of peritoneal macrophages for flow cytometry. Alexa Fluor 488-labeled antibody specific for AMPK phosphorylated on αT172 (24) was produced using the DyLight 488 Antibody Labeling Kit from Pierce Biotechnology (Rockford). Resident peritoneal cells were harvested from control and ob/ob mice, and F4/80+CD11b+ cells were separated from the remainder of the peritoneal cell population using a FACSaria cell sorter (BD Biosciences) as described previously (56). For assessment of T cell populations, phycoerythrin-CD4 (PE-CD4, 0.8 μg/ml) and Alexa Fluor 700-CD3 (A700-CD3, 0.8 μg/ml) were purchased from ebScience. For intracellular Foxp3 staining, CD3+CD4+ cells were processed according to the manufacturer’s instructions using the Anti-Mouse/Rat Foxp3 FITC Staining Set from ebScience. Following incubation, cells were analyzed using a FACS caliber flow cytometer (BD Biosciences) and CellQuest software (BD Biosciences). Gates and compensations were set by using unstained, single-stained, and fluorescence-minus-one control.

Conditioned medium experiments. For conditioned medium experiments, primary hepatocytes were isolated as described previously (71). BMDMs were prepared as above and incubated with 0.5 mM palmitate for 6 hours. Cells were then washed with PBS and recovered in serum-free Williams medium E (Invitrogen) supplemented with 1% antibiotic-antimycotic (Gibco, Invitrogen) for 12 hours. This medium was then removed from BMDMs and transferred onto WT primary hepatocytes for 3 hours. Cells were then harvested for determination of inflammatory gene expression or incubated with 10 nM insulin for a further 4 hours for the determination of gluconeogenic gene expression as described previously (67).

Statistics. All results are shown as mean ± SEM. Results were analyzed using a 2-tailed Student’s t test or 1- or 2-way ANOVA where appropriate, using GraphPad Prism software. A Bonferroni post hoc test was used to test for significant differences revealed by the ANOVA. Significance was accepted at P ≤ 0.05.

Study approval. All experimental protocols used in this study were approved by the St. Vincent’s Hospital and McMaster University Animal Ethics Committees.

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