Interplay between the immune system and adipose tissue in obesity

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Abstract

Obesity is a major risk factor for metabolic disease, with white adipose tissue (WAT) inflammation emerging as a key underlying pathology. Alongside its major role in energy storage, WAT is an important endocrine organ, producing many bioactive molecules, termed adipokines, which not only serve as regulators of systemic metabolism, but also possess immunoregulatory properties. Furthermore, WAT contains a unique immune cell repertoire, including an accumulation of leukocytes that are rare in other locations. These include alternatively activated macrophages, invariant natural killer T cells, and regulatory T cells. Disruption of resident adipose leukocyte homeostasis contributes to obesity-associated inflammation and consequent metabolic disorder. Despite many recent advances in this new field of immuno-metabolism, fundamental questions of why and how inflammation arises as obesity develops are not yet fully understood. Exploring the distinct immune system of adipose tissue is fundamental to our understanding of the endocrine as well as immune systems. In this review, we discuss the roles of adipose tissue leukocytes in the transition to obesity and progression of inflammation and highlight potential anti-inflammatory therapies for combating obesity-related pathology.

Key Words
- CD1d
- NKT cells
- adipocytes
- lipids

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Adipose tissue as an immune organ

Immune organs represent sites of exclusive immunological function; however, the definition of an immune tissue has been extended to organs such as the liver (Doherty & O'Farrelly 2000), uterus (Lynch *et al.* 2007), and small intestine (Camerini *et al.* 1993). The primary function of these organs is of course not immunological, but each has specialized immune mechanisms mediating their physiological roles, as well as providing immune surveillance against pathogens and tumors. Similarly, white adipose tissue (WAT) can now be defined as an immune organ, with important roles in anti-microbial defense, wound healing, and inflammation.

Immune aggregates in human adipose tissue were first described in 1874 and termed 'milky spots' (Ranvier 1874). For a century, surgeons have used the wound healing properties of the omentum to their advantage during surgery; the omentum can adhere to intra-abdominal foreign bodies, including drains and catheters. It also acts as the first defense against peritonitis and isolates sites of inflammation and injury to localize inflammation (Platell *et al.* 2000). Despite the discovery of milky spots and the

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healing characteristics of the omentum, the complex interactions between the adipose immune network and the stromal and adipocyte components of this tissue are only now unfolding.

The two main WAT depots are the visceral (including the omentum; ~10% of body total) and subcutaneous (~85%) adipose tissue beds, although smaller depots are scattered throughout the body, surrounding organs, such as the heart and kidneys, and lymph nodes. Compared with subcutaneous adipose tissue, visceral WAT has enhanced metabolic activity and is more strongly associated with adverse metabolic risk factors, which will be discussed in the sections below (Kershaw & Flier 2004).

Visceral adipose tissue is immunologically dynamic, with a remarkable concentration of resident leukocytes. This population includes CD4 (Winer *et al*. 2009) and CD8 T cells (Nishimura *et al*. 2009), T regulatory (Treg) cells (Feuerer *et al*. 2009), invariant natural killer T (iNKT) cells (Lynch *et al*. 2009, 2012), B cells (Winer *et al*. 2011), mast cells (Liu *et al*. 2009), eosinophils (Wu *et al*. 2011), and macrophages (Weisberg *et al*. 2003, Lumeng *et al*. 2007, Wentworth *et al*. 2010). Resident adipose leukocyte populations represent distinct subsets, with particular functions compared with their equivalent populations elsewhere in the body. Striking examples include iNKT and Tregs, which are specifically enriched in human and murine adipose tissue (Lynch *et al*. 2009, 2012, Brennan *et al*. 2013) and express unique combinations of surface receptors and cytokine profiles compared with resident populations present at other locations (Feuerer *et al*. 2009).

Obesity-related inflammation

Crosstalk between adipocytes and resident leukocytes allows these systems to coordinate available energy stores for survival during times of starvation and pathogen challenge. However, over the last century, the major threat of energy deficit to living organisms has been replaced by overnutrition of humans in the developed (and increasingly in the developing) world. Obesity is now a major public health issue, with the principal cause of morbidity due to metabolic dysfunction (insulin resistance, type 2 diabetes, dyslipidemia, hepatic steatosis, and cardiovascular disease). Progression of clinical pathology has been strongly linked to obesity-associated chronic inflammation of WAT and the resultant increased circulating concentrations of inflammatory markers (Dalmas *et al*. 2011, Odegaard & Chawla 2011).

Chronic overnutrition causes pathological expansion of adipose tissue, where hypertrophic adipocytes fail to efficiently store excess energy, leading to adipose tissue dysfunction, dyslipidemia, and insulin resistance. Increased tissue inflammation through adipocyte release of cytokines (e.g. tumor necrosis factor a (TNFa; Hotamisligil *et al*. 1993, Kern *et al*. 1995)), chemokines (e.g. monocyte chemoattractant protein (MCP1/CCL2; Kanda *et al*. 2006)), and pro-inflammatory fatty acids (Nguyen *et al*. 2007) drives alterations in leukocyte number and phenotype, thereby expanding the inflammatory environment within adipose tissue beds. Altered expression of pro- and anti-inflammatory factors produced by leukocytes acts reciprocally on adipocytes, perpetuating WAT inflammation and dysfunction.

How WAT inflammation is triggered is not completely understood, but it is suggested that lipotoxicity (Unger & Scherer 2010), endoplasmic reticulum (ER) stress due to excess lipid burden (Ozcan *et al*. 2004), hypoxia due to decreased oxygen diffusion into enlarged adipocytes (Halberg *et al*. 2009), and Toll-like receptor activation through free fatty acid sensing (Shi *et al*. 2006) are involved. Each immune cell population present in WAT has been shown to participate in the progression of obesity-related inflammation (Fig. 1), via different mechanisms that will be explained in the subsequent sections. In 2013, the Council on Science and Public Health of the American Medical Association (AMA) 'recognize(s) obesity as a disease state with multiple pathophysiological aspects requiring a range of interventions to advance obesity treatment and prevention'. One potential therapeutic avenue is the immunometabolic interface in adipose tissue.

