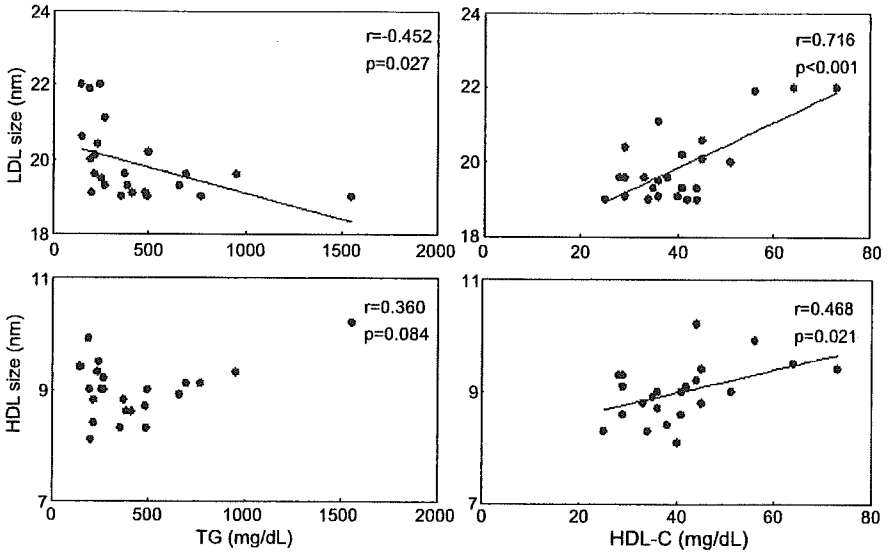

Fig. 1. Correlation between lipid parameters (TG and HDL-C) and particles sizes (LDL and HDL) in study subjects.

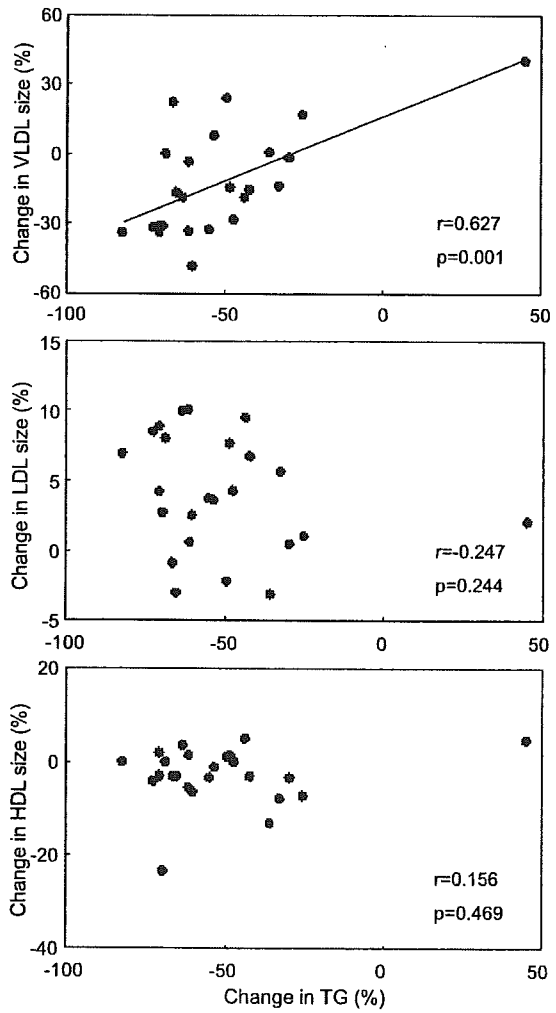

Fig. 2. Correlation between changes in TG and changes in particles sizes (VLDL, IDL and HDL) after bezafibrate treatment.

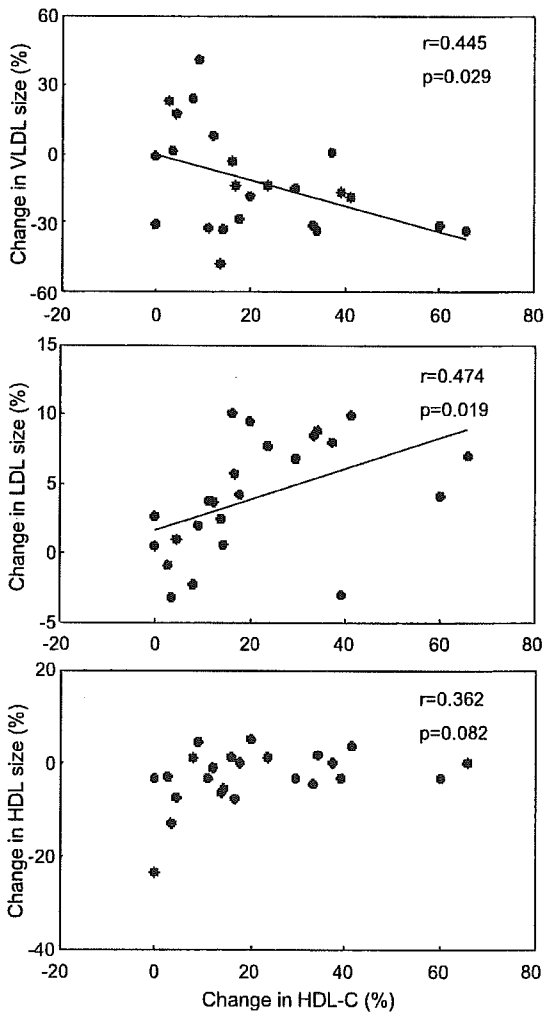

Fig. 3. Correlation between changes in HDL-C and changes in particles sizes (VLDL, IDL and HDL) after bezafibrate treatment.

Table 3
Effects of bezafibrate on MDA-LDL concentration and inflammation markers

	Baseline	Bezafibrate	Change (%)
MDA-LDL (U/l)	91.7±25.8	88.8±33.7	−3.2
MDA-LDL/apoB ($U/mg/10^{-1}$)	0.796±0.151	0.784±0.163	−1.6
hsCRP (mg/l)	1.13±1.50	1.02±1.44	−10.1
PAI-1 (ng/ml)	73.1±64.1	80.8±29.9	10.6
IL-6 (pg/ml)	1.9±1.1	1.8±1.3	−4.5
MCP-1 (pg/ml)	132.2±40.7	121.3±44.5	−8.2

Values are given as mean±S.D.

cant and positive correlations with both LDL and HDL particles size. To further understand the relation between changes in TG, HDL-C and changes in lipoprotein particle size, we correlated percentage changes in lipid parameters and those in particles sizes as shown in Fig. 2 and 3. Changes in TG levels, mostly reduction except one patient, were shown to be correlated with changes in VLDL size, but not with changes in LDL size, indicating that enlargement of LDL particle size was independent of TG-lowering effect by bezafibrate. This relation was not affected by the outliner. Changes in HDL-C showed a strong relation with changes in particles sizes as shown in Fig. 3. The changes in HDL-C negatively correlated with those in VLDL particle size, but positively with those in LDL particle size, while marginally failed to show a significant correlation with those in HDL size.

3.5. *Inflammation markers*

Finally, effects of bezafibrate on inflammation markers are summarized in Table 3. Although small LDL (LDL1) significantly decreased by NMR analysis, neither MDA-LDL or MDA-LDL/apoB did not change by bezafibrate treatment. Likewise, high sensitivity CRP, PAI-1, IL-6 or MCP-1did not show significant changes by bezafibrate treatment.

4. Discussion

In addition to elevated LDL-C, increased TG-rich lipoproteins (increased remnants), decreased HDL-C and small dense LDL comprise a new cluster of atherogenic dyslipidemia. Unlike hypercholesterolemia in which HMG-CoA reductase inhibitors are now widely accepted as the first choice, fibrate derivatives are considered to be an ideal treatment for this type of dyslipidemia. A recent intervention trials further supported this strategy by demonstrating that gemfibrozil provided a benefit when used in CAD patients with low HDL-C levels [18]. In the present study, we employed, for first time in Japan, proton nuclear magnetic resonance spectroscopy for lipoprotein subclasses analysis and herein demonstrated that bezafibrate markedly reduced TG-rich lipoproteins, including atherogenic IDL, increased small HDL particle number and altered LDL particles size in favor of converting small LDL dominant pattern B to large LDL dominant pattern A.

