研究成果の刊行に関する一覧表

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課題名 ： 臨床心不全エピゲノム診断における組織可塑性指標となる新規サロゲートマーカーの開発と治療への応用に関する研究

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Cell Metabolism
Article

p53-Induced Adipose Tissue Inflammation Is Critically Involved in the Development of Insulin Resistance in Heart Failure

Ippei Shimizu,[1,5] Yohko Yoshida,[1,5] Taro Katsuno,[1] Kaoru Tateno,[1] Sho Okada,[1] Junji Moriya,[1] Masataka Yokoyama,[1] Aika Nojima,[1] Takashi Ito,[1] Rudolf Zechner,[2] Issei Komuro,[3] Yoshio Kobayashi,[1] and Tohru Minamino[1,4,*]
[1]Department of Cardiovascular Science and Medicine, Chiba University Graduate School of Medicine, Chiba 260-8670, Japan
[2]Institute of Molecular Biosciences, University of Graz, A-8010 Graz, Austria
[3]Department of Cardiovascular Medicine, Osaka University School of Medicine, Osaka 565-0871, Japan
[4]PRESTO, Japan Science and Technology Agency, Saitama 332-0012, Japan
[5]These authors contributed equally to this work
*Correspondence: t_minamino@yahoo.co.jp
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SUMMARY

Several clinical studies have shown that insulin resistance is prevalent among patients with heart failure, but the underlying mechanisms have not been fully elucidated. Here, we report a mechanism of insulin resistance associated with heart failure that involves upregulation of p53 in adipose tissue. We found that pressure overload markedly upregulated p53 expression in adipose tissue along with an increase of adipose tissue inflammation. Chronic pressure overload accelerated lipolysis in adipose tissue. In the presence of pressure overload, inhibition of lipolysis by sympathetic denervation significantly downregulated adipose p53 expression and inflammation, thereby improving insulin resistance. Likewise, disruption of p53 activation in adipose tissue attenuated inflammation and improved insulin resistance but also ameliorated cardiac dysfunction induced by chronic pressure overload. These results indicate that chronic pressure overload upregulates adipose tissue p53 by promoting lipolysis via the sympathetic nervous system, leading to an inflammatory response of adipose tissue and insulin resistance.

INTRODUCTION

The p53 tumor suppressor pathway coordinates DNA repair, cell-cycle arrest, apoptosis, and senescence to preserve genomic stability and prevent oncogenesis. Activation of p53 is driven by a wide variety of stress signals that have the potential to promote tumor formation, such as DNA damage, telomere shortening, oxidative stress, and oncogene activation (Harris and Levine, 2005; Meek, 2009; Vousden and Prives, 2009). Recently, the contribution of p53 to many undesirable aspects of aging and age-associated diseases, such as cardiovascular and metabolic disorders, has been recognized (Royds and Iacopetta, 2006; Vousden and Lane, 2007). It has been reported that aging is associated with an increase of the p53-mediated transcriptional activity (Edwards et al., 2007) and that slight constitutive overactivation of p53 is associated with premature aging in mice (Maier et al., 2004; Tyner et al., 2002). Activation of p53 has also been observed in aged vessels and failing hearts and has been implicated in atherosclerosis and heart failure (Minamino and Komuro, 2007, 2008; Sano et al., 2007). Recent findings have indicated a role of p53 in determining the response of cells to nutrient stress and in regulating metabolism (Vousden and Ryan, 2009). It has also been demonstrated that excessive calorie intake induces p53-induced inflammation in adipose tissue, leading to insulin resistance and diabetes in mice (Minamino et al., 2009).

A close link between heart failure and diabetes has long been recognized in the clinical setting (Ashrafian et al., 2007; Lopaschuk et al., 2007; Witteles and Fowler, 2008). Many mechanisms have been suggested to explain the increased incidence of heart failure in diabetic patients, including the hypertrophic influence of insulin, the adverse effects of hyperglycemia, increased oxidative stress, and hyperactivity of neurohumoral systems, such as the renin-angiotensin-aldosterone system and the adrenergic system. Recently, increasing attention has been paid to insulin resistance as a distinct cause of cardiac dysfunction and heart failure in diabetic patients. A study of Swedish patients without prior cardiac dysfunction found that insulin resistance predicted the subsequent onset of heart failure independently of established risk factors (Ingelsson et al., 2005). In another clinical study, the plasma level of proinsulin (a marker of insulin resistance) was found to be higher in patients who subsequently developed heart failure than in control patients 20 years before the actual diagnosis of heart failure (Arnlöv et al., 2001). These findings indicate that insulin resistance precedes heart failure rather than being a consequence of it. Evidence has emerged that myocardial insulin resistance is central to altered metabolism in the failing heart and may play a crucial role in the development of heart failure (Ashrafian et al., 2007; Lopaschuk et al., 2007; Witteles and Fowler, 2008). The adaptive response of the failing heart involves a complex series of enzymatic shifts and changes in the regulation of transcriptional factors, which result in an increase of glucose metabolism and a decrease of fatty acid metabolism

to maximize the efficacy of energy production (Neubauer, 2007). Insulin resistance of the myocardium inhibits these adaptive responses, leading to increased reliance on fatty acid metabolism. This increases oxygen consumption and decreases cardiac function, raising the potential for lipotoxicity in the heart (Sharma et al., 2007; Young et al., 2002). Another line of evidence indicates that insulin signaling is upregulated in the failing heart and that excessive cardiac insulin signaling exacerbates systolic dysfunction (Shimizu et al., 2010).

Moreover, there is increasing evidence that heart failure reciprocally augments the risk of insulin resistance and clinical diabetes (Ashrafian et al., 2007). Insulin resistance and abnormal glucose metabolism are very common in heart failure patients, being identified in 43% of these patients, and such abnormalities are associated with decreased cardiac function (Suskin et al., 2000). Surprisingly, the link between heart failure and insulin resistance grows stronger when patients with ischemic heart disease are excluded (Witteles and Fowler, 2008). Heart failure also predicts the development of type 2 diabetes in a graded way (Tenenbaum et al., 2003). Although the above mentioned clinical evidence supports a role of insulin resistance in the occurrence of heart failure, evidence for the reciprocal statement that heart failure promotes insulin resistance is largely associative. Moreover, the role of heart failure in the promotion of insulin resistance has been demonstrated by only a few animal studies (Nikolaidis et al., 2004; Shimizu et al., 2010) and the underlying mechanisms are largely speculative.

Here, we studied the role of heart failure in the development of insulin resistance and sought to elucidate the molecular mechanisms involved. We found that insulin resistance developed in two murine models of heart failure, a chronic pressure overload model and a myocardial infarction model. Heart failure markedly upregulated p53 expression in adipose tissue in association with increased inflammation of adipose tissue. Heart failure accelerated lipolysis in adipose tissue, whereas inhibition of lipolysis by sympathetic denervation or treatment with a lipase inhibitor significantly downregulated adipose tissue p53 expression and inflammation, thereby improving insulin resistance. Likewise, disruption of p53 activation in adipose tissue not only ameliorated inflammation in this tissue and improved insulin resistance but also improved cardiac dysfunction associated with heart failure. We conclude that heart failure upregulates p53 in adipose tissue by promoting lipolysis via activation of the sympathetic nervous system, leading to an inflammatory response of adipose tissue and insulin resistance. Our results indicate that inhibition of p53-induced adipose inflammation is a potential target for treating metabolic abnormalities and systolic dysfunction in patients with heart failure.

RESULTS

Pressure Overload Induces Adipose Tissue Inflammation and Insulin Resistance

To examine the effect of cardiac pressure overload on glucose homeostasis, we produced transverse aortic constriction (TAC) in 11-week-old mice. In this mouse model, systolic cardiac function deteriorated significantly along with left ventricular (LV) dilatation 2–6 weeks after surgery (Figure S1A available online). The insulin tolerance test (ITT) and the glucose tolerance test (GTT) showed that insulin sensitivity and glucose tolerance were impaired at 4–6 weeks after TAC (Figure 1A) without any change of food intake (Figure S1B). In patients with metabolic disorders, the recruitment of inflammatory macrophages to adipose tissue has been shown to increase the production of proinflammatory cytokines, such as tumor necrosis factor (TNF)-α and chemokine (C–C motif) ligand 2 (CCL2), also known as monocyte chemoattractant protein-1 (MCP-1), leading to the development of systemic insulin resistance (Hotamisligil et al., 1993; Kamei et al., 2006; Weisberg et al., 2003). Therefore, we investigated whether pressure overload provokes adipose tissue inflammation. Examination of hematoxylin- and eosin-stained sections demonstrated the infiltration of mononuclear cells into visceral fat, with most of these cells being identified as macrophages by immunofluorescent staining for Mac3 (Figure 1B). Consistent with these results, expression of a marker for macrophages (Egf-like module containing, mucin-like, hormone receptor-like 1; EMR1) and production of proinflammatory cytokines were significantly upregulated in the adipose tissue of TAC mice along with a decrease of adiponectin (Figure 1C) compared with sham-operated mice. Treatment of TAC mice with a neutralizing antibody for Tnf-α significantly improved insulin resistance and glucose intolerance, suggesting a crucial role in the upregulation of proinflammatory cytokines in the development of metabolic abnormalities during heart failure (Figure S1C).