Macrophages

Macrophages are the most abundant leukocyte in adipose tissue and appear to be at the center of obesity-related inflammation (Chawla *et al*. 2011). In lean animals, adipose tissue macrophages are dispersed throughout WAT and display an alternatively activated (M2) anti-inflammatory phenotype (Lumeng *et al*. 2007), promoting insulin sensitivity in adipocytes by secreting interleukin 10 (IL10). Impairment of M2 macrophage activation using genetic models (Weisberg *et al*. 2003, Patsouris *et al*. 2008) enhances susceptibility of rodents to diet-induced obesity and insulin resistance, while potentiation of M2 macrophage activation by pharmacological inhibition (Odegaard *et al*. 2007) confers protection from obesity-associated metabolic dysfunction.

In obese subjects, adipose tissue macrophage numbers increase remarkably, and this population shifts toward the

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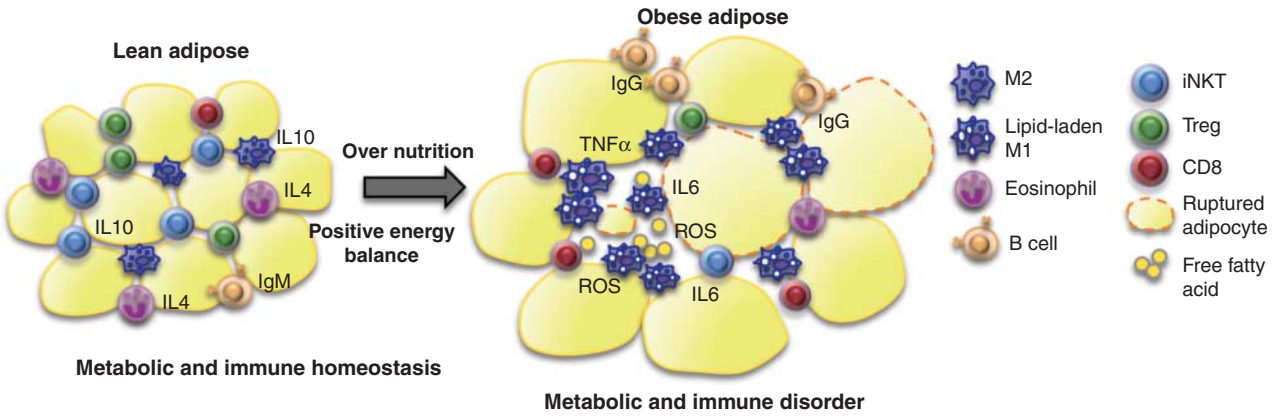

Figure 1

Adipose homeostasis during steady-state and obese conditions. In lean adipose tissue, immune cells and adipocytes are neighbors and interact to maintain homeostasis and regulation of adipocyte lipid handling and storage. The main resident immune cells include iNKT cells, Tregs, eosinophils, IgM-producing B cells, and alternatively activated M2 macrophages. IL10 production by iNKT, Tregs, and M2 macrophages, and IL4 production by eosinophils is important for maintaining a tolerogenic environment. During adipose expansion in obesity, there is a loss of iNKT cells and Tregs, and a phenotypic switch in macrophages from M2 to M1, which accumulate around overloaded and rupturing adipocytes.

classical pro-inflammatory (M1) state. M1 macrophages aggregate around necrotic adipocytes in inflamed tissue, forming 'crown-like structures', and produce substantial amounts of pro-inflammatory cytokines such as IL6 and TNFα (Lumeng *et al.* 2007, Wentworth *et al.* 2010), contributing directly to local and systemic inflammation and insulin resistance. Blockade of inflammatory monocyte and macrophage trafficking into adipose protects mice from obesity-induced inflammation and loss of insulin sensitivity (Arkan *et al.* 2005, Weisberg *et al.* 2006) and, similarly, selective depletion of M1 macrophages in obese animal models reduces WAT inflammation without affecting diet-induced obesity (Patsouris *et al.* 2008).

Of course, separation of macrophages into these defined M1/M2 phenotypes has its limitations; *in vivo*, they exhibit plasticity across the entire spectrum of activation states encompassed by the M1 and M2 nomenclature. Nonetheless, sustained weight loss results in reduced total numbers of adipose tissue macrophages, which is accompanied by a decrease in pro-inflammatory profiles of obese individuals (Cancello *et al.* 2005). This, and the genetic manipulations referred to above, provides strong support for the causative role of macrophage-mediated inflammation in insulin resistance. The triggers for the trafficking and inflammatory activation of macrophages in obesity are still being uncovered, and we refer the reader to recent reviews (Chawla *et al.* 2011, Osborn & Olefsky 2012), which summarize the latest findings.

Eosinophils

Eosinophils have recently been added to the immune sentinels in WAT, which, similar to the other immune populations, influence metabolic regulation. Eosinophils are innate leukocytes with an important role in allergy development and parasitic infection. They are the primary source of adipose IL4, a cytokine that mediates M2 activation of macrophages (Wu *et al.* 2011). In line with this, adipose eosinophil numbers are decreased in obesity, and mice lacking eosinophils exhibit enhanced adipose M1 macrophage activity, weight gain, and systemic insulin resistance (Wu *et al.* 2011). The production of eosinophils in bone marrow and their recruitment into WAT is largely controlled by IL5 (Mould *et al.* 1997, Molofsky *et al.* 2013); mice with tissue eosinophilia (which occurs in IL5 transgenic mice) demonstrate decreased adiposity and improved insulin sensitivity when maintained on a high-fat diet (Wu *et al.* 2011). The source of adipose IL5 is a newly recognized population, innate lymphoid type 2 cells (ILC2s; Molofsky *et al.* 2013). Thus, accumulation of eosinophils and maintenance of adipose M2 macrophages has been shown to depend on ILC2s, and loss of this population in mouse models exacerbates diet-induced obesity and metabolic dysfunction. This latest example adds further complexity to the network of immune cells in adipose tissue, demonstrating how perturbations at any of these levels result in whole-adipose dysfunction and subsequent metabolic sequelae.

