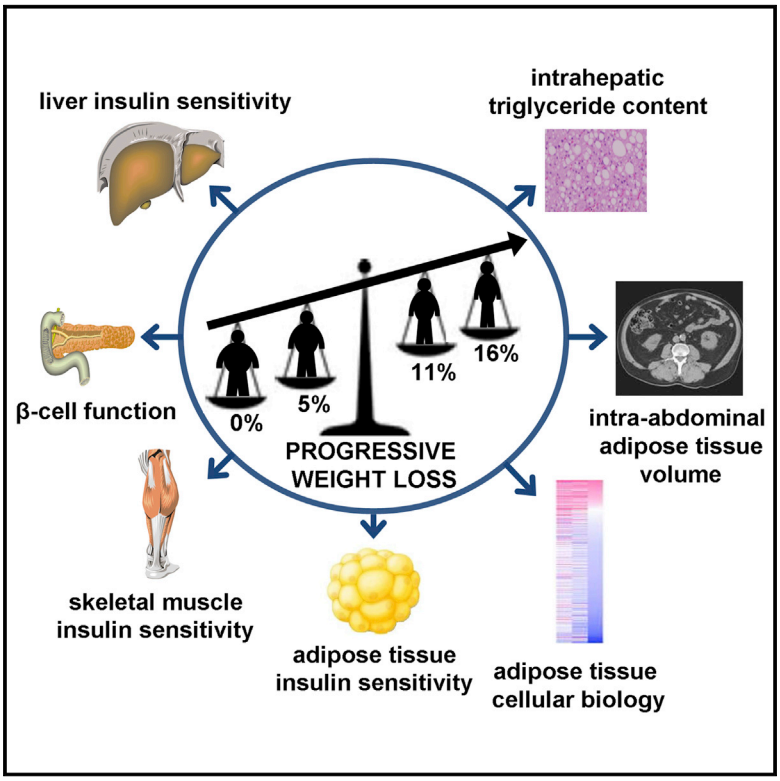
Clinical and Translational Report

Cell Metabolism

Effects of Moderate and Subsequent Progressive Weight Loss on Metabolic Function and Adipose Tissue Biology in Humans with Obesity

Graphical Abstract



Highlights

- Moderate 5% weight loss improves multi-organ insulin sensitivity and β cell function
- Additional weight loss of 11%–16% further increases insulin sensitivity in muscle
- Progressive weight loss causes stepwise changes in adipose tissue biology

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In Brief

Magkos et al. demonstrate the profound therapeutic effects of weight loss on metabolic function in subjects with obesity. Even a moderate 5% weight loss has considerable health benefits, including decreased intra-abdominal and intra-hepatic fat and increased multi-organ insulin sensitivity and β cell function. Additional weight loss further improves many cardiometabolic outcomes.

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Cell Metabolism
Clinical and Translational Report

Effects of Moderate and Subsequent Progressive Weight Loss on Metabolic Function and Adipose Tissue Biology in Humans with Obesity

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SUMMARY

Although 5%–10% weight loss is routinely recommended for people with obesity, the precise effects of 5% and further weight loss on metabolic health are unclear. We conducted a randomized controlled trial that evaluated the effects of 5.1% ± 0.9% (n = 19), 10.8% ± 1.3% (n = 9), and 16.4% ± 2.1% (n = 9) weight loss and weight maintenance (n = 14) on metabolic outcomes. 5% weight loss improved adipose tissue, liver and muscle insulin sensitivity, and β cell function, without a concomitant change in systemic or subcutaneous adipose tissue markers of inflammation. Additional weight loss further improved β cell function and insulin sensitivity in muscle and caused stepwise changes in adipose tissue mass, intrahepatic triglyceride content, and adipose tissue expression of genes involved in cholesterol flux, lipid synthesis, extracellular matrix remodeling, and oxidative stress. These results demonstrate that moderate 5% weight loss improves metabolic function in multiple organs simultaneously, and progressive weight loss causes dose-dependent alterations in key adipose tissue biological pathways.

INTRODUCTION

Obesity is associated with a constellation of cardiometabolic abnormalities including insulin resistance, β cell dysfunction, nonalcoholic fatty liver disease, dyslipidemia, and hypertension, which are important risk factors for the development of serious medical complications such as type 2 diabetes and coronary heart disease (Klein et al., 2002; Kopelman, 2000). Most treatment guidelines, including those recently proposed by several major medical and scientific societies, recommend moderate weight loss of 5%–10% to achieve improvements in metabolic function and health outcomes (Jensen et al., 2014). However, it is much easier to achieve a 5% weight loss than it is to achieve a 10% weight loss, so it is important to understand the cardiometabolic benefits that occur with a 5% weight loss and what additional benefits, if any, can be expected with more weight loss in people with obesity. Several large randomized controlled weight loss trials retrospectively evaluated the effects of different amounts of weight loss on clinical outcomes (Wing et al., 1987; Wing et al., 2011). However, the weight loss stratification used in these studies combined the results from subjects who lost 5% through 10% of their body weight into one group; we are not aware of any trials that separated the weight loss outcomes in those who achieved 5% from those who achieved 10% weight loss, either prospectively or retrospectively.

The mechanism(s) responsible for the beneficial effects of weight loss on cardiometabolic outcomes is not known but presumably involves a reversal of the mechanism(s) responsible for the adverse effects of weight gain. It has been proposed that a pathological expansion of adipose tissue mass causes an increase in adipose tissue inflammation, manifested by alterations in adipose tissue immune cell populations and increased gene expression of pro-inflammatory cytokines and chemokines, which cause systemic inflammation and insulin resistance (Berg and Scherer, 2005; Ferrante, 2007; Hotamisligil, 2006; Sun et al., 2013). However, the importance of decreasing adipose tissue and systemic inflammation in the beneficial metabolic effects of weight loss is unclear because of conflicting results from different studies, reporting decreases, increases, and no changes in markers of inflammation after diet-induced weight loss (Capel et al., 2009; Clément et al., 2004; Dahlman et al., 2005; Johansson et al., 2012; Mališová et al., 2014; Solá et al., 2009). Therefore, a simultaneous assessment of the effects of moderate weight loss on metabolic function and adipose tissue inflammation in people with obesity could help elucidate the potential physiological significance of inflammation on metabolic dysfunction.

The purpose of the present study was to conduct a randomized controlled trial in persons who are obese and have evidence of insulin-resistant glucose metabolism to determine: (1) the therapeutic effects of 5% weight loss on cardiometabolic

Table 1. Effect of 5% Weight Loss on Body Composition and Cardiometabolic Risk Factors

	Weight Maintenance (n = 14)		Weight Loss (n = 19)		Interaction
	Baseline	Weight Maintenance	Baseline	5% Weight Loss	p Value
Weight (kg)	106.6 ± 15.0	106.7 ± 14.7	106.2 ± 16.8	100.8 ± 16.2*	<0.001
BMI (kg/m^2)	37.9 ± 4.4	38.0 ± 4.4	37.8 ± 4.4	35.9 ± 4.3*	<0.001
Body fat (%)	45.4 ± 6.3	45.6 ± 6.5	47.9 ± 4.9	46.3 ± 5.2*	<0.001
Fat mass (kg)	48.7 ± 11.6	49.0 ± 11.8	51.0 ± 10.1	46.7 ± 9.6*	<0.001
Fat-free mass (kg)	57.1 (53.3, 63.4)	56.9 (53.2, 62.4)	53.0 (46.7, 56.8)	51.5 (47.0, 55.5)*	0.032
Intra-abdominal adipose tissue (cm^3)	1,456 ± 593	1,585 ± 733*	1,409 ± 508	1,294 ± 431*	0.004
Intrahepatic triglyceride (%)	7.5 (4.1, 16.2)	6.0 (3.4, 16.8)	6.7 (3.3, 11.2)	3.8 (1.5, 7.8)*	0.023
Free fatty acids, basal (mmol/L)	0.48 (0.40, 0.52)	0.49 (0.44, 0.59)	0.55 (0.47, 0.58)	0.54 (0.45, 0.66)	0.341
Glucose, basal (mg/dL)	98 (91, 101)	98 (93, 104)	95 (92, 103)	91 (88, 96)*†	0.040
Insulin, basal (mU/L)	20.6 (15.7, 29.0)	21.3 (19.1, 26.7)	16.7 (13.3, 22.6)	15.0 (9.6, 18.9)*†	0.028
SBP, 24 hr (mmHg)	117 ± 12	121 ± 13	122 ± 11	118 ± 11*	0.028
DBP, 24 hr (mmHg)	67 (58, 72)	67 (65, 72)	72 (66, 77)	71 (66, 74)	0.176
Heart rate, 24 hr (bpm)	78 ± 9	79 ± 6	78 ± 9	74 ± 9*	0.034
Triglyceride (mg/dL)	107 (86, 141)	114 (63, 158)	153 (106, 201)	105 (69, 162)*	0.023
HDL cholesterol (mg/dL)	47 ± 17	46 ± 15	41 ± 8	40 ± 7	0.724
LDL cholesterol (mg/dL)	119 (88, 136)	105 (91, 114)	100 (90, 126)	98 (86, 121)	0.888
Alanine transaminase (U/L)	17.0 (12.5, 30.5)	17.0 (14.8, 25.5)	18.0 (13.5, 23.5)	15.0 (12.0, 17.0)*†	0.048
Leptin (ng/mL)	45.5 (25.9, 48.8)	40.4 (27.9, 55.9)	47.3 (25.2, 57.8)	38.2 (26.7, 46.2)*	0.006
Adiponectin (μg/mL)	4.36 (2.38, 8.31)	4.89 (2.88, 8.95)	6.06 (4.58, 6.85)	6.06 (4.72, 7.44)	0.408
C-reactive protein (mg/L)	3.59 (1.21, 4.92)	4.36 (8.21, 6.13)	3.70 (2.34, 5.90)	4.68 (2.38, 7.30)	0.538
Interleukin-6 (ng/mL)	2.5 ± 1.0	2.7 ± 1.5	2.0 ± 0.5	2.2 ± 0.7	0.909
MCP-1 (pg/mL)	150 (125, 194)	174 (149, 190)*	136 (115, 168)	144 (123, 166)*	0.260
WBC count (10^3/mL)	6.2 ± 1.4	6.1 ± 1.7	6.8 ± 1.8	7.0 ± 1.7	0.466

Data are means ± SD for normally distributed variables or medians (quartile 1, quartile 3) for not normally distributed variables. The effect of time (before versus after) and differences between groups (weight maintenance versus weight loss) were evaluated with repeated-measures ANOVA for normally distributed variables or Friedman's test for not normally distributed variables. Significant time-by-group interactions were followed by appropriate within- and between-group post hoc tests. *$p < 0.05$ versus baseline and †$p < 0.05$ versus weight maintenance group after the intervention. There were no significant differences between groups at baseline.

