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Microbial Reprogramming Inhibits Western Diet-Associated Obesity

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Abstract

A recent epidemiological study showed that eating ‘fast food’ items such as potato chips increased likelihood of obesity, whereas eating yogurt prevented age-associated weight gain in humans. It was demonstrated previously in animal models of obesity that the immune system plays a critical role in this process. Here we examined human subjects and mouse models consuming Westernized ‘fast food’ diet, and found CD4+ T helper (Th)17-biased immunity and changes in microbial communities and abdominal fat with obesity after eating the Western chow. In striking contrast, eating probiotic yogurt together with Western chow inhibited age-associated weight gain. We went on to test whether a bacteria found in yogurt may serve to lessen fat pathology by using purified Lactobacillus reuteri to ATCC 6475 in drinking water. Surprisingly, we discovered that oral L. reuteri therapy alone was sufficient to change the pro-inflammatory immune cell profile and prevent abdominal fat pathology and age-associated weight gain in mice regardless of their baseline diet. These beneficial microbe effects were transferable into naïve recipient animals by purified CD4+ T cells alone. Specifically, bacterial effects depended upon active immune tolerance by induction of Foxp3+ regulatory T cells (Treg) and interleukin (Il)-10, without significantly changing the gut microbial ecology or reducing ad libitum caloric intake. Our finding that microbial targeting restored CD4+ T cell balance and yielded significantly leaner animals regardless of their dietary ‘fast food’ indiscretions suggests population-based approaches for weight management and enhancing public health in industrialized societies.


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Introduction

The risk of developing obesity rises with a Westernized lifestyle. In industrialized and developing countries obesity contributes to increased mortality by predisposing to serious pathological conditions such as type 2 diabetes, cardiovascular disease, fatty liver, arthritis, asthma, and neoplasia [1–2]. Clinical and experimental data suggest that in obesity the white adipose tissue of obese subjects is in a low-grade, persistent state of chronic inflammation [2–3]. The most prominent inflammatory cell type of the obesity-associated inflammation is the adipose tissue macrophage. Macrophages are recruited and surround dead adipocytes, thus creating the so-called crown-like structures (CLS). These cells along with hypertrophic adipocytes are thought to be the key cells initiating the unique subclinical pro-inflammatory signaling cascade encountered in obesity [2,4–5]. Macrophages, B and T lymphocytes, and up-regulated pro-inflammatory cytokines including TNF-α, IL-1, IL-6, IL-17, and monocyte chemoattractant protein-1 (MCP-1) have been reported to contribute to obesity-associated pathologies. In parallel, regulatory T cells down-regulate host inflammatory responses [2–3,6–10]. It is well documented that ‘fast food’ with high fat and salt content at relatively low cost is a major cause of the obesity epidemic in Western societies. Recent epidemiological research shows while dietary ‘fast food’ contributes to obesity, eating yogurt surprisingly prevents age-associated weight gain, though the mechanism is unknown. It has been thought that slenderizing outcomes of yogurt are due to a probiotic bacteria-mediated mechanism [1]. Dietary probiotic consumption alters gut microbiota and may be an effective strategy not only for weight loss but also for preventing weight regain after loss [11–14]. Furthermore, alterations in the composition of gut microbiota may affect not only gut health but also distant tissues and overall health and longevity via immune-mediated mechanisms [15–20].
Using a mouse model of obesity we found that purified probiotic organisms alone prevented weight gain, and these protective effects were irrespective of the baseline diet. We show that this effect could be isolated to a single purified probiotic microbe, namely *Lactobacillus reuteri*. Importantly, eating *L. reuteri* bacteria acted without changing the existing gastrointestinal (GI) microbial composition in stool or level of calorie consumption; instead, the slenderizing microbial mechanism involved bacteria-triggered changes in the host immune system composition. The effect was in particular dependent on CD4+ T cells and the presence of anti-inflammatory IL-10, as IL-10 deficient animals were resistant to *L. reuteri*-induced effects. Adoptive transfer of purified IL-10 competent *L. reuteri*-induced Foxp3+ Treg cells was sufficient to rescue fat pathology and lessen body fat in naive recipient animals. These data provide a mechanism whereby simple dietary manipulation can have major health impact, highlighting the utility of directly harnessing bacteria for public health initiatives.

