STAT4 contributes to adipose tissue inflammation and atherosclerosis

A D Dobrian1, M A Hatcher1, J J Brotman1, E V Galkina2, P Taghavie-Moghadam2, H Pei4, B A Haynes1 and J L Nadler3

Departments of 1Physiological Sciences, 2Microbiology and Molecular Cell Biology, and 3Internal Medicine, Eastern Virginia Medical School, 700W Olney Road, Norfolk, Virginia 23505, USA
4Division of Inflammation Biology, La Jolla Institute for Allergy and Immunology, San Diego, La Jolla, California, USA

Correspondence should be addressed to A D Dobrian
Email dobriaad@evms.edu

Abstract

Adipose tissue (AT) inflammation is an emerging factor contributing to cardiovascular disease. STAT4 is a transcription factor expressed in adipocytes and in immune cells and contributes to AT inflammation and insulin resistance in obesity. The objective of this study was to determine the effect of STAT4 deficiency on visceral and peri-aortic AT inflammation in a model of atherosclerosis without obesity. Stat4−/− Apoe−/− mice and Apoe−/− controls were kept either on chow or Western diet for 12 weeks. Visceral and peri-aortic AT were collected and analyzed for immune composition by flow cytometry and for cytokine/chemokine expression by real-time PCR. Stat4−/− Apoe−/− and Apoe−/− mice had similar body weight, plasma glucose, and lipids. Western diet significantly increased macrophage, CD4+, CD8+, and NK cells in peri-aortic and visceral fat in Apoe−/− mice. In contrast, in Stat4−/− Apoe−/− mice, a Western diet failed to increase the percentage of immune cells infiltrating the AT. Also, IL12p40, TNFa, CCL5, CXCL10, and CX3CL1 were significantly reduced in the peri-aortic fat in Stat4−/− mice. Importantly, Stat4−/− Apoe−/− mice on a Western diet had significantly reduced plaque burden vs Apoe−/− controls. In conclusion, STAT4 deletion reduces inflammation in peri-vascular and visceral AT and this may contribute via direct or indirect effects to reduced atheroma formation.

Key Words
► peri-aortic fat
► T lymphocytes
► chemokines
► macrophages

Introduction

Excessive accumulation of visceral adipose tissue (AT) is independently associated with cardiovascular disease (See et al. 2007). In addition, the fat around the conduit vessels such as the aorta as well as the pericardial fat were shown to play a role in the progression of atherosclerosis (Ohman et al. 2011) and were associated with coronary atherosclerotic plaque formation in humans (Konishi et al. 2010a,b). Therefore, both visceral and perivascular AT accumulation and inflammation emerge as key contributors to atherosclerosis. The Apoe−/− mouse model of atherosclerosis displays accelerated plaque formation on high cholesterol diet. However, this mouse model neither gains weight nor develops insulin resistance as a result of high fat diet feeding (Gao et al. 2007, Kawashima et al. 2009). This phenotype was attributed, at least in part, to the inability of visceral AT to accumulate excess lipids resulting in a more sensitive adipocyte phenotype and reduced inflammation (Huang et al. 2006, 2013, Hofmann et al. 2008). This raises the question whether various AT depots may contribute to the development of
atherosclerosis in this model. While the contribution of visceral fat in atherosclerosis development in this model was not reported, the peri-vascular fat was proven causal for the development of atherosclerosis in Apoe\(^{-/-}\) mice fed a Western diet (Ohman et al. 2011).

The mechanisms contributing to atherosclerosis by visceral and perivascular fat are incompletely understood. In atherosclerotic Apoe\(^{-/-}\) mice, peri-adventitial AT produces elevated levels of interleukin 6 (IL6), IL1A, and MIP1A (Lohmann et al. 2009) and in a model of obesity with angiotensin II infusion peri-aortic AT induces inflammation and enhances aneurism formation (Police et al. 2009). The TLR/JAK–STAT pathway is activated in human peri-vascular adipocytes from patients with atherosclerosis (Police et al. 2009). STAT4 is downstream of the Jak/Tyk kinases and, upon phosphorylation in response to IL12 or other cytokines, induces expression of genes involved in the proliferation and differentiation of various hematopoietic and non-hematopoietic cells (Darnell 1997, Horvath & Darnell 1997, Imada & Leonard 2000, Leonard & Lin 2000). STAT4 is expressed in T and NK cells and has a prominent role for IL12-induced Th1 cell differentiation and for NK cell activation (Watford et al. 2004, Kaplan 2005, Good et al. 2009). IL12 is also highly expressed in rodent and human atherosclerotic lesions and several studies have shown that approaches to reduce IL12 levels prevent atherosclerosis (Zhao et al. 2002, Davenport & Tipping 2003, Hauer et al. 2005, Zhang et al. 2006, Eid et al. 2009). Importantly, recent findings indicate that STAT4 has a determinant role for optimal human Th1 lineage development (Chang et al. 2009). Our group showed that STAT4 is markedly activated in the balloon injured carotid artery of the obese Zucker rat, and that an IL12-signaling inhibitor can reduce STAT4 activation and vascular injury responses (Pei et al. 2006). In addition, STAT4-deficient mice are protected from developing insulin resistance on a high fat diet, in part due to reduced immune cell trafficking in visceral AT and reduced pro-inflammatory cytokine production by adipocytes (Dobrian et al. 2013). Collectively, these results suggest that activation of STAT4 may participate in vascular inflammatory responses in part via modulation of AT inflammation. To directly address this hypothesis we examined the effect of STAT4 deficiency on visceral and peri-aortic AT inflammation in Stat4\(^{-/-}\) Apoe\(^{-/-}\) mice, a model of atherosclerosis lacking the confounding effects of insulin resistance and obesity. A key finding is the significant effect of STAT4 deficiency on immune composition as well as pro-inflammatory cytokine and chemokine production mainly in the peri-aortic fat. The anti-inflammatory effect of STAT4 deficiency was significant in the mice fed a high cholesterol diet and was associated with the reduced atherosclerotic plaque burden, suggesting that the activation of this pathway in AT may be a contributor to accelerated diet-related atherosclerosis.