Abbreviations: SBP, systolic blood pressure; DBP, diastolic blood pressure; HDL, high-density lipoprotein; LDL, low-density lipoprotein; MCP-1, monocyte chemoattractant protein-1; WBC, white blood cell.

outcomes, including body composition (total body fat mass, intra-abdominal fat volume, and intrahepatic triglyceride content), 24 hr ambulatory blood pressure and heart rate, plasma lipid profile, β cell function, and multi-organ (adipose tissue, liver, and muscle) insulin sensitivity; (2) whether 5% weight loss-induced cardiometabolic benefits are associated with a reduction in systemic or subcutaneous adipose tissue markers of inflammation; and (3) the effects of progressive 5%, 10%, and 15% weight loss on cardiometabolic outcomes and global adipose tissue gene expression profile.

RESULTS AND DISCUSSION

Weight Loss Targets Were Effectively Achieved

40 subjects were randomized to either weight maintenance (n = 20; 14 completed [five withdrew after being informed of their randomization and one subsequently dropped out], 46 ± 13 years old, 11 women and 3 men) or diet-induced weight loss (n = 20; 19 completed [one dropped out], 43 ± 11 years old; 16 women and 3 men) (Figure S1). 19 subjects in the weight loss group achieved the initial targeted 5% weight loss (5.1% ± 0.9% actual weight loss); 9 of these subjects (44 ± 12 years old; 8 women and 1 man) successfully achieved the subsequent weight loss targets of ~10% and ~15% (the actual mean weight losses achieved were 10.8% ± 1.3% and 16.4% ± 2.1%). Subjects were studied when they were weight stable (<2% weight change for at least 3 weeks; Figure S2) before and after a median (quartiles) of 6.1 (5.9, 6.7) months in the weight maintenance group and after 5% weight loss at 3.5 (2.9, 4.6) months, 11% weight loss at 6.8 (6.0, 8.6) months, and 16% weight loss at 10.4 (9.6, 11.4) months in the weight loss group.

5% Weight Loss Improves Body Composition and Multiple Risk Factors for Cardiometabolic Disease, and Progressive Weight Loss Causes further Benefits

5% weight loss resulted in a 2% ± 2% decrease in fat-free mass (FFM), an 8% ± 3% decrease in body fat mass, a 7% ± 12% decrease in intra-abdominal adipose tissue (IAAT) volume, and a 40% ± 21% decrease in intrahepatic triglyceride (IHTG) content (Table 1). 5% weight loss significantly decreased the plasma concentrations of some risk factors for cardiometabolic disease (glucose, insulin, triglyceride, alanine transaminase, and leptin)

Table 2. Effect of Progressive Weight Loss on Body Composition and Cardiometabolic Risk Factors

	Progressive Weight Loss (n = 9)				Effect of Time
	Baseline	5% Weight Loss	11% Weight Loss	16% Weight Loss	p Value
Weight (kg)†	103.8 ± 16.4	97.9 ± 15.7*	92.5 ± 14.4*	87.0 ± 14.9*	<0.001
BMI (kg/m^2)†	37.7 ± 4.5	35.5 ± 4.3*	33.6 ± 3.9*	31.6 ± 4.1*	<0.001
Body fat (%)†	48.3 ± 4.3	46.3 ± 4.8*	44.2 ± 4.5*	42.2 ± 5.0*	<0.001
Fat mass (kg)†	50.3 ± 10.2	45.4 ± 9.6*	41.1 ± 8.6*	36.9 ± 8.8*	<0.001
Fat-free mass (kg)†	53.0 (46.3, 55.6)	51.5 (45.7, 54.1)*	50.2 (45.2, 53.2)*	49.0 (44.1, 51.4)*	<0.001
Intra-abdominal adipose tissue (cm^3)†	1,656 ± 559	1,501 ± 469	1,277 ± 474*	1,154 ± 457*	<0.001
Intrahepatic triglyceride (%)†‡	8.5 (3.9, 25.9)	7.4 (3.0, 12.5)*	4.1 (1.1, 10.2)*	3.0 (1.1, 5.2)*	<0.001
Free fatty acids, basal (mmol/L)†	0.56 (0.55, 0.65)	0.56 (0.48, 0.64)	0.49 (0.46, 0.58)	0.47 (0.44, 0.55)*	0.050
Glucose, basal (mg/dL)	92.7 ± 8.9	89.4 ± 4.9	89.3 ± 5.7	88.6 ± 2.7	0.288
Insulin, basal (mU/L)†	18.3 ± 7.7	15.5 ± 6.1	12.6 ± 5.5*	9.5 ± 2.8*	<0.001
Triglyceride (mg/dL)†	153 ± 56	130 ± 71	110 ± 59*	97 ± 39*	0.003
HDL cholesterol (mg/dL)	43 ± 10	41 ± 7	42 ± 7	44 ± 7	0.261
LDL cholesterol (mg/dL)	115 (95, 135)	98 (91, 127)	101 (90, 136)	91 (85, 125)	0.162
Alanine transaminase (U/L)†	18.0 (11.5, 25.0)	15.0 (12.0, 16.5)	11.0 (10.0, 16.0)	11.0 (9.5, 14.5)*	0.015
Leptin (ng/mL)†	43.0 ± 13.5	32.8 ± 13.6*	27.1 ± 9.9*	18.6 ± 6.5*	<0.001
Adiponectin (μg/mL)†‡	6.23 ± 2.73	6.34 ± 2.35	6.87 ± 2.63	8.30 ± 3.51*	<0.001
C-reactive protein (mg/L)†‡	4.69 (3.44, 7.84)	4.74 (2.40, 11.24)	5.47 (2.27, 8.30)	3.14 (1.01, 4.43)*	0.019
Interleukin-6 (ng/mL)	2.0 ± 0.6	2.1 ± 0.8	2.1 ± 0.7	2.3 ± 1.0	0.826
MCP-1 (pg/mL)	136 (124, 159)	144 (127, 162)	140 (122, 153)	138 (129, 173)	0.790
WBC count (10^3/mL)	6.8 ± 1.4	7.5 ± 1.5	7.4 ± 1.8	6.8 ± 1.3	0.056

Data are means ± SD for normally distributed variables or medians (quartile 1, quartile 3) for not normally distributed variables. The main effect of time was evaluated with repeated-measures ANOVA for normally distributed variables or Friedman's test for not normally distributed variables. Significant effects of time were followed by simple contrasts to assess differences from baseline and trend analysis to assess the linear, quadratic, and cubic components of the overall time-related change. *$p < 0.05$ versus baseline; †$p < 0.05$ for linear component and ‡$p < 0.05$ for quadratic component. Abbreviations: HDL, high-density lipoprotein; LDL, low-density lipoprotein; MCP-1, monocyte chemoattractant protein-1; WBC, white blood cell.

but did not affect others (free fatty acids, low- and high-density lipoprotein [LDL and HDL, respectively] cholesterol, and adiponectin) (Table 1). 5% weight loss decreased 24 hr ambulatory heart rate and 24 hr ambulatory systolic, but not diastolic, blood pressure (Table 1). The reductions in FFM, fat mass, IAAT volume, IHTG content, fasting plasma insulin, leptin, and triglyceride concentrations continued with progressive weight loss up to 16% of initial body weight in a predominantly linear fashion, whereas plasma free fatty acid and CRP concentrations decreased and plasma adiponectin concentration increased significantly only after 16% weight loss (Table 2).

5% Weight Loss Improves Multi-organ Insulin Sensitivity, and Progressive Weight Loss Has Organ-Specific and Dose-Dependent Effects

5% weight loss did not affect standard measures of glycemic control evaluated by using the oral glucose tolerance test (OGTT), including the 2 hr plasma glucose concentration and total glucose area under the curve (AUC) (Table 3). In contrast, more sensitive measures of organ-specific insulin action, assessed by using a two-stage hyperinsulinemic-euglycemic clamp procedure in conjunction with infusion of stable isotopically labeled tracers, demonstrated an improvement in adipose tissue insulin sensitivity (insulin-mediated suppression of palmitate rate of appearance [Ra] in plasma), liver insulin sensitivity (insulin-mediated suppression of glucose Ra in plasma), and skeletal muscle insulin sensitivity (insulin-mediated stimulation of glucose rate of disappearance [Rd] from plasma) (Table 3). The improvements in insulin-mediated suppression of palmitate Ra and glucose Ra plateaued after 5% weight loss, whereas insulin-mediated stimulation of glucose Rd increased further with 11%–16% weight loss (Table 4).