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B cells

In lean animals, resident adipose B cells provide immunity against infection by mounting initial responses against local peritoneal antigens, including bacteria from intestinal perforations, or antigens associated with abdominal injuries (Rangel-Moreno *et al*. 2009). Herein, B cells produce antibodies, undergo isotype switching, and somatic hyper-mutation, and can regulate immune function. However, two independent studies have shown that during obesity, B cells undergo functional changes, leading them to play a pathogenic role in inflammation and insulin resistance (Winer *et al*. 2011, DeFuria *et al*. 2013). Obesity is associated with increased IgG production, and infiltration of IgG^+B cells into adipose tissue (Winer *et al*. 2011). Serum IgG or major histocompatibility complex (MHC) class II-expressing B cells isolated from obese mice and transferred into B cell-deficient lean mice induce insulin resistance in these animals (Winer *et al*. 2011). Both of these events compound differentiation of M1 macrophages: B cell pathogenic antibody production directly activates macrophages, and B cells from obese mice promote inflammatory responses by T cells and affect Treg survival negatively (effect of which is discussed in further detail below; DeFuria *et al*. 2013). In agreement, diet-induced obese mice lacking B cells exhibit decreased inflammation, and an increase in adipose Tregs, associated with improved metabolism, despite typical weight gain (Winer *et al*. 2011).

Treg cells

Tregs are critical to the maintenance of peripheral immunological tolerance and immune homeostasis, as evidenced by the catastrophic consequences of Treg ablation. Treg loss causes spontaneous development of severe autoimmune disease, allergy, and immunopathology in humans and rodents (Gavin *et al*. 2007). Tregs are highly enriched in adipose of lean mice (Feuerer *et al*. 2009), compared with their frequencies in other lymphoid and non-lymphoid tissue. Their number declines in obese mouse models and obese human patients (Feuerer *et al*. 2009) and modulation of WAT Treg number to selectively increase or decrease this population, improves or worsens inflammation and metabolic dysfunction respectively (Feuerer *et al*. 2009). These data suggest that Tregs are required for maintenance of an anti-inflammatory environment at steady state in lean adipose tissue. Indeed, adipose Tregs have a distinct cytokine profile, expressing large amounts of IL10, which maintains macrophages in the alternatively activated M2 state (Feuerer *et al*. 2009). IL10 may also directly affect adipocyte function, as adipocytes also express IL10 receptor. When adipocytes are treated with IL10, they phosphorylate Akt, decrease their expression of macrophage chemoattractant CCL2, and importantly, insulin-stimulated glucose uptake is dramatically enhanced (Lumeng *et al*. 2007). Thus, Tregs are a key population that prevents self-destructive immune responses in adipose tissue, and their loss during obesity aggravates the inflammatory milieu, through effects on their neighboring immune cells and on adipocytes.

Interestingly, adipose Tregs also express lipid receptors, and most surprisingly, the adipogenic transcription factor peroxisome proliferator-activated receptor gamma (PPARγ; Cipolletta *et al*. 2012), which is crucial for Treg WAT anti-inflammatory function. Initially PPARγ was thought to be unique to adipocytes, but it has later been shown as an important receptor of macrophages and myeloid cells, facilitating their uptake of oxidized lipids (Tontonoz *et al*. 1998). Its expression by adipose Tregs is the first description of PPARγ in T cells, and it appears to control Treg accumulation in adipose tissue (Cipolletta *et al*. 2012). Ligands for PPARγ include naturally occurring fatty acids and the thiazolidinedione (TZD) class of anti-diabetic drugs. Tregs, through their expression of PPARγ seem to be necessary for the optimal effect of thiazolidinedione treatment in obese diabetic mice (Cipolletta *et al*. 2012).

iNKT cells

iNKT cells are innate-type T cells, so called because they express an invariant T cell receptor α-chain, Vα24Jα18, paired with Vβ11 in humans and Vα14Jα18 coupled with either Vβ7, Vβ8.2, or Vβ2 in mice (Matsuda *et al*. 2000, Brigl & Brenner 2004, Gumperz 2006, Bendelac *et al*. 2007, Berzins *et al*. 2011). Unlike adaptive T cells, that recognize peptide antigens presented by MHC class molecules, iNKT cells recognize lipids presented by CD1d antigen-presenting molecules (Matsuda *et al*. 2000, Brigl & Brenner 2004, Gumperz 2006). Despite advances in identifying endogenous lipids recognized by iNKT cells (Brutkiewicz 2006), the most studied lipid antigen is alpha-galactosylceramide (αGC) (Matsuda *et al*. 2000, Gumperz 2006), which was originally isolated from a marine sponge and is a potent activator of iNKT cells.