**Results**

**Eating Westernized ‘Fast Food’ Style Diet Restructures the Gut Microbiome and Accelerates Age-associated Obesity in Mice**

Knowing that eating ‘fast food’ contributes to age-associated weight gain in humans, we first used animal models to test specific roles for diet and the gastrointestinal (GI) tract microbiome in obesity. Genetically outbred Swiss mice were fed an ad libitum diet of Westernized chow mimicking typical human ‘fast food’ diets that are high in fat and sugar, and low in fiber and vitamins B and D, that lead to age-associated obesity (Figure 1a). Abdominal fat examined histologically at five months of age revealed increased crown-like structures (CLS) (Figs. 1a and 1b) and a type of pyogranulomatous inflammation characteristic of obesity in humans [2]. Although both genders exhibited significant increases in fat pathology after Western chow, both CLS and pyogranulomatous inflammation lesions were more pronounced in male mice than in female mice when examined at five months of age (Fig. S1). Gastrointestinal tract microbial communities in mice changed within weeks after beginning Western diet formula (Fig. 1c; Fig. S1), showing that altered gut microbes may be associated with weight gain and obesity [1,11].

**Subjects Dining on Westernized ‘Fast Food'-style Diet Exhibit Th17-biased Immunity**

It is well established that intestinal microbes modulate host health through activities of CD4+ T cells [21–22], at least in part through IL-6-dependent reciprocal functions of anti-inflammatory Foxp3+ Treg cells and pro-inflammatory Th17 cells [6,23]. Thus, we examined T cell subpopulations and found that obese mice eating Western chow had increased frequencies of IL-17 expressing cells which is in line with a previous report [6] (Fig. 1b and 1d). Importantly, when examining peripheral blood of human subjects frequently dining on ‘fast food’ we found a similar pro-inflammatory Th17-biased profile (Fig. 1c).

**Dietary Supplementation with Probiotic Yogurt Inhibits Obesity Due to Westernized ‘Fast Food’ Style Diet**

Recent epidemiological research shows eating “yogurt” prevents age-associated weight gain in humans [1]. To examine whether this epidemiologic observation could be modeled in genetically outbred experimental animals, and as a prelude to testing isolated microbes, we first examined the effect of a commercially available probiotic yogurt by feeding 0.8ml/mouse...
mice chose similar calories when compared with obese animals, regardless of baseline diet, highlighting potential for translational medicine [6]. Fat histology: Hematoxylin and eosin, Bars = 50 μm; MLN Immunohistochemistry: Diaminobenzidine chromogen, hematoxylin counterstain, Bars = 8.3 μm.

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Probiotics Inhibit Weight Gain from Fast Food Diet

Probiotic Bacteria-consuming Slim Mice Chose Similar Calorics as Obese Animals

Another possible explanation for significantly slimmer physiques after eating L. reuteri was reduced caloric intake when eating probiotic bacteria. In order to test this, we calculated daily ‘free choice’ consumption of mouse chow in animals with L. reuteri bacteria added to their drinking water versus regular water controls. We found that L. reuteri-consuming slim mice chose similar caloric to those of the regular-water drinking obese animals (Fig. 1f), in spite of large (p<0.001) body weight discrepancies.

Probiotic Microbes Inhibit Fat Pathology by an IL-10-dependent Mechanism

Recognizing that eating probiotics made mice thin without restructuring their microbial communities or reducing food intake, we hypothesized that probiotic organisms may protect from obesity by up-regulating anti-inflammatory immune activities; in particular, levels of anti-inflammatory cytokine IL-10. This reasoning was based upon data that interleukin-10 is pivotal in mounting immune tolerance to microbes along intestinal mucosal interfaces [25–26]. In support of this concept, it was found that the Swiss mice eating L. reuteri exhibited higher levels of IL-10 protein in serum than matched control mice (Fig. 1d). To test this further, we examined C57BL/6 strain mice with deletion of the Il-10 gene and thus entirely lacking IL-10. Importantly, we found that Il-10-null animals eating Western chow with yogurt or Western chow with L. reuteri failed to benefit from probiotic bacteria and instead became obese (Fig. 3b). Likewise, C57BL/6 Rag2-deficient mice (that entirely lack functional lymphocytes) eating Westernized diets were unprotected from obesity after eating L. reuteri (N = 7 mice/group; body weight of mice eating Western diet + L. reuteri = 41.78±1.45, p = 0.1 not significant). Taken together these data indicated that probiotic microbes acted to inhibit fat pathology by an IL-10-dependent adaptive immune cell mechanism.