These data show that the relationship between weight loss and improvement in insulin sensitivity is organ specific; maximal benefits in insulin-mediated suppression of hepatic glucose production and adipose tissue lipolytic activity occur after 5% weight loss, whereas insulin-stimulated muscle glucose uptake continues to increase with greater amounts of weight loss. In addition, these results help clarify the relationship between weight loss and skeletal muscle insulin sensitivity. The minimum amount of weight loss needed to increase skeletal muscle insulin sensitivity has been unclear because of conflicting data from different studies reporting either no change or increased insulin-stimulated glucose uptake after 6%–8% weight loss (Kirk et al., 2009; Petersen et al., 2005; Petersen et al., 2012). However, those studies were conducted in small numbers of subjects, which might have limited their ability to detect statistically significant effects. Our results, obtained from a much larger group, demonstrate that 5% weight loss increases insulin-stimulated glucose uptake by ~25% in people who are obese and have some degree of insulin resistance, but not diabetes. Furthermore, skeletal muscle insulin sensitivity continued to

Table 3. Effect of 5% Weight Loss on Multi-organ Insulin Sensitivity and β Cell Function

	Weight Maintenance (n = 14)		Weight Loss (n = 19)		Interaction
	Baseline	Weight Maintenance	Baseline	5% Weight Loss	p Value
Glucose, 2 hr (mg/dL)	157 ± 29	151 ± 36	138 ± 22	141 ± 24	0.295
Glucose AUC (mg/dL·min)	18,115 (15,844, 19,883)	17,876 (15,237, 20,352)	16,991 (15,182, 19,244)	16,692 (15,612, 18,084)	0.889
Insulin AUC (mU/L·min)	12,379 (10,591, 17,468)	13,912 (11,919, 17,370)	12,365 (8,515, 18,250)	12,554 (6,952, 18,063)	0.346
Insulin secretion rate AUC (pmol/L)	34,606 ± 5,470	34,468 ± 5,658	31,820 ± 9,706	32,700 ± 12,059	0.717
Φ-static (10^9/min)	63.6 (45.4, 85.9)	67.5 (49.1, 84.9)	66.9 (48.8, 104.3)	72.0 (56.1, 134.4)	0.556
Φ-dynamic (10^9)	939 (700, 1,975)	1,201 (803, 1,599)	1,263 (733, 1,934)	1,340 (822, 2,214)	0.750
Φ-total (10^9/min)	35.2 (32.2, 40.9)	35.3 (33.5, 42.1)	32.8 (27.2, 42.7)	36.6 (27.9, 43.4)	0.952
Insulin clearance rate (pools/min)	0.39 ± 0.10	0.36 ± 0.07	0.37 ± 0.08	0.41 ± 0.11*	0.023
β cell function[a]	6,555 ± 3,768	6,195 ± 3,692	7,102 ± 4,321	9,165 ± 3,609*†	0.026
Basal palmitate Ra (μmol/kg FFM·min)	2.0 (1.7, 2.2)	2.1 (1.6, 2.8)	2.1 (1.7, 2.7)	1.9 (1.4, 2.3)*	0.047
Palmitate Ra suppression (%)	53 ± 14	49 ± 13	52 ± 12	58 ± 14*†	0.009
Basal glucose Ra (μmol/kg FFM·min)	15.7 ± 1.3	16.4 ± 2.3	16.4 ± 2.5	15.9 ± 2.0	0.088
Glucose Ra suppression (%)	70 (51, 76)	64 (46, 74)	71 (66, 76)	75 (64, 83)*†	0.026
Basal glucose Rd (μmol/kg FFM·min)	16.2 ± 1.3	16.9 ± 2.3	16.9 ± 2.6	16.4 ± 2.0	0.084
Glucose Rd stimulation (%)	161 (103, 236)	139 (98, 216)	185 (109, 248)	235 (179, 421)*†	0.002

Data are means ± SD for normally distributed variables or medians (quartile 1, quartile 3) for not normally distributed variables. The effect of time (before versus after) and differences between groups (weight maintenance versus weight loss) were evaluated with repeated-measures ANOVA for normally distributed variables or Friedman's test for not normally distributed variables. Significant time-by-group interactions were followed by appropriate within- and between-group post hoc tests. *$p < 0.05$ versus baseline and †$p < 0.05$ versus weight maintenance group after the intervention. There were no significant differences between groups at baseline.

Abbreviations: AUC, area under the concentration versus time curve; Ra, rate of appearance; FFM, fat-free mass; Rd, rate of disappearance.

[a]An index of β cell function was calculated as the product of Φ-total assessed during the oral glucose tolerance test and the relative increase in glucose Rd during high-dose insulin infusion (stage 2) of the clamp procedure.

increase with greater weight loss. Although a maximal 2-fold increase in insulin-stimulated glucose uptake was observed after 11%–16% weight loss in our subjects, we cannot exclude the possibility that greater weight loss would result in even greater improvement. However, we previously found that 20% weight loss induced by bariatric surgery also caused a 2-fold increase in insulin-stimulated glucose uptake (Bradley et al., 2012), suggesting that most of the beneficial effect of weight loss on muscle insulin action in people occurs after an 11%–16% decline in body weight.

Weight Loss Increases Insulin Clearance and Improves β Cell Function

5% weight loss significantly increased insulin clearance rate but did not affect indices of insulin secretion, determined by modeling the data from the OGTT, including insulin concentration AUC, insulin secretion rate AUC, and β cell responsivity (Φ-dynamic, which is a measure of insulin secretion in response to the rate of change in glucose concentration; Φ-static, which is a measure of insulin secretion in response to a given glucose concentration; and Φ-total, which is a measure of the total insulin secretory response) (Table 3). However, 5% weight loss improved overall β cell function, determined by an assessment of insulin secretion in response to glucose ingestion in relationship to insulin sensitivity (product of Φ-total during the OGTT and the relative increase in insulin-stimulated glucose disposal during the hyperinsulinemic euglycemic clamp procedure) (Table 3). Progressive weight loss decreased insulin AUC during the OGTT after 16% weight loss but did not affect the insulin secretory response to plasma glucose (Φ-static, Φ-dynamic, and Φ-total indices of β cell responsivity and total insulin secretion rate AUC) (Table 4). These results suggest the decrease in plasma insulin concentration was primarily due to an increase in insulin clearance, not a decrease in insulin secretion. The overall index of β cell function increased with progressive weight loss in concert with the improvement in muscle insulin sensitivity (Table 4).

The assessment of overall β cell function is more informative than simply measuring the insulin secretory response alone because the insulin secretion rate and plasma insulin concentration needed to maintain normal glucose homeostasis depends on a person's sensitivity to insulin (Bergman et al., 2002). Accordingly, a lower plasma insulin concentration is needed to maintain normal glucose homeostasis in insulin-sensitive compared to insulin-resistant people, and a compensatory increase in insulin secretion can maintain normal glucose homeostasis in those who are insulin resistant. The improvement in overall β cell function observed in our subjects was primarily due to an increase in insulin sensitivity without a significant change in the insulin secretory response to plasma glucose. However, plasma insulin concentrations in response to glucose ingestion decreased with progressive weight loss because of a progressive increase in insulin clearance. Weight loss-induced changes in β cell function have important clinical implications in preventing and treating type 2 diabetes: impaired β cell

Table 4. Effect of Progressive Weight Loss on Multi-organ Insulin Sensitivity and β Cell Function

	Progressive Weight Loss (n = 9)				Effect of Time
	Baseline	5% Weight Loss	11% Weight Loss	16% Weight Loss	p Value
Glucose, 2 hr (mg/dL)	132.6 ± 24.6	136.8 ± 29.1	140.2 ± 24.0	143.8 ± 37.3	0.659
Glucose AUC (mg/dL·min)	16,558 (15,031, 18,463)	15,790 (15,190, 18,785)	17,300 (15,772, 19,977)	16,665 (16,211, 18,812)	0.182
Insulin AUC (mU/L·min)	12,365 (9,025, 21,012)	12,950 (7,352, 17,370)	11,137 (7,965, 17,654)	9,534 (6,548, 14,417)*	0.024
Insulin secretion rate AUC (pmol/L)	33,269 ± 9,105	33,550 ± 9,246	33,952 ± 10,172	31,648 ± 8,859	0.727
Φ-static (10^9/min)	67.1 (51.5, 113.4)	59.7 (53.8, 118.7)	70.5 (62.0, 74.8)	69.4 (57.1, 84.4)	0.865
Φ-dynamic (10^9)	1,264 (735, 1,861)	1,206 (769, 1,985)	1,125 (981, 1,605)	1,243 (769, 1,390)	0.435
Φ-total (10^9/min)	36.1 ± 9.3	35.7 ± 7.6	38.3 ± 9.1	36.7 ± 10.1	0.839
Insulin clearance rate (pools/min)†	0.36 ± 0.09	0.40 ± 0.12	0.41 ± 0.11	0.48 ± 0.14*	0.016
β cell function[a]	6,860 ± 4,808	8,130 ± 3,565	10,607 ± 2,508*	11,107 ± 2,666*	0.003
Basal palmitate Ra (μmol/kg FFM·min)†	2.7 ± 1.1	2.4 ± 1.0	2.0 ± 0.5*	1.9 ± 0.4*	0.022
Palmitate Ra suppression (%)†‡	53 ± 12	63 ± 14*	67 ± 11*	62 ± 15*	0.006
Basal glucose Ra (μmol/kg FFM·min)	16.8 ± 2.3	16.3 ± 2.3	16.4 ± 2.8	16.1 ± 1.3	0.573
Glucose Ra suppression (%)†	71 ± 13	77 ± 10*	76 ± 11*	80 ± 6*	0.028
Basal glucose Rd (μmol/kg FFM·min)	17.2 ± 2.3	16.7 ± 2.3	16.8 ± 2.8	16.5 ± 1.3	0.530
Glucose Rd stimulation (%)†	168 (94, 297)	207 (149, 306)*	326 (233, 379)*	311 (248, 388)*	0.009

Data are means ± SD for normally distributed variables or medians (quartile 1, quartile 3) for not normally distributed variables. The main effect of time was evaluated with repeated-measures ANOVA for normally distributed variables or Friedman's test for not normally distributed variables. Significant effects of time were followed by simple contrasts to assess differences from baseline and trend analysis to assess the linear, quadratic, and cubic components of the overall time-related change. *$p < 0.05$ versus baseline; †$p < 0.05$ for linear component and ‡$p < 0.05$ for quadratic component.
Abbreviations: AUC, area under the concentration versus time curve; Ra, rate of appearance; FFM, fat-free mass; Rd, rate of disappearance.
[a]An index of β cell function was calculated as the product of Φ-total assessed during the oral glucose tolerance test and the relative increase in glucose Rd during high-dose insulin infusion (stage 2) of the clamp procedure.

function is an important risk factor for future development of type 2 diabetes (Lorenzo et al., 2010), and an improvement in β cell function after weight loss induced by Roux-en-Y gastric bypass surgery is an important determinant of which patients will achieve diabetes remission (Khanna et al., 2015; Lund et al., 2015).

