ABCA1 in adipocytes regulates adipose tissue lipid content, glucose tolerance and insulin sensitivity

Abbreviated title: Adipocyte ABCA1 regulates glucose tolerance

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ABSTRACT

Adipose tissue contains one of the largest reservoirs of cholesterol in the body. Adipocyte dysfunction in obesity is associated with intracellular cholesterol accumulation and alterations in cholesterol homeostasis have been shown to alter glucose metabolism in cultured adipocytes. The ATP Binding Cassette transporter (ABC) A1 plays a major role in cholesterol efflux, suggesting a role for ABCA1 in maintaining cholesterol homeostasis in the adipocyte. However, the impact of adipocyte ABCA1 on adipose tissue function and glucose metabolism is unknown. Our aim was to determine the impact of adipocyte ABCA1 on adipocyte lipid metabolism, body weight and glucose metabolism in vivo. To address this, we used mice lacking ABCA1 specifically in adipocytes (ABCA1<sup>ad/-ad</sup>). When fed a high fat high cholesterol diet, ABCA1<sup>ad/-ad</sup> mice showed increased cholesterol and triglyceride stores in adipose tissue, developed enlarged fat pads and had increased body weight. Associated with these phenotypic changes we observed significant changes in the expression of genes involved in cholesterol and glucose homeostasis including ldlr, abcg1, glut-4, adiponectin and leptin. ABCA1<sup>ad/-ad</sup> mice also demonstrated impaired glucose tolerance, lower insulin sensitivity and decreased insulin secretion. We conclude that ABCA1 in adipocytes influences adipocyte lipid metabolism, body weight and whole body glucose homeostasis.

**Keywords:** Adipose Tissue, Cholesterol, Glucose Homeostasis, Insulin Resistance, Lipid Metabolism, Obesity, Type II Diabetes
INTRODUCTION

Adipose tissue has a crucial role in energy metabolism since it is the major storage site for triglycerides (TG). Furthermore, adipose tissue is an important exocrine organ secreting various adipokines important in metabolism (1, 2). In addition to being the main site for TG storage, adipose tissue also contains one of the largest pools of cholesterol in the body (3, 4). Cholesterol and TG are taken up by adipocytes from plasma lipoproteins via lipoprotein receptors including the LDL receptor (LDLR), Scavenger Receptor B1 (SR-B1) and CD36 (3-5). Triglycerides leave adipose tissue as non-esterified fatty acids (NEFA) after TG lipolysis (6), while cholesterol is removed from adipocytes via transporters such as ATP Binding Cassette transporter (ABC) A1 and ABCG1 (7, 8).

ABCA1 is responsible for the efflux of cholesterol to apoA1 and small high density lipoprotein (HDL) particles, and is the rate limiting protein in HDL production (9, 10). ABCA1 is widely expressed (11), has been shown to be a crucial regulator of intracellular cholesterol stores, and has an important role in the function of multiple tissues (12, 13). For example, lack of ABCA1 in the brain leads to changes in motor activity and sensorimotor function (12), whereas ABCA1 deficiency in beta cells reduces insulin release (14). ABCA1 has been shown to be expressed and functional in adipocytes (7, 8). Gonadal adipose tissue lacking ABCA1 has reduced cholesterol efflux concomitant with increased cholesterol stores (9, 15), indicating that ABCA1-mediated cholesterol efflux is important in adipocyte cholesterol metabolism. Changes in adipocyte cholesterol homeostasis are associated with adipose dysfunction and obesity (3, 16, 17). However, the role of ABCA1 and intracellular cholesterol in adipose function with regard to body weight and glucose metabolism is unclear.

Intracellular cholesterol has been suggested to play a role in adipose tissue dysfunction (3, 16, 17). Adipocytes from obese individuals contain increased stores of both TG and
cholesterol (3, 17). Furthermore, in 3T3 adipocytes, stimulation of TG lipolysis has been shown to induce cholesterol efflux (7). Therefore, it has been suggested that cholesterol may directly affect TG stores (16, 17). This also suggests that ABCA1 may be linked to TG metabolism in adipocytes and adipose tissue function. Adipose tissue dysfunction is a characteristic of obesity (18), and is an important risk factor for insulin resistance, glucose intolerance and for the eventual development of type II diabetes (18, 19). Adipose tissue dysfunction affects glucose tolerance through altered release of NEFA and adipokines in plasma. (1, 2, 19, 20). NEFA release from adipose tissue reduces insulin sensitivity and insulin secretion (19, 21). Expression and release of the various adipokines regulate insulin sensitivity, insulin release and glucose tolerance (2, 19, 21).