CD1d is expressed by professional antigen-presenting cells, including dendritic cells and macrophages, as well as B and T cells. It is also found on the surface of non-hematopoietic cells including some epithelial cells,

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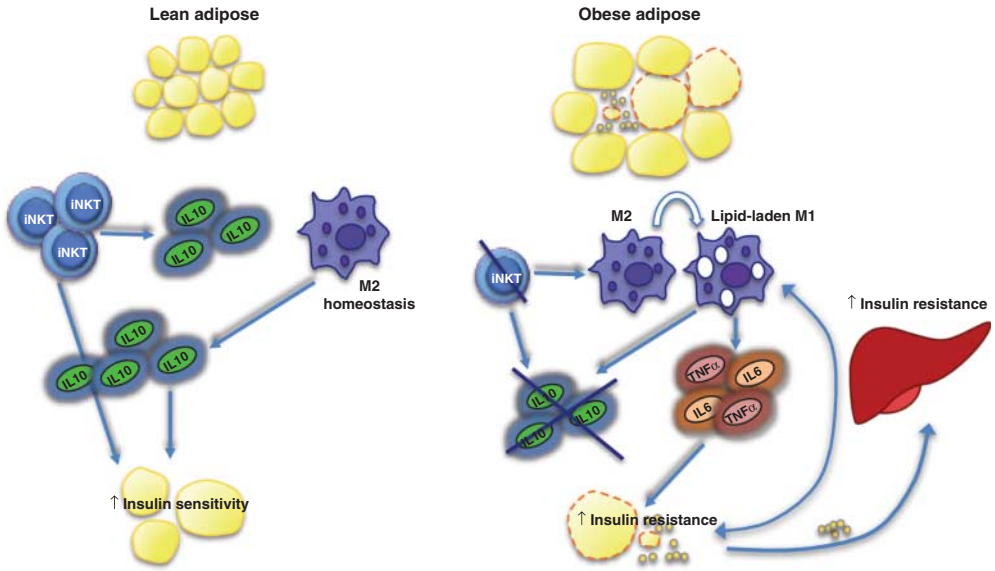

Figure 2

iNKT cells and macrophages are important gatekeepers of adipose homeostasis. During steady state, anti-inflammatory iNKT cells accumulate in adipose tissue and produce IL10, which regulates macrophage M2 phenotype and adipocyte insulin sensitivity. M2 macrophages are also a source of IL10, propagating a tolerogenic environment. In obesity, the loss of iNKT cells results in decreased adipose IL10, which may play a role in macrophage polarization to an anti-inflammatory state. Accumulation of M1 macrophages is probably beneficial to 'mopping up' excess lipids from overloaded adipocytes. However, their chronic activation and production of pro-inflammatory cytokines lead to a vicious cycle, resulting in insulin resistance in adipose tissue and increased circulating pro-inflammatory markers. Adipose lipid spillover can relocate to liver and, in concert with increased systemic inflammation, leads to peripheral insulin resistance.

hepatocytes, and adipocytes (Bendelac *et al*. 2007, Schipper *et al*. 2012). Therefore, in adipose tissue, several cell types can directly interact with iNKTs. A striking feature of iNKT cells is their rapid production of both Th1 and Th2 cytokines upon activation with CD1d-presented αGC (Bendelac *et al*. 2007, Matsuda *et al*. 2008, Berzins *et al*. 2011), equipping them with considerable immunological potential. Indeed, iNKT are involved in a multitude of disease states including cancer, type 1 diabetes, atherosclerosis, and rheumatoid arthritis (Simoni *et al*. 2013).

Human and murine adipose tissues are highly enriched for iNKT cells (Lynch *et al*. 2009, 2012). Analogous to adipose Tregs, iNKTs not only accumulate in adipose tissue, but also represent a unique subset of iNKT cells compared with elsewhere in the body. Microarray analysis revealed that adipose iNKT cells express a distinct genetic profile (L Lynch & MB Brenner, unpublished observations). This includes increased anti-inflammatory cytokine expression, such as IL10, which as discussed previously, promotes alternative M2 macrophage activation, suppressing WAT inflammation. In agreement with this, mice lacking iNKT cells harbor more proinflammatory M1 macrophages at steady state and in high-fat diet-induced obesity. Therefore, IL10 production by iNKT cells, and their enhancement of M2 macrophages, which produce further IL10, suggests that iNKT cells can directly and indirectly enhance the ability of adipocytes to control metabolism (Fig. 2).

Loading of CD1d with lipid antigen occurs in the ER, and is essential for the correct assembly and surface expression of CD1d (Gumperz 2006, Bendelac *et al*. 2007). Obesity is associated with increased ER stress in WAT, due to activation of the unfolded protein response (UPR). Importantly, the UPR has been linked to the loss of CD1d in obese liver (Li *et al*. 2004), which in turn affects iNKT cell levels.

As adipose expands in obesity, iNKT cells become reversibly depleted, with numbers restored following weight loss (Lynch *et al*. 2009, 2012). Adoptive transfer of iNKT cells into obese mice or *in vivo* activation of iNKTs with αGC administration causes weight loss, improvement of glucose handling, and insulin sensitivity (Lynch *et al*. 2012). However, there remains some controversy concerning the beneficial effects of iNKT cells in controlling adipose weight as well as metabolic syndrome. The consensus that restoring iNKT activity (adoptive transfer; iNKT stimulation) is clear, and although a number of reports observe that genetic ablation of iNKT is deleterious in all obesity measures taken, others find no change, or in

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Table 1 Protective or detrimental effect of NKT on adipose weight gain, type 2 diabetes, and non-alcoholic fatty liver disease (as available in each paper) in mouse: findings of published papers to date