5% Weight Loss Does Not Affect Systemic or Subcutaneous Adipose Tissue Markers of Inflammation, but Progressive Weight Loss Causes Progressive Changes in Subcutaneous Adipose Tissue Metabolic Pathways Involved in Regulating Lipid Metabolism, Extracellular Matrix Remodeling, and Oxidative Stress

Markers of inflammation in the systemic circulation (plasma concentrations of interleukin-6 [IL-6], C-reactive protein [CRP], and white blood cell [WBC] count) and in subcutaneous adipose tissue (gene expression of *IL-6*, monocyte chemoattractant protein-1 [*MCP1*], and *CD68*) were increased in subjects with obesity compared with a group of lean adults that we studied previously (Yoshino et al., 2012) (Table S1 and Figure S3). However, 5% weight loss did not decrease the plasma concentrations of several circulating inflammatory markers, such as IL-6, MCP1, CRP, or WBC count (Table 1), and did not significantly alter, or tend to increase, subcutaneous adipose tissue gene expression of the pro-inflammatory cytokines *IL-6* and tumor necrosis factor (*TNF*), major chemokines (*MCP1* and regulated on activation normal T cell expressed and secreted [*RANTES*]), and macrophage markers (*CD68* and *EMR1*) (Figure 1).

Parametric analysis of gene-set enrichment (PAGE) was performed on microarray data to determine global transcriptional changes in abdominal subcutaneous adipose tissue induced by progressive weight loss (Figure 2A and Table S2). Biological pathways related to lipid flux (e.g., REACTOME_HDL_MEDIATED_LIPID_TRANSPORT and REACTOME_LIPOPROTEIN_METABOLISM) were significantly upregulated by weight loss, whereas numerous pathways related to lipid synthesis (e.g., KEGG_BIOSYNTHESIS_OF_UNSATURATED_FATTY_ACIDS and REACTOME_TRIGLYCERIDE_BIOSYNTHESIS), extracellular matrix (ECM) remodeling (e.g., NABA_MATRISOME, REACTOME_CELL_EXTRACELLULAR_MATRIX_INTERACTIONS, and KEGG_FOCAL_ADHESION), and oxidative stress (e.g., OXIDOREDUCTASE_ACTIVITY and RESPONSE_TO_OXIDATIVE_STRESS) were markedly downregulated by weight loss (Figure 2B). Consistent with these alterations in biological pathways, progressive weight loss caused a progressive increase in subcutaneous adipose tissue expression of genes involved in cholesterol flux (*ABCG1*, *ABCA1*, *APOE*, and *CETP*) and a progressive decrease in adipose tissue expression of genes involved in lipid synthesis (*SCD*, *FADS1*, *FADS2*, and *ELOVL6*), ECM remodeling (*SPARC*, *MAFP5*, *LOX*, *LOXL2*, *ANGPT1*, and *ADAM12*), and oxidative stress (*NQO1*, *DHCR24*, and *UCHL1*) (Figure 2C). In addition, progressive weight loss moderately decreased (*COL3A1*) or did not affect (*COL1A1* and *COL6A1*) gene expression of ECM structural markers and decreased gene expression of selected markers of adipogenesis (*PPARG* and *CEBPA*) in subcutaneous adipose tissue (Figures S4A and S4B, respectively).

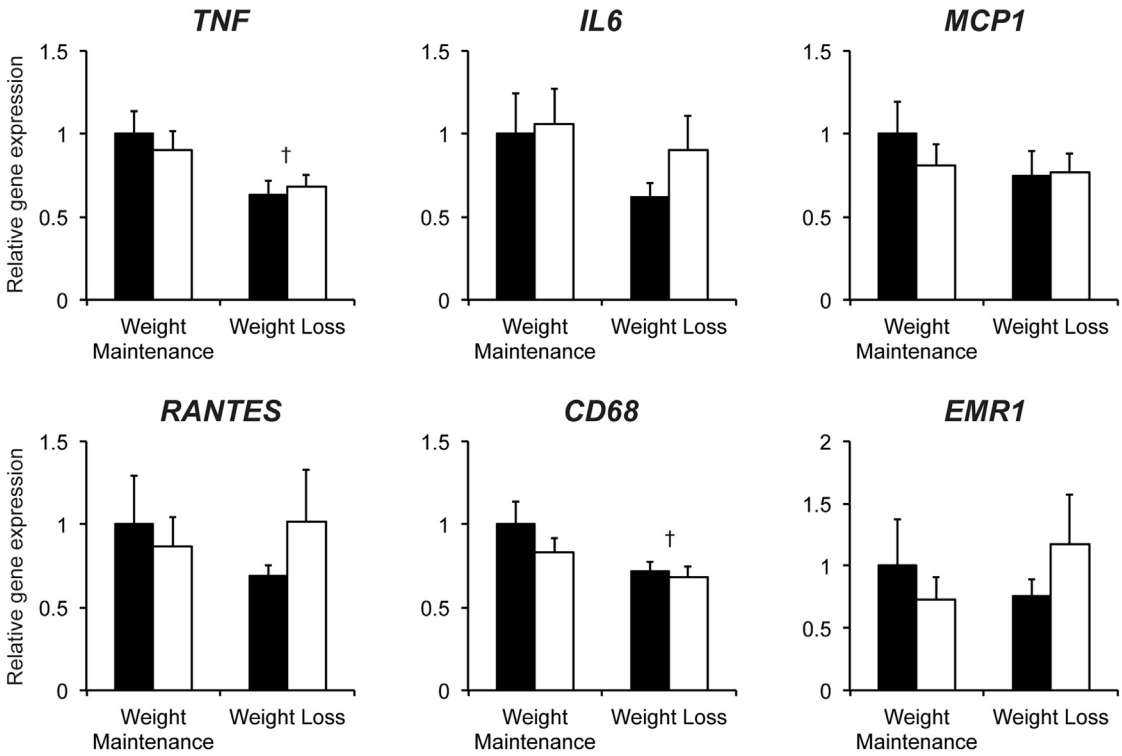

Figure 1. Effect of 5% Weight Loss on Subcutaneous Adipose Tissue Gene Expression of Inflammatory Markers

Subcutaneous abdominal adipose tissue expression of genes involved in inflammation was determined by real-time PCR before (black bars) and after (white bars) 5% weight loss (n = 19) or weight maintenance (n = 12). The effect of time (before versus after) and differences between groups (weight maintenance versus weight loss) were evaluated by using repeated-measures ANOVA. Significant time-by-group interactions were followed by appropriate within- and between-group post hoc tests. Not normally distributed variables were log transformed for analysis and back transformed for presentation. Data are means ± SEM. No effects of weight loss were detected. $^{\dagger}p < 0.05$ versus weight maintenance group before and after the intervention.

Abbreviations: *TNF*, tumor necrosis factor; *IL6*, interleukin 6; *MCP1*, monocyte chemoattractant protein 1; *RANTES*, regulated on activation normal T cell expressed and secreted; *CD68*, cluster of differentiation 68; *EMR1*, EGF-like module-containing mucin-like hormone receptor-like 1.

There was also a trend toward an increase in subcutaneous adipose tissue biological pathways involved in immune function and inflammation (e.g., REACTOME_ADAPTIVE_IMMUNE_SYSTEM, REACTOME_IMMUNE_SYSTEM, IMMUNE_SYSTEM_PROCESS) after 5% weight loss, followed by a subsequent decline in these pathways with progressive weight loss and a significant decrease after 16% weight loss (Figure S4C). Progressive weight loss tended to downregulate subcutaneous adipose tissue expression of genes involved in inflammation after 11%–16% weight loss (Figure S4D).

Our findings demonstrate that adipose tissue is a dynamic organ that is extraordinarily responsive to diet-induced weight loss. Adipose tissue biological pathways and genes involved in cholesterol flux progressively increased, whereas those involved in lipid synthesis, ECM remodeling, and oxidative stress progressively decreased, with continued 5%–16% weight loss. Data from studies conducted in rodent models demonstrate that adipocyte-specific genetic manipulation of many of the same metabolic pathways that were affected by diet-induced weight loss in our subjects, namely the cholesterol transporter ABCA1 (de Haan et al., 2014), regulators of cellular oxidative stress (Chutkow et al., 2010; Xue et al., 2013), and production of ECM components (Halberg et al., 2009; Sun et al., 2013), can influence insulin sensitivity and whole-body glucose and lipid metabolism. Moreover, it was recently shown that increased adipose tissue markers of oxidative stress are associated with high-calorie diet-induced insulin resistance in people (Boden et al., 2015). Although our study cannot determine whether the weight loss-induced changes in adipose tissue biological pathways contributed to the improvement observed in multi-organ insulin sensitivity, our data support the mechanistic links between whole-body metabolic function and adipose tissue cholesterol transport, ECM formation, and oxidative stress identified in animal models.

People with obesity and metabolic abnormalities often have concomitant systemic and adipose tissue "inflammation," manifested by increased circulating inflammatory proteins and white blood cells, and increased subcutaneous adipose tissue macrophages, pro-inflammatory $CD4^{+}$ T-lymphocytes, and increased gene expression of pro-inflammatory cytokines and chemokines (Fabbrini et al., 2013; Weisberg et al., 2003). Although a mechanistic relationship between inflammation and metabolic dysfunction has been demonstrated in rodent models (Berg and Scherer, 2005; Brestoff and Artis, 2015; Ferrante, 2007; Hotamisligil, 2006; Hotamisligil et al., 1995; Sun et al., 2013), the importance of low-grade inflammation in the pathogenesis of obesity-related insulin resistance in people is not clear, and moderate 5%–6% weight gain decreases insulin sensitivity in people without