Adipocyte cholesterol may also directly regulate glucose homeostasis in the adipocyte. Membrane cholesterol depletion from the adipocyte using methyl-β-cyclodextrin reduces glut-4 expression and impairs insulin stimulated adipocyte glucose transport in 3T3 cells (16). This provides further evidence for a direct link between cholesterol and adipocyte glucose homeostasis.

Collectively this evidence suggests that cholesterol regulation in adipocytes may have important implications for glucose homeostasis. ABCA1 has been shown to regulate adipocyte cholesterol levels (7, 8). However, the role of ABCA1 in adipocyte function with regard to body weight and glucose metabolism is unknown. In this study we suggest a link between the regulation of cholesterol in adipocytes by ABCA1 with TG storage, body weight and whole body glucose homeostasis.
MATERIALS AND METHODS

Animals
Mice lacking ABCA1 in the adipose tissue (ABCA1<sup>-ad/-ad</sup>) were generated by crossing ABCA1 floxed mice with mice expressing the cre transgene under the adipose specific aP2 promoter (Jacksons laboratory, Bar Harbor, ME, USA). These mice have been shown to be deficient in ABCA1 specifically in their adipose tissues (15). Mice were on a C57BL/6 background, were housed under 12h light dark cycles and had ad libitum access to chow or high fat high cholesterol (HFHC) diet and water. Male mice were used for all experiments. To study the role of adipocyte ABCA1 in diet induced obesity, mice were fed a HFHC diet containing 21% milk fat w/w and 0.21% of cholesterol (Western diet D12079B, Research diets, New Brunswick, NJ, USA) at 10 weeks of age. All experiments were in conformity with PHS policy, approved by the UBC Animal Care Committee and conducted in accordance with their guidelines.

Tissue analysis
Mice were sacrificed using CO<sub>2</sub> after 4 hours fasting and tissues were isolated, frozen in liquid nitrogen and stored at -80°C. Subcutaneous adipose tissue (SAT) was isolated from the hip region and brown adipose tissue (BAT) from the intrascalpular region. For qPCR RNA was isolated using Trizol (Invitrogen, Carlsbad, CA, USA) according to manufacturer’s protocol, cDNA was synthesized using the superscript first strand syntheseses kit (Invitrogen) and PCR was performed using sybr green (ABI, Carlsbad, CA, USA) in a 7500 ABI fast machine. Lipids were isolated from tissues after homogenization in 10 μl/mg methanol, 25 μl homogenate was added to 225 μl methanol, 675 μl chloroform was added, samples were mixed, centrifuged and the supernatant containing lipids was dried and lipids were dissolved in 2% Triton X-100. TG were measured with TG reagent (Roche, Penzberg, Germany), and cholesterol with infinity
cholesterol reagent (Fisher Waltham, MA, USA). For western blotting tissue lysates were prepared, separated by SDS-PAGE, blotted to a PVDF membrane and proteins were detected using the following antibodies: LDLR, (Abcam, Cambridge MA, USA) actin, gapdh (Millipore, Billerica, MA, USA), GLUT-4, AKT and pAKT (cell signalling, Danvers MA, USA) anti mouse alexa fluor 800 (Rockland, Gilbertsville, PA) and anti rabbit alexa fluor 680 (Molecular Probes, Invitrogen) and visualized and analysed using Licor (Licor Biosciences, Lincoln NE, USA). ABCA1 was detected with our in house antibody, HRP labeled secondary antibodies (Jackson ImmunoResearch, West Grove PA, USA) and visualized using ECL (Pierce Rockford IL USA). For the lipolysis assay adipose tissue was isolated, minced and cultured in DMEM F12. Adipose tissue was treated with isoproterenol (Sigma) and glycerol release in the medium was measured over a 4 hour period using glycerol and TG reagent (Roche, Penzberg, Germany) and glycerol release per hour normalized by tissue weight was calculated.

Plasma analysis

Blood samples were drawn from mice from the saphenous vein after 4 hours fasting (8am-12am). Blood glucose was measured with a glucose meter (onetch) or using quantichrom glucose assay reagents (BioAssay systems, Hayward, CA) according to manufacturers protocol. Insulin was measured using the Mouse Insulin ELISA (Mercodia, Uppsala, Sweden). TG were measured with TG reagent (Roche, Penzberg, Germany), non-esterified fatty acids (NEFA) with NEFA half micro test (Roche, Penzberg, Germany) and cholesterol with infinity cholesterol reagent (Fisher Waltham, MA, USA). HDL cholesterol was measured after precipitation of apoB containing lipoproteins from plasma using heparin (500 U/mL) and MnCl₂ (0.2M) 2:1:1(22). Adiponectin visfatin and leptin were measured with commercially available ELISA kits (adiponectin: Alpco. Salem, NH, USA, visfatin: Abnova Tapei City, Taiwan; leptin: Abcam, Cambridge UK)
Glucose tolerance and insulin sensitivity testing