Besides elevated LDL-C, small dense LDL has been a new member as independent risk factor for CAD [19]. LDL phenotype pattern B was dominant (79.2%) prior to the bezafbrate treatment, but markedly decreased to 33.3% by the end of 4 weeks treatment, mirroring a significant decrease in small LDL (LDL1) as well as increases in intermediate (LDL2) and large LDL (LDL3). This is consistent to the previous findings in which LDL particle size was evaluated by GGE method [3, 4]. Enlargement of LDL is supposedly translated to be less atherogenic, whereby counterbalancing the mild elevation of LDL-C by bezafibrate.

Although baseline TG concentrations, together with HDL-C levels, are determinants for LDL particle sizes (Fig. 1), changes in LDL particle size after bezafibrate treatment was not correlated with those in TG level (Fig. 2), indicating that enlargement of LDL by bezafibrate is not primarily mediated by TG lowering function. Interestingly, enlargement of LDL did correlate with the increase in HDL-C level. This is a puzzling observation based on a significant inverse correlation between changes in TG and HDL-C ($r=-0.47$, $p=0.02$) by bezafibrate, which indicates that TG-rich lipoproteins and HDL may be metabolically associated. In contrast to our correlation results, Hirano et al. [4] found that an increase in LDL size was associated with a decrease in TG level, but not with an increase in HDL-C level. At present, we are not certain about the exact reasons underlying this discrepancy. Since sample sizes in both studies are relatively small (24 in this study and 17 in their study), this could be due simply to "by chance". There are, however, some differences in baseline lipid profiles and responses to bezafibrate treatment by which the discrepancy might be explained. Our study subjects had higher TG levels (427 vs. 195 mg/dl as the mean) and lower LDL-C levels (124 vs. 148 mg/dl) as compared with their study subjects. LDL-C modestly increased in the present study (+11.7%), whereas decreased in their study (−13%). Despite similar baseline HDL-C levels, HDL-C increased to a greater extent (+44%) in their study relative to the present study (+19.8%). A closer look on TG response to bezafibrate (Fig. 3 in their manuscript) also indicates that their study subjects show larger variations relative to the present study subjects, thus leading to a greater probability of changes in TG to significantly associate with changes in LDL size. Conversely, as evident from Figs. 2 and 3, our study subjects showed greater variation in HDL-C response to bezafibrate relative to TG. In our opinion, there could be several potential explanations for the positive relation between LDL size enlargement and HDL elevation by bezafibrate. First, if HDL-C elevation is due to the suppression of cholesteryl ester transfer protein activity as reported previously [20], this, in turn, affects lipids exchange among VLDL, LDL and HDL, whereby resulting to modulate LDL particle size.

Second, bezafibrate affects lipoprotein lipase including lipoprotein lipase and hepatic triglyceride lipase, lipases known to be involved in synthesis and remodeling of both LDL and HDL. These mechanisms remain to be speculations since we did not measure these enzyme activities or masses, thus deserving a future study.

In the present study, we confirmed a favorable and potent effect of bezafibrate on HDL metabolism as evidenced by the 19.8% increase in HDL-C. NMR analysis further extended this effect by demonstrating that bezafibrate markedly increased intermediate and small HDL subclasses with the average HDL size to be significantly decreased from 9.0 to 8.7nm. This finding is compared favorably to the increase in HDL_3 evaluated by GGE methods in previous studies [3,20]. An increase in preβ1-HDL at the expense of HDL_{2b} using native two-dimensional gel electrophoresis [21] also supports our finding. These small HDL are believed to be better acceptors for cholesterol as compared with larger counterparts, as evidenced by a finding that free cholesterol effluxing capacity was markedly increased by bezafibrate treatment [22]. Overall, the decrease in HDL size, together with the increase in HDL particle number, makes bezafibrate to be an ideal agent to strengthen anti-atherogenic properties of HDL when used in hypertriglyceridemic patients.

Of note is a marked reduction of RLP-C, a parameter of atherogenic remnants, in this study. Although not significant, this favorable effect is further supported by NMR analysis showing 46% reduction. Since development of CAD is not always associated with elevated LDL-C [23], improved remnant metabolism, together with favorable effect on HDL metabolism, may account for the benefit observed in the recent intervention trials using fibrate [2,18].

Lundman et al. [24] reported an increased plasma concentration of CRP in hyperlipidemic subjects. This is in agreement to our study in which the average CRP level (1.13 mg/l) are comparable to that study (1.5 mg/l). Bezafibrate, however, did not modulate CRP concentration in this study. The effect of bezafibrate on CRP is controversial with positive [25] and negative [26] results. In previous studies [25,27], bezafibrate was found to reduce IL-6, an effect being attributable to the activation of the peroxisome proliferator-activated receptor (PPAR)-α with a consequent reduction of NF-κβ activation. The IL-6 levels, however, remained unchanged in this study. These discrepancies may be due to the differences in inflammatory status at baseline, duration of the study period, or the lack of control group. The exact reasons for these observations are not clear at present, thus deserving a placebo-control and long term follow-up study in future.

There are some limitations in the present study. First, this study lacks control group to which bezafibrate group can be compared. We therefore installed run-in period to maintain steady state throughout the study period. Nonetheless, placebo-control study should be carried out to draw a solid conclusion in future. Second, most of the study subjects were male, thus it should be cautious to extend our results to hypertriglyceridemic women. Third, duration of the treatment was relatively short (4 weeks). In this regard, our results are considered to be short-term effects, which may be different from long-term effects.

In summary, the results of the present study demonstrated that, in addition to its potent TG lowering effect, bezafibrate effectively improved proatherogenic lipoproteins profiles by reducing remnants, small LDL as well as increasing small HDL particles. Therefore, it will be of great importance as to whether bezafibrate may provide a long-term benefit in hypertriglyceridemic patients at risk for coronary artery disease, typically patients with metabolic syndrome.

Acknowledgements

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Roles of degree of fat deposition and its localization on VEGF expression in adipocytes

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Miyazawa-Hoshimoto, Saori, Kazuo Takahashi, Hideaki Bujo, Naotake Hashimoto, Kazuo Yagui, and Yasushi Saito. Roles of degree of fat deposition and its localization on VEGF expression in adipocytes. *Am J Physiol Endocrinol Metab* 288: E1128–E1136, 2005. First published December 21, 2004; doi:10.1152/ajpendo.00003.2004.—Vascular endothelial growth factor (VEGF) is an important angiogenic factor and is expressed in wide variety of cell types. In this study, we investigated the mechanism of VEGF production in adipocytes in three sets of experiments. First, to clarify the relation between plasma VEGF concentrations and their expressions in adipose tissues, we investigated the genetically obese *db/db* and KK-A^y mice. Plasma VEGF concentrations in obese mice were significantly higher than in control and were related to adiposity. VEGF expressions in visceral fat were enhanced during growth and were related to fat deposition. Next, to demonstrate the relation between VEGF production and lipid accumulation in adipocytes, we analyzed VEGF mRNA expression and its protein secretion in 3T3-L1 cells. VEGF production was enhanced during lipid accumulation in 3T3-L1 cells after adipocyte conversion. Next, to clarify the role of anatomic localization on VEGF expression in adipocytes, we implanted 3T3-L1 cells into visceral or subcutaneous fat in athymic mice. 3T3-L1 cells implanted into the mesenteric area expressed more VEGF mRNA than that into the subcutaneous area. Plasma VEGF concentration in the mice implanted in visceral fat was higher than in controls. These results suggest that both the anatomic localization and the lipid accumulation are important for the VEGF production in adipocytes.

vascular endothelial growth factor; fat distribution; cytokine; gene expression; 3T3-L1 cells

VASCULAR ENDOTHELIAL GROWTH FACTOR (VEGF) is a very potent angiogenic factor that induces migration and proliferation of vascular endothelial cells (9). VEGF also enhances vascular permeability and modulates thrombogenicity (18). It has therefore been implicated in normal blood vessel development as well as in pathological vessel formation (6). Pathogenic neovascularization plays a major role in the development of atherosclerosis (20), tumor growth (18), rheumatoid arthritis (9, 16), and various retinopathies (2, 3). VEGF mRNA expression has been identified in various cell types, including endothelial, epithelial, and mesenchymal cells (9, 18). It has also been reported that VEGF mRNA is expressed in 3T3-F442A cells, an established preadipocyte cell line (4).

VEGF is encoded by a single gene; however, four isoforms of 205, 188, 164, and 120 amino acids long are produced as a result of alternative splicing. The 164-amino acid-long isoform is the most abundant. We have reported that serum concentration of the 164-amino acid-long isoform of VEGF in human obese subjects is dependent on the intra-abdominal fat accumulation determined using computed tomography scan at the umbilical level (15). Furthermore, the elevated VEGF level or the accumulated visceral fat in the obese subjects was decreased after body weight reduction (15). These observations revealed that the VEGF secretion from adipose tissues, particularly from visceral adipose tissues, might regulate its serum concentration.