**Materials and methods**

**Animals and diets**

All procedures involving animals were approved by the IACUC of Eastern Virginia Medical School and University of Virginia at Charlottesville. Female Stat4\(^{-/-}\) Apoe\(^{-/-}\) or Apoe\(^{-/-}\) mice were bred in our colonies and at 8–10 weeks of age were either fed a Western diet (0.15% cholesterol, Harlan, Madison, WI, USA) or were maintained on regular rodent chow for 12 weeks (n = 6–10 mice/group). All of the mice were between 20 and 22 weeks of age at euthanasia. Mice were housed in a pathogen-free facility, and food and water were provided a regular supply of food and allowed to feed ad libitum throughout the experiment. Body weights were measured weekly.

**Lipids, glucose, and insulin**

Lipids, glucose, and insulin were measured in all of the groups in non-fasted terminal plasma. Triglycerides, total cholesterol, LDL, and HDL cholesterol were measured using a colorimetric kit from Wako (Richmond, VA, USA). Plasma glucose was measured according to manufacturer’s instructions using a colorimetric method (BioVision, Inc., Milpitas, CA, USA). Insulin was measured by ELISA using a commercially available kit (Mercodia, Winston Salem, NC, USA).

**Stromal vascular fraction preparation**

Samples of peri-gonadal (visceral) and peri-aortic AT (0.1–0.3 g) were digested with collagenase as described before with minor modifications (Weisberg et al. 2003, Cole et al. 2010). The floating adipocytes were collected and washed and the infranatant was removed and centrifuged at 500 g for 5 min to pellet the stromal vascular fraction (SVF). SVF was used for flow cytometry to determine immune cell content.

**Flow cytometry**

Counted SVF cells were incubated for 30 min, at room temperature with one of the following combinations of fluorophore-conjugated primary antibodies: Cocktail1 (for macrophage phenotyping): CD11b-Pacific Blue,
CD45-PerCP, Cd11c-PE, F4/80-Alexa 647, and CD206-FITC; Cocktail2 (for T cell phenotyping): CD3-Pacific Orange; CD4-APC; CD8-FITC; CD45-PerCP, NK40.6-Pacific Blue. All of the antibodies were from BD Pharmingen (San Jose, CA, USA) or from BioLegend (San Diego, CA, USA). Cells were analyzed on a BD upgraded FACS Caliber Flow Cytometer (eight-colors) using FlowJo Software (Tree Star, Inc., Ashland, OR, USA).

**Immunohistochemistry**

ATs were fixed in 10% buffered formalin overnight then embedded in paraffin and following antigen retrieval were incubated overnight with polyclonal rabbit anti-mouse antibody for CD45 (Abcam, Cambridge, MA, USA; 1:100 dilution) or rat anti-mouse F4/80 antibody (Abcam; 1:100 dilution). Secondary antibody staining was performed using the Vectastain ABC Kit (Vector Laboratories, Burlingame, CA, USA) and detected with 3,3′-diaminobenzidine. Slides were counterstained using Mayer’s hematoxylin. Sections incubated with non-immune IgG (Pierce, Rockford, IL, USA) instead of the primary antibody were used as method controls. All pictures were captured with an Olympus microscope using 200× magnification. Quantification of the immunohistochemical data was done using a MetaMorph Software ver6.3 (Molecular Devices, Downingtown, PA, USA) with an established arbitrary threshold. Data was normalized to section area and expressed as arbitrary units.