Mice were fasted for 4 hours (8am-12am) and were injected i.p. with 1g/kg (HFHC) or 2g/kg (chow) glucose (Sigma, St. Louis, MO) in PBS for glucose tolerance testing or with 1U/kg insulin (Novo Nordisk Bagsværd, Denmark) in PBS for insulin sensitivity testing. Blood was drawn via the saphenous vein before injection and at 15, 30, 60 and 90 minutes after injection and was assayed for glucose.

Insulin secretion

Islets were isolated from mice anesthetised with avertin i.p. the pancreas was perfused with collagenase (Sigma) in calcium free HBSS via the bile duct. The pancreas was homogenized after digestion at 37°C and islets were handpicked in RPMI 10% FBS and pen/strep. For glucose secretion experiments islets were incubated in krebs buffer for 2 hours followed by 1 hour incubation in low or high glucose krebs buffer (1.67 vs. 16.7 mM). Insulin secreted in the supernatant was assayed using mouse insulin ELISA (Mercodia, Uppsala, Sweden).

Statistical analysis

Data are expressed as means +/- SEM. Data were interpreted using student t-test or two way ANOVA followed by bonferroni post-hoc test using prism 5.0a (Graphpad, La Jolla, CA USA). Differences were considered statistically significant when P < 0.05.
RESULTS

**Adipocyte ABCA1 deficiency increases adipose tissue cholesterol content**

ABCA1 protein expression in adipose tissue was measured by western blotting to confirm the specific loss of ABCA1 in adipose tissue from ABCA1^{−/−-ad} mice. A significant reduction in adipocyte ABCA1 protein levels in ABCA1^{−/−-ad} mice was observed (Fig. 1A). To ensure ABCA1 knockdown due to expression of the ap2-cre transgene was only localized to adipocytes, we also measured ABCA1 in liver, muscle and brain and found no change in ABCA1 protein levels (Suppl. Fig. 1A).

Since ABCA1 is a major mediator of cholesterol efflux (9, 10), we evaluated whether loss of ABCA1 in adipocytes raises adipose cholesterol content. We observe a significant increase in the cholesterol content in gonadal adipose tissue (GAT), subcutaneous adipose tissue (SAT) and mesenteric adipose tissue (MAT) in ABCA1^{−/−-ad} mice compared to wild type control mice (ABCA1^{+/+}) on a chow diet (Fig1B). Following a HFHC diet, we observed a significant increase of cholesterol in GAT, SAT as well as brown adipose tissue (BAT) in ABCA1^{−/−-ad} mice. (Fig. 1C).

To maintain intracellular cholesterol homeostasis, cholesterol has been shown to regulate the expression of genes affecting cholesterol metabolism via Sterol Regulatory Element-Binding Protein (SREBP)2 and the liver X receptor (LXR) (16, 17, 23). Thus, we evaluated how the loss of adipocyte ABCA1 affects the expression of genes involved in maintaining cholesterol homeostasis. An increase in abcg1 mRNA expression as well as a reduction in ldlr gene expression and LDLr protein levels was observed (Fig. 1D,E). ABCG1 is a cholesterol transporter important in the maintenance of tissue cholesterol homeostasis by mediating cholesterol efflux to HDL (24). The LDLr mediates uptake of cholesterol by cells (25, 26). Our results indicate that the loss of ABCA1 significantly alters adipose tissue cholesterol
homeostasis and that adipocytes compensate for disturbances in lipid homeostasis by altering the expression of genes involved in cholesterol metabolism.

**Adipocyte ABCA1 deficiency increases fat pad weight on a high fat high cholesterol diet**

Obesity is associated with the accumulation of both cholesterol and TG in adipose tissue (3, 17). We evaluated whether changes in adipocyte ABCA1 expression and cholesterol content influence body weight, fat pad weight and adipocyte TG levels.

On a chow diet, ABCA1\(^{-}\text{ad-ad}\) mice demonstrated no difference in body weight, fat pad weight and adipose tissue TG content compared to wild-type littermate controls (Fig. 2A,B). However, on a HFHC diet containing 21% milk fat (w/w) and 0.21% of cholesterol (w/w), ABCA1\(^{-}\text{ad-ad}\) mice gain more weight than their littermate controls (Fig. 2C,D). To assess whether these changes in body weight gain were reflected in changes to adipose tissue mass, we isolated adipose tissue depots. Concomitant with increased body weight gain, GAT and SAT depots showed a significant increase in weight (Fig. 2E). To evaluate changes in TG content, we extracted lipids from different types of adipose tissue depots and observed that TG content was significantly increased in GAT, SAT and MAT following correction for protein levels (Fig. 2F). Our results indicate that lack of adipocyte ABCA1 leads to cholesterol accumulation, increased TG content in adipocytes, enlarged fat pads and increased body weight.