Adipose tissues have been reported to express and release various secretary molecules, such as leptin (10, 11), tumor necrosis factor-α (TNF-α) (7), plasminogen activator inhibitor-1 (PAI-1) (20), and IL-6 (22). Especially, the expression levels of TNF-α and PAI-1 in adipocytes are shown to be directly related to the degree of differentiation from preadipocytes and to be dependent on their anatomic location (12, 14, 20, 21).

Therefore, it is very important to clarify the mechanism of VEGF production in adipocytes from the point of view of the adipocyte differentiation process and the site of fat accumulation. In this study, we examined VEGF production from intrinsic adipocytes in *db/db* and KK-A^y mice during growth, from 3T3-L1 cells depending on the differentiation in culture, and from 3T3-L1 cells that were implanted into the visceral or subcutaneous fat area.

MATERIALS AND METHODS

Materials. MCDB131, FBS, and trypsin were purchased from Invitrogen (Carlsbad, CA). PBS was from Nissui Pharmaceuticals (Tokyo, Japan). DMEM, human insulin, dexamethasone, and 3-isobutyl-1-methylxanthine were obtained from Sigma-Aldrich (St. Louis, MO). Collagenase-S1 was from Nitta Gelatin (Osaka, Japan). Growth Factor Reduced BD Matrigel matrix was from Nippon Becton-Dickinson (Tokyo, Japan). ISOGEN reagent was from NIPPON GENE (Tokyo, Japan). RNeasy Mini Kits and QIAGEN OneStep RT-PCR Kit were from Qiagen (Tokyo, Japan). 3T3-L1 cells, an established preadipocyte cell line, was obtained from the American Type Culture Collection (Manassas, VA). Human umbilical vein endothelial cells (HUVECs) and EBM-2 medium were from BioWhittaker (Walkersville, MD).

Obese mice. BKS.Cg-+ Lepr^{db}/+ Lepr^{db}/Jcl (*db/db*) and KK-A^y/TaJcl (KK-A^y) mice, and control littermates BKS.Cg-m +/+ Lepr^{db}/Jcl (*db/+*) and C57BL/6JJcl (C57BL/6), respectively, were obtained from CLEA Japan (Tokyo, Japan) at 5 wk of age. The mice were maintained in a temperature-, humidity-, and light-controlled room (12:12-h light-dark cycle) with free access to water and standard

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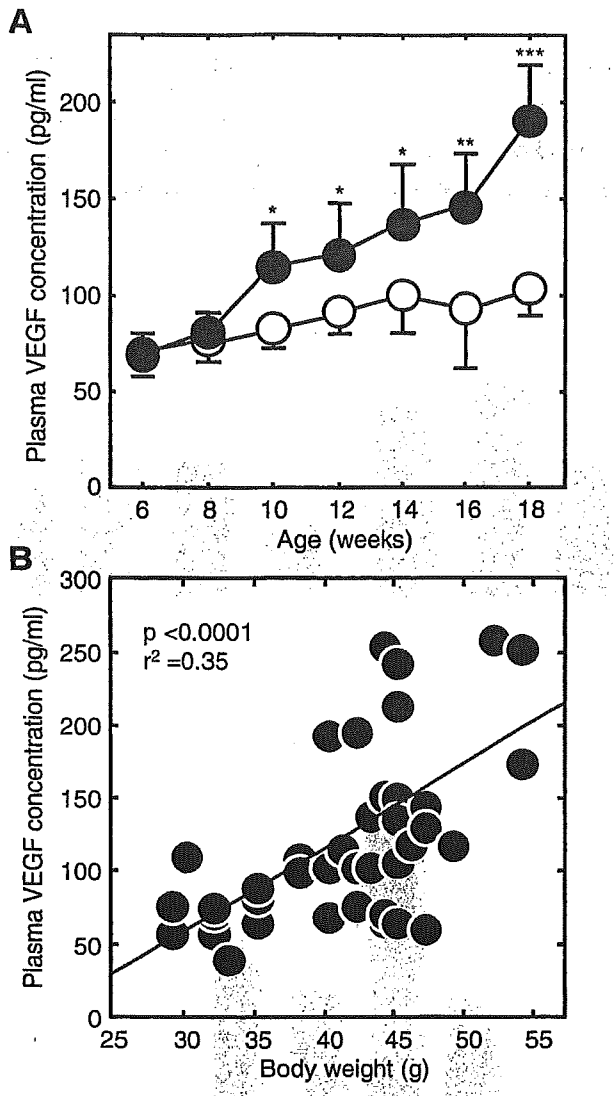

Fig. 1. Growth-dependent change of plasma vascular endothelial growth factor (VEGF) concentration in *db/db* mice. *A*: time course changes of plasma VEGF concentrations in *db/db* (●) and *db/+* (○) mice. Plasma VEGF concentrations were measured every 2 wk from 6 to 18 wk of age in *db/db* and *db/+* mice. Results are represented as means and SD. After 10 wk of age, plasma VEGF concentrations in *db/db* mice were significantly higher than in *db/+* mice. *B*: correlation between body weight and plasma VEGF concentrations in *db/db* mice. Plasma VEGF concentrations were significantly correlated with body weight in *db/db* mice. $*P < 0.05$ vs. *db/+* mice; $**P < 0.01$ vs. *db/+* mice; $***P < 0.001$ vs. *db/+* mice.

rodent chow (352 kcal/100 g, CE-2; CLEA Japan). Male mice were used in the studies reported here. Animal care and procedures were approved by the Animal Care Committee of Chiba University School of Medicine.

Body weight and adiposity. Body weights of *db/db* and *db/+* mice were measured at every 2 wk from the time they were 6 wk old throughout the study. Blood samples were also obtained from the retroorbital venous plexus of the mice fasted more than 16 h. The *db/db* and *db/+* mice were killed at 6, 10, 14, and 18 wk of age by cervical dislocation before white adipose tissues were collected. Mesenteric adipose tissues were used as visceral fat, and inguinal subcutaneous adipose tissues were used as subcutaneous fat in the studies reported here. The white adipose tissues were weighed on an analytic balance and processed for cell counts as described previously (13). Briefly, minced adipose tissues were incubated with PBS containing collagenase S-1. The tissue fragments were removed by passage through a 250-μm nylon screen. The isolated cells were then stained with methylene blue, and aliquots were placed on a Neubauer hemocytometer. Total cell counts were measured using a light microscope.

Total RNA and protein extraction from adipose tissues in obese mice. Mesenteric and subcutaneous adipose tissues of *db/db* and *db/+* mice were processed for total RNA isolation using ISOGEN reagents according to the manufacture's instructions. In another set of experiments, the adipose tissues were homogenized in an ice-cold buffer containing 50 mM Tris·HCl (pH 7.4), 1 mM EDTA, 1 mM dithiothreitol, 5 mM $MgCl_2$, 130 mM NaCl, 1% NP-40, 10 μM 4-amidinophenylmethanesulfonyl fluoride, and 5 μM leupeptin. Insoluble materials in the tissue were removed by centrifugation at 12,000 *g* at 4°C for 20 min. After centrifugation, tissue extracts were collected. Moreover, total RNA in the isolated adipocytes of mesenteric fat was also prepared. The mesenteric adipose tissue was digested with collagenase S-1 and passed through a 250-μm nylon screen to remove tissue debris. Then, the isolated cells, containing adipocytes and vascular-stromal cells, were separated by centrifugation. After the adipocytes were allowed to float, the vascular-stromal cells were removed from the bottom layer. The floating layer, as adipocyte fraction, was washed three times with PBS. Finally, the isolated adipocytes were collected and processed for cell counts, using a Neubauer chamber as described above. To compare directly the cellular expression of VEGF in adipocyte, 2×10^4 cells were processed for total RNA isolation using ISOGEN reagent. The KK-A^y and C57BL/6 mice were killed at 16 wk of age by cervical dislocation before mesenteric and inguinal subcutaneous fat was collected for total RNA isolation.

3T3-L1 cells culture and differentiation. 3T3-L1 preadipocytes were cultured with DMEM containing 10% FBS at 37°C in a 5% CO_2 incubator. Adipocyte differentiation was carried out by changing to a differentiation medium containing 10 μg/ml insulin, 0.25 μM dexamethasone, and 0.5 mM 3-isobutyl-1-methylxanthine. After 48 h, the medium was replaced with a maturation medium containing 5 μg/ml insulin, and cells were maintained in this medium until use. Every week after differentiation, the cells were washed with PBS and then cultured in fresh DMEM medium alone. After incubation for 24 h, the conditioned media were collected. In another set of experiments, the cells were processed for total RNA isolation using an RNeasy Mini Kit.