Pressure Overload Increases Lipolysis and Induces p53-Dependent Inflammation in Adipose Tissue during Heart Failure

Computed tomography (CT) showed a significant decrease of visceral fat after the creation of pressure overload (Figure 1D). It is well accepted that sympathetic activity increases with heart failure (Floras, 2009), and norepinephrine regulates lipolysis in adipose tissue. We found that the norepinephrine levels of plasma and adipose tissue increased significantly and plasma fatty acid levels were markedly elevated in TAC mice compared with sham-operated mice, suggesting acceleration of lipolysis via the sympathetic nervous system in response to pressure overload (Figure 1E). It has been reported that exposure to an excess of fatty acids leads to p53 activation in various cells (Zeng et al., 2008) and that p53 is crucially involved in the regulation of adipose tissue inflammation in obese animals (Minamino et al., 2009). Therefore, we hypothesized that chronic pressure overload promotes lipolysis and the resultant increase of fatty acids leads to p53-induced inflammation in adipose tissue.

Consistent with this concept, we found that p53 expression was upregulated in the adipose tissue of TAC mice at 2–4 weeks after surgery and the change was sustained until 6 weeks (Figures 2A and S2A). To further investigate the role of adipose tissue p53 in the response to pressure overload, we performed TAC in adipocyte-specific p53 knockout (adipo-p53 KO) mice. The pressure overload-induced increase of p53 expression was attenuated in adipo-p53 KO mice compared with littermate controls (Figure S2B). Production of proinflammatory cytokines as well as cyclin-dependent kinase inhibitor 1A (*Cdkn1a*) expression was also decreased in adipo-p53 KO mice, along with a decline in the infiltration of macrophages into visceral fat

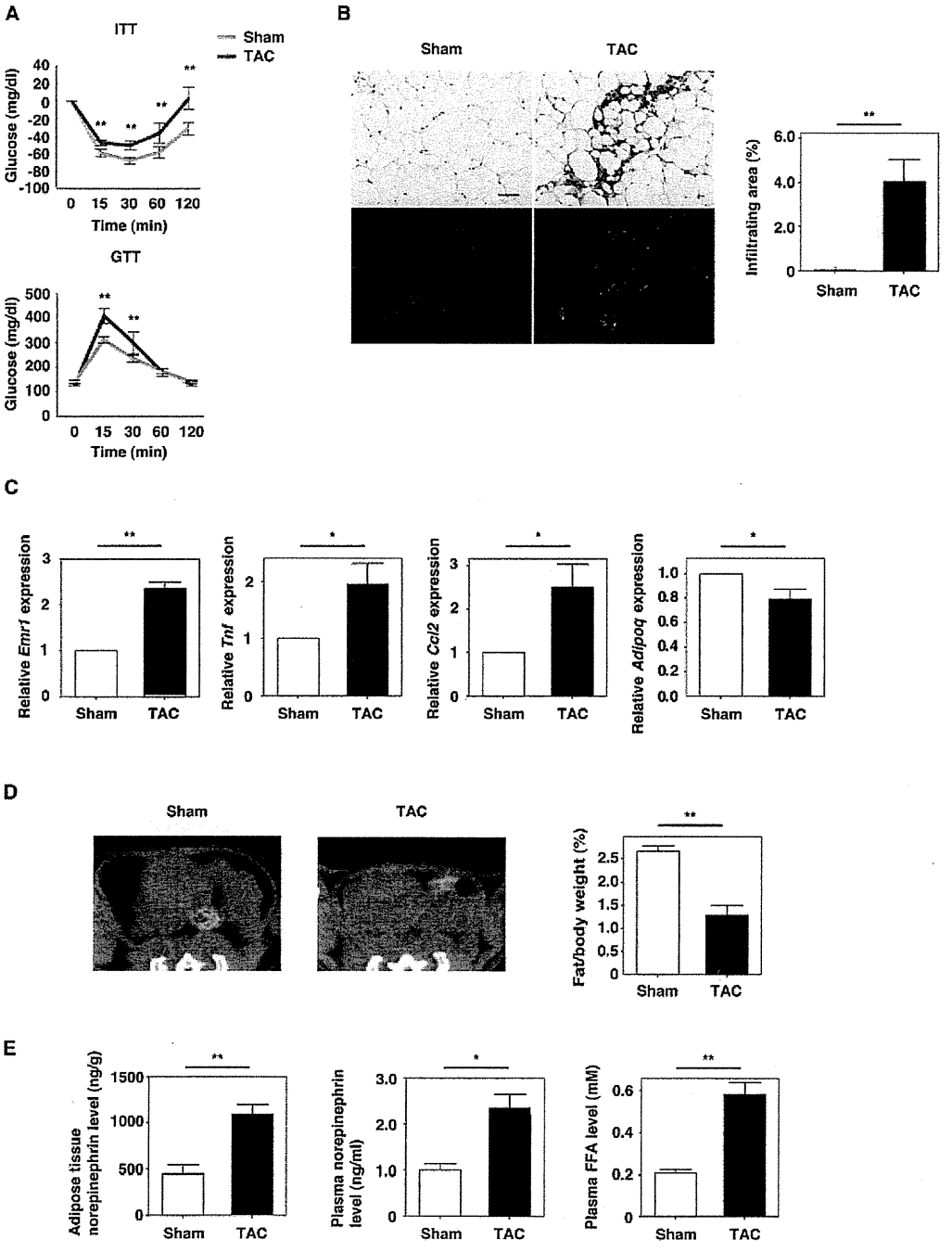


Figure 1. Pressure Overload Induces Systemic Insulin Resistance and Adipose Tissue Lipolysis and Inflammation

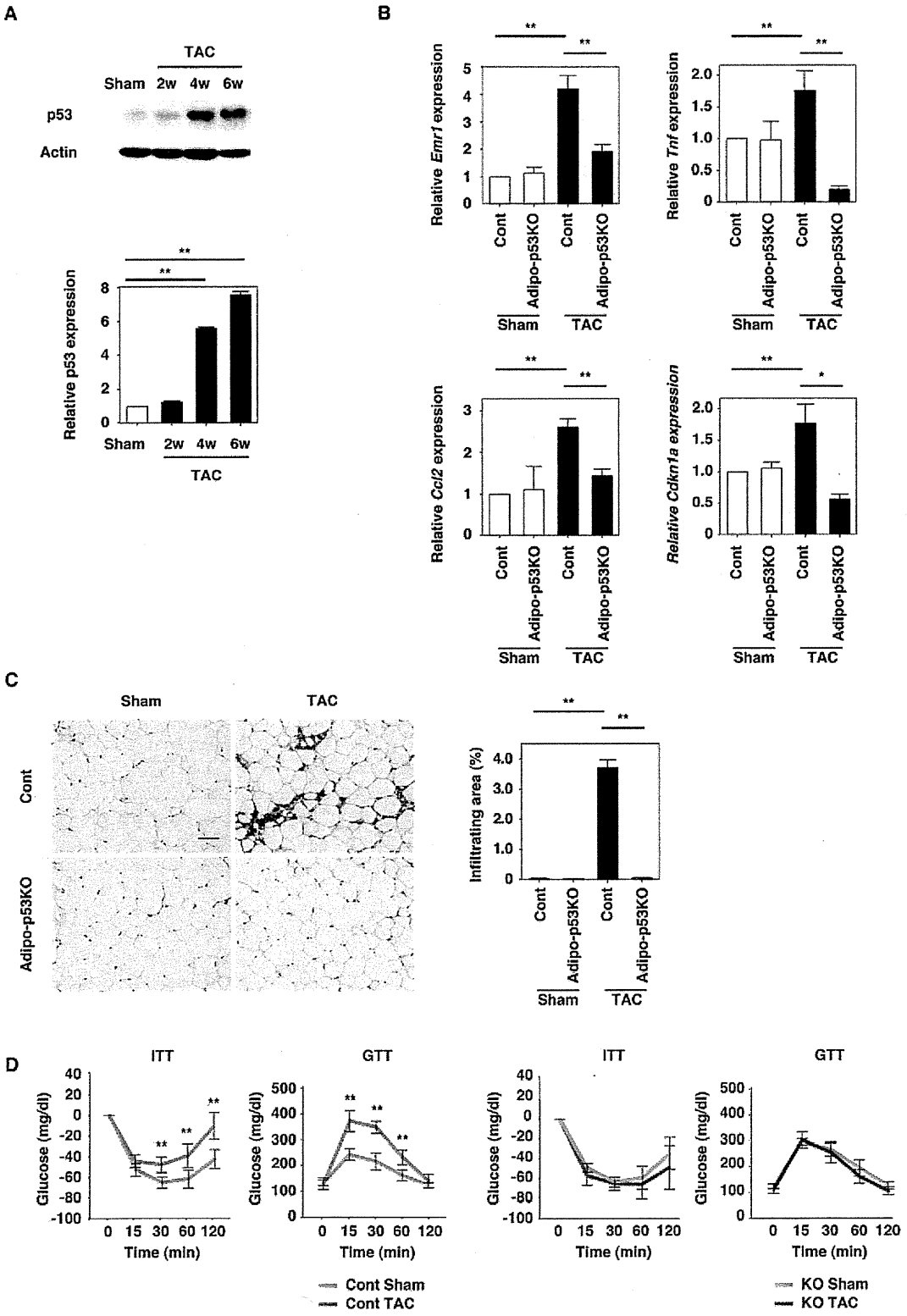
(A) Insulin tolerance test (ITT) and glucose tolerance test (GTT) in mice at 6 weeks after sham operation (Sham) or TAC (n = 30).