**Macrophage polarization**

Peritoneal macrophages were isolated by lavage with sterile PBS and cultured in RPMI-1640 media supplemented with 10% FBS, 1% penicillin/streptomycin, 1% glutamax, 1% HEPES, 0.5% non-essential amino acids (NEAA), 0.5% sodium pyruvate, and 50 μM beta-mercaptoethanol (BME). After 24 h, the adherent cells were treated with either a combination of IFNγ (150 U/ml) and LPS (100 ng/ml) or with IL4 (20 U/ml) and IL13 (15 U/ml) for additional 24 h to induce polarization towards ‘classically’ (M1) or ‘alternatively’ (M2) activated macrophage phenotypes respectively. Bone-marrow-derived macrophages (BMDM) were isolated from the femoral and tibial bones and were differentiated in culture for 7 days using RPMI-1640 media supplemented with 10% FBS, 1% penicillin/streptomycin, 1% glutamax, and 10 ng/ml M-CSF. Subsequently, cells were treated for 24 h to induce ‘classical’ M1 activation (as described above) or ‘metabolic’ activation (MMe) using a combination of glucose (30 mM), insulin (10 nM), and palmitate (0.4 mM), as described by Kratz et al. (2014).

**Real-time PCR**

RNA from total AT was extracted and reverse transcribed as previously described (Dobrian et al. 2010). Real-time PCR was performed using TaqMan probes from Applied Biosystems. β-actin was used to normalize the data. Results were expressed as fold change by the 2−ΔΔCt method using Apoe−/− mice as a control group.

**En face staining**

The aortic trees of mice were collected, fixed in situ by perfusion with PBS containing 4% paraformaldehyde, then additionally fixed for 24 h and stained with Sudan IV (Tangirala et al. 1995). En face stained aortic tissues were analyzed for the percent surface areas occupied by lesions using Photoshop Software.

**In vitro chemokine production by aortic cells in response to STAT4-dependent AT secretome**

Visceral AT from Stat4−/−Apoe−/− and Apoe−/− mice was excised and minced into ~1 mm3 pieces and incubated for 24 h in DMEM supplemented with 1% penicillin/streptomycin. The following day, aortic suspensions were generated by collagenase digestion from Apoe−/− mice. The aortic cells were incubated with the AT conditioned media (CM) at ~106 cells/well for 24 h and then cells were washed, collected by centrifugation and processed for RNA extraction and gene expression analysis by real-time PCR.

**Statistical analysis**

Statistical analysis was performed using GraphPad Prism Software (GraphPad Software, Inc., La Jolla, CA, USA). Student’s t-test unpaired analysis was used for all data comparisons between the Stat4−/−Apoe−/− and Apoe−/− controls. For comparisons of more than two groups, one-way ANOVA was used for data analysis. For experiments including two independent variables (diet and genotype), data was analyzed using two-way ANOVA. Data were expressed as mean ± S.E.M. and the null hypothesis was rejected for a P value <0.05.

**Results**

**STAT4 deficiency does not change body weight, systemic lipids, glucose, nor insulin**

Stat4−/−Apoe−/− or Apoe−/− control mice were kept on either a chow or a Western diet for 12 weeks. Mice on both
chow (not shown) and Western diets (Table 1) had similar body weights. Also, randomly fed plasma glucose, insulin, triglycerides, total, HDL, and LDL cholesterol were similar between the two groups for both the chow-fed and Western-diet-fed mice. The lipid profile in the Western-diet-fed mice were in the expected range with significantly elevated triglycerides and LDL + VLDL plasma cholesterol levels (Table 1).

**Effect of STAT4 deficiency on lymphocyte population in visceral and peri-aortic ATs**

STAT4 is abundantly expressed in the T and NK cells of mice and humans, where it plays an important role in Th1 polarization and in the cytotoxic response of NK cells following cytokine challenge. Therefore, we compared the lymphocyte composition in the STAT4-deficient and -sufficient Apoε−/− mice. Flow cytometry analysis of perivascular and visceral ATs of Stat4−/− and Apoε−/− mice on a Western diet showed significantly increased numbers of CD45+ cells in the peri-aortic AT of both groups of mice (Fig. 1A). While CD45+ cellularity was similar in the visceral fat of Stat4−/− and Apoε−/− mice, the numbers of CD45+ cells was significantly reduced in the peri-aortic fat of Stat4−/− compared to Apoε−/− controls (Fig. 1A). Similar results were obtained by AT immunohistochemistry using a CD45 antibody (Fig. 1B). To further determine the composition of the CD45+ lymphocytes, we next analyzed the CD3+ T and NK cell populations in the visceral and peri-aortic ATs of mice on chow or Western diets. In the Stat4−/− and Apoε−/− chow-fed mice, the relative percentages of CD3+, CD3+CD4+, CD3+CD8+, and NK cells were similar for both fat depots (not shown). In the Western-diet-fed mice, the relative percentages of CD3+ cells in the CD45+ gate were also similar for both groups in both AT depots (Fig. 1C and D). However, significant differences of the relative percentages of CD4+, CD8+, and NK+ cells were found between the Stat4−/− and Apoε−/− mice in both the visceral and peri-aortic depots. In visceral and peri-aortic fat of Stat4−/− and Apoε−/− mice, we found a predominant population of CD3+CD4+ (≈20%) compared to the low relative percentages of CD3+CD8+ cells (8.2 and 2.1% in peri-aortic and visceral fat respectively) (Fig. 1C and D). Collectively, this data indicates that in response to Western diet feeding, in Stat4−/− mice, the increase in the CD3+ cells in AT is biased towards a CD4+ vs a CD8+ population in a depot-independent fashion, while in the Apoε−/− mice there is a predominant CD8+ population in both depots. Also, the relative percentage of visceral and peri-aortic AT NK40.6+ cells is dramatically reduced in Stat4−/− compared to Apoε−/− mice on a Western diet.