**Adipocyte ABCA1 deficiency alters lipolysis but does not lead to major changes in genes involved in TG metabolism**

Adipose tissue stores large amounts of TG which can act as sources of energy and can be used to synthesize membrane and signalling lipids. However, in order to cross the adipocyte plasma membrane and be released into the plasma, adipocyte TG must be hydrolysed into fatty acids by a process known as lipolysis (6).
Sustained lipolysis has been shown to stimulate cholesterol efflux through ABCA1 (7). This suggests that there may be an association between ABCA1 function and TG lipolysis. In order to address this relationship, we investigated whether ABCA1 expression can affect TG lipolysis. We stimulated lipolysis using isoproterenol and observed reduced glycerol release in the medium from adipose tissue lacking ABCA1 (Fig. 3A). This suggest that ABCA1 mediated cholesterol efflux activity may influence TG lipolysis.

TG stores in adipose tissue are regulated by the combined effect of TG uptake, TG synthesis and lipolysis. To further explore possible mechanisms linking adipocyte ABCA1 and TG homeostasis, we assessed the expression of ten major genes in TG metabolism. A significant increase was observed only in dgat2 mRNA expression (Fig. 3B). DGAT2 is a crucial enzyme involved in TG biosynthesis (27). However, the consequence of increased dgat2 mRNA on TG metabolism is unclear as protein levels of DGAT2 were unaltered (Fig. 3C).

**Adipocyte ABCA1 deficiency alters plasma and liver lipid levels**

In humans, adipose dysfunction is associated with dyslipidemia including elevated plasma TG levels and low HDL (19, 28). In order to assess the contribution of adipocyte ABCA1 to plasma lipid metabolism, we measured total cholesterol, HDL, TG and non esterified fatty acids (NEFA) in the plasma of wild-type and ABCA1<sup>ad/-ad</sup> mice. We would expect decreased plasma cholesterol levels, due to decreased efflux of cholesterol from adipose tissue in ABCA1<sup>ad/-ad</sup> mice. We indeed observed a decrease in plasma cholesterol levels, however plasma levels of HDL cholesterol showed no significant difference (Table 1). There was a significant increase in plasma TG levels in ABCA1<sup>ad/-ad</sup> mice (Table 1). Plasma NEFA levels were not significantly affected (Table 1).

Obesity and adipose dysfunction not only have consequences on plasma lipids but have also been associated with hepatosteatosis (21). Although the precise mechanism by which adipose
tissue affects lipid accumulation in the liver remains unclear, increased NEFA flux, decreased adiponectin and visfatin expression and as well as insulin resistance may all play a role (1, 20, 21, 28). To assess the effect of adipose ABCA1 on the liver, we measured liver weight and hepatic lipid content in ABCA1-/- mice. After a HFHC diet ABCA1-/- mice had an increased liver weight and demonstrated elevated levels of TG and cholesterol content in hepatic tissue (Suppl. Fig. 3 A,B).

**Adipocyte ABCA1 deficiency alters the expression of proteins involved in glucose homeostasis**

Adipose tissue is critical in regulating whole-body glucose homeostasis through the release of adipokines such as leptin, adiponectin and visfatin (1, 2). These act on various tissues including the pancreas to stimulate insulin secretion and the muscle to enhance insulin sensitivity. Low adiponectin levels are associated with reduced insulin secretion, insulin resistance and hepatosteatosis. Visfatin is an insulin mimicking protein while leptin levels increase with weight gain and serves to regulate food intake and energy expenditure (1, 2, 20). Obesity and adipose dysfunction can alter adipokine expression and secretion.

We evaluated whether adipose tissue dysfunction due to the loss of ABCA1 could affect the expression of adipokine genes critical to whole body glucose homeostasis. In ABCA1 deficient adipose tissue we found that mRNA expression of *leptin* was significantly increased, whereas *adiponectin* and *visfatin* expression were significantly reduced (Fig. 4A). Plasma leptin and visfatin levels were unaltered (supplemental figure 2D,E). High molecular weight adiponectin levels showed a 30% decrease (p<0.05) (Fig. 4C). These changes in adipokine expression may affect glucose tolerance.