Probiotic-triggered Protection from Fat Pathology is Transferable to Naïve Hosts via Purified CD4+ T Cells

Based upon our earlier work [27], and that of others [7,28–30], we postulated that probiotic organisms such as L. reuteri protected from obesity by IL-10-mediated induction of lymphocytes [21–22]. To test whether probiotic-triggered lymphocytes were sufficient for reduced fat pathology we used adoptive transfer of purified CD4+ T cells into naive syngeneic C57BL/6 Rag2-deficient mice. For these experiments, cell donors were fed supplementary probiotic yogurt or ate only baseline diets, and exhibited fat pathology typical for that treatment. We found that Rag2-null recipients of cells from donor mice eating the probiotic bacteria had reduced abdominal fat pathology when compared with recipients of cells from untreated control mice (Fig. 4). Moreover, subcutaneous fat was significantly reduced in regular-chow Rag2-knockout recipients of cells from L. reuteri-consuming mice (Fig. 4a). Importantly, these protective effects required IL-10-competency in cell donor mice (Fig. 4b–c). These data showed that eating L. reuteri had a GI tract microbiome output that was not significantly different from their matched diet counterparts eating either regular chow or Western diet. Although probiotics didn’t restructure resident microbiota communities, a pre-existing diverse microbial community was required for optimal slenderizing effects as illustrated by the fact that mice raised under germ-free conditions, and then fed L. reuteri under general housing conditions, fail to benefit from eating probiotic organisms (Fig. S1h).

Eating L. reuteri Daily did not Change the Existing Gut Microbiome

Knowing that eating probiotics made mice slim, we next tested whether purified probiotic L. reuteri may act to change the microbial ecology in the gut. Using paired-end Illumina sequencing targeting the V4 region of the 16S rRNA gene on animal stools, it was found that daily intake of probiotic organisms did not change the existing gut microbiome profile (Fig. 1c). Thus, animals...
the microbe-imbued protection from obesity resided in IL-10-dependent functions of CD4+ T cells, confirming the findings of Feuerer et al (2009) who observed that protective IL-10-dependent Treg cells are associated inversely with adiposity [31].

Feeding of Purified *L. reuteri* Restores Foxp3+ Treg/Th17 Balance

Based upon earlier work by DiGiacinto et al (2005), we postulated that probiotic organisms protect from obesity by IL-10-mediated induction of anti-inflammatory Treg cells [21–22,28]. We tested whether feeding of *L. reuteri* may restore host immunity from a diet-induced pro-inflammatory Th17 bias towards a beneficial anti-inflammatory Treg cell dominated immunity. We found that slim mice eating Westernized chow plus probiotic *L. reuteri* showed significantly increased anti-inflammatory Foxp3+ Treg cells and also lower levels of IL-17A protein within abdominal lymph tissues when compared with mice feeding on Westernized *‘fast food’*-style chow alone (Figs. 1a and 1b). Further, humans frequently eating *‘fast food’* displayed a pro-inflammatory Th17-dominant phenotype when compared with control subjects who exhibited more Foxp3+ cells and fewer Th17 cells in the peripheral blood (Fig. 1e). These data are in line with an earlier study showing the importance of anti-inflammatory Treg for prevention of adiposity and insulin resistance in mouse models [31]. Thus feeding *L. reuteri* specifically induced Foxp3+ Treg cells and restored the Treg/Th17 balance observed in lean animals.
**L. reuteri** Induced Effects are Dependent on Active Immune Regulation by Foxp3+ Treg Cells

To test whether probiotic-triggered Foxp3+ regulatory T cells were the key population and sufficient for reduced fat pathology in Western diet-fed mice, we used adoptive transfer of purified CD4+Foxp3+ Treg cells delivered by intraperitoneal injection into naive syngeneic C57BL/6 Rag2-deficient mice. For these experiments, cell donors were green fluorescent protein (gfp)-Foxp3 transgenic C57BL/6 mice that had received *L. reuteri* in their drinking water, in addition to Western-style chow. We found significantly reduced abdominal fat pathology in recipients of *L. reuteri*-treated cells when compared with cells from donors eating Western diet alone (Fig. 4d). These adoptive transfer model data showed that probiotic-mediated protection from obesity resided in functions of Foxp3+ regulatory T cells. In line with these observations, selectively depleting Tregs by targeting CD25 showed similar effects. We found eight-week-old Swiss mice eating *L. reuteri* and also simultaneously treated with anti-CD25 antibody rapidly developed morbid obesity, sluggish demeanor, and profound abdominal fat pathology during the ensuing three months (Fig. 5a); whereas control animals eating *L. reuteri* and treated with sham isotype matched IgG had reduced fat pathology and slender outcomes (Figs. 5a and 5b). Requirements for CD25+ cells for slenderizing benefits of *L. reuteri* were also evident in abdominal fat weights that were significantly increased after CD25 depletion (Fig. 5c). A role for CD25 in controlling inflammatory cytokines was displayed in peripheral blood in this model (Fig. 1d). Thus, dietary supplementation with *L. reuteri* seems to restore beneficial balanced Th17/Treg host immunity, even in individuals otherwise suffering from a pro-inflammatory immunity and chronic inflammation when dining on Westernized ‘fast food’-style diets (Fig. 6).