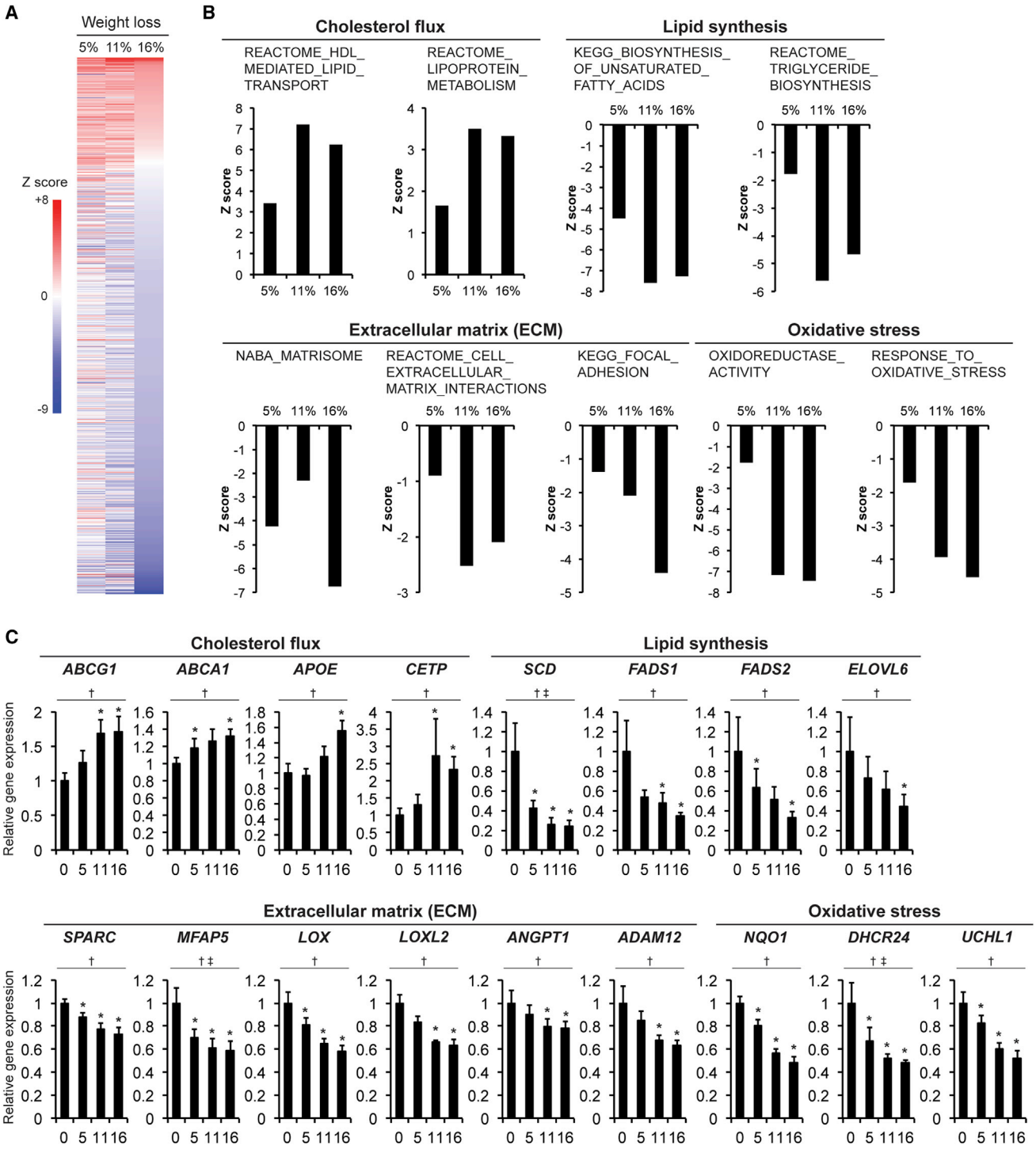

Figure 2. Effect of Progressive Weight Loss on Subcutaneous Adipose Tissue Gene Expression Profile

Parametric analysis of gene-set enrichment (PAGE) was performed on microarray data to identify biological pathways in subcutaneous abdominal adipose tissue that increased (red) or decreased (blue) with progressive weight loss in subjects with obesity (n = 9).

(A) Biological pathways that were significantly affected by 5%, 11%, or 16% weight loss, based on the Z score between baseline (before weight loss) and 16% weight loss.

(B) Biological pathways involved in regulating cholesterol flux were significantly upregulated, and pathways involved in lipid synthesis, regulating extracellular matrix (ECM) remodeling, and oxidative stress were significantly downregulated by progressive weight loss.

(C) Subcutaneous abdominal adipose tissue expression of genes involved in regulating cholesterol flux, synthesis, ECM remodeling, and oxidative stress was determined by real-time PCR before (0) and after progressive 5% (5), 11% (11), and 16% (16) weight loss.

(legend continued on next page)

increasing systemic or subcutaneous adipose tissue markers of inflammation (Boden et al., 2015; Fabbrini et al., 2015). Therefore, we sought to evaluate the effect of moderate 5% weight loss and progressively greater amounts of weight loss on the relationship between metabolic function and both systemic and adipose tissue markers of inflammation. Our data demonstrate that the improvement in multi-organ insulin sensitivity after 5% weight loss was not accompanied by an improvement in either systemic or subcutaneous adipose tissue markers of inflammation. However, 11%–16% weight loss was associated with a reduction in both systemic and subcutaneous adipose tissue inflammation. This biphasic adipose tissue immune response to weight loss observed in our subjects is consistent with the early increase and subsequent decrease in adipose tissue macrophage content observed after calorie restriction and weight loss in obese mice (Kosteli et al., 2010). In fact, it is possible that a moderate increase in adipose tissue inflammation during early weight loss provides a beneficial adaptive response to energy restriction, because adipose tissue inflammation could be required for appropriate adipose tissue remodeling (Rutkowski et al., 2015; Wernstedt Asterholm et al., 2014). Together, these findings suggest that the beneficial effect of 5% weight loss on insulin action is not mediated by a reduction in subcutaneous adipose tissue inflammation. However, we did not evaluate potential alterations in inflammation in other adipose tissue depots, such as intra-abdominal fat, or evaluate the potential paracrine effects of adipose tissue cytokines that would not be detected by our study methods. Moreover, we cannot exclude the possibility that decreased adipose tissue inflammation contributes to the improvement in insulin sensitivity observed with greater weight loss, e.g., after bariatric surgery-induced 20% weight loss that has been associated with decreased gene expression of pro-inflammatory cytokines and macrophage number in adipose tissue of people with obesity (Bradley et al., 2012; Cancello et al., 2005; Moschen et al., 2010).

Perspective

Although 5%–10% weight loss is a commonly recommended therapeutic target for people with obesity (Jensen et al., 2014), the differences between 5% and 10% weight loss and the effects of additional diet-induced weight loss on body composition, adipose tissue biology, and cardiometabolic health outcomes are not clear. Therefore, we conducted a randomized controlled trial to determine: (1) the effects of 5% weight loss on metabolic function and both systemic and subcutaneous adipose tissue markers of inflammation; and (2) the effects of subsequent progressive weight loss on body composition, metabolic function, and global adipose tissue gene expression profile. The major findings from our study demonstrate that 5% weight loss improves multi-organ (adipose tissue, liver, and skeletal muscle) insulin sensitivity, β cell function, and multiple risk factors for cardiometabolic disease. These therapeutic effects occurred without a concomitant change in systemic or subcutaneous adipose tissue markers of inflammation, demonstrating that improvement of these selected markers of inflammation is not necessary for weight loss-induced improvements in metabolic function. Progressive 11% and 16% weight loss caused stepwise reductions in body fat mass, IAAT volume and IHTG content, progressive changes in adipose tissue biology (i.e., upregulation of metabolic pathways and genes involved in cholesterol flux and downregulation of metabolic pathways and genes involved in lipid synthesis, ECM remodeling and oxidative stress), further improvement in skeletal muscle, but not liver or adipose tissue, insulin sensitivity, and continued improvement in β cell function.

The results from the present study demonstrate the profound therapeutic effects of weight loss on metabolic function and other risk factors for cardiometabolic disease in people with obesity. Even a moderate 5% weight loss has considerable health benefits, including decreased IAAT volume, IHTG content, systolic blood pressure and plasma triglyceride concentration, and increased multi-organ insulin sensitivity and β cell function. Additional weight loss further improves many cardiometabolic outcomes and has a progressive effect on adipose tissue expression of genes involved in cholesterol flux, lipid synthesis, ECM remodeling, and oxidative stress. Future studies are needed to determine whether the weight loss-induced changes in adipose tissue biology contribute to the observed beneficial effects on cardiometabolic outcomes.

EXPERIMENTAL PROCEDURES

Study Subjects

40 sedentary (<2 hr of exercise/week) men and women (44 ± 12 years old) who were obese (BMI = 37.9 ± 4.3 kg/m^2) participated in this study (ClinicalTrials.gov, NCT01299519). All subjects completed a screening history and physical examination, a resting electrocardiogram, and standard blood tests. Subjects with obesity had evidence of multi-organ insulin resistance (based on a homeostasis model assessment of insulin resistance score >2.0 [Levy et al., 1998] and results of a hyperinsulinemic-euglycemic clamp procedure conducted in conjunction with infusion of stable isotopically labeled tracers) and an increase in both systemic and adipose tissue markers of inflammation (compared with a group of lean adults that we studied previously) (Yoshino et al., 2012) (Table S1 and Figure S3). No subject had evidence of serious illness or organ dysfunction (e.g., diabetes), were taking medications that could interfere with insulin action, consumed excessive alcohol (>14 drinks/week for women and >21 drinks/week for men) or smoked tobacco products. This study was approved by the Institutional Review Board of Washington University School of Medicine in St. Louis, MO, and written informed consent was obtained from all subjects before their participation.

Study Design

Subjects were randomly assigned to weight loss (n = 20) or weight maintenance (n = 20) therapy. Subjects in both groups participated in a lifestyle intervention

The main effect of time was evaluated with repeated-measures ANOVA, which revealed significant linear changes for all genes. Not normally distributed variables were log transformed for analysis and back transformed for presentation. Data are means ± SEM. *$p < 0.05$ versus baseline; †$p < 0.05$ for linear component and ‡$p < 0.05$ for quadratic component.