(B) Hematoxylin and eosin staining of adipose tissues of mice at 6 weeks after sham operation (Sham) or TAC (upper panel). In the lower panel, the infiltration of macrophages was evaluated by immunofluorescent staining for Mac3 (green). Nuclei were stained with Hoechst dye (blue). Scale bar, 50 μm. The right graph indicates the quantitative data on the infiltration of macrophages (n = 5).

(C) Real-time PCR assessing the expression of *Emr1*, *Tnf* (Tnfα), *Ccl2* (MCP1), and *Adipoq* (Adiponectin) levels in adipose tissues of mice at 6 weeks after sham operation (Sham) or TAC (n = 10).

(D) CT analysis of mice at 6 weeks after sham operation (Sham) or TAC. The graph shows the ratio of visceral fat tissue weight estimated by CT to whole body weight (n = 7).

(E) Norepinephrine level in adipose tissue (left) and plasma (middle), and plasma free fatty acid (FFA) level (right) of mice at 6 weeks after sham operation (Sham) or TAC (n = 10). Data are shown as the means ± S.E.M. *p < 0.05, **p < 0.01.


A
TAC
Sham 2w 4w 6w
p53
Actin
Relative p53 expression
Sham 2w 4w 6w
TAC
B
Relative Emr1 expression
Relative Tnf expression
Relative Ccl2 expression
Relative Cdkn1a expression
Cont
Adipo-p53KO
Sham
TAC
C
Sham
TAC
Cont
Adipo-p53KO
Infiltrating area (%)
D
ITT
GTT
Glucose (mg/dl)
Time (min)
Cont Sham
Cont TAC
KO Sham
KO TAC

(Figures 2B and 2C). Consequently, adipo-p53 KO mice showed improved insulin sensitivity and glucose tolerance after induction of pressure overload compared with littermate controls (Figure 2D) without any change of food intake (Figure S2C). These results suggest that p53 has a critical role in the regulation of adipose tissue inflammation and insulin resistance during pressure overload. In contrast, a decrease of fat mass and an increase of plasma free fatty acids were observed to a similar extent in both adipo-p53 KO and control mice after TAC (Figures S2D–S2F), suggesting that pressure overload accelerates lipolysis in a p53-independent manner.

Pressure Overload Promotes Lipolysis via the Sympathetic Nervous System

We inhibited sympathetic activity in epididymal fat tissue by surgical denervation and then performed TAC. As a result, surgical denervation effectively inhibited an increase of the norepinephrine level of adipose tissue and attenuated lipolysis after the onset of pressure overload (Figures S3A and S3B and data not shown). Histological examination of adipose tissue showed that infiltration of inflammatory cells after TAC was attenuated by denervation (Figures S3C and S3D). Likewise, disruption of the sympathetic efferent nerves significantly reduced pressure overload-induced upregulation of *Emr1*, a proinflammatory cytokine expression in adipose tissue (Figure 3A), and this reduction was associated with significant improvement of insulin resistance and glucose tolerance in TAC mice (Figure 3B). Surgical denervation attenuated pressure overload-induced upregulation of p53 and *Cdkn1a* expression in adipose tissue (Figures 3A and 3C). We also pharmacologically inhibited the sympathetic activity in adipose tissue by injecting guanethidine directly into epididymal fat and then performed TAC. As a result, pharmacological denervation also significantly inhibited lipolysis (Figures S3A and S3B) and attenuated upregulation of p53 and *Cdkn1a* expression and inflammation in adipose tissues (Figures S3C, S3D, S4A and S4B). Mice treated with guanethidine showed better insulin sensitivity and glucose tolerance after creation of pressure overload (Figure S4C), indicating that pressure overload-induced activation of the sympathetic nervous system accelerates lipolysis and, thus, leads to adipose tissue inflammation and insulin resistance in TAC mice.

Role of Lipolysis in the Regulation of Adipose p53 Expression and Inflammation

To examine the role of lipolysis in influencing adipose tissue expression of p53 and inflammation after TAC, we inhibited lipolysis by administering acipimox, a selective inhibitor of lipolysis, to mice with TAC. Treatment with acipimox markedly inhibited lipolysis and also reduced infiltration of inflammatory cells into adipose tissue during pressure overload (Figures S3A–S3D). Inhibition of lipolysis also significantly reduced pressure overload-induced upregulation of *Emr1* and proinflammatory cytokine production in adipose tissue (Figure 4A), along with significant improvement of insulin resistance and glucose intolerance in TAC mice (Figure 4B). Furthermore, treatment with acipimox attenuated pressure overload-induced upregulation of p53 and *Cdkn1a* expression in adipose tissue (Figures 4A and 4C), confirming a close relationship between lipolysis and p53 expression.

Next, we promoted lipolysis by administering isoproterenol to mice via an infusion pump. Treatment with isoproterenol significantly decreased the visceral fat mass and increased plasma fatty acid levels (Figures S5A–S5C) and increased p53 expression in adipose tissue (Figure 5A). Isoproterenol also induced adipose tissue inflammation (Figures 5B and 5C). To further investigate the role of lipolysis in the regulation of p53 expression and inflammation in adipose tissue, we tested the influence of deleting adipose triglyceride lipase (patatin-like phospholipase domain containing protein 2, encoded by *Pnpla2*; hereafter referred to as Atgl) on adipose tissue expression of p53. It has been reported that Atgl homozygous KO mice show massive accumulation of lipids in the heart, causing cardiac dysfunction and premature death (Haemmerle et al., 2006). When we generated TAC mice, we also noted that cardiac function was worse and LV enlargement was more marked in Atgl heterozygous KO mice compared with their littermates (Figure S5D). In fact, most of the KO mice died of heart failure within 4 weeks after TAC. Therefore, we utilized Atgl-deficient adipose tissue for ex vivo experiments. We cultured epididymal fat pad tissues from Atgl KO mice or wild-type littermates and examined the effect of isoproterenol on p53 expression. Treatment of wild-type fat pads with isoproterenol significantly induced lipolysis (Figure 5D) and upregulated the expression of both p53 and *Cdkn1a* expression (Figures 5E and 5F). Disruption of Atgl inhibited isoproterenol-induced lipolysis (Figure 5D) and prevented the upregulation of adipose p53 and *Cdkn1a* expression (Figures 5E and 5F), suggesting a crucial role of lipolysis in the regulation of p53 expression and inflammation in adipose tissue.

Myocardial Infarction Induces Adipose Tissue Inflammation and Insulin Resistance

To investigate whether myocardial infarction (MI) induced insulin resistance, we created MI in 11-week-old mice and assessed the animals 6 weeks after surgery. Insulin sensitivity and glucose tolerance were significantly impaired in MI mice compared with sham-operated mice (Figure S5E). Significant loss of fat tissue was also observed in MI mice (Figures S5F and S5G) and this was associated with upregulation of adipose

Figure 2. p53-Dependent Adipose Tissue Inflammation Provokes Systemic Insulin Resistance during Heart Failure

(A) Expression of p53 was examined in adipose tissues of mice by western blot analysis at indicated time points after sham operation (Sham) or TAC. Actin was used as an equal loading control. The graph indicates the quantitative data on p53 expression (n = 3).