**Discussion**

We devised an animal model to examine the mechanisms of diet [i.e., ‘fast food’ or ‘yogurt’] previously shown to impact obesity in humans [1]. Genetically outbred mice consuming ‘fast food’ mimicked adiposity patterns in people [1] and displayed enteric microbial similarities with other models and humans [11]. Mice eating yogurt – a food item most strongly linked with lean physique in human subjects [1] - were leaner than matched control animals. We demonstrate that a purified lactic acid microbe was sufficient to mediate this effect. Importantly, we show that 1) this lean outcome was achievable even while dining on Westernized chow, 2) eating probiotic microbes did not significantly change the established control or Westernized diet microbiome in stool, 3) *L. reuteri* consumption did not significantly alter the caloric intake even though mice were significantly slimmer, and 4) lean outcomes involved microbe-triggered CD4+ Foxp3+ regulatory T cells, dependent on IL-10. These observations led us to propose a circular mechanistic model where both lactic acid organisms and the resident GI microbiome [1,11] affect...
host immunity [21–22], which in turn affects obesity [31], which impact host immunity, and so forth. Once initiated, adiposity may then become a self-sustaining condition.

Consuming Westernized ‘fast food’-style chow rapidly restructured the murine microbiome coincident with increased IL-17 protein levels and developing obesity in our mouse models [11]. In our human subjects, a Th17 biased profile also emerged when eating fast food, matching that seen in animals eating the Western chow. Although the New Western diet for mice was selected specifically to mimic human ‘fast food’, the ‘potato chip’ diet of humans also includes high salt and other factors not included in mouse chow. Nonetheless, these mice exhibited elevated levels of IL-17A, whether a result of the diet, or microbes, or from the obesity itself [6]. Following this line of reasoning, the insertion of dietary probiotics may break this inflammatory-adiposity cycle. Although a Th17 pro-inflammatory bias has been clearly linked with obesity, there’s evidence of a dichotomy in effects of IL-17A in adipogenesis [6,33–34]. One possible explanation for this might be the recently uncovered heterogeneity amongst Th17 cells [35–37]. As a result, such complex immune feedback mechanisms are difficult to interrupt without untoward consequences to the host, making pro-inflammatory molecules TNF-α, IL-6 and IL-17

Figure 4. Diet-associated fat pathology is transferable to naive animals using purified T-lymphocytes. Adoptive transfer of purified CD4+ cells from C57BL/6 wild type donor mice eating probiotics into C57BL/6 Rag2-null mice was sufficient to significantly reduce recipient body fat depots such as subcutaneous fat, as well as ameliorate abdominal fat pathology (a). Control diet-fed mice used as donors for lymphocyte transfer experiments showed IL10-dependent L. reuteri benefits including significantly less CLS in their abdominal fat (b). This immune-mediated protection requires IL10, as adoptive transfer of CD4+ cells from probiotic-fed IL10-deficient donors did not protect the recipient mice from obesity and associated fat pathology (c). Purified wild type CD4+ FoxP3+ Treg cells from mice eating L. reuteri were sufficient for beneficial effects in Rag2-null recipient mice rescuing them from obesity-associated pathology (d). Skin and fat histology: Hematoxylin and eosin. Bars skin = 250 μm, epididymal fat = 50 μm. doi:10.1371/journal.pone.0068596.g004
Figure 5. Anti-obesity protection of oral probiotics in outbred Swiss mice requires CD25+ immune cells. Depletion of CD4+CD25+ Treg cells entirely inhibits probiotic-induced protection from age-associated obesity and abdominal fat pathology (a). Probiotics protect from weight gain unless mice were simultaneously treated with anti-CD25 antibody, in which case animals rapidly became obese. Frequency of prototype crown-like structures was increased in abdominal fat after depletion of CD25+ cells but not in sham IgG-treated control animals (b). Fat histology: Hematoxylin and eosin. Bars = 100 μm.
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Diverse disorders such as asthma and autoimmune disorders associated with Westernized living are widely believed to result from insufficient levels of IL-10 and insufficient immune calibration essential for sustained systemic health [60]. Westernized diets are also low in vitamin D, a nutrient that normally works together with IL-10 to enforce immune tolerance and protect against inflammatory disorders [61–63] and some types of cancer [64].