Abbreviations: *ABCG1*, ATP-binding cassette sub-family G member 1; *ABCA1*, ATP-binding cassette transporter ABCA1; *APOE*, apolipoprotein E; *CETP*, cholesteryl ester transfer protein; *SCD*, stearoyl-CoA desaturase; *FADS1*, fatty acid desaturase 1; *FADS2*, fatty acid desaturase 2; *ELOVL6*, elongation of very long chain fatty acids protein 6; *SPARC*, secreted protein acidic and rich in cysteine; *MFAP5*, microfibrillar-associated protein 5; *LOX*, lysyl oxidase; *LOXL2*, lysyl oxidase homolog 2; *ANGPT1*, angiopoietin 1; *ADAM12*, disintegrin and metalloproteinase domain-containing protein 12; *NQO1*, NAD(P)H dehydrogenase, quinone 1; *DHCR24*, 24-dehydrocholesterol reductase; *UCHL1*, ubiquitin carboxyl-terminal esterase L1.

program that included weekly individual behavior education sessions and dietary counseling. Initial dietary recommendations were based on an estimate of each subject's total daily energy expenditure (1.5× measured resting energy expenditure, assessed by using an automated metabolic measurement system [TrueOne 2400, ParvoMedics]) to help ensure subjects in the weight maintenance group maintained the same body weight for 6 months and that subjects in the weight loss group achieved their weight loss targets. All subjects were able to achieve a 5% weight loss by consuming a low-calorie diet of self-prepared foods. Solid and liquid meal replacements were provided to participants, as needed, to achieve the 10% (11% actual weight loss) and 15% (16% actual weight loss) weight loss targets. The precise intervention was individualized based on the judgment of the study dietitian and behavioral psychologist after discussion with the participant. More details about the lifestyle intervention program are provided in the Supplemental Information. All 20 subjects in the weight loss group were required to lose 5% of their weight; half (n = 10) were assigned to continue to lose ~10% and then ~15% of their initial body weight. After subjects achieved each weight loss target, a weight maintenance diet was prescribed to maintain a stable body weight (<2% change) for at least 3 weeks before repeat testing was performed. Subjects were studied at baseline and after 6 months in the weight maintenance group and after targeted weight loss in the weight loss group.

Body Composition

Body fat mass and FFM were determined by dual-energy X-ray absorptiometry, IAAT volume by MRI, and IHTG content by magnetic resonance spectroscopy (Fabbrini et al., 2015).

24 hr Ambulatory Blood Pressure and Heart Rate

Subjects were fitted with a portable blood pressure recording device (Ultralite 90217 monitor, Spacelabs Healthcare) to monitor 24 hr ambulatory blood pressure and heart rate (every 20 min from 0600 hr to 2400 hr, and every hour from 2400 hr to 0600 hr).

Oral Glucose Tolerance Test

After subjects fasted for 12 hr overnight, they were admitted to the Clinical Research Unit at 0700 hr. An intravenous catheter was placed into a hand vein, which was heated to 55°C by using a thermostatically controlled box, to obtain arterialized venous blood samples. After three blood samples were obtained at 5 min intervals, subjects ingested a 75 g glucose drink, and additional blood samples were collected at 10, 20, 30, 60, 90, and 120 min after glucose ingestion to determine plasma glucose, insulin, and C-peptide concentrations.

Hyperinsulinemic-Euglycemic Clamp Procedure and Adipose Tissue Biopsies

Subjects were admitted to the Clinical Research Unit in the afternoon and consumed a standard evening meal. After subjects fasted for 12 hr overnight, a 10.5 hr, two-stage hyperinsulinemic-euglycemic clamp procedure in conjunction with stable isotopically labeled tracer infusions and subcutaneous abdominal adipose tissue biopsies from the periumbilical area were performed as previously described (Fabbrini et al., 2015).

Sample Analyses and Calculations

Real-Time PCR

Total RNA was isolated from frozen subcutaneous adipose tissue samples by using QIAzol and RNeasy mini kit (QIAGEN). Gene expression was determined by using an ABI 7500 real-time PCR system (Invitrogen) and SYBR Green Master Mix (Invitrogen) as previously described (Fabbrini et al., 2015; Yoshino et al., 2014). The expression of each gene was determined by normalizing the cycle threshold value of each sample to the housekeeping control gene, ribosomal protein (*36B4*). Primer details are listed in Table S3.

Microarray

Microarray analyses were performed with the GeneChip Human Gene 1.0 ST array (Affymetrix). To identify biological pathways that were significantly altered by weight loss, normalized data were subjected to PAGE as previously described (Fabbrini et al., 2015; Pearson et al., 2008; Yoshino et al., 2011). Canonical pathway and GO gene sets used in PAGE were obtained from http://www.broad.mit.edu/gsea/msigdb/msigdb_index.html (C2: curated gene sets collection and C5: GO gene sets collection). Z scores and p values were calculated for each gene set.

Other sample analyses and calculations used to evaluate metabolic function are available in the Supplemental Information.

Statistical Analyses

Multi-organ insulin sensitivity and intrahepatic triglyceride content were the primary outcomes of our study; other components of body composition and other metabolic variables were secondary outcomes; and adipose tissue gene expression was an exploratory outcome. The effect of weight loss and differences between groups were evaluated by using repeated-measures ANOVA for normally distributed variables or Friedman's test for not normally distributed variables. Significant time-by-group interactions in the statistical analysis of the effect of 5% weight loss, and significant main effects of time in the statistical analysis of the effect of progressive weight loss, were followed by appropriate between- and within-group post hoc tests to adjust for multiple comparisons. Results are shown as means ± SD for normally distributed variables or medians (quartile 1, quartile 3) for not normally distributed variables, unless otherwise indicated. Based on the intra-individual variability of insulin sensitivity we have observed previously (Magkos et al., 2011), we estimated that 8 subjects per group would be needed to detect between-group differences of $\geq$19% in hepatic, $\geq$25% in adipose tissue, and $\geq$29% in skeletal muscle insulin sensitivity, with a power of 0.8 and an α value of 0.05. Therefore, we estimated that 15–20 subjects would need to be recruited in each group to ensure that an adequate number of subjects completed the study. Fewer subjects would be needed to detect differences of similar magnitude within the same group (Magkos et al., 2011).

ACCESSION NUMBERS

The accession number for all microarray data used in this study is NCBI GEO: GSE70529.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, four figures, and three tables and can be found with this article online at http://dx.doi.org/10.1016/j.cmet.2016.02.005.

AUTHOR CONTRIBUTIONS

Conceptualization, S.K.; Methodology, S.K.; Validation, S.C.K., A.L.O., and B.W.P.; Investigation, F.M., G.F., C.L., K.K., and S.H.; Formal Analysis, F.M. and J.Y.; Writing – Original Draft, F.M.; Writing – Review & Editing, G.F., J.Y, C.L., S.C.K., K.K., L.d.l.F., S.H., A.L.O., B.W.P, and S.K.; Supervision, F.M., J.Y. and S.K.; Resources, S.K.; Funding Acquisition, S.K.

CONFLICT OF INTEREST

S.K. is a shareholder of Aspire Bariatrics and has served on scientific advisory boards for Takeda Pharmaceuticals and NovoNordisk.

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Supplemental Information

Effects of Moderate and Subsequent Progressive Weight Loss on Metabolic Function and Adipose Tissue Biology in Humans with Obesity

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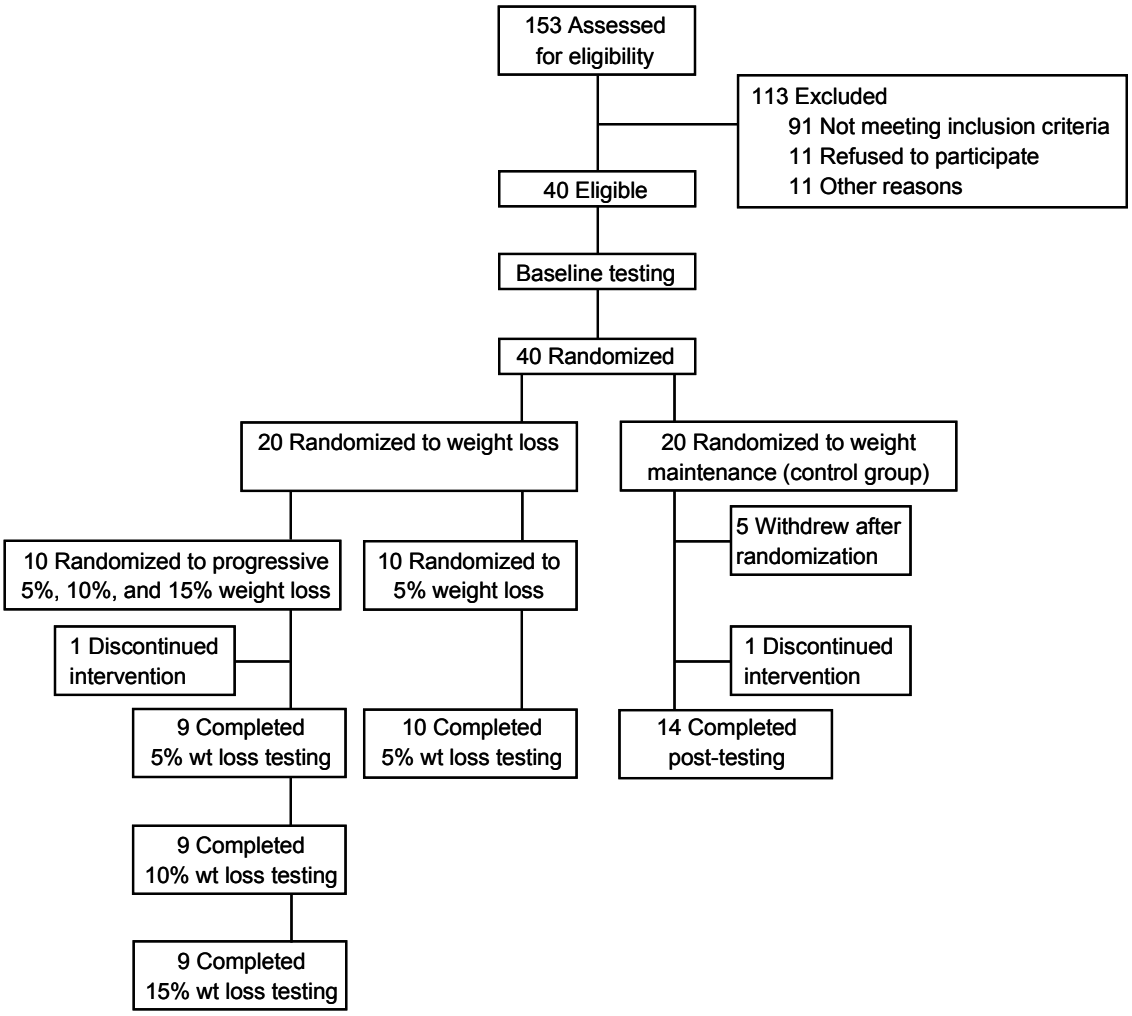
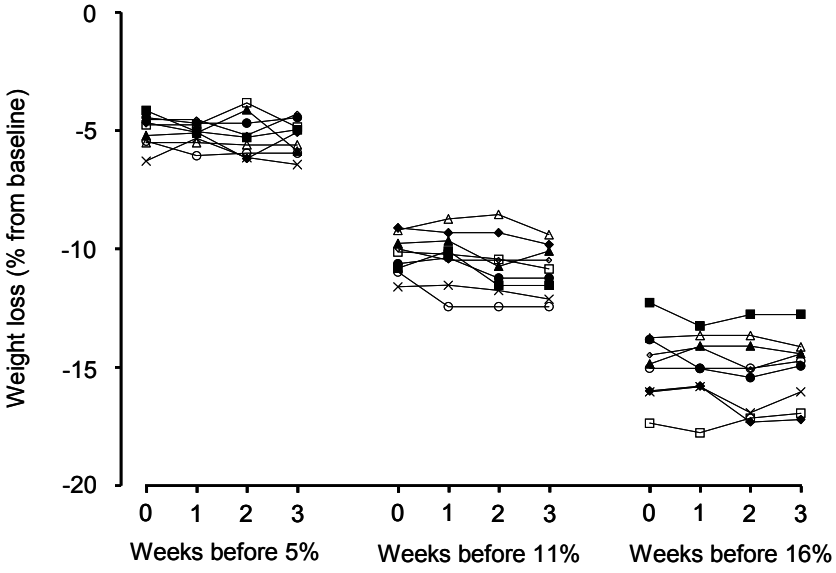
Supplemental Figure S1, related to Experimental Procedures: CONSORT Flow Diagram