(B) Real-time PCR assessing the expression of *Emr1*, *Tnf* (Tnfα), *Ccl2* (MCP1), and *Cdkn1a* (p21) levels in adipose tissue of adipocyte-specific p53-deficient mice (adipo-p53 KO) and littermate controls (Cont) at 6 weeks after sham operation or TAC procedure (n = 12).

(C) Hematoxylin and eosin staining of adipose tissues of adipocyte-specific p53-deficient mice (adipo-p53 KO) and littermate controls (Cont) at 6 weeks after sham operation (Sham) or TAC procedure. Scale bar, 50 μm. The right graph indicates the quantitative data on the infiltration of macrophages (n = 4).

(D) Insulin tolerance test (ITT) and glucose tolerance test (GTT) in adipocyte-specific p53-deficient mice (KO) and littermate controls (Cont) at 6 weeks after sham operation (Sham) or TAC procedure (n = 16). Data are shown as the means ± S.E.M. *$p < 0.05$, **$p < 0.01$.

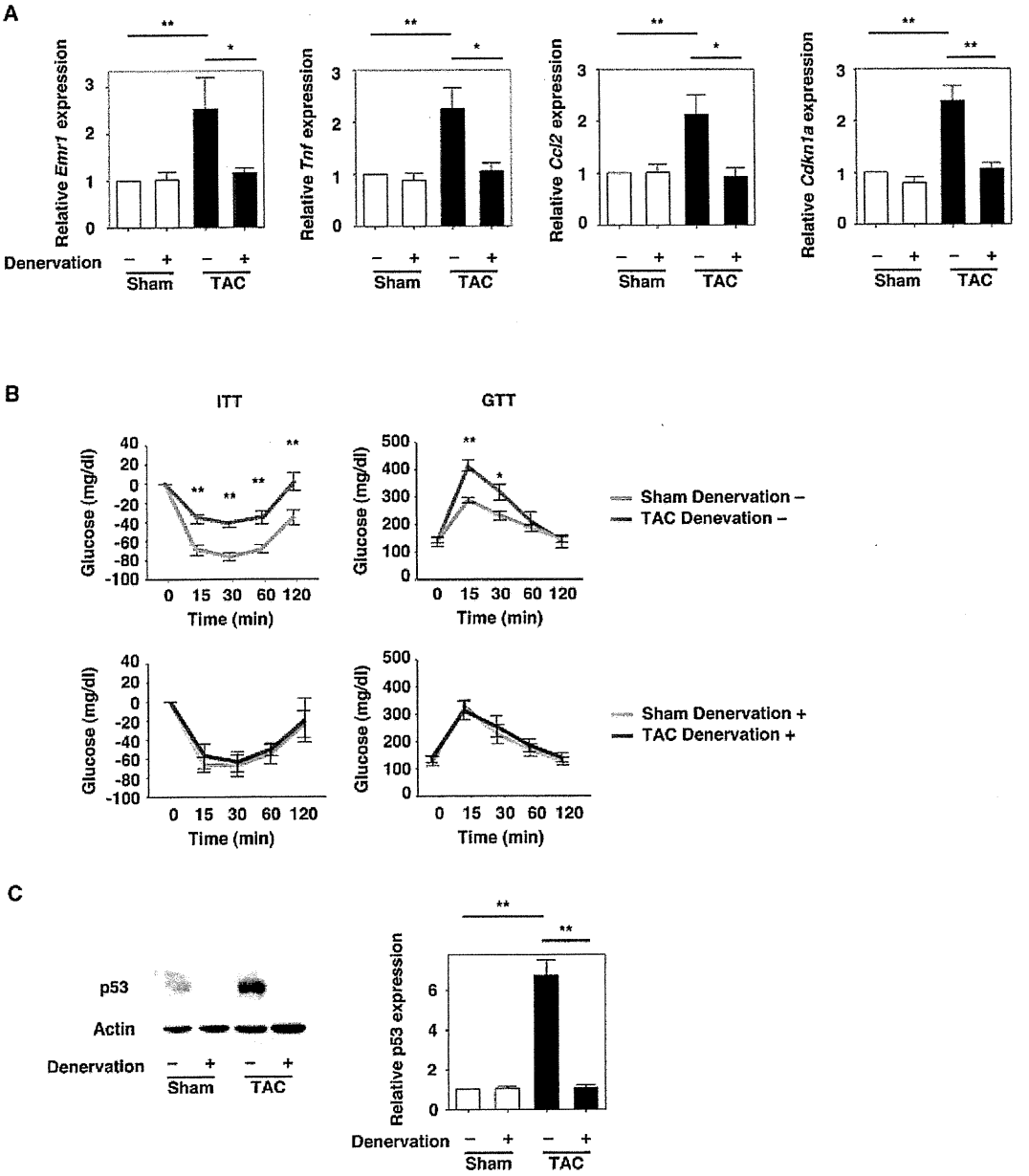


Figure 3. Surgical Transection of the Sympathetic Nerves Attenuates Adipose Tissue Inflammation and Systemic Insulin Resistance

(A) Real-time PCR assessing the expression of *Emr1*, *Tnf* (Tnfα), *Ccl2* (MCP1), and *Cdkn1a* (p21) levels in adipose tissues of mice at 6 weeks after sham operation (Sham) or TAC with or without surgical transection of the sympathetic nerves (Denervation) of epididymal fat (n = 8).

(B) Insulin tolerance test (ITT) and glucose tolerance test (GTT) of mice at 6 weeks after sham operation (Sham) or TAC with or without surgical denervation (n = 20).

(C) Western blot analysis of p53 in adipose tissues of mice at 6 weeks after sham operation (Sham) or TAC with or without surgical denervation. The right graph indicates the quantitative data on p53 expression (n = 3). Data are shown as the means ± S.E.M. *$p < 0.05$, **$p < 0.01$.

tissue p53 expression and inflammation (Figures S5H–S5J). Inhibition of p53 activation in adipose tissue by genetic disruption significantly attenuated inflammation of this tissue and improved metabolic abnormalities (Figures S5K and S5L). These results suggest that the same mechanism underlies insulin resistance associated with heart failure due to both pressure overload and MI.

Influence of Inhibiting p53-Induced Adipose Tissue Inflammation on Cardiac Function

To investigate whether inhibition of p53-induced adipose tissue inflammation could influence cardiac function in the development of heart failure, we performed TAC and monitored cardiac function in adipo-p53 KO mice. We found that adipo-p53 KO mice showed significantly better cardiac function and less LV