In vitro endothelial tube formation assay. HUVECs were grown in EBM-2 medium containing 10% FBS. Formation of capillary tube-like structures by HUVECs was assessed in a Matrigel-based assay as previously described (8). Briefly, HUVECs were incubated with MCDB131 containing 2% FBS for 48 h prior to tube formation assay. Cells (7×10^4) were plated onto 300 μl of Growth Factor Reduced BD Matrigel matrix (7 mg/ml protein), pregelled at 37°C in 24-well culture plates. Then, the cells were incubated for 13 h at 37°C with 150 μl of MCDB131 and 150 μl of the conditioned medium derived from pre- or postdifferentiated 3T3-L1 cells in the presence or absence of anti-mouse VEGF-neutralizing antibody. Three different phase-contrast microscopic low-power fields (×100) per well were photographed. The total length of capillary tubes in each photograph was measured using a scale ruler.

Preadipocyte transplantation. 3T3-L1 cells were implanted into athymic mice as described previously (19). Briefly, 3T3-L1 preadipocytes were grown to near confluence, trypsinized, and suspended in DMEM with 10% FBS. After centrifugation, cell pellets were resuspended in PBS and injected 1×10^7 cells (500 μl) through 22-gauge needles into the mesenteric area near the small intestine or the subcutaneous fat area of athymic mice of the BALB/C strain under

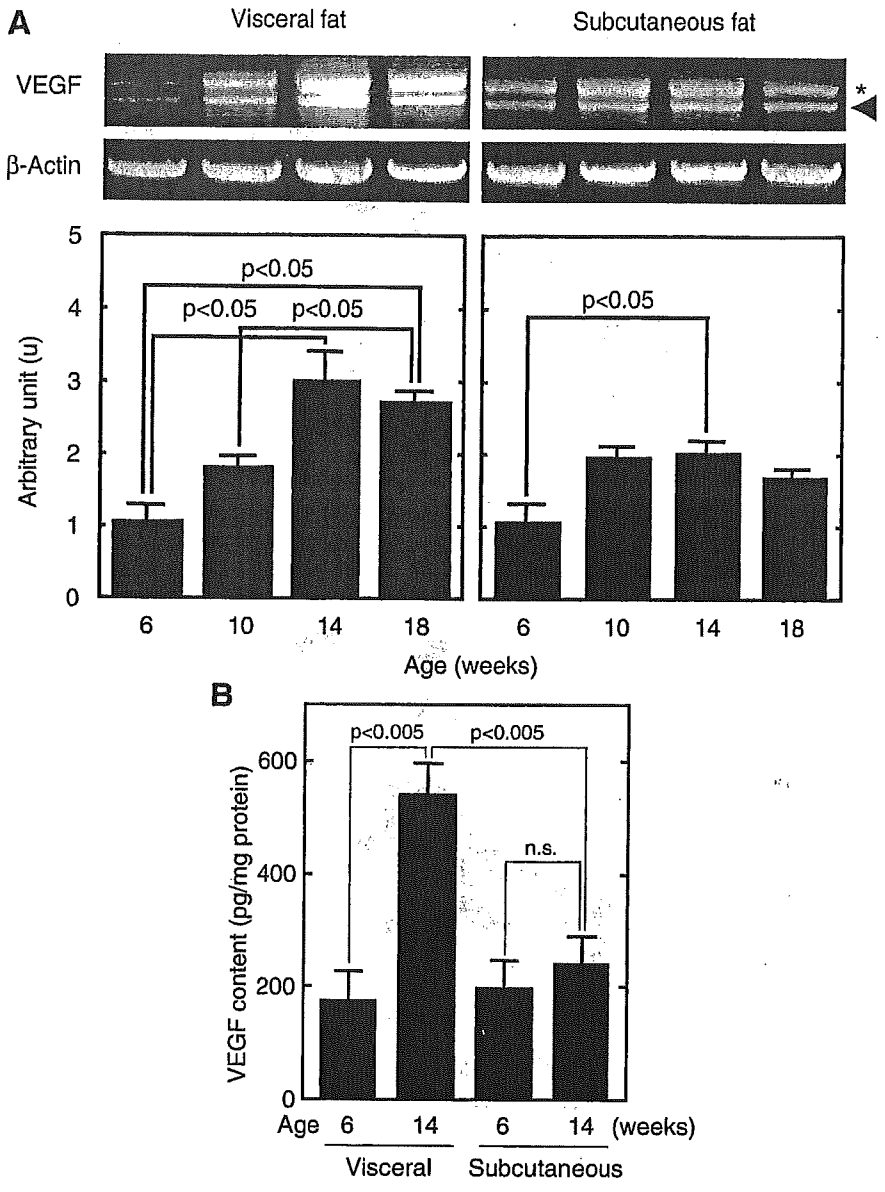

Fig. 2. Growth-dependent changes of mRNA expressions and protein contents of VEGF in mesenteric and subcutaneous adipose tissues of *db/db* mice. *A*: Time course changes of VEGF gene expressions in visceral and subcutaneous adipose tissues of *db/db* mice. Images show RT-PCR products of VEGF amplified from total RNA in mesenteric and subcutaneous adipose tissues at 6, 10, 14, and 18 wk after birth. PCR products of VEGF were densitometrically analyzed, and relative amounts at 6 wk old were set to 1.0. Results are represented as means and SD. Arrowhead, 644 bp ($VEGF_{164}$); *, 716 bp ($VEGF_{188}$). *B*: Tissue VEGF contents in mesenteric and subcutaneous fat. Tissues were extracted with a buffer containing 50 mmol/l Tris·HCl (pH 7.4), 1 mmol/l EDTA, 1 mmol/l DTT, 5 mmol/l $MgCl_2$, 130 mmol/l NaCl, 1% NP-40, 10 μmol/l APMSF, and 5 μmol/l leupeptin. Tissue extracts were processed for VEGF measurement using an ELISA system.

anesthetization by intraperitoneal injection with pentobarbital sodium. Mice were housed in microisolator cages under specific pathogen-free conditions during whole experiments. Four weeks after implantation, the mice were killed by cervical dislocation under anesthetization before mesenteric or subcutaneous fat area was collected. Total RNA of mesenteric and subcutaneous fat was isolated using ISOGEN reagent. Blood samples were also obtained from the retroorbital venous plexus of the mice fasted more than 16 h.

Measurement of immunoreactive VEGF. Plasma samples were prepared by centrifugation at 1,500 *g* for 15 min at 4°C. After centrifugation, the plasma fraction was collected and stored at −70°C until use. The extracts of adipose tissues and the conditioned media from pre- and postdifferentiated 3T3-L1 cells were also stored at −70°C until use. VEGF concentrations of plasma, extracts from adipose tissues, and conditioned media were measured with an enzyme-linked immunosorbent assay system (R&D Systems, Minneapolis, MN).

RT-PCR. To evaluate the contents of VEGF expression in adipose tissues and 3T3-L1 cells, 0.4 μg of total RNA was amplified by OneStep RT-PCR kit using the indicated specific primers. To compare directly the VEGF expressions in adipocytes of mesenteric fat during growth, total RNA prepared from 2×10^4 cells was also amplified using the specific primers. The contents of GLUT4, peroxisome proliferator-activated receptor-γ (PPARγ), and β-actin were also amplified by RT-PCR. The RT-PCR products were run on 1.5% agarose and stained with ethidium bromide. The relative signal intensities of the PCR products were determined with luminescent image analyzer LAS-1000 (Fuji Photo Film, Tokyo, Japan). mRNA amounts were normalized to levels of β-actin mRNA, which served as endogenous standard.

Primers. The following primers were designed for RT-PCR analysis using in this study: VEGF, 5′-GCGGGCTGCCTCGCAGTC-3′ (forward) and 5′-TCACCGCCTTGGCTTGTCAC-3′ (reverse); β-actin, 5′-TGGAATCCTGTGGCATCCATGAAAC-3′ (forward) and 5′-TAAAACGCAGCTCAGTAACAGTCCG-3′ (reverse); GLUT4, 5′-GGCATGTGTGGCTGTGCCATC-3′ (forward) and 5′-GGGTTTCACCTCCTGCTCTAA-3′ (reverse); PPARγ, 5′-GACATCCAA-

GACAACCTGCTG-3′ (forward) and 5′-GCAATCAATAGAAG-GAACACG-3′ (reverse). RT-PCR products for VEGF were 716 bp ($VEGF_{188}$), 644 bp ($VEGF_{164}$), and 512 bp ($VEGF_{120}$), respectively. The signal intensity of the 644-bp product was analyzed in this study. Products of 349, 413, and 258 bp were predicted for β-actin, GLUT4, and PPARγ, respectively.