**Effect of STAT4 deficiency on antigen-presenting cells and macrophage polarization in visceral and peri-aortic AT**

The antigen-presenting cells are important contributors to AT inflammation. STAT4 is expressed in activated blood monocytes and dendritic cells, and therefore STAT4 deficiency may impact numbers and phenotype of resident AT APC directly or via indirect changes in adaptive immunity and inflammation. In contrast to C57Bl6 mice on a high fat diet (Lumeng et al. 2007a,b), visceral AT of Western-diet-fed Apoε−/− mice has lower percentages of CD11b+F4/80+ cells (33.5%) in the CD45+ gate (Fig. 2B). Virtually all of these cells were CD11c+F4/80+ canonical macrophages, characterized by a pro-inflammatory phenotype, while only ~2.5% were CD206+F4/80+ alternatively activated (M2) macrophages. In peri-aortic fat of the same mice, the percentage of CD11b+F4/80+ cells in the CD45+ gate was ~1.86%. Most of the cells had an ‘alternatively’ activated M2
macrophage phenotype, while only ~0.6% of the cells were CD11c+F4/80+ canonical macrophages (Fig. 2A and B). Compared to Apoe−/− mice on the Western diet, the Stat4−/−Apoe−/− mice had ~1/3 of the percentage of CD11b+F4/80+ cells and three- to 3.5-fold higher percentage of CD206+F4/80+ M2 macrophages in both the visceral and peri-aortic depots (Fig. 2B). Also, the relative abundance of the F4/80+ macrophages was 2.5-fold higher in visceral fat of Apoe−/− mice compared to Stat4−/−Apoe−/− mice, as determined by immunohistochemistry (Fig. 2C). Also, Stat4−/−Apoe−/− mice had virtually no CD11c+F4/80+ canonical macrophages in either of the depots (Fig. 2A and B). Interestingly, Apoe−/− mice on a high fat diet showed a significant increase (~6.5-fold) in the percentage of CD11c+F4/80− cells (dendritic cells) compared to Stat4−/−Apoe−/− mice in the peri-aortic but not visceral fat. Also, Apoe−/− and Stat4−/−Apoe−/− mice on a chow diet have very low percentages of CD11b+F4/80+ macrophages (~3.5%) and of CD11c+F4/80− (dendritic cells) (<1%) of the total CD45+ cells in visceral fat and even lower numbers in the peri-aortic fat and no significant differences were found between the groups (not shown). Collectively, this data show that in face of dietary challenge, STAT4 deficiency leads to reduced proportion of pro-inflammatory ‘canonical’ macrophages and increased percentage of ‘alternatively activated’ macrophages in AT depots. These changes may result in reduced overall cytokine production and inflammation in Stat4−/−Apoe−/− mice compared to Apoe−/− controls.

To determine if the differences found in the phenotype of AT macrophages upon STAT4 deficiency are due to intrinsic differences in response to cytokines or metabolic cues, we isolated peritoneal and BMDM and induced in vitro polarization with various combinations of cytokines or metabolic activators. Peritoneal macrophages isolated from Apoe−/− and Stat4−/−Apoe−/− mice were treated in vitro with either LPS+IFNC or with IL4+IL13 to