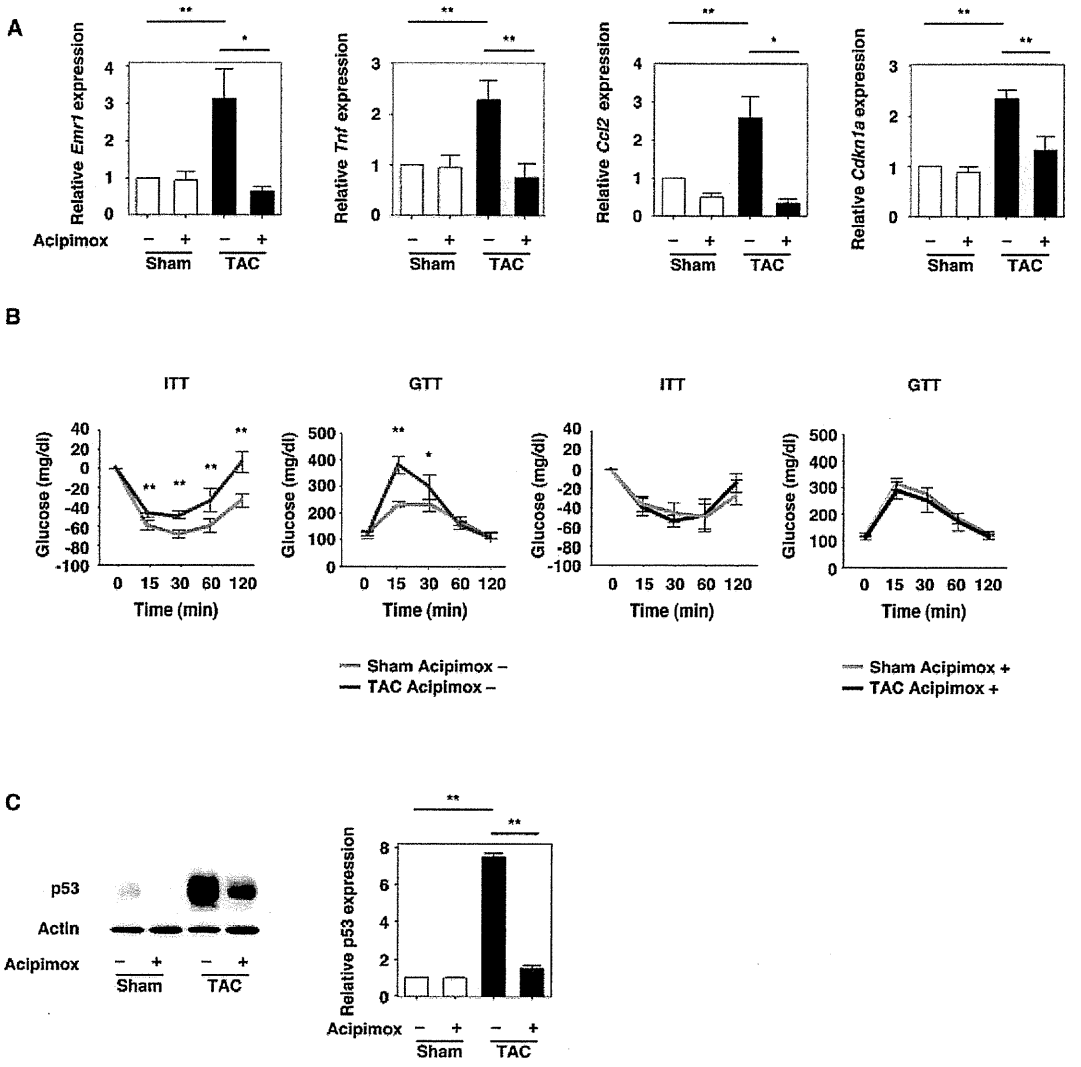


Figure 4. Treatment with a Lipolysis Inhibitor Ameliorates Adipose Tissue Inflammation and Systemic Insulin Resistance

(A) Real-time PCR assessing the expression of *Emr1*, *Tnf* (Tnfα), *Ccl2* (MCP1), and *Cdkn1a* (p21) levels in adipose tissue of mice at 6 weeks after sham operation (Sham) or TAC with or without acipimox treatment (n = 8).

(B) Insulin tolerance test (ITT) and glucose tolerance test (GTT) of mice at 6 weeks after sham operation (Sham) or TAC with or without acipimox treatment (n = 32).

(C) Western blot analysis of p53 in adipose tissues of mice at 6 weeks after sham operation (Sham) or TAC with or without acipimox treatment. Actin was used as an equal loading control. The right graph indicates the quantitative data on p53 expression (n = 3). Data are shown as the means ± S.E.M. *p < 0.05, **p < 0.01.

enlargement compared with their littermate controls (Figure 6A). They also showed better survival during the chronic phase of heart failure (Figure 6B). Similar results were observed in another model of heart failure induced by MI (Figure S6A). Furthermore, administration of a p53 inhibitor (pifithrin-α) into the adipose tissue of the TAC or MI model mice after the onset of heart failure improved cardiac dysfunction, as well as adipose tissue inflammation, and metabolic abnormalities (Figures 6C–6E and S6B–S6D), indicating that inhibition of p53 may be useful for the treatment of heart failure and its associated metabolic abnormalities. Moreover, we noted significant improvement of cardiac function after sympathetic nerve blockade (Figures S6E and S6F). However, treatment of TAC mice with acipimox was found to exacerbate cardiac dysfunction (Figure S6G), presumably because it impaired fatty acid metabolism and energy production in cardiomyocytes, as reported previously (Tuunanen et al., 2006).

Mechanism of p53-Induced Adipose Tissue Inflammation during Heart Failure

Because our results indicated that adrenergic activation induced lipolysis that upregulated p53 and promoted adipose tissue inflammation, we speculated that an excess of fatty acids might be involved in the upregulation of p53 in adipose tissue. Therefore, we examined the effect of palmitic acid on cultured preadipocytes. Treatment with palmitic acid significantly increased the

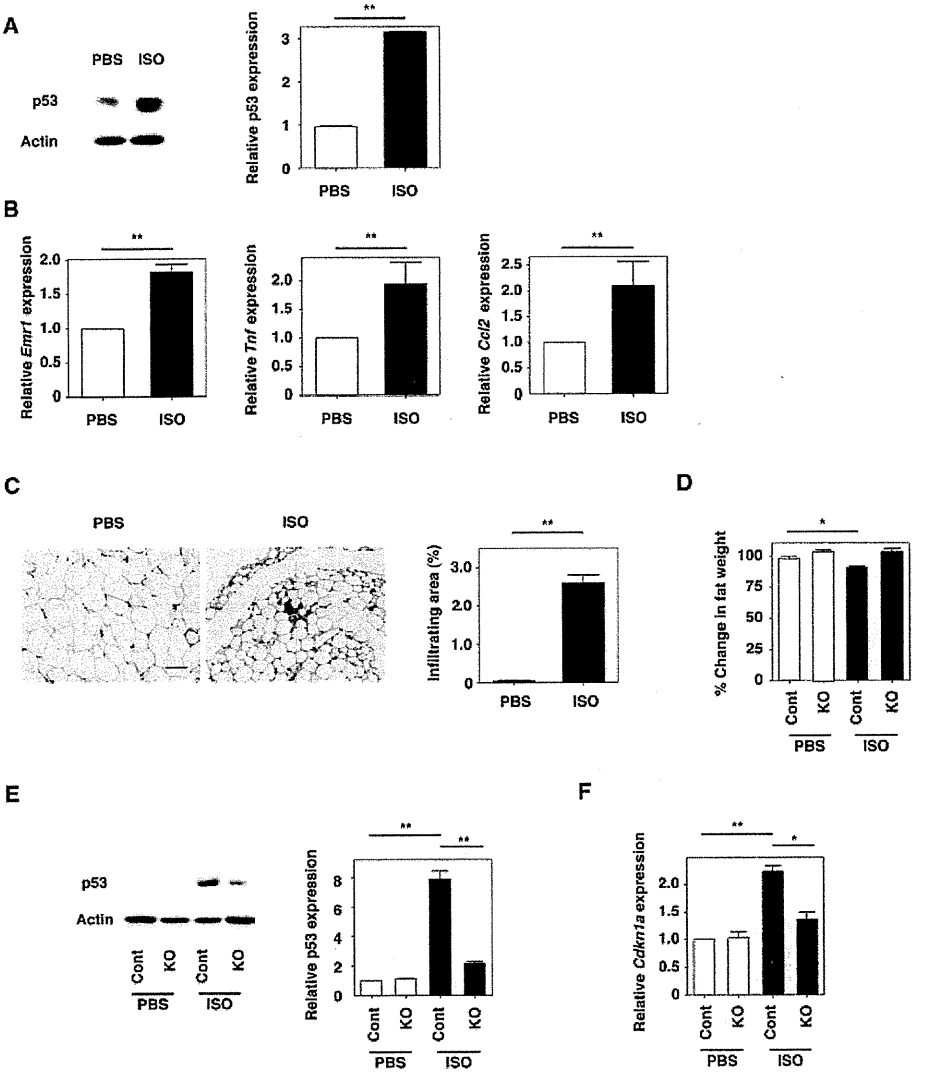


Figure 5. Role of Lipolysis in the Regulation of Adipose p53 Expression and Inflammation

(A) Western blot analysis of p53 in adipose tissues of wild-type mice treated with PBS or isoproterenol (ISO). Actin was used as an equal loading control. The right graph indicates the quantitative data on p53 expression (n = 3).

(B) Real-time PCR assessing the expression of *Emr1*, *Tnf* (Tnfα), and *Ccl2* (MCP1) levels in adipose tissues of wild-type mice treated with PBS or isoproterenol (ISO) (n = 8).

(C) Hematoxylin and eosin staining of adipose tissues of wild-type mice treated with PBS or isoproterenol (ISO). Scale bar, 50 μm. The right graph indicates the quantitative data on macrophage infiltration (n = 4).

(D) The changes in weight of adipose tissues isolated from Atgl-deficient mice (KO) and littermate controls (Cont) after treatment with PBS or isoproterenol (ISO) (n = 6).

(E) Expression of p53 was examined in adipose tissues of Atgl-deficient mice (KO) and littermate controls (Cont) treated with PBS or isoproterenol (ISO) by western blot analysis. The right graph indicates the quantitative data on p53 expression (n = 3).