Feeding of palatable probiotic organisms offers potentially potent, cost-effective and practical options for public weight management. Apparent requirements for other beneficial resident commensal microbes may be further tested using gnotobiotic models [41,65–66]. Such microbial re-programming may ultimately target other diseases linked with obesity and inflammation such as diabetes [2], cancer [8], and multiple sclerosis [13] for healthful longevity to combat a growing Westernized ‘fast food’ public health crisis.

**Experimental Procedures**

**Animals**

Genetically outbred CD-1 mice (Charles River; Wilmington, MA), inbred *wild type* or Interleukin 10-deficient C57BL/6 strain mice (Jackson Labs, Bar Harbor, ME), plus inbred Rag2-deficient C57BL/6 strain mice and outbred Swiss Webster mice (Taconic; Germantown, NY) were housed and handled in Association for Assessment and Accreditation of Laboratory Animal Care (AAALAC)-accredited facilities with diets, experimental methods, and housing as specifically approved by the Institutional Animal Care and Use Committee. The MIT CAC (IACUC) specifically approved the studies as well as the housing and handling of these animals. Mice were bred in-house to achieve experimental groups. The experimental design was to expose mice to diets starting at age = eight weeks, and then continue the treatment for 12 weeks until euthanasia using carbon dioxide at five months of age, unless otherwise specified (Fig. S1). Each experiment included 5–15 animals per group with two replications (total N = 10–30 mice per group). For microbiome analyses, fresh stools were collected twice weekly and stored in RNA-later at −20°C for later testing. Other tissues were collected upon necropsy.

**Human Subjects and Specimen Collection**

The PhenoGenetic Cohort of Brigham and Women’s Hospital including 1200 healthy control subjects provided subject recruitment and sample collection, in compliance with the Declaration of Helsinki with local ethics committee approval before initiation, and written informed consent from all subjects. The Brigham and Womens Institutional Review Board (IRB): Partners Human Research Committee specifically approved the studies. Subjects had the following characteristics: female/male sex ratio was 60:40%; race distribution was 14% African American, 12% Asian American, 60% white, and 6% Hispanic; mean age was 24.3 y (range, 18–50 y); mean body mass index was 22.5 (range, 13–50). Blood samples were processed on the day of collection. Dietary and lifestyle behaviour was assessed by questionnaire on day of the

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**Figure 6. Proposed mechanistic overview.** In order to explain the ‘fast food’ versus ‘yogurt’ age-associated weight disparity observed in human subjects, we propose that Western-style dietary habits alter gut microbiota fueling an IL-6 driven, IL-17-dominant, systemic smoldering inflammatory milieu, ultimately leading to a vicious circle of obesity and inflammation. On the other hand, individuals consuming probiotic yogurt enrich their gut with probiotic bacteria that stimulate the anti-inflammatory arm of the immune system. Potent IL-10-associated Treg responses in these individuals rescue them from the inflammation-obesity cycle, thus increasing likelihood of a leaner physique.
visit. Total N = 23 for high fast food intake, and N = 26 for low fast food intake.

**Special Diets for Animals**

Mice of 6–8 wks were placed on experimental diets: control AIN-76A (Harlan-Teklad Madison WI), and a Westernized diet with high fat and low fiber with substandard levels of Vitamin D (TD:96096; Harlan-Teklad) starting at 8 weeks of age until euthanasia at 3 months of age. Subgroups were supplemented with commercially available vanilla probiotic yogurt (0.8 ml/mouse 3X weekly) containing a microbial cocktail including S. thermoduricus, L. acidophilus, Bifidobacterium bifidus, L. casei, and L. rhamnosus cultured as described elsewhere [24] using a dosage of 3.5×10⁵ organisms/mouse/day, or a sham E. coli K12 3.5×10⁵ organisms/mouse/day in drinking water. Drinking water was replaced at least weekly. Viability of *L. reuteri* organisms in drinking water was assessed using standard aerobic plate culture methods and determined to be too numerous to count (TNTC) at day one and less than ten colonies by day seven.