Figure 1
Effect of STAT4 deficiency on lymphocyte numbers and relative composition in visceral and peri-aortic adipose tissue (AT) (A) CD45+ cells in peri-aortic and visceral ATs were determined by flow cytometry and normalized to tissue weight; * significant compared to visceral AT for the same mice group. Also shown is a representative gating strategy for the forward scattered and CD45+ gates in Apoe−/− mice. (B) Immunohistochemistry for CD45 in the peri-aortic and visceral fat of Stat4−/−Apoe−/− and Apoe−/− mice. Relative percentages of CD3+, CD3+CD4+, CD3+CD8+, and NK40.6+ were determined in the CD45+ gate in peri-aortic (C) and visceral (D) ATs of mice on a Western diet. Representative FACS plots in visceral fat are also shown. Data is from n = 5 to 7 mice/group. #, significant compared to visceral AT. A full colour version of this figure is available at http://dx.doi.org/10.1530/JOE-15-0098.
Figure 2
Effect of STAT4 deficiency on macrophage abundance, polarization, and inflammatory profile. Relative composition of macrophages in peri-aortic fat (A) and visceral fat (B) of mice on a Western diet (n = 5–7); representative FACS plots for CD11c+ F4/80+ are also shown. (C) Representative micrographs and quantitation of F4/80 staining in visceral adipose tissue of Stat4+/–, Apoe−/−, and Apoe+/– mice on a Western diet (n = 4/group); AU, arbitrary units. (D) M1 and M2 macrophage markers upon respective stimulations (Fig. 2D). Inter- estingly, CD206 expression was significantly increased in M1 and M2 markers upon respective stimulations (Fig. 2D). Interestingly, CD206 expression was significantly increased (∼1.8-fold) in macrophages of Stat4+/–/Apoe−/– mice compared to Apoe−/– controls following in vitro treatments (Fig. 2D) paralleling the phenotype of resident AT macrophages found in vivo. BMDM from both mice groups were also generated by in vitro culture of bone marrow cells in presence of M-CSF. Recent evidence showed that in vitro metabolic challenge induces a distinct macrophage phenotype that resembles the M1 classically activated macrophages but also expresses anti-inflammatory markers such as PPARC. Similar to peritoneal macrophages, unstimulated BMDM from both mice groups had similar expression of all of the tested genes (not shown). Also, BMDM from both mice groups showed robust activation via free access.
of several M1 markers such as iNOS and arginase along with pro-inflammatory cytokines such as TNFα and IL1β (Fig. 2E). In addition, M1 macrophages from Stat4−/−/Apoe−/− mice showed decreased iNOS and IL1β expression compared to Apoe−/−/mice (Fig. 2E). Interestingly, expression of Abca1 gene was also significantly increased in M1 macrophages from Stat4−/−/Apoe−/− mice compared to controls, suggesting a potential ability of these macrophages to limit lipid loading by upregulating cellular cholesterol efflux (Fig. 2E). BMDM were also treated with a combination of insulin/glucose/palmitic acid to achieve ‘metabolic activation’ (MMe; Kratz et al. 2014). MMes from Stat4−/−/Apoe−/− mice showed reduced activation of the pro-inflammatory markers iNOS and TNFα, expression of IL12p40 was twofold compared to controls, suggesting a potential ability of these macrophages to limit lipid loading by upregulating cellular cholesterol efflux (Fig. 2E). BMDM were also treated with a combination of insulin/glucose/palmitic acid to achieve ‘metabolic activation’ (MMe; Kratz et al. 2014). MMes from Stat4−/−/Apoe−/− mice showed reduced activation of the pro-inflammatory markers iNOS and TNFα, arginase, and Plin2 (Fig. 2E). These findings indicate that macrophages from Apoe−/−/mice assume a lower pro-inflammatory phenotype compared to controls. Briefly, we excised and incubated AT from Stat4−/−/Apoe−/− and Apoe−/− mice in DMEM, and collected the 24-h CM. The CM was further incubated for 24 h with fresh preparations of aortic cell suspensions from Apoe−/−/mice (Fig. 4A). Following incubation, aortic cells were washed and collected by centrifugation and gene expression of various macrophage and T cell chemokines and activation markers were performed by real-time PCR (Fig. 4B). Gene expression for CX3CL1, CCLS, TNFα, and IL12p40 was not detectable in Apoe−/−/aortic cells incubated with either of the CM. However, in cells incubated with Apoe−/−/CM, mRNA expression of CCL2 was significantly higher compared to cells incubated with Stat4−/−/Apoe−/− CM (Fig. 4B). This result shows that visceral fat secretome may induce chemokine expression in aortic cells, at least in part, via a STAT4-dependent mechanism. Interestingly, we found no significant difference in the expression of the macrophage activation marker I-A^k (MHC-II) between aortic cells incubated with AT CM from Stat4−/−/Apoe−/− or Apoe−/− mice (Fig. 4B). This result suggests that visceral AT secretome can directly induce increased expression of some of the pro-inflammatory genes in cells of the aortic wall and that STAT4 deficiency may limit inflammation.

![Image of aorta with inflammation](https://example.com/aorta_inflammation.png)

**Figure 3**
Expression of pro-inflammatory cytokines and chemokines in Stat4−/−/Apoe−/− and Apoe−/− mice on a Western diet. Cytokine gene expression was measured in visceral (A) and peri-aortic (B) adipose tissue (AT) using real-time PCR; results are expressed as fold change in gene expression in Apoe−/−/mice compared to Stat4−/−/Apoe−/− group and represent mean ± S.E.M. of n=8 mice/group; chemokine expression in peri-aortic AT (C) was also measured by real-time PCR in n=6 mice/group; *significantly different (P<0.05) compared to Stat4−/−/Apoe−/− group.

### Pro-inflammatory response of aortic cells to STAT4-deficient visceral AT secretome

To determine whether STAT4 may effect aortic wall pro-inflammatory gene expression via the STAT4 dependent AT secretome we examined *in vitro* the response of aortic cells from Apoe−/−/mice to CM generated from visceral AT of Stat4−/−/Apoe−/− or Apoe−/− controls. Briefly, we excised and incubated AT from Stat4−/−/Apoe−/− and Apoe−/− mice in DMEM, and collected the 24-h CM. The CM was further incubated for 24 h with fresh preparations of aortic cell suspensions from Apoe−/−/mice. Following incubation, aortic cells were washed and collected by centrifugation and gene expression of various macrophage and T cell chemokines and activation markers were performed by real-time PCR (Fig. 4B). Gene expression for CX3CL1, CCLS, TNFα, and IL12p40 was not detectable in Apoe−/−/aortic cells incubated with either of the CM. However, in cells incubated with Apoe−/−/CM, mRNA expression of CCL2 was significantly higher compared to cells incubated with Stat4−/−/Apoe−/− CM (Fig. 4B). This result shows that visceral fat secretome may induce chemokine expression in aortic cells, at least in part, via a STAT4-dependent mechanism. Interestingly, we found no significant difference in the expression of the macrophage activation marker I-A^k (MHC-II) between aortic cells incubated with AT CM from Stat4−/−/Apoe−/− or Apoe−/− mice (Fig. 4B). This result suggests that visceral AT secretome can directly induce increased expression of some of the pro-inflammatory genes in cells of the aortic wall and that STAT4 deficiency may limit inflammation.