(F) Real-time PCR assessing the expression of *Cdkn1a* (p21) level in adipose tissues isolated from Atgl-deficient mice (KO) and littermate controls (Cont) after treatment with PBS or isoproterenol (ISO) (n = 6). Data are shown as the means ± S.E.M. *$p < 0.05$, **$p < 0.01$.

intracellular level of reactive oxygen species (ROS) and caused DNA damage, as demonstrated by the increase of γH2AX, which in turn upregulated p53 expression (Figures 7A–7C, S7A, and S7B). This upregulation of p53 was associated with an increase of NF-κB activity and proinflammatory cytokine expression (Figures 7D and 7E). Because it has been reported that p53 enhances the activity of NF-κB, which regulates various cytokines including *TNF-α* and *CCL2* (Benoit et al., 2006; Ryan et al., 2000), we examined the relationship between p53 expression and NF-κB activation. We demonstrated that the disruption of p53 expression significantly attenuated palmitic acid-induced activation of NF-κB and upregulation of *Ccl2*

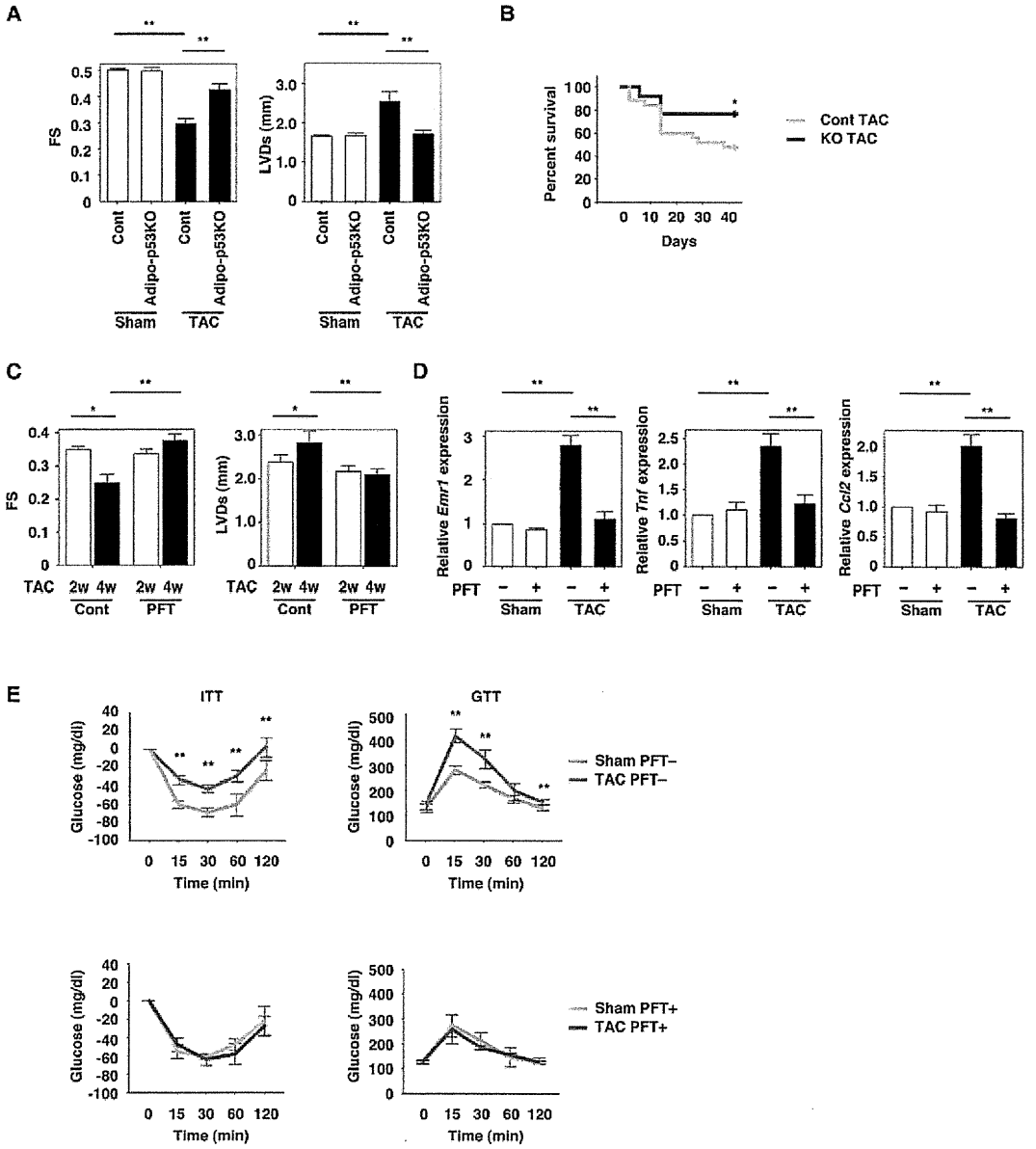


Figure 6. Influence of Inhibiting p53-Induced Adipose Tissue Inflammation on Cardiac Function

(A) Echocardiography to assess systolic function (FS) and ventricular size (LVDs) in adipocyte-specific p53-deficient mice (adipo-p53 KO) and littermate controls (Cont) at 6 weeks after sham operation or TAC (n = 8). FS, fractional shortening; LVDs, left ventricular end-systolic diameter.

(B) Survival rate of adipocyte-specific p53-deficient mice (adipo-p53 KO) and littermate controls (Cont) after TAC procedure (n = 25).

(C) Pifithrin-α (PFT) was administered into the adipose tissue of mice at 2–4 weeks after TAC, and systolic function (FS) and ventricular size (LVDs) were estimated before (2w, 2 weeks after TAC) and after (4w, 4 weeks after TAC) treatment by echocardiography (n = 5).

(D) Real-time PCR assessing the expression of *Emr1*, *Tnf* (Tnfα), and *Ccl2* (MCP1) levels in adipose tissue of mice at 4 weeks after sham operation or TAC with or without pifithrin-α (PFT) treatment (n = 4).

(E) Insulin tolerance test (ITT) and glucose tolerance test (GTT) of mice at 4 weeks after sham operation or TAC with or without pifithrin-α (PFT) treatment (n = 12).

Data are shown as the means ± S.E.M. *$p < 0.05$, **$p < 0.01$.

(Figures 7D and 7E), whereas knockdown of the NF-κB component p50 markedly inhibited palmitic acid-induced upregulation of *Ccl2* (Figure 7E). In addition, treatment with an antioxidant inhibited palmitic acid-induced DNA damage and upregulation of p53 (Figures S7A and S7B). We also found that ROS and γH2AX expression were increased in the adipose tissue of mice with heart failure (Figures 7F and 7G). Furthermore, nuclear localization of p50 was enhanced in adipose tissue during heart failure (Figures 7H and S7C). This increase of nuclear p50 expression and the upregulation of proinflammatory cytokines