Statistical analysis. Statistical analyses were performed using Statview J-4.5. Statistical analysis was performed with a *t*-test. All of the results reported herein were confirmed by repeating the experiments with different occasions. A value of $P < 0.05$ indicated statistical significance.

RESULTS

Growth-dependent changes of plasma VEGF concentration in db/db mice. We measured circulating VEGF concentrations in *db/db* mice, a strain of the mouse models for obesity, to demonstrate the role of fat accumulation and its effect on VEGF levels in vivo. Plasma VEGF concentrations were increased during growth in both *db/+* and *db/db* mice (Fig. 1*A*). At 10 wk old, plasma VEGF concentrations in *db/db* mice were significantly higher than in *db/+* mice. Moreover, plasma VEGF concentrations were significantly correlated with body weight (Fig. 1*B*).

Growth-dependent changes of VEGF mRNA expressions and protein contents in visceral and subcutaneous fat of db/db mice. VEGF mRNA was detected in both visceral and subcutaneous fat in *db/db* mice. Expression levels of VEGF mRNA in visceral fat were increased 3.0-fold in 14-wk-old mice compared with those in 6-wk-old mice (Fig. 2*A*). VEGF expressions in subcutaneous fat were also increased during growth, but its enhancement was smaller than in visceral fat. Moreover, tissue contents of VEGF in visceral fat were significantly increased in 14-wk-old mice compared with those in 6-wk-old mice (Fig. 2*B*). However, the VEGF contents in subcutaneous fat were almost the same in 6- and 14-wk-old mice. These data suggest that an enhanced expression of the VEGF gene in visceral fat mainly contributes to the elevated plasma concentrations.

Effect of fat accumulation on VEGF expression in white adipose tissues of db/db mice. Whole tissue weights of mesenteric and subcutaneous fat were increased gradually during growth (Fig. 3*A*). Total cell counts were significantly decreased during growth only in mesenteric adipose tissues (Fig. 3*B*). A significant correlation between fat weight and VEGF expression levels was observed in mesenteric adipose tissue but not in subcutaneous adipose tissue (Fig. 4*A*). Moreover, cellular levels of VEGF expression were calculated from the results of mRNA expression levels and total cell counts in adipose tissues and positively correlated for adiposity in mesenteric adipose tissue but not in subcutaneous adipose tissue (Fig. 4*B*).

Growth-dependent change of VEGF expression in adipocytes of visceral area of db/db mice. VEGF expressions in adipocyte fraction were increased during growth (Fig. 5). Cellular expression levels of VEGF mRNA in visceral adipocytes were increased sevenfold in 18-wk-old mice compared

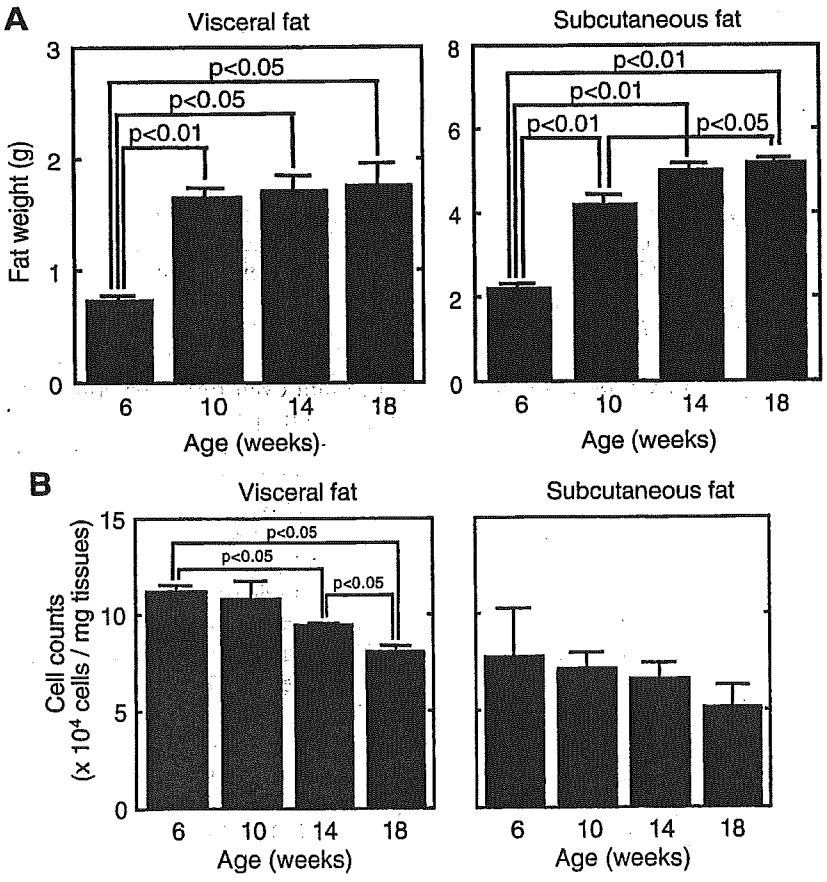

Fig. 3. Growth-dependent changes of fat weight and adiposity in mesenteric and subcutaneous adipose tissues. *A*: Time course changes of mesenteric and subcutaneous adipose tissue weights in *db/db* mice. The *db/db* mice were killed by cervical dislocation at 6, 10, 14, and 18 wk of age before adipose tissues were collected. Mesenteric and subcutaneous fat was weighed on an analytic balance. Results are represented as means + SD. *B*: Time course change of adiposity of mesenteric and subcutaneous adipose tissues in *db/db* mice. Mesenteric and subcutaneous fat was digested with collagenase S-1 and processed for cell counts using a Neubauer chamber. Results are represented as means + SD.

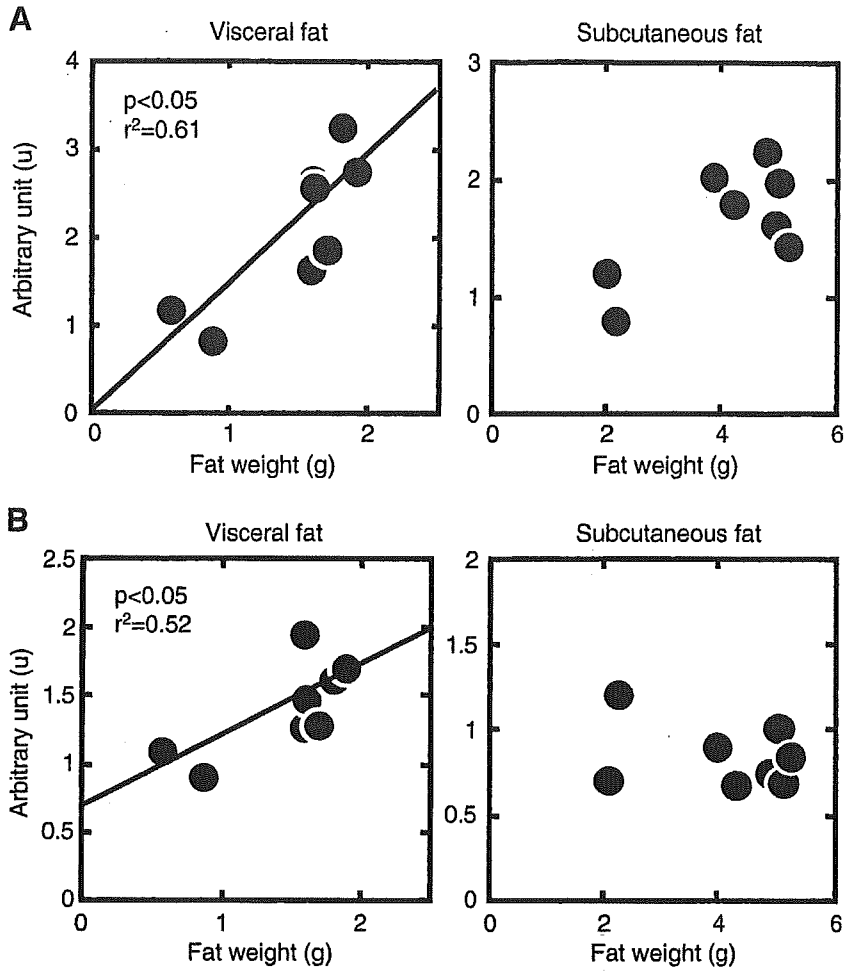

Fig. 4. Correlation between fat weight or adiposity and VEGF expressions in mesenteric adipose tissue. *A*: positive correlation between fat weight and tissue VEGF expression in mesenteric adipose tissues. *B*: positive correlation between fat weight and cellular VEGF expression in mesenteric adipose tissues.

with those in 6-wk-old mice. These results suggest that circulating VEGF concentrations in *db/db* mice were increased by the enhancement of VEGF mRNA expression in visceral adipocytes.