### Role of STAT4 deficiency on AT cytokines and chemokines expression

We further investigated whether the reduced pro-inflammatory phenotype of macrophages from Stat4−/−/Apoe−/− mice found both *in vivo* and *in vitro* is mirrored by a reduction in pro-inflammatory cytokine and chemokine gene expression in ATs. We found that in Apoe−/−/mice on a Western diet, gene expression of IL12p40 was twofold increased in visceral fat and approximately sixfold increased in the peri-aortic fat compared to Stat4−/−/Apoe−/− mice (Fig. 3A and B). In the peri-aortic fat there was also approximately fourfold increased TNFα gene expression in Apoe−/−/mice compared to Stat4−/−/Apoe−/−/mice. Expression of PPARγ was reduced approximately twofold in Apoe−/−/mice in both fat depots compared to Stat4−/−/Apoe−/−/mice (Fig. 3A and B). In addition, expression of CCL5, CXCL10, and CX3CL1 were all significantly increased in the peri-aortic fat of the Apoe−/−/mice compared to Stat4−/−/Apoe−/−/mice while expression of CCL2 and CXCL16 was similar between groups (Fig. 3C).
STAT4 deficiency reduces aortic plaque burden in mice on a Western diet

In this study we analyzed a small sample of mice (n=4 on chow and n=8 on a Western diet) to confirm previous data showing reduced atherosclerosis in Stat4−/−Apoe−/− mice compared to Apoe−/− controls (manuscript under revision). Our data shows that compared to Apoe−/− controls, the Stat4−/−Apoe−/− mice on a Western diet have a prominent and significant ~41% reduction in aortic plaque area by en face staining (Fig. 5). In age-matched Stat4−/−Apoe−/− mice on chow diet, the plaque burden is also slightly but not significantly reduced (Fig. 5). There is significant interaction between the diet and the genotype (P<0.05), indicating that STAT4 deficiency is particularly protective in the context of high dietary cholesterol challenge.

Discussion

The contribution of AT to systemic inflammation and cardiovascular disease is well documented. In this study we report for the first time the effect of STAT4 deficiency on peri-vascular and visceral AT inflammation in atherosclerotic Apoe−/− mice. STAT4 deficiency also reduces the development of atherosclerosis, suggesting that reduction of peri-vascular and visceral inflammation may have a contributing athero-protective role. We show that STAT4 deficiency reduces pro-inflammatory cytokines and chemokines as well as lymphocyte number and composition and macrophage polarization in peri-vascular fat of mice on a Western diet. In Apoe−/− mice, the increased atherosclerotic burden on a Western diet compared to chow is largely due to a dramatic increase in circulating VLDL+LDL cholesterol (Plump et al. 1992). We show that protection by STAT4 deficiency is independent of circulating lipids as the STAT4-deficient mice have similarly increased levels of LDL+VLDL cholesterol to Apoe−/− controls (Table 1).