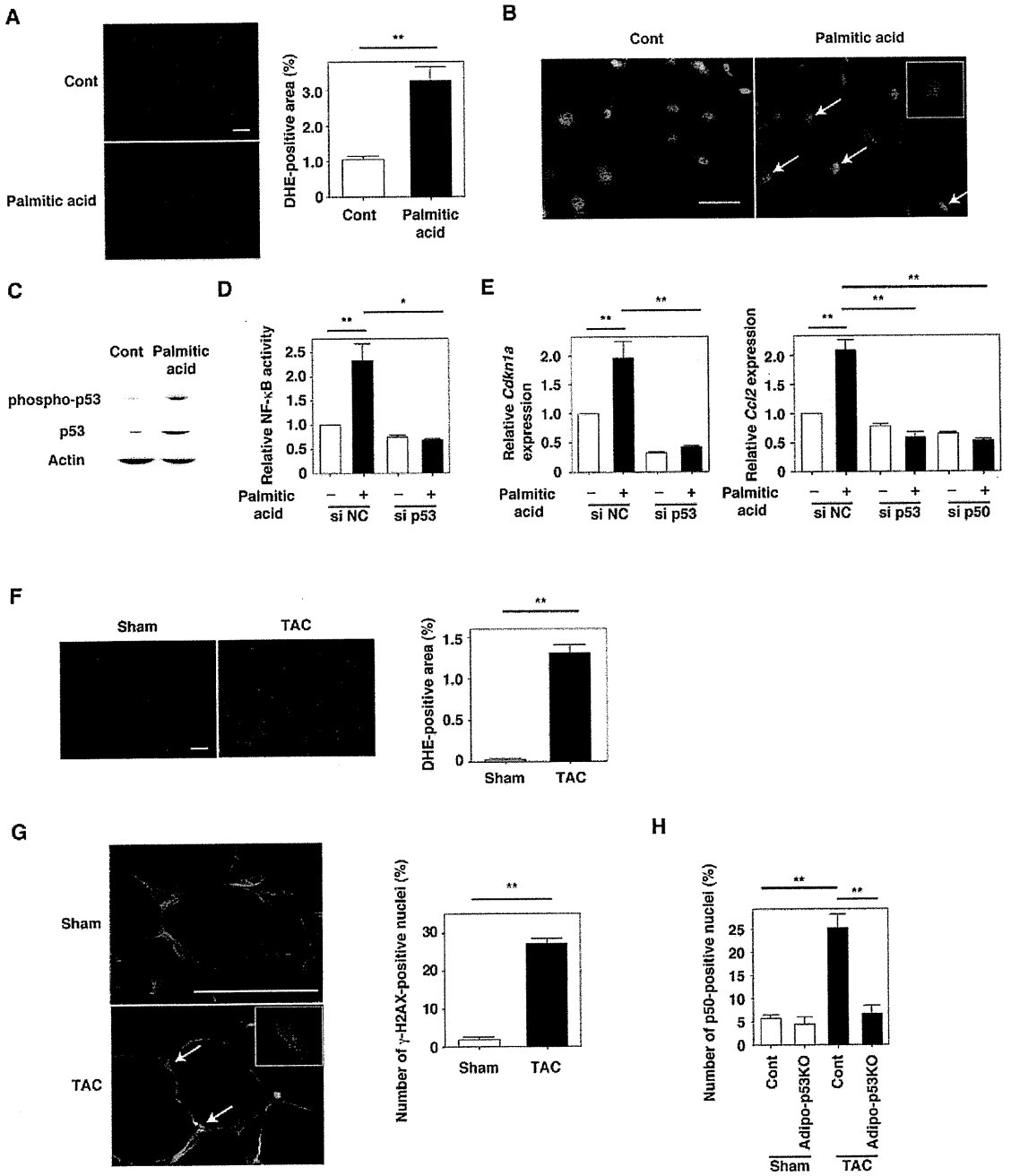


Figure 7. Mechanism of p53-Induced Adipose Tissue Inflammation during Heart Failure

(A) Dihydroethidium (DHE) staining (red) of preadipocytes treated with vehicle (Cont) or palmitic acid (500 μM) for 10 min. Nuclei were stained with Hoechst dye (blue). Scale bar indicates 50 μm. The right graph indicates the quantitative data on DHE-positive area (n = 4).

(B) Immunofluorescent staining for γ-H2AX (red) in preadipocytes treated with vehicle (Cont) or palmitic acid (500 μM) for 1 hr. Nuclei and plasma membranes were stained with Hoechst dye (blue) and Wheat Germ agglutinin lectin (green). Scale bar indicates 50 μm.

(C) Western blot analysis of phospho-p53 and p53 expression in preadipocytes treated with vehicle (Cont) or palmitic acid (500 μM).

(D) Small-interfering RNA targeting p53 (sip53) or negative control RNA (siNC) was introduced into preadipocytes treated with or without palmitic acid (500 μM) for 12 hr. The NF-κB activity was examined by luciferase assay (n = 5).

(E) Real-time PCR assessing the expression of *Cdkn1a* (p21) and *Ccl2* (MCP1) levels in preadipocytes prepared in Figure 7D (n = 9). The effect of small-interfering RNA targeting the NF-κB component p50 (sip50) on the expression of *Ccl2* (MCP1) was also examined (n = 9).

(F) Dihydroethidium (DHE) staining (red) in adipose tissue from sham-operated (Sham) and TAC mice. Nuclei were stained with Hoechst dye (blue). Scale bar indicates 20 μm. The right graph indicates the quantitative data on DHE-positive area (n = 5).

were inhibited by disruption of p53 in adipose tissue (Figures 2B, 7H, and S7C). Moreover, treatment with a lipolysis inhibitor significantly inhibited the heart failure-induced increase of ROS and nuclear p50 expression (Figures S7D and S7E). Inhibition of NF-κB activation in adipose tissue by BAY 11-7082 also significantly attenuated adipose tissue inflammation and improved metabolic abnormalities and cardiac dysfunction in TAC mice (Figures S7F–S7H). These results indicate that adrenergic activation by heart failure induces lipolysis in adipose tissue, which increases DNA damage due to ROS and thus upregulates p53. Activation of p53 then induces adipose tissue inflammation and metabolic abnormalities by upregulating the expression of NF-κB-dependent proinflammatory cytokines.

DISCUSSION

Although treatments that achieve neurohumoral antagonism have successfully reduced the morbidity and mortality of heart failure, the death rate remains unacceptably high (Kannel, 2000). Various metabolic abnormalities are associated with heart failure, and recent data have suggested that heart failure itself promotes adverse changes of metabolism, such as systemic insulin resistance (Ashrafian et al., 2007; Witteles and Fowler, 2008). Thus, a detrimental vicious cycle may be postulated, in which heart failure induces insulin resistance that in turn accelerates cardiac dysfunction (Opie, 2004). However, studies on the molecular mechanisms of such metabolic abnormalities in heart failure are largely preliminary and the results have sometimes been conflicting. In the present study, we demonstrated a causal role for heart failure in the development of insulin resistance by using two mouse models of heart failure, and we elucidated the underlying mechanisms. We found that the hyperadrenergic state of heart failure initiated a vicious metabolic cycle by promoting lipolysis in adipose tissue that increased the release of free fatty acids and upregulated p53 expression and proinflammatory cytokine production in adipose tissue, which then promoted systemic insulin resistance. Cardiac insulin resistance is considered to contribute to the development of heart failure. Because excessive cardiac insulin signaling has been reported to exacerbate systolic dysfunction in both TAC and MI models (Shimizu et al., 2010), hyperinsulinemia associated with systemic insulin resistance may also have a pathological role in heart failure until insulin resistance becomes evident in the myocardium. Inhibition of lipolysis by sympathetic denervation or by treatment with a lipolysis inhibitor improved insulin resistance in our heart failure model. Plasma free fatty acid levels were significantly elevated after the onset of heart failure, whereas this increase was attenuated by inhibition of lipolysis with acipimox, denervation, or guanethidine. Disruption of p53 in adipose tissue also markedly attenuated adipose inflammation and metabolic abnormalities associated with heart failure, whereas fatty acid levels were unaffected. Thus, adipose tissue inflammation rather than the increase of plasma free fatty acids per se is involved in the impairment of insulin sensitivity and glucose tolerance associated with heart failure. We also noted that p53 was modestly upregulated in the liver and skeletal muscle, presumably due to the increase of circulating free fatty acids. However, we did not detect a strong inflammatory response in those tissues under our experimental conditions (I. Shimizu and T. Minamino, unpublished data), suggesting that upregulation of adipose tissue p53 is more important for the development of metabolic abnormalities during heart failure. This concept is further supported by our finding that disruption of p53 activation in adipose tissue nearly normalized insulin resistance and glucose intolerance provoked by heart failure.

We observed that systolic cardiac function and survival with chronic heart failure were significantly better for adipo-p53 KO mice than their control littermates. Suppression of p53 activity in adipose tissue by administration of a p53 inhibitor after the onset of heart failure improved cardiac dysfunction and also reduced adipose tissue inflammation and metabolic abnormalities in both the TAC and MI models. Inhibition of NF-κB activity in adipose tissue also improved cardiac dysfunction, as well as adipose tissue inflammation and insulin resistance. Improvement of cardiac dysfunction by disruption of p53 in adipose tissue was not associated with a decrease of plasma free fatty acid levels. Systemic inhibition of lipolysis (Atgl deficiency or acipimox treatment) and disturbance of lipolysis in adipose tissue (denervation or guanethidine treatment) significantly reduced plasma free fatty acid levels (Haemmerle et al., 2006). However, the former intervention accelerated heart failure, whereas cardiac dysfunction was improved by the latter. Thus, the beneficial effect of inhibiting p53-induced adipose tissue inflammation on cardiac function is independent of changes in circulating free fatty acid levels, and lipolysis in cardiomyocytes appears to have a crucial role in cardiac metabolism and energy production. Although there is evidence suggesting that p53 has a protective role against damage due to ROS and lipotoxicity (Bazuine et al., 2009), our results indicate that chronic activation of p53 in adipose tissue causes inflammation and that inhibition of p53-induced adipose tissue inflammation is a potential target for treating metabolic abnormalities and systolic dysfunction in patients with heart failure.