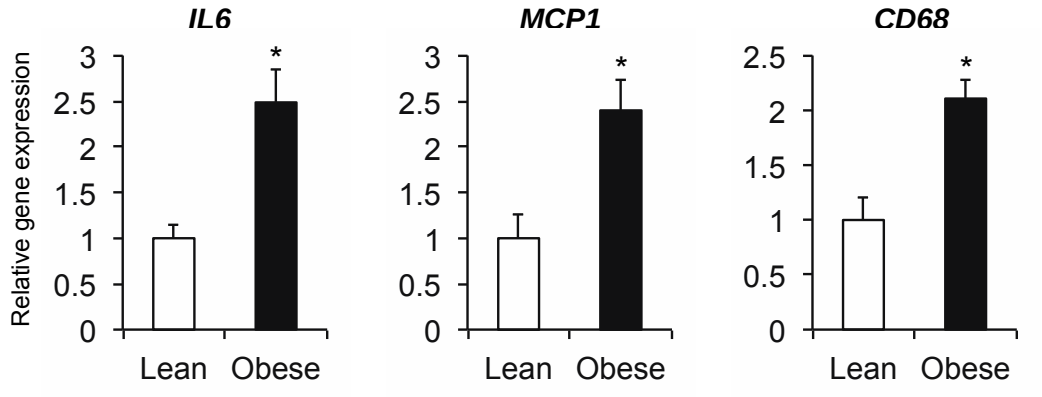
Flow of participants through screening procedures, baseline testing, randomization into weight loss and weight maintenance, and post-intervention testing.

Supplemental Figure S2, related to Experimental Procedures: Weight loss during the three weeks preceding metabolic testing



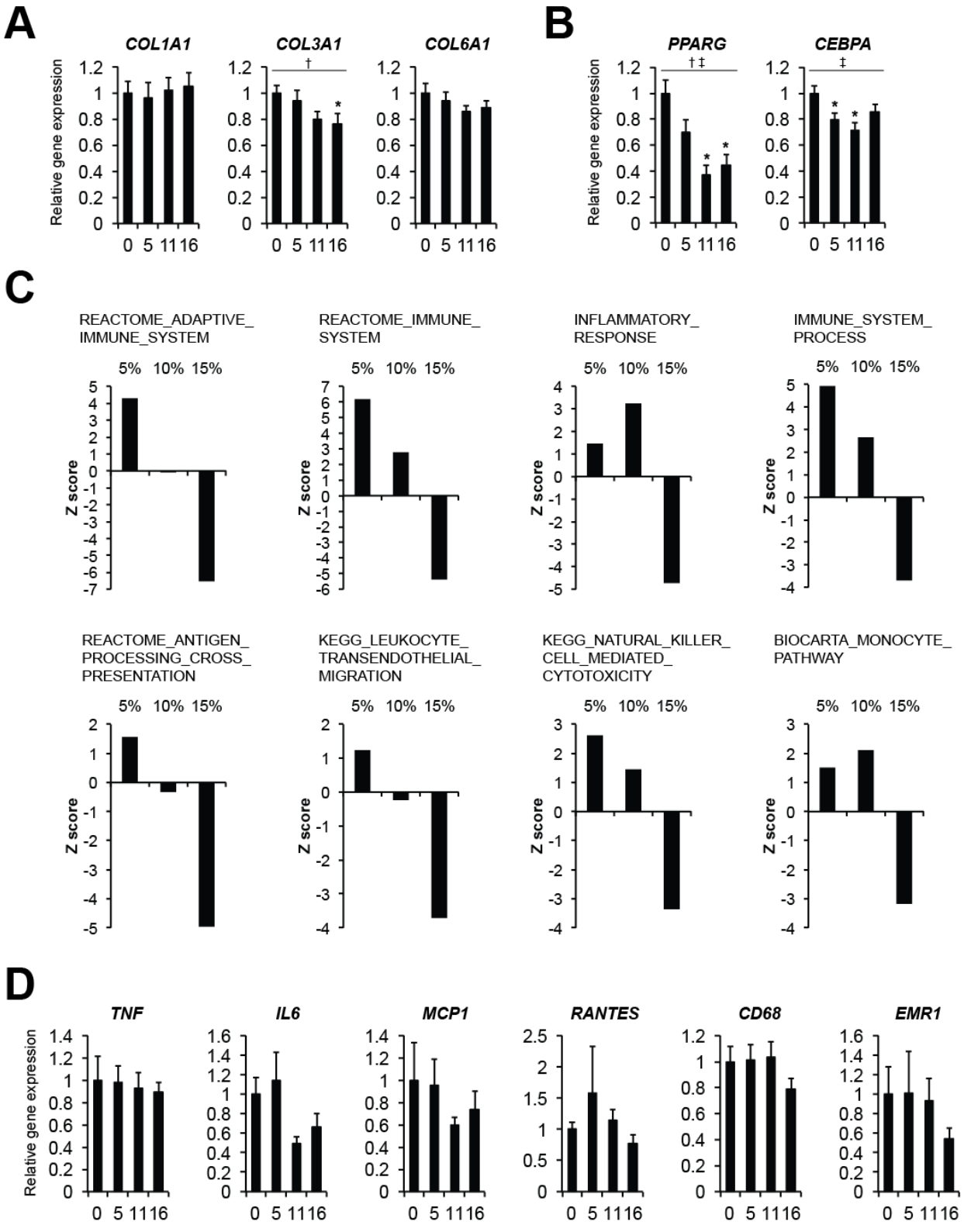
Weight loss data for individual subjects are shown (n = 9) for the three weeks preceding metabolic testing at each weight loss interval. Individual changes ranged from 0.1% to 1.7% at 5% weight loss, 0.5% to 1.5% at 11% weight loss, and 0.3% to 1.6% at 16% weight loss; the average change was 0.9% in all three instances.

Supplemental Figure S3, related to Table 1: Obesity is associated with adipose tissue inflammation



Subcutaneous adipose tissue expression of genes involved in inflammation was determined by real-time PCR in people who were lean (n=12, white bars) and obese (n=31, black bars). Data are means ± SEM. The differences between groups (lean vs. obese) were evaluated with the Student's t-test for normally distributed variables or the Mann-Whitney U test for not normally distributed variables. *P<0.05 vs. lean.
Abbreviations: *IL6*, interleukin-6; *MCP1*, monocyte chemotactic protein 1; *CD68*, cluster of differentiation 68.

Supplemental Figure S4, related to Figure 2: Effect of progressive weight loss on selected markers of extracellular matrix (ECM) structure, adipogenesis, and inflammation in subcutaneous adipose tissue



Subcutaneous adipose tissue gene expression of selected markers of ECM structure (A) and adipogenesis (B), representative biological pathways involved in immune function and inflammation (PAGE) (C), and gene expression of inflammatory markers (D) in subcutaneous adipose tissue, before (0) and after progressive 5% (5), 11% (11), and 16% (16) weight loss (n = 9). Non-normally distributed variables were log transformed for analysis and back transformed for presentation. Data are means ± SEM. **P*<0.05 vs. baseline; †*P*<0.05 for the linear component and ‡*P*<0.05 for the quadratic component of the main effect of time.

Abbreviations: *COL1A1*, collagen, type I, alpha 1; *COL3A1*, collagen, type III, alpha 1; *COL6A1*, collagen, type VI, alpha 1; *PPARG*, peroxisome proliferator-activated receptor gamma; *CEBPA*, CCAAT/enhancer-binding protein alpha; *TNF*, tumor necrosis factor; *IL6*, interleukin-6; *MCP1*, monocyte chemotactic protein 1; *RANTES*, regulated on activation, normal T cell expressed and secreted; *CD68*, cluster of differentiation 68; *EMR1*, EGF-like module-containing mucin-like hormone receptor-like 1.