Plasma concentration and tissue expression of VEGF in KK-A^y mice. To demonstrate the correlation between VEGF expression and adiposity in another model of obesity, we analyzed KK-A^y mice. Plasma VEGF concentrations were significantly increased in both 8- and 16-wk-old KK-A^y mice compared with those in age-matched control mice (Fig. 6*A*). Moreover, expression levels of VEGF mRNA in visceral fat were significantly increased in KK-A^y mice compared with those in control mice (Fig. 6*B*). These results suggest that circulating VEGF concentrations in KK-A^y mice as well as in *db/db* mice were increased by the enhancement of VEGF mRNA expression in visceral fat.

Change of VEGF expressions during differentiation and maturation process in 3T3-L1 cells. We performed RT-PCR analysis for the gene expression of VEGF, PPARγ, and GLUT4 in cultured 3T3-L1 cells. VEGF mRNA was expressed even in the preadipocyte condition (Fig. 7*A*), and its expression was enhanced during adipocyte conversion. Especially, the expression levels of VEGF mRNA were significantly increased 14 days after differentiation (Fig. 7*B*). Both PPARγ and GLUT4 expressions were gradually enhanced during differentiation (Fig. 7*A*). These results suggest that expression levels of VEGF mRNA in 3T3-L1 cells were enhanced during lipid accumulation.

VEGF concentrations of conditioned media cultured with pre- and postdifferentiated 3T3-L1 cells. 3T3-L1 cells secreted VEGF proteins into culture medium even in the preadipocyte condition (Table 1), and the VEGF protein secretion was enhanced during adipocyte conversion. Especially, the VEGF concentrations in conditioned medium were increased fourfold 14 days after differentiation compared with those of predifferentiation. These results suggest that protein secretion as well as mRNA expression of VEGF in 3T3-L1 cells were enhanced during lipid accumulation. The biological activity of VEGF should be examined to know the role of VEGF in physiological and pathological conditions. Therefore, we demonstrated the angiogenic activity of conditioned medium from cultured adipocytes.

Enhancement of tube formation activity in HUVECs by addition of conditioned medium cultured with 3T3-L1 cells. VEGF secreted from both pre- and postdifferentiated 3T3-L1 cells had stimulatory activity toward HUVECs in tube formation (Fig. 8, *A* and *B*). The stimulatory activity in the condi-

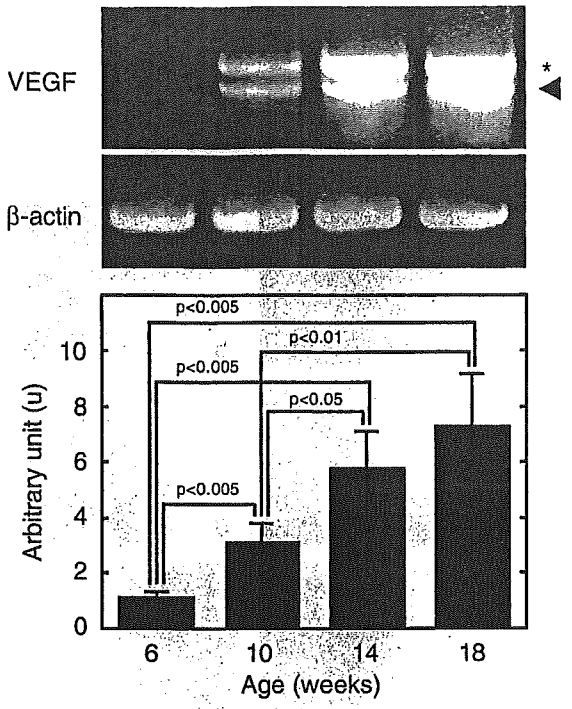

Fig. 5. Time course change of VEGF expressions in adipocyte fraction prepared from mesenteric fat of *db/db* mice. Visceral fat was cut into small pieces and digested using collagenase S-1. Then, the tissues were suspended with PBS and separated by centrifugation. The floating layer was collected as adipocyte fraction. Images show RT-PCR products of VEGF amplified from total RNA prepared from 2×10^4 cells of adipocytes at 6, 10, 14, and 18 wk after birth. The PCR products of VEGF were densitometrically analyzed, and the relative amounts at 6 wk old were set to 1.0. Results are represented as means and SD. Arrowhead, $VEGF_{164}$; *, $VEGF_{188}$.

tioned medium derived from postdifferentiated 3T3-L1 cells was three times higher than in predifferentiated cells. Moreover, anti-VEGF-neutralizing antibody apparently inhibited the stimulatory tube formation activity in both pre- and postdifferentiated 3T3-L1 cells. These findings suggest that 3T3-L1 cells secrete the bioactive form of VEGF protein.

Effect of implantation of 3T3-L1 preadipocytes into mesenteric or subcutaneous fat area of nude mice on VEGF expression. We performed RT-PCR analysis for gene expressions of VEGF, PPARγ, and GLUT4 in the mesenteric or subcutaneous fat area implanted with 3T3-L1 cells. As shown in Fig. 9*A*, the content of VEGF expression was increased fourfold in the mesenteric fat implanted with 3T3-L1 cells compared with those in sham-operated control mice. In contrast, VEGF expression of subcutaneous fat was almost the same in the mice implanted with 3T3-L1 cells into the subcutaneous area and controls. Moreover, PPARγ expression was enhanced only in mesenteric fat implanted with 3T3-L1 cells but not in subcutaneous fat. The expression levels of GLUT4 in both mesenteric and subcutaneous fat implanted with 3T3-L1 cells were higher than in controls.

The plasma VEGF concentration increased after implantation with 3T3-L1 cells into the mesenteric area, and these reached 381 ± 63 pg/ml at 4 wk. However, the mice injected in the subcutaneous area did not show any difference from control mice (Fig. 9*B*).

DISCUSSION

In the first set of experiments, we showed that the plasma VEGF concentrations gradually increased during growth in both *db/db* and *db/+* mice. After 10 wk of age, however, plasma VEGF concentrations were higher in *db/db* mice than in *db/+* mice. The *db/db* mice are considered to be an obesity model because fat deposition is the primary change. Then we analyzed the correlation between plasma VEGF concentration and body weight. The plasma VEGF concentration in *db/db*

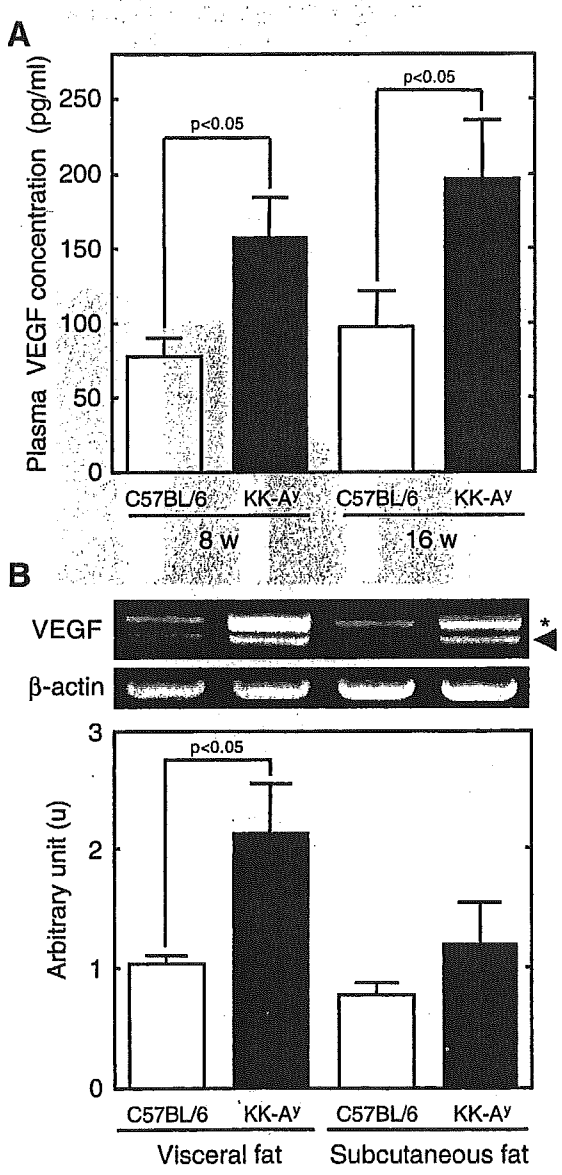

Fig. 6. Plasma concentration and tissue expression of VEGF in KK-A^y mice. *A*: comparison of plasma VEGF concentrations between KK-A^y and C57BL/6 mice. Plasma VEGF concentrations were measured in 8- and 16-wk-old KK-A^y and C57BL/6 mice. Results are represented as means + SD. *B*: comparison of VEGF gene expressions in visceral and subcutaneous adipose tissues between KK-A^y and C57BL/6 mice. Images show RT-PCR products of VEGF amplified from total RNA in mesenteric and subcutaneous adipose tissues at 16 wk after birth. The PCR products of VEGF were densitometrically analyzed, and the relative amounts in visceral adipose tissues of control mice were set to 1.0. Results are represented as means + SD. Arrowhead, $VEGF_{164}$; *, $VEGF_{188}$.