Adipose tissue was traditionally considered to be a simple energy storage organ, but it is now appreciated that it also has endocrine functions and secretes a variety of factors referred to as adipokines (Donath and Shoelson, 2011; Hotamisligil, 2006; Ouchi et al., 2011). With high calorie intake, the size and number of adipocytes increase, and hypertrophic adipocytes shift the balance toward production of proinflammatory adipokines. This shift in the adipokine profile causes the modification of adipose tissue macrophages from the anti-inflammatory M2 type to the proinflammatory M1 type, and further increases the production of proinflammatory molecules, which in turn

(G) The number of γ-H2AX-positive nuclei (white arrows and inset) in adipose tissue of mice at 6 weeks after sham operation (Sham) or TAC procedure was estimated by immunofluorescent staining for γ-H2AX (red) (n = 5). Nuclei and plasma membranes were stained with Hoechst dye (blue) and Wheat Germ agglutinin lectin (green). Scale bar indicates 50 μm.
(H) The number of p50-positive nuclei in adipose tissue of adipocyte-specific p53-deficient mice (adipo-p53 KO) and littermate controls (Cont) at 6 weeks after sham operation (Sham) or TAC procedure was estimated by immunofluorescent staining for p50 (n = 6). Data are shown as the means ± S.E.M. *$p < 0.05$, **$p < 0.01$.

accelerates the recruitment of activated macrophages into inflamed fatty tissue. Adipokines produced by inflamed adipose tissue have been suggested to play a crucial role in the regulation of glucose and lipid metabolism and to contribute to the development of diabetes (Donath and Shoelson, 2011; Hotamisligil, 2006; Ouchi et al., 2011). It has been reported that excessive calorie intake leads to accumulation of ROS in adipose tissue and subsequently causes DNA damage that activates p53 (Minamino et al., 2009). In contrast to obesity, heart failure decreases body fat tissue mass by inducing lipolysis. Accelerated lipolysis and a subsequent increase of free fatty acids are likely to cause p53 activation because we found that the promotion of lipolysis by treatment with isoproterenol upregulated adipose tissue expression of p53, whereas inhibition of lipolysis by acipimox or disruption of lipase activity attenuated p53 expression. These results are consistent with a recent report describing that fasting-induced lipolysis promotes an immune response in murine adipose tissue (Kosteli et al., 2010). Various molecular mechanisms of p53 activation by heart failure may be postulated, including hypoxia, increased oxidative stress, and induction of endoplasmic reticulum stress (Harris and Levine, 2005; Schenk et al., 2008). Our in vitro and in vivo studies have indicated that an increase of free fatty acids causes ROS-induced DNA damage that upregulates p53 in adipose tissue. Activation of p53 then upregulates the expression of proinflammatory adipokines via the NF-κB signaling pathway and promotes systemic insulin resistance.

The β-blockers are competitive antagonists of β-adrenergic receptors. At one time, β-blockers were contraindicated in patients with heart failure due to their negative inotropic effect. However, several large-scale clinical trials demonstrated the efficacy of β-blockers for reducing morbidity and mortality in heart failure patients with impaired systolic function, so β-blockers are now recommended as first-line agent for these patients (Hjalmarson et al., 2000; Leizorovicz et al., 2002; Packer et al., 2001, 2002). A reduction of heart rate due to inhibition of cardiac β_1-adrenergic receptors is believed to be responsible for most of the therapeutic benefits associated with β-blocker treatment, although this is not the only mechanism of action that may be important in heart failure. It is interesting that treatment with a nonselective β-blocker (carvedilol) achieved a more marked improvement of survival in patients with chronic heart failure than treatment with a β_1-selective blocker (metoprolol) (Poole-Wilson et al., 2003), whereas new-onset diabetes was frequent in heart failure patients during treatment with the β_1-selective blocker (Torp-Pedersen et al., 2007). It has been reported that carvedilol antagonizes the β_3-adrenergic receptor as well as the $\beta_{1/2}$-adrenergic receptors (Schnabel et al., 2000). Taking our results together with these reports, it seems that inhibition of β_3-adrenergic activity in adipose tissue partially accounts for the better clinical outcome in patients treated with this nonselective β-blocker. Recent evidence has suggested that treatment with insulin sensitizers improves systolic function of the failing heart in animal models (Asakawa et al., 2002; Nemoto et al., 2005) but such treatment increases the incidence of heart failure in diabetic patients, presumably because of sodium retention (Home et al., 2009). Inhibition of p53-induced adipose tissue inflammation could be an alternative therapeutic target to block the metabolic vicious cycle in patients with heart failure.

EXPERIMENTAL PROCEDURES

Animal Models

All animal study protocols were approved by the Chiba University review board. C57BL/6 mice were purchased from the SLC Japan (Shizuoka, Japan). TAC and MI were performed in 11-week-old male mice as described previously (Harada et al., 2005; Sano et al., 2007). Sham-operated mice underwent the same procedure except for aortic constriction. Mice that expressed Cre recombinase in adipocytes (Fabp4-Cre) were purchased from Jackson Laboratories. We then crossed Fabp4-Cre mice (with a C57BL/6 background) with mice that carried floxed *Trp53* alleles with a C57BL/6 background (Marino et al., 2000) to generate adipocyte-specific p53 knockout mice. The genotype of littermate controls was Fabp4-Cre$^-$ *Trp53* $^{flox/flox}$. The generation and genotyping of Atgl-deficient mice has been described previously (Haemmerle et al., 2006). Surgical or chemical denervation was performed before TAC operation as described previously (Demas and Bartness, 2001; Foster and Bartness, 2006), with slight modification. In brief, the epididymal fat pad was gently separated from the skin and the abdominal wall by using a dissecting microscope. For surgical denervation, a drop of 1% toluidine blue was applied to the fat pad to facilitate visualization of the nerves. The nerves were then freed from the surrounding tissue and vasculature and cut in two or more locations, and the segments were removed to prevent possible reconnection. Chemical denervation was performed by the local injection of guanethidine sulfate (400 μg, Santa Cruz) into bilateral epididymal fat. Sham-operated mice for surgical denervation underwent the same procedure except for transection of the nerve. For the control group for chemical denervation, saline was injected into adipose tissue rather than guanethidine. Acipimox (Sigma) were provided in drinking water (at a concentration of 0.05%) for 6 weeks after TAC operation as described previously (Guo et al., 2009). Isoproterenol (30 mg/kg/day, Sigma) were delivered by infusion pump (DURECT Corporation) for 2 weeks as described previously (Iaccarino et al., 1999). The local injection of pifithrin-α (2.2 mg/kg/week, Carbiochem) or BAY 11-7082 (20 mg/kg/week, Carbiochem) into bilateral epididymal fat was performed to inhibit adipose p53 or NF-κB activity, respectively, from 2 weeks to 4 weeks after operation.

Physiological and Histological Analyses

Echocardiography was performed with a Vevo 770 High Resolution Imaging System (Visual Sonics Inc, Toronto, Ontario, Canada). To minimize variation of the data, the heart rate was always approximately 550–650 beats per minute when cardiac function was assessed. Epididymal fat samples were harvested and fixed in 10% formalin overnight. The samples were embedded in paraffin and sectioned (Narabyouri research Co., Ltd). The sections were subjected to immunohistochemistry or HE staining. The antibodies used are Mac3-specific primary antibody (PharMingen) for macrophages, p50-specific primary antibody (Cell signaling), and phospho-H2AX-specific antibody (Cell signaling).

Laboratory Tests

For the intraperitoneal glucose tolerance test (IGTT), mice were starved for 6 hr and were given glucose intraperitoneally at a dose of 2 g / kg (body weight) in the early afternoon. For the insulin tolerance test, mice were given human insulin intraperitoneally (1 U / kg body weight) at 1:00 pm without starvation. Blood glucose levels were measured with a glucose analyzer (Roche Diagnostics). We analyzed free fatty acid (Biovision, Inc) and norepinephrine levels (LDN) by using ELISA-based immunoassay kits according to the manufacturer's instruction.

Western Blot Analysis

The lysates were resolved by SDS-polyacrylamide gel electrophoresis. Proteins were transferred to a polyvinylidene difluoride membrane (Millipore, Bedford, MA), which was incubated with the primary antibody followed by anti-rabbit or anti-mouse immunoglobulin-G conjugated with horseradish peroxidase (Jackson, West Grove, PA).

Cell Culture

Human preadipocytes were purchased from Sanko (Tokyo, Japan) and were cultured according to the manufacturer's instructions. NIH 3T3-L1 cells were cultured in high-glucose DMEM plus 10% fetal bovine serum.

Ex Vivo Culture

Epididymal fat was extracted from Atgl-deficient or littermate mice at 17 weeks of age. Freshly isolated fat pads (100–120 mg) were incubated in Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum in the presence of isoproterenol (10 μM) for 48 hr. Fat pads were treated with PBS instead of isoproterenol in the control group.

Statistical Analysis

Data are shown as the mean ± SEM. Differences between groups were examined by Student's t-test or ANOVA followed by Bonferroni's correction for comparison of means. For survival analysis, the Kaplan-Meier method and log-rank test were used. For all analyses, $p < 0.05$ was considered statistically significant.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures and seven figures and can be found with this article online at doi:10.1016/j.cmet.2011.12.006.

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