References	Strains	Diet % kcal fat	CD1$^{-/-}$ relative to WT	Jα18$^{-/-}$ relative to WT	iNKT transfer protective	iNKT stimulation protective
Miyagi *et al.* (2010)	BALB/c	57		+		
Mantell *et al.* (2011)	C57BL/6	44	NS			
Kotas *et al.* (2011)	C57BL/6	60	+	NS		
Lynch *et al.* (2012)	C57BL/6	60	++	++	++	++
Wu *et al.* (2012)	C57BL/6	60	−	−		−
Satoh *et al.* (2012)	C57BL/6	32	−	NS		
Schipper *et al.* (2012)	C57BL/6	10	+	+		
		45	+			
Ji *et al.* (2012)	C57BL/6	60				++
Huh *et al.* (2013)	C57BL/6	60		++		
Subramanian *et al.* (2013)	C57BL/6	36			−[a]	
Strodthoff *et al.* (2013)	C57BL/6	35		−		
Hams *et al.* (2013)	C57BL/6	60	NS	NS	++	++
Martin-Murphy *et al.* (2014)	BALB/c	58	++			

'+', positive effect; '++', strongly positive effect; '−', negative effect.
[a]Vα14 transgenic mice; increased iNKT cell numbers in spleen, liver, and adipose tissue.

some cases, a level of protection (Table 1). A number of technical differences partly account for these varying results, including employment of different strategies to manipulate NKT levels (Cd1d$^{-/-}$ vs Jα18$^{-/-}$), and use of variable high-fat diet compositions and durations. Moreover, other potential disparities that could lead to a dramatic shift in experimental outcome. For example, there are well-established links between the circadian clockwork and inflammatory pathways (Bechtold *et al.* 2010). Thus, time-of-day differences in tissue collection/experimental challenge might affect the results. Additionally, recent studies have highlighted an interesting relationship between the microbiome and host immune functions. Specifically, iNKT homeostasis is modified by early life changes in the microbiome (Olszak *et al.* 2012), and thus subtle alterations in the microbiota of the models used (and use of non-littermate controls) in the aforementioned studies could alter the data obtained.

Conclusions

It has become increasingly clear that endocrine–immune interactions are crucially involved in a reciprocal regulatory system, which in the lean state adopts a 'virtuous cycle' with an anti-inflammatory 'flavor', but which in obesity develops an increasingly vicious circle promoting chronic adipose inflammation and metabolic dysfunction. Loss- and gain-of-function studies implicate multiple leukocyte subpopulations in the pathology of obesity-related WAT inflammation, underlining the complexity of this system.

Additional investigations are necessary to address the primary functions of the individual leukocyte groups in adipose and the mechanisms underlying their alterations in WAT during obesity. Therapeutic interventions that target the molecular components of this phenomenon could prove effective in reducing inflammation, inducing weight loss, and improving metabolic disorder in obese type 2 diabetic patients. One possible target could be iNKT cells. Lipid antigens that target iNKTs have already been used clinically to treat patients with melanoma (Richter *et al.* 2013). Furthermore, parenteral administration of lipid can activate iNKT cells, making the idea of targeting adipose iNKT cells in obesity a promising and viable strategy. Whether shifting the balance of obese adipose in favor of a tolerogenic immune environment will have meaningful clinical effects remains yet to be determined.

Declaration of interest
M A E has equity in NKT Therapeutics, Inc.

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References

Arkan MC, Hevener AL, Greten FR, Maeda S, Li ZW, Long JM, Wynshaw-Boris A, Poli G, Olefsky J & Karin M 2005 IKK-β links inflammation to obesity-induced insulin resistance. *Nature Medicine* **11** 191–198. (doi:10.1038/nm1185)

Bechtold DA, Gibbs JE & Loudon AS 2010 Circadian dysfunction in disease. *Trends in Pharmacological Sciences* **31** 191–198. (doi:10.1016/j.tips.2010.01.002)

Bendelac A, Savage PB & Teyton L 2007 The biology of NKT cells. *Annual Review of Immunology* **25** 297–336. (doi:10.1146/annurev.immunol.25.022106.141711)

Berzins SP, Smyth MJ & Baxter AG 2011 Presumed guilty: natural killer T cell defects and human disease. *Nature Reviews. Immunology* **11** 131–142. (doi:10.1038/nri2904)

Brennan PJ, Brigl M & Brenner MB 2013 Invariant natural killer T cells: an innate activation scheme linked to diverse effector functions. *Nature Reviews. Immunology* **13** 101–117. (doi:10.1038/nri3369)

Brigl M & Brenner MB 2004 CD1: antigen presentation and T cell function. *Annual Review of Immunology* **22** 817–890. (doi:10.1146/annurev.immunol.22.012703.104608)

Brutkiewicz RR 2006 CD1d ligands: the good, the bad, and the ugly. *Journal of Immunology* **177** 769–775. (doi:10.4049/jimmunol.177.2.769)

Camerini V, Panwala C & Kronenberg M 1993 Regional specialization of the mucosal immune system. Intraepithelial lymphocytes of the large intestine have a different phenotype and function than those of the small intestine. *Journal of Immunology* **151** 1765–1776.

Cancello R, Henegar C, Viguerie N, Taleb S, Poitou C, Rouault C, Coupaye M, Pelloux V, Hugol D, Bouillot JL *et al.* 2005 Reduction of macrophage infiltration and chemoattractant gene expression changes in white adipose tissue of morbidly obese subjects after surgery-induced weight loss. *Diabetes* **54** 2277–2286. (doi:10.2337/diabetes.54.8.2277)

Chawla A, Nguyen KD & Goh YP 2011 Macrophage-mediated inflammation in metabolic disease. *Nature Reviews. Immunology* **11** 738–749. (doi:10.1038/nri3071)

Cipolletta D, Feuerer M, Li A, Kamei N, Lee J, Shoelson SE, Benoist C & Mathis D 2012 PPAR-γ is a major driver of the accumulation and phenotype of adipose tissue Treg cells. *Nature* **486** 549–553. (doi:10.1038/nature11132)

Dalmas E, Clement K & Guerre-Millo M 2011 Defining macrophage phenotype and function in adipose tissue. *Trends in Immunology* **32** 307–314. (doi:10.1016/j.it.2011.04.008)