GLUT-4 is a protein crucial for insulin stimulated glucose uptake. Depletion of membrane adipocyte cholesterol by methyl-β-cyclodextrin *in vivo* reduces *glut-4* mRNA expression and
decreases insulin stimulated glucose uptake (16). Moreover, GLUT-4 deficiency in adipose tissue has been shown to affect whole body glucose tolerance (29). We evaluated whether ABCA1 affects glut-4 mRNA expression and GLUT-4 protein levels in adipose tissue. Both mRNA and protein expression of GLUT-4 were reduced in GAT from ABCA1^{-ad/-ad} mice (Fig. 4A,B). The changes in adipokine expression and reduced glut-4 expression suggest that adipose tissue dysfunction as a result of ABCA1 deficiency may impact whole body glucose tolerance and insulin sensitivity.

**Adipocyte ABCA1 deficiency impairs glucose tolerance, reduces insulin sensitivity, and impairs beta cell function**

We demonstrate that adipose ABCA1 deficiency increases cholesterol and TG storage in adipocytes, and reduces adiponectin, visfatin and glut-4 expression. These alteration in lipid homeostasis and gene expression are linked to impaired glucose tolerance and reduced insulin sensitivity (1, 2, 19, 20). Based on these findings, we hypothesize that adipocyte ABCA1 deficiency leads to glucose intolerance and insulin resistance in vivo.

To address this, we assessed glucose tolerance in ABCA1^{-ad/-ad} versus control mice. Although we observed that glucose tolerance was unaltered in mice lacking adipocyte ABCA1 on a chow diet (data not shown), ABCA1^{-ad/-ad} mice had significantly impaired glucose tolerance following a HFHC diet (Fig. 5A,B). To determine whether impaired glucose tolerance could be explained by a reduction in insulin sensitivity, we measured the response in plasma glucose levels after i.p. insulin injection. A significant impairment of insulin sensitivity was observed in ABCA1^{-ad/-ad} mice (Fig. 5C,D). We then evaluated in which tissues insulin sensitivity is affected through measurement of AKT phosphorylation, a marker for intracellular insulin signalling. Since basal pAKT levels were too low to quantify (data not shown), we stimulated AKT phosphorylation by giving mice an i.p. insulin injection followed by tissue extraction and
immunoblotting analysis. Western blots revealed that the pAKT/AKT ratio is reduced in muscle from ABCA1-/- mice following insulin injection. The pAKT/AKT ratio was unaltered in adipose tissue (Fig. 5E,F). In the liver AKT levels were very low, even following the injection of insulin and we found no obvious changes in pAKT/AKT ratio (data not shown). Thus, adipocyte ABCA1 deficiency specifically impairs muscle tissue insulin sensitivity.

Decreased insulin sensitivity in peripheral tissues results in increased insulin secretion by the pancreas to compensate for this insulin resistance (30, 31). Increased production of insulin may eventually lead to beta cell failure and reduced insulin secretion (30, 31). This is consistent with our findings as ABCA1-/- mice demonstrated both decreased insulin sensitivity in muscle tissue, and a significant increase in circulating plasma insulin levels on a HFHC diet (Table 1). To explore whether beta cell function was affected, pancreatic islets were isolated from ABCA1-/- and wild type mice and incubated in KRB buffer with low (1.67 mM) or high (16.67 mM) glucose and insulin secretion in the media was measured. We observed that insulin secretion from beta cells was reduced in islets from ABCA1-/- mice after HFHC feeding (Fig. 5G). Our findings support the paradigm that reduced beta cell function can result from an increase in insulin demand as a consequence of insulin resistance in tissues. Collectively, our data suggest that intracellular cholesterol homeostasis in adipocytes is maintained by ABCA1 and is crucial for glucose tolerance, insulin sensitivity and beta cell function.
DISCUSSION

Adipose tissue contains one of the largest pools of cholesterol in the body, is the primary storage depot for TG and is crucial in energy metabolism (20). Alterations in adipocyte cholesterol are associated with adipose dysfunction and obesity and ABCA1 has been shown to mediate cholesterol efflux from adipose tissue (7, 9, 15). Adipose tissue dysfunction is an important risk factor for the development of glucose intolerance, insulin resistance and type II diabetes (3, 19, 28), this indicates a role for adipocyte cholesterol and ABCA1 in these conditions.