We previously showed that STAT4 deficiency improves glucose tolerance and increases insulin sensitivity in a mouse model of obesity and insulin resistance (Dobrian et al. 2013). This effect was accompanied by reduced AT inflammation due to more insulin-sensitive and less hypertrophic adipocytes and reduced lymphocyte infiltration in the visceral AT. However, Apoe−/− mice are lean and insulin sensitive even when fed a Western diet (Gao et al. 2007, Kawashima et al. 2009). Therefore, the anti-inflammatory effects of STAT4 in this model cannot be attributed to an improved metabolic profile or to reduced visceral adiposity. Indeed, we did not find any differences in glucose, insulin or body weight between the Stat4−/−Apoe−/− mice and the Apoe−/− controls (Table 1).
In this study we focused our investigation on two of the more relevant fat depots, visceral and peri-aortic, known to exert vasocine effects in both mice and humans (Lakka et al. 2002, Berg & Scherer 2005, Yudkin et al. 2005, Lohmann et al. 2009, Ouwens et al. 2010). While visceral AT contributes to accelerated atherosclerosis in Apoe⁻/⁻ mice, the peri-vascular AT in particular plays a causative role in atherosclerotic plaque formation in this mouse model (Ohman et al. 2008, 2011). Our data shows significantly higher numbers of CD45⁺ lymphocytes in the peri-aortic but not in the visceral fat of Apoe⁻/⁻ compared to Stat4⁻/⁻/Apoe⁻/⁻ mice on a Western diet (Fig. 1). In particular, the number of CD3⁺CD8⁺ T lymphocytes was dramatically increased in the peri-aortic fat in Apoe⁻/⁻ mice on a Western diet compared to Stat4⁻/⁻/Apoe⁻/⁻ mice. Previous studies indicated that expansion of CD3⁺ subsets in response to IL12 stimulation is dependent on Stat4 (Yoo et al. 2002). We found that in visceral fat of Stat4⁻/⁻/Apoe⁻/⁻ mice expression of IL12p40 subunit is reduced compared to Apoe⁻/⁻ controls, suggesting lower levels of functional IL12. In this study we also found that expression of a number of potent chemokines for T lymphocytes or monocytes, such as CCL5, CXCL10, and CX3CL1, is reduced in the peri-aortic fat of Stat4⁻/⁻/Apoe⁻/⁻ mice compared to controls (Fig. 3). Stat4 is involved in the regulation of several chemokine receptors that are preferentially expressed in Th1 cells, such as CXCR3 and CCR5 (Kim et al. 2006). We have previously shown (Dobrian et al. 2013) that the expression of these and other chemokine receptors are selectively decreased in CD8⁺ but not CD4⁺ cells of Stat4-deficient mice, compared to WT controls. It is therefore possible that reduced chemokine/cytokine production in peri-aortic and visceral fat combined with reduced migratory capacity of CD8⁺ cells due to a reduction in the chemokine receptors results in a relative reduction of CD8⁺ cells recruited in the ATs of Stat4⁻/⁻/Apoe⁻/⁻ mice. Cytotoxic CD8⁺(+) T lymphocytes represent up to 50% of the total numbers of leukocytes found in advanced human atheromas and dominate early immune responses in mouse lesions (Gewaltig et al. 2008, Kolbus et al. 2010). A recent publication showed that depletion of this lymphocyte subset in Apoe⁻/⁻ mice fed a high fat diet ameliorates atherosclerosis (Kyaw et al. 2013). Therefore, peri-vascular and possibly visceral fat may constitute a reservoir of CD8⁺ cells for the aortic wall and reduction of this T cell subset may be part of the mechanism responsible for athero-protection reported in this paper and by our group in preliminary observations in Stat4⁻/⁻/Apoe⁻/⁻ mice (manuscript under revision). An in-depth analysis of the atherosclerotic phenotype and related vascular mechanisms in Stat4⁻/⁻/Apoe⁻/⁻ mice are under publication elsewhere.

There was also a prominent reduction in the number of NK40.6⁺ cells in Stat4⁻/⁻/Apoe⁻/⁻ mice on a Western diet compared to Apoe⁻/⁻ controls, in both peri-aortic and visceral fat. Like CD8⁺ cells, NK cells appear to play an important role in the development of atherosclerosis (Major et al. 2004, Kolbus et al. 2010). Stat4 is abundantly expressed in NK cells and is key for IFNγ production and increased cytotoxicity. Therefore, reduction in the relative composition of NK cells in visceral and peri-aortic fat may also contribute to reduced vascular wall inflammation in Stat4-deficient mice.