DeFuria J, Belkina AC, Jagannathan-Bogdan M, Snyder-Cappione J, Carr JD, Nersesova YR, Markham D, Strissel KJ, Watkins AA, Zhu M *et al.* 2013 B cells promote inflammation in obesity and type 2 diabetes through regulation of T-cell function and an inflammatory cytokine profile. *PNAS* **110** 5133–5138. (doi:10.1073/pnas.1215840110)

Doherty DG & O'Farrelly C 2000 Innate and adaptive lymphoid cells in the human liver. *Immunological Reviews* **174** 5–20. (doi:10.1034/j.1600-0528.2002.017416.x)

Feuerer M, Herrero L, Cipolletta D, Naaz A, Wong J, Nayer A, Lee J, Goldfine AB, Benoist C, Shoelson S *et al.* 2009 Lean, but not obese, fat is enriched for a unique population of regulatory T cells that affect metabolic parameters. *Nature Medicine* **15** 930–939. (doi:10.1038/nm.2002)

Gavin MA, Rasmussen JP, Fontenot JD, Vasta V, Manganiello VC, Beavo JA & Rudensky AY 2007 Foxp3-dependent programme of regulatory T-cell differentiation. *Nature* **445** 771–775. (doi:10.1038/nature05543)

Gumperz JE 2006 The ins and outs of CD1 molecules: bringing lipids under immunological surveillance. *Traffic* **7** 2–13. (doi:10.1111/j.1600-0854.2005.00364.x)

Halberg N, Khan T, Trujillo ME, Wernstedt-Asterholm I, Attie AD, Sherwani S, Wang ZV, Landskroner-Eiger S, Dineen S, Magalang UJ *et al.* 2009 Hypoxia-inducible factor 1alpha induces fibrosis and insulin resistance in white adipose tissue. *Molecular and Cellular Biology* **29** 4467–4483. (doi:10.1128/MCB.00192-09)

Hams E, Locksley RM, McKenzie AN & Fallon PG 2013 Cutting edge: IL-25 elicits innate lymphoid type 2 and type II NKT cells that regulate obesity in mice. *Journal of Immunology* **191** 5349–5353. (doi:10.4049/jimmunol.1301176)

Hotamisligil GS, Shargill NS & Spiegelman BM 1993 Adipose expression of tumor necrosis factor-alpha: direct role in obesity-linked insulin resistance. *Science* **259** 87–91. (doi:10.1126/science.7678183)

Huh JY, Kim JI, Park YJ, Hwang IJ, Lee YS, Sohn JH, Lee SK, Alfadda AA, Kim SS, Choi SH *et al.* 2013 A novel function of adipocytes in lipid antigen presentation to iNKT cells. *Molecular and Cellular Biology* **33** 328–339. (doi:10.1128/MCB.00552-12)

Ji Y, Sun S, Xu A, Bhargava P, Yang L, Lam KS, Gao B, Lee CH, Kersten S & Qi L 2012 Activation of natural killer T cells promotes M2 macrophage polarization in adipose tissue and improves systemic glucose tolerance via interleukin-4 (IL-4)/STAT6 protein signaling axis in obesity. *Journal of Biological Chemistry* **287** 13561–13571. (doi:10.1074/jbc.M112.350066)

Kanda H, Tateya S, Tamori Y, Kotani K, Hiasa K, Kitazawa R, Kitazawa S, Miyachi H, Maeda S, Egashira K *et al.* 2006 MCP-1 contributes to macrophage infiltration into adipose tissue, insulin resistance, and hepatic steatosis in obesity. *Journal of Clinical Investigation* **116** 1494–1505. (doi:10.1172/JCI26498)

Kern PA, Saghizadeh M, Ong JM, Bosch RJ, Deem R & Simsolo RB 1995 The expression of tumor necrosis factor in human adipose tissue. Regulation by obesity, weight loss, and relationship to lipoprotein lipase. *Journal of Clinical Investigation* **95** 2111–2119. (doi:10.1172/JCI117899)

Kershaw EE & Flier JS 2004 Adipose tissue as an endocrine organ. *Journal of Clinical Endocrinology and Metabolism* **89** 2548–2556. (doi:10.1210/jc.2004-0395)

Kotas ME, Lee HY, Gillum MP, Annicelli C, Guigni BA, Shulman GI & Medzhitov R 2011 Impact of CD1d deficiency on metabolism. *PLoS ONE* **6** e25478. (doi:10.1371/journal.pone.0025478)

Li Z, Oben JA, Yang S, Lin H, Stafford EA, Soloski MJ, Thomas SA & Diehl AM 2004 Norepinephrine regulates hepatic innate immune system in leptin-deficient mice with nonalcoholic steatohepatitis. *Hepatology* **40** 434–441. (doi:10.1002/hep.20320)

Liu J, Divoux A, Sun J, Zhang J, Clement K, Glickman JN, Sukhova GK, Wolters PJ, Du J, Gorgun CZ *et al.* 2009 Genetic deficiency and pharmacological stabilization of mast cells reduce diet-induced obesity and diabetes in mice. *Nature Medicine* **15** 940–945. (doi:10.1038/nm.1994)

Lumeng CN, Bodzin JL & Saltiel AR 2007 Obesity induces a phenotypic switch in adipose tissue macrophage polarization. *Journal of Clinical Investigation* **117** 175–184. (doi:10.1172/JCI29881)

Lynch L, Golden-Mason L, Eogan M, O'Herlihy C & O'Farrelly C 2007 Cells with haematopoietic stem cell phenotype in adult human endometrium: relevance to infertility? *Human Reproduction* **22** 919–926. (doi:10.1093/humrep/del456)