**Stool Microbiome Analyses**

Genomic DNA was extracted from stool samples using the Qiagen QIAamp DNA Stool Mini Kit. Samples for paired-end Illumina sequencing were constructed using a two-step PCR amplonc approach targeting the V4 region of the 16S rRNA gene (U515F and E786R) as described in [67] and reads were quality filtered and clustered into operational taxonomic units (OTUs) at 97% nucleotide identity. Principal coordinates analysis is based on the Jensen-Shannon divergence between samples, and differences in microbiome composition were tested for significance using an empirical p-value estimated by permutation. Data presented in Fig. 1 were from stool collected at 5 days after onset of treatments.

**Human T Cell Isolation and Stimulation**

Peripheral blood mononuclear cells (PBMC) were separated by Ficoll-Paque PLUS (GE Healthcare, Piscataway, NJ) gradient centrifugation. Untouched CD4⁺ T cells were isolated from PBMC by negative selection via the CD4⁺ lymphocytes isolated from wild type or IL-10-deficient mice or inbred C57BL/6 mice began eating special diets at 8–9 months-of-age and 9-month-old (aged L. reuteri-consumming) mice respectively in mouse tissue. Immunohistochemistry and morphometric analysis was performed using a 2-tailed student’s t-test; a p-value <0.05 was considered statistically significant.

**Supporting Information**

**Figure S1 Dietary probiotic bacteria protect mice from obesity.** The experimental time line depicts how outbred Swiss mice or inbred C57BL/6 mice began eating special diets at 8-weeks-of-age. *Ad libitum* diets were fed continuously for three months duration until mice were humanely euthanized at 5-months-of-age (a). A significantly slender body weight effect was achieved by adding 3×10⁵ *L. reuteri* organisms/mouse/day to drinking water, but similar addition of 3×10⁵ *E. coli* K12 organisms/mouse/day to drinking water did not cause significant differences when compared with untreated controls (b). Female Swiss mice eating either probiotic yogurt or purified *L. reuteri* organisms have significantly lower body weights than their non-probiotic-fed counterparts. Data are shown in 5-month-old (yogurt consuming) and 9-month-old (aged *L. reuteri*-consuming) mice (c). Similarly to what has been observed in male mice, probiotics protect female mice from abdominal fat pathology, upregulate Foxp3+ cells in the MLNs and downregulate IL-17 expression in the abdominal fat and the MLNs (d). CLS in the abdominal fat of obese male and female mice are often characterized by a robust inflammatory response with high numbers of macrophages, lymphocytes, neutrophils and myeloid precursor cells. In contrast, CLS of probiotic-fed mice maintain their typical quiescent inflammatory lesion appearance with macrophages and occasional lymphocytes bordering dead adipocytes (e). IL-17 specific immunohistochemistry shows the abundant cytoplasmic and fluorescent protein (gfp)-Foxp3, and then further purified sorting gfp⁺ expression to achieve purified populations of CD4⁺ FoxP3⁺ TREG lymphocytes injected intraperitoneally at 3×10⁵ cells/mouse into C57BL/6 Rag2⁻/⁻ recipient mice.
extracellular IL-17 found in the MLNs of western-diet fed obese Swiss mice but not in the MLNs of mice consuming the same diet plus probiotics (f). Obesity-associated adipose tissue pathology was noticed in all fat depots of the mouse body examined including the mesenteric fat shown here. Probiotics universally suppressed this pathology (g). Experiments in germ-free mice suggest that diverse bacteria are required for slim outcomes since these mice did not benefit after eating probiotics (h). p<0.05, ** p<0.001, *** p<0.0001, Hematoxylin and eosin (c and d); Diaminobenzidine chromogen, hematoxylin counterstain (d). Bars = 25 μm (c and d); 100 μm (e).

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**Author Contributions**

Conceived and designed the experiments: TP MK EJA DAH SEE. Performed the experiments: TL TP BJV YMJ RKL SM SB SMK ACG AE. Analyzed the data: TP CS MK DAH EJA SEE. Contributed reagents/materials/analysis tools: TP CS EJA. Wrote the paper: TP MK CS DAH EJA SEE.

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