Macrophages represent a major component of visceral AT in rodents (Lumeng et al. 2007a,b) but are less abundant in the peri-vascular fat. In Apoe⁻/⁻ mice, the number of macrophages is reportedly very low in various AT depots. We also found that only a minor proportion of up to ~2.2% of the total CD45⁺ cells in peri-aortic fat of Apoe⁻/⁻ mice is represented by CD11b⁺F4/80⁺ macrophages and is similar for Stat4⁻/⁻/Apoe⁻/⁻ mice (Fig. 2). Even in visceral fat, the proportion of CD11b⁺F4/80⁺ cells is ~30% in Apoe⁻/⁻ mice and only ~10% in Stat4⁻/⁻/Apoe⁻/⁻ mice. Therefore, in these mice the tropism of macrophages may be more prominent for other tissues, including the aorta. Interestingly, we found that Stat4 deficiency induces a bias towards CD206⁺ macrophages in both depots in vivo and that peritoneal macrophages of Stat4⁻/⁻/Apoe⁻/⁻ mice have a more robust response to ‘alternative’ activation in vitro (Fig. 2). It is known that the CD206⁺ (alternatively activated) macrophages are a source of the anti-inflammatory IL10 and IL4 cytokines as opposed to the M1 macrophages that are an abundant source of IL12, IL6, IL1B, and other pro-inflammatory cytokines (Lee et al. 2012). We also found that in the peri-aortic fat, gene expression of IL12p40 and TNFA was decreased in Stat4⁻/⁻/Apoe⁻/⁻ mice. The data suggests that Stat4 deficiency drives M2 polarization of AT macrophages without affecting the number of resident cells. This conclusion is also supported by reduced in vitro propensity of the Stat4-deficient BMDM to differentiate into a M1 phenotype (Fig. 2) as well as increased PPARC expression in AT (Fig. 3) known to promote M2 polarization (Bouhlel et al. 2007, Odegaard et al. 2007). Also, virtually the entire population of F4/80⁺ macrophages was CD11c⁺ in both visceral and peri-aortic fat of Apoe⁻/⁻ mice, while in Stat4⁻/⁻/Apoe⁻/⁻ mice the CD11c⁺ macrophages were not detectable.Canonical CD11c⁺ macrophages are known to have a marked pro-inflammatory phenotype
in both mice and humans (Geissmann et al. 2010) and can therefore be a source of circulating cytokines and chemokines impacting on immune cell recruitment and inflammation in the vascular wall. Importantly, several recent studies have described a combined M1/M2 phenotype of macrophages in obesity in mice and humans, suggesting they can adapt a more complex phenotype (Zeyda et al. 2007, Riboldi et al. 2013). Although mice on the Apoe-/- background are lean and normoglycemic, we tested the paradigm that metabolic activation of BMDM from Stat4-/-/Apoe-/- mice may lead to phenotypically different macrophages compared to Apoe-/- cells. Indeed, in vitro stimulation of BMDM with a combination of insulin/glucose/palmitate resulted in significantly reduced expression of IL1B and iNOS in cells from Stat4-/-/Apoe-/- mice compared to Apoe-/- controls. Also, metabolic activation has been shown to up-regulate anti-inflammatory genes such as PPARC and lead to more efficient metabolism due to an increase in Abca1 and Plin2 genes (Kratz et al. 2014). In Stat4-/-/Apoe-/- macrophages PPARC gene expression was significantly elevated compared to Apoe-/-, suggesting a more efficient anti-inflammatory response in the former in response to metabolic activation. This may be relevant especially upon Western diet feeding when circulating lipids are dramatically increased and may lead to a predominant pro-inflammatory macrophage phenotype. Finally, we found that Abca1 gene expression was significantly increased in MMe macrophages of Stat4-/-/Apoe-/- mice compared to Apoe-/- controls. This finding suggests that STAT4 deficiency promotes a more efficient cholesterol efflux from macrophages and therefore could contribute to the reduced atheroma formation in Stat4-/-/Apoe-/- mice on a Western diet via a reduction of foam cells.

Many studies demonstrate a link between the inflammation within AT, insulin resistance and accelerated atherosclerosis (Mazurek et al. 2008). AT releases inflammatory cytokines and bioactive mediators that are potent inducers of structural and functional changes in the vasculature (Brown et al. 2014). Collectively referred to as the AT secretome, these factors may originate from adipocytes or other cells in AT, such as immune cells and vascular cells. We examined the effect of STAT4-sufficient and -deficient AT secretome on aortic gene expression of pro-inflammatory cytokines and chemokines in Apoe-/- mice. Interestingly, we found that CCL2 expression in aortic cells of Apoe-/- mice following incubation with AT CM of Stat4-/-/Apoe-/- mice is significantly lower compared to CM from Apoe-/- mice (Fig. 4). This finding indicates that visceral AT secretome can support inflammation and atherosclerosis development at least through changes in the aortic expression of CCL2, one of the major chemokines necessary for MF recruitment into the aorta. Although we did not test the effect of peri-aortic fat secretome on aortic cells due to the limited tissue availability, the similarly immune cells composition and phenotype found between visceral and peri-aortic depots suggest comparable responses. Also, although the CM component or combination responsible for the response is unknown, the effect is STAT4-related and further studies are granted to pinpoint the mechanism.

Collectively our data show that STAT4 deficiency in Apoe-/- mice reduces immune cell infiltration, pro-inflammatory cytokine and chemokine expression and macrophage polarization in peri-aortic and visceral AT. These effects may contribute to the athero-protective effect of STAT4 deficiency in this model, particularly in mice on a Western diet. Potential mechanisms include reduction of the reservoir of pro-inflammatory cells or pro-inflammatory cytokines and chemokines to the aortic wall or blunted expression of pro-inflammatory genes in cells of the aortic wall. Ultimately, STAT4 deficiency limits vascular inflammation potentially leading to reduced plaque burden in diet-induced accelerated atherosclerosis. Our study suggests that selective inhibitors of the Jak/Tyk/STAT4 pathway may have possible cardiovascular health benefits beyond their current indications as therapeutics for autoimmune and chronic inflammatory diseases.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

Funding
This work was supported by the PO1 HL55798 to J L N and by the RO1 HL112605 to J L N and A D D.

Acknowledgements
The authors wish to thank Dr Mark Kaplan for providing the STAT4 null mice. The authors also acknowledge the excellent technical support of Lindsey Glenn BS, Jack Lindsey MS, Ashley James BS, and Mr Ciriaco Villafior.

References


Arteriosclerosis, Thrombosis, and Vascular Biology 24 2351–2357. (doi:10.1161/01.ATV.0000147112.84168.87)


Yoo JK, Cho JH, Lee SW & Sung YC 2002 IL-12 provides proliferation and survival signals to murine CD4+ T cells through phosphatidylinositol 3-kinase/Akt signaling pathway. Journal of Immunology 169 3637–3643. (doi:10.4049/jimmunol.169.7.3637)


Received in final form 25 July 2015
Accepted 5 August 2015