Lynch L, O'Shea D, Winter DC, Geoghegan J, Doherty DG & O'Farrelly C 2009 Invariant NKT cells and CD1d(+) cells amass in human omentum and are depleted in patients with cancer and obesity. *European Journal of Immunology* **39** 1893–1901. (doi:10.1002/eji.200939349)

Lynch L, Nowak M, Varghese B, Clark J, Hogan AE, Toxavidis V, Balk SP, O'Shea D, O'Farrelly C & Exley MA 2012 Adipose tissue invariant NKT cells protect against diet-induced obesity and metabolic disorder through regulatory cytokine production. *Immunity* **37** 574–587. (doi:10.1016/j.immuni.2012.06.016)

Mantell BS, Stefanovic-Racic M, Yang X, Dedousis N, Sipula IJ & O'Doherty RM 2011 Mice lacking NKT cells but with a complete complement of CD8+ T-cells are not protected against the metabolic abnormalities of diet-induced obesity. *PLoS ONE* **6** e19831. (doi:10.1371/journal.pone.0019831)

Martin-Murphy BV, You Q, Wang H, De La Houssaye BA, Reilly TP, Friedman JE & Ju C 2014 Mice lacking natural killer T cells are more susceptible to metabolic alterations following high fat diet feeding. *PLoS ONE* **9** e80949. (doi:10.1371/journal.pone.0080949)

Matsuda JL, Naidenko OV, Gapin L, Nakayama T, Taniguchi M, Wang CR, Koezuka Y & Kronenberg M 2000 Tracking the response of natural killer T cells to a glycolipid antigen using CD1d tetramers. *Journal of Experimental Medicine* **192** 741–754. (doi:10.1084/jem.192.5.741)

http://joe.endocrinology-journals.org
DOI: 10.1530/JOE-13-0516

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Matsuda JL, Mallevaey T, Scott-Browne J & Gapin L 2008 CD1d-restricted iNKT cells, the 'Swiss-Army knife' of the immune system. *Current Opinion in Immunology* **20** 358–368. (doi:10.1016/j.coi.2008.03.018)

Miyagi T, Takehara T, Uemura A, Nishio K, Shimizu S, Kodama T, Hikita H, Li W, Sasakawa A, Tatsumi T *et al.* 2010 Absence of invariant natural killer T cells deteriorates liver inflammation and fibrosis in mice fed high-fat diet. *Journal of Gastroenterology* **45** 1247–1254. (doi:10.1007/s00535-010-0272-y)

Molofsky AB, Nussbaum JC, Liang HE, Van Dyken SJ, Cheng LE, Mohapatra A, Chawla A & Locksley RM 2013 Innate lymphoid type 2 cells sustain visceral adipose tissue eosinophils and alternatively activated macrophages. *Journal of Experimental Medicine* **210** 535–549. (doi:10.1084/jem.20121964)

Mould AW, Matthaei KI, Young IG & Foster PS 1997 Relationship between interleukin-5 and eotaxin in regulating blood and tissue eosinophilia in mice. *Journal of Clinical Investigation* **99** 1064–1071. (doi:10.1172/JCI119234)

Nguyen MT, Favelyukis S, Nguyen AK, Reichart D, Scott PA, Jenn A, Liu-Bryan R, Glass CK, Neels JG & Olefsky JM 2007 A subpopulation of macrophages infiltrates hypertrophic adipose tissue and is activated by free fatty acids via Toll-like receptors 2 and 4 and JNK-dependent pathways. *Journal of Biological Chemistry* **282** 35279–35292. (doi:10.1074/jbc.M706762200)

Nishimura S, Manabe I, Nagasaki M, Eto K, Yamashita H, Ohsugi M, Otsu M, Hara K, Ueki K, Sugiura S *et al.* 2009 CD8+ effector T cells contribute to macrophage recruitment and adipose tissue inflammation in obesity. *Nature Medicine* **15** 914–920. (doi:10.1038/nm.1964)

Odegaard JI & Chawla A 2011 Alternative macrophage activation and metabolism. *Annual Review of Pathology* **6** 275–297. (doi:10.1146/annurev-pathol-011110-130138)

Odegaard JI, Ricardo-Gonzalez RR, Goforth MH, Morel CR, Subramanian V, Mukundan L, Red Eagle A, Vats D, Brombacher F, Ferrante AW *et al.* 2007 Macrophage-specific PPARγ controls alternative activation and improves insulin resistance. *Nature* **447** 1116–1120. (doi:10.1038/nature05894)

Olszak T, An D, Zeissig S, Vera MP, Richter J, Franke A, Glickman JN, Siebert R, Baron RM, Kasper DL *et al.* 2012 Microbial exposure during early life has persistent effects on natural killer T cell function. *Science* **336** 489–493. (doi:10.1126/science.1219328)

Osborn O & Olefsky JM 2012 The cellular and signaling networks linking the immune system and metabolism in disease. *Nature Medicine* **18** 363–374. (doi:10.1038/nm.2627)

Ozcan U, Cao Q, Yilmaz E, Lee AH, Iwakoshi NN, Ozdelen E, Tuncman G, Görgün C, Glimcher LH & Hotamisligil GS 2004 Endoplasmic reticulum stress links obesity, insulin action, and type 2 diabetes. *Science* **306** 457–461. (doi:10.1126/science.1103160)

Patsouris D, Li PP, Thapar D, Chapman J, Olefsky JM & Neels JG 2008 Ablation of CD11c-positive cells normalizes insulin sensitivity in obese insulin resistant animals. *Cell Metabolism* **8** 301–309. (doi:10.1016/j.cmet.2008.08.015)

Platell C, Cooper D, Papadimitriou JM & Hall JC 2000 The omentum. *World Journal of Gastroenterology* **6** 169–176.