Previous studies showing that cholesterol may be crucial in adipocyte function were mainly carried out in the 3T3 adipocyte cell line or observations in obese mice (3, 4, 16). In our study, we directly investigate how adipocyte ABCA1 affects adipose lipid content and adipose function using a mouse model specifically lacking ABCA1 in adipocytes. In this study we demonstrate significantly increased intracellular cholesterol levels in the adipose tissue of adipocyte ABCA1 deficient mice. Concomitant with increased cholesterol levels, we observe an enlargement of fat pads and an accumulation of TG in the adipose tissue of ABCA1$^{-ad/-ad}$ mice on a HFHC diet. These changes in adipose tissue have significant metabolic consequences as we demonstrate that ABCA1$^{-ad/-ad}$ mice manifest with impaired glucose tolerance, reduced muscle insulin sensitivity and lower glucose-stimulated insulin secretion from beta cells ex vivo.

Using ABCA1$^{-ad/-ad}$ mice, we show that cholesterol accumulates in ABCA1 deficient adipose tissue in mice on both a chow and a HFHC diet. This increase in cholesterol content is likely a direct effect of reduced ABCA1-mediated cholesterol efflux from adipose tissue. Increased intracellular cholesterol has a major impact on lipid metabolism as cholesterol regulates the expression of multiple genes involved in intracellular lipid homeostasis. For example, increased intracellular cholesterol reduces the expression of hmgcoA reductase and
the *ldlr* via SREBP2 to reduce cholesterol synthesis and uptake (16, 17). In addition, the generation of oxysterols from intracellular cholesterol activates the LXR transcription factor which increased the expression of cholesterol efflux genes including *abca1* and *abcg1* (16, 23). In this study we observed decreased *ldlr* expression, and an increase in *abcg1* expression in ABCA1 deficient adipose tissue. We believe that the absence of ABCA1 induces cholesterol accumulation and influences various compensatory mechanisms to regulate cholesterol balance in adipocytes. Increased ABCG1 to enhance cholesterol efflux, and decreased LDLR to reduce cholesterol uptake suggest compensatory mechanisms are conserved in the adipocyte to regulate cholesterol homeostasis.

It has been suggested that intracellular cholesterol influences TG stores in adipose tissue (3, 17). This hypothesis is also supported by our data, as we observe that ABCA1 deficient adipose tissue accumulates TG and cholesterol in response to a HFHC diet. It has been shown *in vitro* that increased ABCA1-mediated cholesterol efflux from adipocytes occurs following the stimulation of TG lipolysis (7, 8). This may indicate a possible link between ABCA1 and TG lipolysis in adipocytes. We demonstrate that TG lipolysis is reduced ex vivo in adipose tissue from ABCA1$^{-/}$ad mice. This suggests that ABCA1 may directly influence TG levels and lipolysis. Reduced TG lipolysis may contribute to the TG accumulation we observe in adipose tissue from ABCA1$^{-/}$ad mice on a HFHC diet. We ruled out feeding behaviour causing weight gain as we did not observe a difference in food intake between ABCA1$^{-/}$ad mice and control littermates (Suppl. Fig 2C).

ABCA1$^{-/}$ad mice demonstrated increased body weight, an impairment in glucose tolerance and increased insulin resistance on a HFHC diet. This suggests that adipocyte ABCA1 is crucial for proper adipose tissue function in response to dietary fat and cholesterol. Our observations also indicate that loss of adipocyte ABCA1 and subsequent increase in intracellular cholesterol levels are sufficient to influence whole body glucose tolerance.
Increased body weight and adipocyte TG accumulation are associated with adipocyte dysfunction which may lead to a number of metabolic disturbances including glucose intolerance, insulin resistance and hepatosteatosis (18, 19, 21, 32).

Metabolic disturbances are affected by adipose tissue through the release of NEFA and adipokines in plasma (1, 2, 19, 20). Increased NEFA flux from adipose tissue to liver, muscle and pancreas has been shown to reduce insulin sensitivity and secretion (19, 21). However, we did not observe significantly altered NEFA levels in the plasma of our ABCA1<sup>-ad/-ad</sup> mice. Expression and release of adiponectin shows an inverse correlation with adipose mass (2, 19, 21). Decreased levels of adiponectin reduce insulin sensitivity and stimulate hepatic lipid accumulation (2, 19, 21). In our ABCA1<sup>-ad/-ad</sup> model, we observe reduced adiponectin, gene expression as well as a reduction in visfatin and glut-4 gene expression along with increased leptin expression. In plasma we observed a decrease in high molecular weight adiponectin which is the metabolically most active form of adiponectin. This decrease in plasma high molecular weight adiponectin may therefore contribute to the insulin resistance and glucose intolerance as well as the hepatic lipid accumulation we observe in our mouse model. GLUT-4 deficiency in adipose tissue has been shown to impair whole body glucose tolerance and muscle insulin resistance, but this effect is independent of circulating NEFA, TG or leptin (29). This suggests that other, unknown mechanisms associated with GLUT-4 may play a role in modulating insulin resistance.