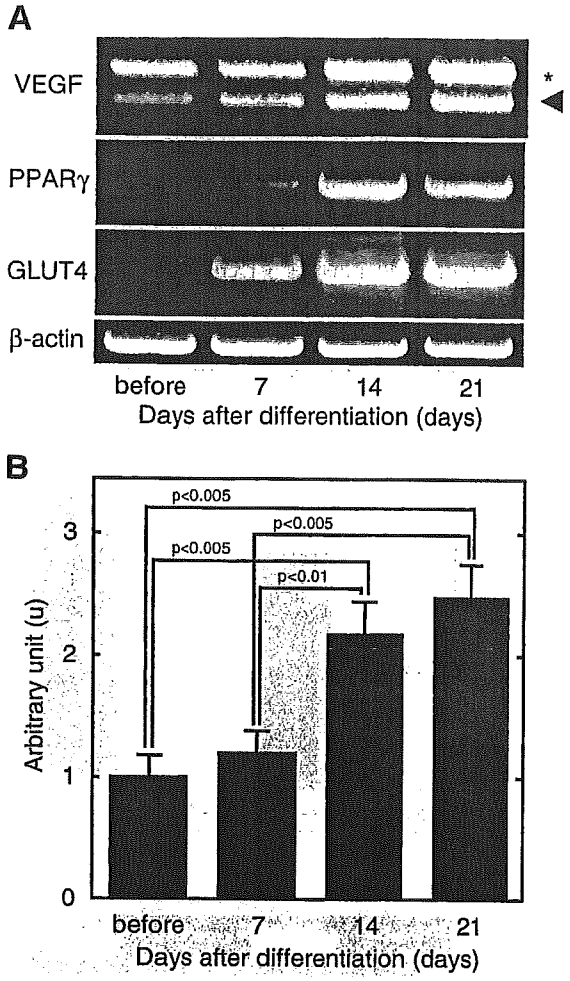

Fig. 7. Time course changes of VEGF, peroxisome proliferator-activated receptor-γ (PPARγ), and GLUT4 expressions in 3T3-L1 cells during adipocyte differentiation. *A*: gene expression profiles in 3T3-L1 cells during adipocyte differentiation. Images show RT-PCR products of VEGF, PPARγ, and GLUT4 amplified from total RNA in 3T3-L1 cells at 0, 7, 14, and 21 days after differentiation. *B*: relative amounts of VEGF expressions in 3T3-L1 cells during adipocyte differentiation. The PCR products of VEGF were densitometrically analyzed, and the relative amounts in predifferentiated 3T3-L1 cells were set to 1.0. Results are represented as means + SD. Arrowhead, $VEGF_{164}$; *, $VEGF_{188}$.

mice was significantly related to their body weight, the same as our previous results in human subjects (15). These results suggest that plasma VEGF may be determined by body fat deposition in mice.

In our previous report (15), plasma VEGF concentrations were revealed to be dependent on visceral fat accumulation. Therefore, to clarify the VEGF expressions with regard to whether subcutaneous or visceral adipose tissue affects plasma VEGF concentration in *db/db* mice, we examined mRNA expressions and protein contents of VEGF in visceral and subcutaneous adipose tissues during growth. The mRNA ex-

Table 1. *VEGF concentrations of conditioned media cultured with pre- and postdifferentiated 3T3-L1 cells*

Differentiation periods	Days 0	7	14	21
VEGF concentration, ng/ml	0.6±0.1	0.9±0.2	2.4±0.5	2.6±0.2
Total protein concentration, mg/ml	0.4±0.1	0.4±0.1	0.4±0.2	0.4±0.2

Values are means ± SD. VEGF, vascular endothelial growth factor.

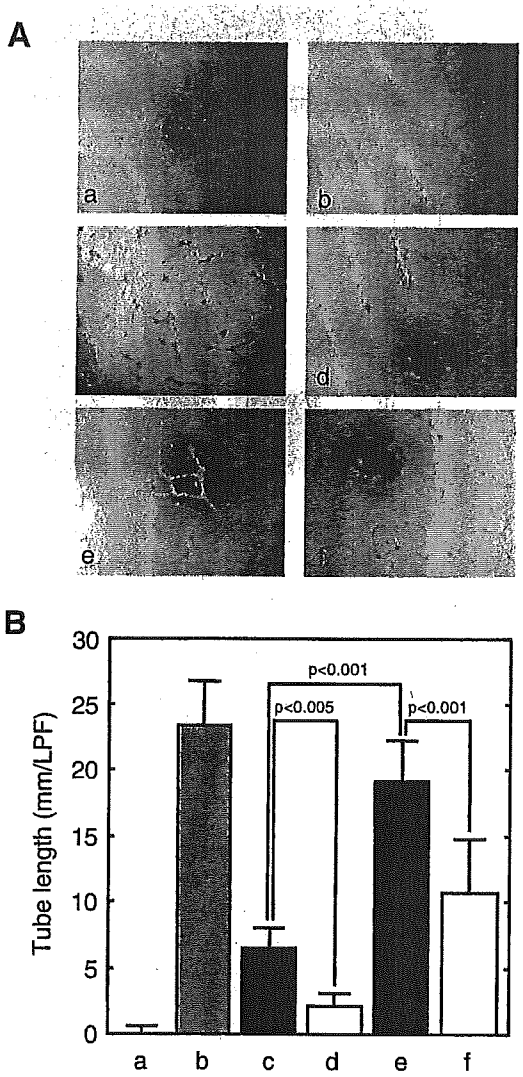

Fig. 8. Effect of conditioned media cultured with pre- and postdifferentiated 3T3-L1 cells on tube formation activity in human umbilical vein endothelial cells (HUVECs). *A*: light microscopic findings of tube formation of HUVECs in various conditions. Formation of capillary tube-like structures by HUVECs was assessed in a Matrigel-based assay as previously described (8). HUVECs were seeded on Growth Factor Reduced BD Matrigel matrix with conditioned medium derived from pre- or postdifferentiated 3T3-L1 cells in the presence or absence of anti-mouse VEGF-neutralizing antibody or recombinant VEGF protein. After 13 h of stimulation, phase-contrast microscopic low-power fields (×100) were photographed. *a*: medium alone; *b*: stimulated with recombinant VEGF (5 ng/ml); *c* and *d*: with conditioned medium from predifferentiated 3T3-L1 cells; *e* and *f*: with conditioned medium from postdifferentiated 3T3-L1 cells; *c* and *e*: in the absence of anti-VEGF antibody; *d* and *f*: in the presence of anti-VEGF antibody. *B*: tube length of HUVECs stimulated with conditioned medium prepared from pre- or postdifferentiated 3T3-L1 cells. The total length of capillary tubes formed by HUVECs in 3 different photographs per well were measured using a scale ruler. *Bar a*, medium alone; *bar b*, recombinant VEGF (5 ng/ml); *bar c*, conditioned medium from predifferentiated 3T3-L1 cells alone; *bar d*, conditioned medium from predifferentiated 3T3-L1 cells with anti-VEGF antibody; *bar e*, conditioned medium from postdifferentiated 3T3-L1 cells alone; *bar f*, conditioned medium from postdifferentiated 3T3-L1 cells with anti-VEGF antibody.