Supplemental Table S1, related to Table 1: Metabolic characteristics and markers of inflammation in lean and obese subjects

	Lean (n = 12)	Obese (n = 33)	*P*-value
Weight (kg)	62.3 ± 4.4	106.4 ± 15.8	<0.001
Body mass index (kg/m^2)	22.9 ± 1.3	37.9 ± 4.3	<0.001
Body fat (%)	34.3 ± 5.5	46.9 ± 5.6	<0.001
Fat free mass (kg)	40.6 ± 3.3	56.1 ± 9.5	<0.001
Visceral adipose tissue (cm^3)	715 ± 403	1428 ± 534	<0.001
Intrahepatic triglyceride (%)	1.6 (1.2, 3.3)	7.0 (4.1, 12.7)	<0.001
Glucose (mg/dL)	94 ± 5	97 ± 8	0.304
Insulin (mU/L)	5.2 (2.1, 6.7)	19.2 (13.8, 23.0)	<0.001
HOMA-IR score	1.2 (0.5, 1.5)	4.4 (3.0, 5.7)	<0.001
Triglyceride (mg/dL)	85 (59, 111)	131 (89, 131)	0.010
HDL-cholesterol (mg/dL)	58 (51, 76)	42 (33, 48)	0.010
LDL-cholesterol (mg/dL)	114 (101, 141)	102 (90, 129)	0.472
Leptin (ng/mL)	16.7 ± 9.5	43.1 ± 18.2	<0.001
Adiponectin (µg/mL)	14.6 (9.8, 19.6)	5.2 (4.0, 6.9)	<0.001
C-reactive protein (mg/L)	0.75 (0.26, 1.59)	3.70 (2.32, 4.89)	<0.001
Interleukin-6 (ng/mL)	1.1 ± 0.4	2.2 ± 0.8	<0.001
WBC count (10^3/mL)	5.3 ± 1.1	6.6 ± 1.8	0.026
Palmitate Ra suppression (%)	69.5 ± 10.2	52.3 ± 12.4	<0.001
Glucose Ra suppression (%)	75.3 (67.5, 85.0)	70.1 (63.1, 75.5)	<0.001
Glucose Rd stimulation (%)	389 (331, 498)	183 (109, 221)	<0.001

Data are means ± SD for normally distributed variables or medians (quartile 1, quartile 3) for not normally distributed variables. The differences between groups (lean vs. obese) were evaluated with the Student t-test for normally distributed variables or the Mann-Whitney U test for not normally distributed variables.
Abbreviations: HOMA-IR, homeostasis model assessment of insulin resistance; HDL, high-density lipoprotein; LDL, low-density lipoprotein; WBC, white blood cell.

Supplemental Table S2, related to Figure 2: Adipose tissue biological pathways significantly affected by progressive weight loss

Please refer to the separate Excel spreadsheet.

Supplemental Table S3, related to Experimental Procedures: Sequence of primers for real-time PCR

Gene	Accession Number	Forward primer (5'-3')	Reverse primer (5'-3')
36B4	NM_001002	GTGATGTGCAGCTGATCAAGACT	GATGACCAGCCCAAAGGAGA
TNF	NM_000594	GAGGCCAAGCCCTGGTATG	CGGGCCGATTGATCTCAGC
IL6	NM_000600	ACTCACCTCTTCAGAACGAATTG	CCATCTTTGGAAGGTTCAGGTTG
MCP1	NM_002982	CAGCCAGATGCAATCAATGCC	TGGAATCCTGAACCCACTTCT
RANTES	NM_002985	CCAGCAGTCGTCTTTGTCAC	CTCTGGGTTGGCACACACTT
CD68	NM_001251	CTTCTCTCATTCCCCTATGGACA	GAAGGACACATTGTACTCCACC
EMR1	NM_001256255	GCTGTGATACTGTTCTTGATGGT	CAGCATCGGCAGCCCATAA
ABCG1	NM_016818	ATTCAGGGACCTTTCCTATTCGG	CTCACCACTATTGAACTTCCCG
ABCA1	NM_005502	ACCCACCCTATGAACAACATGA	GAGTCGGGTAACGGAAACAGG
APOE	NM_000041	GTTGCTGGTCACATTCCTGG	GCAGGTAATCCCAAAAGCGAC
CETP	NM_000078	GGCCAAGTCAAGTATGGGTTG	ACAGACACGTTCTGAATGGAGA
SCD	NM_005063	ACACTTGGGAGCCCTGTATG	GCAGCCGAGCTTTGTAAGA
FADS1	NM_013402	CTACCCCGCGCTACTTCAC	CGGTCGATCACTAGCCACC
FADS2	NM_004265	TGACCGCAAGGTTTACAACAT	AGGCATCCGTTGCATCTTCTC
ELOVL6	NM_024090	AACGAGCAAAGTTTGAACTGAGG	TCGAAGAGCACCGAATATACTGA
SPARC	NM_003118	TGAGGTATCTGTGGGAGCTAATC	CCTTGCCGTGTTTGCAGTG
MFAP5	NM_003480	GGGTCAATAGTCAACGAGGAGA	CTGTAGCGGGATCATTCACCA
LOX	NM_001178102	CGGCGGAGGAAAACTGTC	TCGGCTGGGTAAGAAATCTGA
LOXL2	NM_002318	GGGTGGAGGTGTACTATGATGG	CTTGCCGTAGGAGGAGCTG
ANGPT1	NM_001146	AGCGCCGAAGTCCAGAAAAC	TACTCTCACGACAGTTGCCAT
ADAM12	NM_021641	CGAGGGGTGAGCTTATGGAAC	GCTTTCCCGTTGTAGTCGAATA
NQO1	NM_001025433	GAAGAGCACTGATCGTACTGGC	GGATACTGAAAGTTCGCAGGG
DHCR24	NM_014762	GCCGCTCTCGCTTATCTTCG	GTCTTGCTACCCTGCTCCTT
UCHL1	NM_004181	CCTGTGGCACAATCGGACTTA	CATCTACCCGACATTGGCCTT
COL1A1	NM_000088	GAGGGCCAAGACGAAGACATC	CAGATCACGTCATCGCACAAC
COL3A1	NM_000090	GGAGCTGGCTACTTCTCGC	GGGAACATCCTCCTTCAACAG
COL6A1	NM_001848	ACAGTGACGAGGTGGAGATCA	GATAGCGCAGTCGGTGTAGG
PPARG	NM_015869	ATGGGTGAAACTCTGG	CGACATTCAATTGCCA
CEBPA	NM_001287435	AGGGTCTCTAGTTCCACGCC	CAAGGGGAAGCCCAGCCTATA

Supplemental Experimental Procedures, related to Experimental Procedures

Lifestyle intervention program

The dietary intervention included a low-calorie diet of self-prepared foods to achieve 5% weight loss, followed by the use of solid and liquid meal replacements, as needed, to achieve the 10% and 15% weight loss targets. The macronutrient content of the diet throughout the study was comprised of ~50-55% of energy as carbohydrate, 30% of energy as fat, and 15-20% of energy as protein. Diet and behavioral education were provided in individual weekly 1-hour sessions, led by an experienced weight management dietitian or behavioral psychologist, throughout the study. A structured meal plan was emphasized, and the recommended meal pattern consisted of 3 meals and 2 snacks daily. The behavioral program used cognitive-behavioral techniques to foster dietary adherence, and handouts that summarized the educational content were provided. The initial recommended dietary energy intake was individualized based on the participant's estimated daily energy expenditure (determined by each subject's measured resting energy expenditure multiplied by 1.5). Dietary intake was adjusted as needed based on each subject's rate of weight loss to help ensure weight loss and weight maintenance targets were achieved. Participants who were not achieving the desired rate of weight loss received additional support from the study dietitian or behavioral psychologist, including more intense self-monitoring, re-evaluating previous goals and setting new short-term goals, and more aggressive use of meal replacements.

Sample processing and analyses

Metabolite concentrations. Plasma glucose concentration was determined by the glucose oxidase method on an automated glucose analyzer (Yellow Spring Instruments Co, Yellow Springs, OH). Plasma insulin and C-peptide concentrations were measured by using electrochemiluminescence technology (Elecsys 2010; Cobas / Roche Diagnostics, Indianapolis, IN). Total plasma triglyceride, LDL and HDL cholesterol, and ALT concentrations were determined by following standard procedures in the Barnes Jewish Hospital Clinical Core laboratory. Plasma concentrations of leptin and adiponectin (EMD Millipore, St Charles, MO), CRP, IL-6, and MCP-1 (R&D Systems, Minneapolis, MN) were measured by using commercially available enzyme-linked immunosorbent assay (ELISA) kits. Plasma FFA concentrations were quantified by using gas chromatography with flame ionization detection (Hewlett-Packard 5890-II, Palo Alto, CA).

Tracer-to-tracee ratios. Plasma glucose and palmitate tracer-to-tracee ratios (TTR) were determined by using electron impact ionization gas chromatography-mass spectroscopy (GC-MS; MSD 5973 system with capillary column; Hewlett-Packard; Palo Alto, CA).

Calculations used to evaluate metabolic function

Substrate kinetics. The Ra of glucose in plasma was calculated by dividing the glucose tracer infusion rate by the average plasma glucose TTR during the last 30 min of the basal period, stage 1, and stage 2 of the hyperinsulinemic euglycemic-clamp procedure. Glucose Ra during basal conditions represents endogenous glucose Ra, an index of hepatic glucose production rate, which equals basal glucose Rd from plasma. During the clamp procedure, hepatic glucose production rate was calculated by subtracting the glucose infusion rate (i.e., dextrose solution plus tracer added to it) from total glucose Ra (endogenous plus exogenous); glucose Rd was calculated as total glucose Ra (i.e., the sum of endogenous glucose Ra and the rate of infused glucose). Palmitate Ra, an index of FFA flux and adipose tissue lipolysis, was calculated by dividing the palmitate tracer infusion rate by the average plasma palmitate TTR obtained during the final 30 min of the basal period and stage 1 of the clamp procedure.

Insulin sensitivity. Hepatic and adipose tissue insulin sensitivity were assessed as the relative decrease in glucose and palmitate Ra, respectively, from basal to low-dose insulin infusion (stage 1) of the clamp procedure. Skeletal muscle insulin sensitivity was determined as the relative increase in glucose Rd from basal to high-dose insulin infusion (stage 2) of the clamp procedure.

Glucose tolerance, insulin clearance, and β-cell function. Glucose, insulin and C-peptide areas-under-the-curve (AUCs) were calculated by using the trapezoidal rule to assess glucose tolerance and insulin clearance (insulin AUC relative to C-peptide AUC). The β-cell insulin secretion rate (ISR) response sensitivity to plasma glucose was assessed by using oral minimal model analysis of plasma C-peptide concentrations (Breda et al., 2002) (SAAM II version 2, University of Washington, Seattle, WA), to obtain Φ-static (ISR response sensitivity to glucose concentration), Φ-dynamic (ISR response sensitivity to the rate of increase in glucose concentration), and Φ-total (overall ISR response sensitivity to glucose). Overall β-cell function, which provides an assessment of insulin secretory response in relationship to insulin sensitivity (Bergman et al., 2002), was calculated as the product of total β-cell responsivity (Φ-total) and the insulin-stimulated increase in glucose Rd during high-dose insulin infusion.

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