Rangel-Moreno J, Moyron-Quiroz JE, Carragher DM, Kusser K, Hartson L, Moquin A & Randall TD 2009 Omental milky spots develop in the absence of lymphoid tissue-inducer cells and support B and T cell responses to peritoneal antigens. *Immunity* **30** 731–743. (doi:10.1016/j.immuni.2009.03.014)

Ranvier L 1874 Du development et de l'accroisement des vaisseux sanguins. *Arch de Physiol* **1** 429–450.

Richter J, Neparidze N, Zhang L, Nair S, Monesmith T, Sundaram R, Miesowicz F, Dhodapkar KM & Dhodapkar MV 2013 Clinical regressions and broad immune activation following combination therapy targeting human NKT cells in myeloma. *Blood* **121** 423–430. (doi:10.1182/blood-2012-06-435503)

Satoh M, Andoh Y, Clingan CS, Ogura H, Fujii S, Eshima K, Nakayama T, Taniguchi M, Hirata N, Ishimori N *et al.* 2012 Type II NKT cells stimulate diet-induced obesity by mediating adipose tissue inflammation, steatohepatitis and insulin resistance. *PLoS ONE* **7** e30568. (doi:10.1371/journal.pone.0030568)

Schipper HS, Rakhshandehroo M, van de Graaf SF, Venken K, Koppen A, Stienstra R, Prop S, Meerding J, Hamers N, Besra G *et al.* 2012 Natural killer T cells in adipose tissue prevent insulin resistance. *Journal of Clinical Investigation* **122** 3343–3354. (doi:10.1172/JCI62739)

Shi H, Kokoeva MV, Inouye K, Tzameli I, Yin H & Flier JS 2006 TLR4 links innate immunity and fatty acid-induced insulin resistance. *Journal of Clinical Investigation* **116** 3015–3025. (doi:10.1172/JCI28898)

Simoni Y, Diana J, Ghazarian L, Beaudoin L & Lehuen A 2013 Therapeutic manipulation of natural killer (NK) T cells in autoimmunity: are we close to reality? *Clinical and Experimental Immunology* **171** 8–19. (doi:10.1111/j.1365-2249.2012.04625.x)

Strodthoff D, Lundberg AM, Agardh HE, Ketelhuth DF, Paulsson-Berne G, Arner P, Hansson GK & Gerdes N 2013 Lack of invariant natural killer T cells affects lipid metabolism in adipose tissue of diet-induced obese mice. *Arteriosclerosis, Thrombosis, and Vascular Biology* **33** 1189–1196. (doi:10.1161/ATVBAHA.112.301105)

Subramanian S, Turner MS, Ding Y, Goodspeed L, Wang S, Buckner JH, O'Brien K, Getz GS, Reardon CA & Chait A 2013 Increased levels of invariant natural killer T lymphocytes worsen metabolic abnormalities and atherosclerosis in obese mice. *Journal of Lipid Research* **54** 2831–2841. (doi:10.1194/jlr.M041020)

Tontonoz P, Nagy L, Alvarez JG, Thomazy VA & Evans RM 1998 PPARγ promotes monocyte/macrophage differentiation and uptake of oxidized LDL. *Cell* **93** 241–252. (doi:10.1016/S0092-8674(00)81575-5)

Unger RH & Scherer PE 2010 Gluttony, sloth and the metabolic syndrome: a roadmap to lipotoxicity. *Trends in Endocrinology and Metabolism* **21** 345–352. (doi:10.1016/j.tem.2010.01.009)

Weisberg SP, McCann D, Desai M, Rosenbaum M, Leibel RL & Ferrante AW Jr 2003 Obesity is associated with macrophage accumulation in adipose tissue. *Journal of Clinical Investigation* **112** 1796–1808. (doi:10.1172/JCI200319246)

Weisberg SP, Hunter D, Huber R, Lemieux J, Slaymaker S, Vaddi K, Charo I, Leibel RL & Ferrante AW Jr 2006 CCR2 modulates inflammatory and metabolic effects of high-fat feeding. *Journal of Clinical Investigation* **116** 115–124. (doi:10.1172/JCI24335)

Wentworth JM, Naselli G, Brown WA, Doyle L, Phipson B, Smyth GK, Wabitsch M, O'Brien PE & Harrison LC 2010 Pro-inflammatory CD11c+CD206+ adipose tissue macrophages are associated with insulin resistance in human obesity. *Diabetes* **59** 1648–1656. (doi:10.2337/db09-0287)

Winer S, Chan Y, Paltser G, Truong D, Tsui H, Bahrami J, Dorfman R, Wang Y, Zielenski J, Mastronardi F *et al.* 2009 Normalization of obesity-associated insulin resistance through immunotherapy. *Nature Medicine* **15** 921–929. (doi:10.1038/nm.2001)

Winer DA, Winer S, Shen L, Wadia PP, Yantha J, Paltser G, Tsui H, Wu P, Davidson MG, Alonso MN *et al.* 2011 B cells promote insulin resistance through modulation of T cells and production of pathogenic IgG antibodies. *Nature Medicine* **17** 610–617. (doi:10.1038/nm.2353)

Wu D, Molofsky AB, Liang HE, Ricardo-Gonzalez RR, Jouihan HA, Bando JK, Chawla A & Locksley RM 2011 Eosinophils sustain adipose alternatively activated macrophages associated with glucose homeostasis. *Science* **332** 243–247. (doi:10.1126/science.1201475)

Wu L, Parekh VV, Gabriel CL, Bracy DP, Marks-Shulman PA, Tamboli RA, Kim S, Mendez-Fernandez YV, Besra GS, Lomenick JP *et al.* 2012 Activation of invariant natural killer T cells by lipid excess promotes tissue inflammation, insulin resistance, and hepatic steatosis in obese mice. *PNAS* **109** E1143–E1152. (doi:10.1073/pnas.1200498109)

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