In an effort to identify other mechanisms by which adipocyte ABCA1 deficiency affects whole body glucose homoeostasis, we investigated the expression of genes and proteins involved in glucose metabolism in the liver. We did not observe altered levels of pAKT in the liver. Expression of the gluconeogenesis genes phosphoenolpyruvate carboxykinase and glucose 6-phosphatase in the liver were also unaltered (data not shown). We cannot exclude
however that the hepatosteatosis we observe in ABCA1<sup>−ad</sup>-<sup>ad</sup> mice could contribute to glucose intolerance by altering hepatic glucose output or uptake (21).

When blood glucose levels rise due to insulin resistance, the pancreas attempts to compensate by increasing beta cell insulin secretion. However elevated insulin secretion may eventually result in beta cell dysfunction and failure (31, 33, 34). We observed that adipocyte specific ABCA1 knockout mice have increased fasting insulin levels while insulin secretion from beta cells in response to glucose was reduced. We conclude that changes in adipose tissue indirectly lead to beta cell dysfunction as a result of insulin resistance in the muscle of ABCA1<sup>−ad</sup>-<sup>ad</sup> mice.

The generation of mice specifically lacking ABCA1 in adipocytes has given us a unique opportunity to directly assess the role of adipocyte ABCA1 in glucose and lipid metabolism in vivo. Our data suggest a critical role for adipocyte intracellular cholesterol maintained by ABCA1 in the adipocyte in whole body glucose homeostasis. Our findings indicate that adipocyte ABCA1 regulates adipocyte cholesterol and TG stores and thereby influences muscle insulin sensitivity and glucose tolerance. We conclude that ABCA1 in the adipocyte is an important regulator of intracellular lipid stores and has significant effects on glucose metabolism.
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REFERENCE LIST


LEGENDS TO FIGURES

Figure 1. Adipocyte ABCA1 deficiency increases adipose tissue cholesterol content

GAT was isolated form ABCA1+/+ and ABCA1⁻⁰⁻⁻ mice and ABCA1 levels were measured by western blotting (A). Adipose tissue depots were isolated from 10 weeks old ABCA1+/+ mice and ABCA1⁻⁰⁻⁻ mice fed a chow diet and were assessed for cholesterol content (B). ABCA1+/+ mice and ABCA1⁻⁰⁻⁻ mice were fed a HFHC diet from 10 weeks of age until 18 weeks of age and adipose tissue was extracted for quantification of cholesterol content (C), mRNA expression of genes in cholesterol homeostasis were measured by rtPCR (D) and protein levels of the LDLR were assessed by western blotting (E). Values are means +/− SEM; N=4 (A) N=5-6 (B, E) N=6-10 (D) N=6-7 (C). * P<0.05, ** P<0.01; GAT gonadal adipose tissue, SAT subcutaneous adipose tissue, MAT mesenteric adipose tissues, BAT brown adipose tissue. Abcg1: ATP Binding Cassette transporter G1; Hmg-co red: 3-Hydroxy-3-Methyl-Glutaryl-CoA Reductase; Ldlr Lipoprotein Receptor; Sr-b1 Scavenger Receptor B1; Srebp: Sterol Regulatory Element-Binding Protein.

Figure 2. Adipocyte ABCA1 deficiency increases fat pad weight and adipose TG content on a HFHC diet

Adipose tissue depots were isolated from 10 weeks old ABCA1+/+ and ABCA1⁻⁰⁻⁻ mice on chow diet, weighted (A) and TG content was measured (B). ABCA1+/+ mice and ABCA1⁻⁰⁻⁻ mice were fed a HFHC diet starting at 10 weeks of age and were weighed biweekly to assess weight gain (C,D). After 8 weeks of diet, adipose depots were isolated, weighed (E) and TG content was quantified (F). Values are means +/− SEM; N=5-6 (A,B) N=15 (C,D) N=6-7 (E-F) * P<0.05, ** P<0.01. GAT gonadal adipose tissue, SAT subcutaneous adipose tissue, MAT mesenteric adipose tissues, BAT brown adipose tissue.
Figure 3. Adipocyte ABCA1 deficiency reduces lipolysis

GAT was isolated from ABCA1^{+/+} and ABCA1^{ad/ad} mice, and isoproterenol stimulated lipolysis was assessed ex vivo (A). In addition, mRNA expression of genes involved in TG homeostasis were measured in GAT by rtPCR (B) and DGAT2 protein levels were measured by western blotting (C). Values are means +/− SEM; * P<0.05. N=4-6 (A) N=10 (B) N=5-6 (C) Atgl: Adipose Triglyceride Lipase; Dgat: Diglyceride Acyltransferase; Fas: Fatty Acid Synthase; Gpat: Glycerol 3-Phosphate Acyltransferase; Hsl: Hormone Sensitive Lipase; Lpl: Lipoprotein Lipase; Mgl: Monoglyceride Lipase; Srebp: Sterol Regulatory Element-Binding Protein.

Figure 4. Adipocyte ABCA1 deficiency influences expression of genes in glucose metabolism

Levels of mRNA expression of genes involved in glucose homeostasis were assessed in GAT from ABCA1^{+/+} mice and ABCA1^{ad/ad} mice fed a HFHC for 8 weeks by rtPCR (A). GLUT-4 levels were measured using western blotting (B) and plasma adiponectin levels were measured using ELISA (C). Values are means +/− SEM; N=6-7 (A) N=9-10 (B) N=14-15 (C) * P<0.05; ** P<0.01. HMW: High Molecular Weight.

Figure 5. Adipocyte ABCA1 deficiency impairs glucose tolerance

ABCA1^{+/+} mice and ABCA1^{ad/ad} mice fed a HFHC diet received an i.p. injection of 1g/kg glucose in PBS, blood samples were drawn at the indicated time points and glucose was measured to assess glucose tolerance (A,B). Insulin sensitivity was assessed by injecting mice i.p. with 1U/Kg insulin in PBS, and glucose was measured at the indicated time points (C,D). To assess tissue specific insulin sensitivity, mice were injected with 10U/KG insulin and tissues were isolated and phosphorylated AKT and total AKT levels were measured by western blotting (E,F).
Pancreatic islets were isolated from ABCA1<sup>+/+</sup> mice and ABCA1<sup>ad/ad</sup> mice fed a HFHC diet, incubated in low (1.67 mM) and high glucose (16.7 mM) medium and insulin secretion was measured (G). Values are means +/- SEM; N=6-7 (A-D) ; N=3-4 (E,F) N=10-13 (G) * P<0.05, ** P<0.01.
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</tr>
<tr>
<td>TG</td>
<td>1.06/+/-0.06</td>
<td>1.22/+/-0.04</td>
<td>0.030</td>
</tr>
<tr>
<td>NEFA</td>
<td>0.31/+/-0.017</td>
<td>0.31/+/-0.014</td>
<td>0.780</td>
</tr>
<tr>
<td>Glucose</td>
<td>9.01/+/-0.28</td>
<td>9.91/+/-0.22</td>
<td>0.017</td>
</tr>
<tr>
<td>Insulin</td>
<td>0.84/+/-0.09</td>
<td>0.96/+/-1.00</td>
<td>0.410</td>
</tr>
<tr>
<td>HFHC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cholesterol</td>
<td>3.94/+/-0.22</td>
<td>3.59/+/-0.10</td>
<td>0.260</td>
</tr>
<tr>
<td>HDL</td>
<td>3.25/+/-0.23</td>
<td>3.07/+/-0.31</td>
<td>0.643</td>
</tr>
<tr>
<td>TG</td>
<td>0.71/+/-0.01</td>
<td>0.79/+/-0.08</td>
<td>0.047</td>
</tr>
<tr>
<td>NEFA</td>
<td>0.36/+/-0.043</td>
<td>0.43/+/-0.041</td>
<td>0.340</td>
</tr>
<tr>
<td>Glucose</td>
<td>8.65/+/-0.49</td>
<td>9.45/+/-0.21</td>
<td>0.240</td>
</tr>
<tr>
<td>Insulin</td>
<td>1.11/+/-0.09</td>
<td>1.92/+/-0.32</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Table 1. Plasma parameters in adipose ABCA1 knockout mice. Blood was drawn from the saphenous vein after 4 hours fasting and assessed for the parameters above. Values are means +/-SEM, chow n=15 (Chol, TG, glucose, HDL) n=6/7 n=5-10 (insulin, NEFA); HFHC n=8-6.
Figure 1. Adipocyte ABCA1 deficiency increases adipose tissue cholesterol content
Figure 2. Adipocyte ABCA1 deficiency increases fat pad weight and adipose TG content on a HFHC diet.
Figure 3. Adipocyte ABCA1 deficiency reduces lipolysis.
Figure 4. Adipocyte ABCA1 deficiency influences expression of genes in glucose metabolism.
A

Plasma glucose (mM)

Time after glucose injection (min)

ANOVA P<0.01

B

Glucose tolerance (AUC)

C

Plasma glucose (mM)

Time after insulin injection (min)

ANOVA P<0.05

D

Insulin sensitivity (AUC)
Figure 5. Adipocyte ABCA1 deficiency impairs glucose tolerance