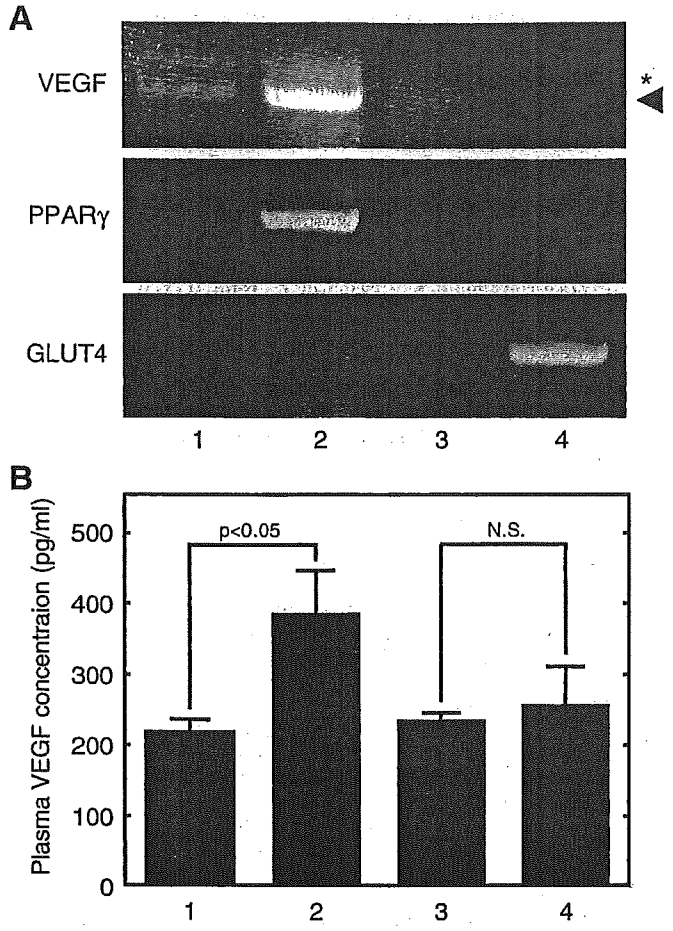

Fig. 9. Comparison of VEGF, PPARγ, and GLUT4 expressions among mice implanted with 3T3-L1 cells into mesenteric or subcutaneous fat area and controls. *A*: gene expression profiles in 3T3-L1 cells implanted into adipose tissues of nude mice. Images show RT-PCR products of VEGF, PPARγ, and GLUT4 amplified from total RNA in adipose tissues. *Lane 1*, mesenteric adipose tissues injected with PBS alone; *lane 2*, mesenteric adipose tissues injected with 3T3-L1 cells; *lane 3*, subcutaneous adipose tissues injected with PBS alone; *lane 4*, subcutaneous adipose tissues injected with 3T3-L1 cells. Arrowhead, $VEGF_{164}$; *, $VEGF_{188}$. *B*: plasma VEGF concentrations in mice implanted with 3T3-L1 cells. Plasma VEGF concentrations were measured at 4 wk after implantation with 3T3-L1 cells. *Lane 1*, mice injected with PBS alone into mesenteric area; *lane 2*, mice injected with 3T3-L1 cells into mesenteric area; *lane 3*, mice injected with PBS alone into subcutaneous area; *lane 4*, mice injected with 3T3-L1 cells into subcutaneous area.

pression levels of VEGF in visceral fat were more enhanced than in subcutaneous fat. Furthermore, the protein contents were enhanced in visceral fat but not in subcutaneous fat. These results suggest that plasma VEGF concentrations are revealed to be dependent on visceral fat accumulation even in mice.

The expression levels of TNF-α and PAI-1 in adipocytes are reported to be directly related to the degree of differentiation from preadipocytes and to be dependent on their anatomic location (12, 14, 20, 21). Therefore, we demonstrated the degree of fat accumulation in adipocytes and the correlation between VEGF mRNA expressions and adiposity in subcutaneous and mesenteric adipose tissues. Whole tissue weights of mesenteric and subcutaneous fat were increased gradually during growth. However, total cell counts were significantly decreased during growth in mesenteric fat but not in subcutaneous fat. A significant correlation between VEGF mRNA expressions and weight and adiposity in mesenteric adipose tissue was observed, but not in subcutaneous adipose tissue. These results suggest that the increase of weight in mesenteric adipose tissue is dependent on fat accumulation in adipocytes but not in subcutaneous adipose tissue. Moreover, VEGF expression is dependent on the levels of fat deposition in adipocytes. Then, we isolated the adipocyte fraction from mesenteric fat and examined VEGF mRNA expression in adipocytes. VEGF expression levels in the adipocyte fraction were also increased during growth.

Next, we examined the relation between VEGF expression and degree of differentiation using 3T3-L1 cells, an established adipocyte cell line. VEGF mRNA was expressed even in the preadipocyte condition, and its expression was enhanced after adipocyte conversion. Especially, the expression levels of VEGF mRNA were significantly increased 14 days after differentiation. Furthermore, the levels of VEGF protein secretion were almost the same level as gene expression. These results suggest that VEGF production may be dependent on the lipid accumulation (maturation) as well as the time lapse after adipocyte conversion rather than adipocyte differentiation from preadipocytes in 3T3-L1 cells.

We next determined whether VEGF protein secreted from 3T3-L1 cells has some biological activities. To know the role of VEGF in physiological or pathological conditions, we examined the effect of conditioned medium derived from 3T3-L1 cells on in vitro tube formation activity in HUVECs. The conditioned media from pre- and postdifferentiated 3T3-L1 cells enhanced angiogenesis in vascular endothelial cells. These results suggest that VEGF protein secreted from adipocytes may play some roles in the pathological neovascularization observed in diabetic retinopathy or atherosclerosis.

In the third set of experiments, the effects of anatomic localization on fat accumulation and VEGF production in adipocytes were analyzed using a cell implantation technique. 3T3-L1 cells implanted into the mesenteric area of athymic mice expressed more VEGF mRNA than that implanted into the subcutaneous area. The expression of PPARγ was also higher in 3T3-L1 cells implanted into the mesenteric area than into the subcutaneous area, and plasma VEGF concentrations in the mice implanted with 3T3-L1 cells into the mesenteric area were higher than in the subcutaneous area. These results suggest that a certain mechanism may exist in the visceral fat area to make implanted 3T3-L1 cells for enhanced VEGF production.

In summary, these results from in vitro and in vivo experiments indicate that VEGF expression in adipocytes is possibly differentiation as well as time (age) dependent after adipocyte conversion and may be determined by the site of body distribution. Further experiments are required to clarify the mechanism of enhanced expression of VEGF in visceral fat.

GRANTS

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Adiponectin and other Adipocytokines as Predictors of Markers of Triglyceride-Rich Lipoprotein Metabolism

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Background: **Adipocytokines are bioactive peptides that may play an important role in the regulation of glucose and lipid metabolism. In this study, we investigated the association of plasma adipocytokine concentrations with markers of triglyceride-rich lipoprotein (TRL) metabolism in men.**

Methods: **Fasting adiponectin, leptin, resistin, interleukin-6 (IL-6), tumor necrosis factor-α (TNF-α), apolipoprotein (apo) B-48, apo C-III, and remnant-like particle (RLP)-cholesterol concentrations were measured by immunoassays and insulin resistance by homeostasis assessment (HOMA) score in 41 nondiabetic men with a body mass index of 22–35 kg/m^2. Visceral and subcutaneous adipose tissue masses (ATMs) were determined by magnetic resonance imaging and total ATM by bioelectrical impedance.**

Results: **In univariate regression, plasma adiponectin and leptin concentrations were inversely and directly associated with plasma apoB-48, apoC-III, RLP-cholesterol, triglycerides, VLDL-apoB, and VLDL-triglycerides (P <0.05). Resistin, IL-6, and TNF-α were not significantly associated with any of these variables, except for a direct correction between apoC-III and IL-6 (P <0.05). In multivariate regression including HOMA, age, nonesterified fatty acids, and adipose tissue compartment, adiponectin was an independent predictor of plasma apoB-48 (β coefficient = −0.354; P = 0.048), apoC-III (β coefficient = −0.406; P = 0.012), RLP-cholesterol (β coefficient = −0.377; P = 0.016), and triglycerides (β coefficient = −0.374; P = 0.013). By contrast, leptin was not an independent predictor of these TRL markers. Plasma apoB-48, apoC-III, RLP-cholesterol, and triglycerides were all significantly and positively associated with plasma insulin, HOMA, and visceral, subcutaneous, and total ATMs (P <0.05).**

Conclusions: **These data suggest that the plasma adiponectin concentration may not only link abdominal fat, insulin resistance, and dyslipidemia, but may also exert an independent role in regulating TRL metabolism.**

Obesity is strongly associated with insulin resistance and dyslipidemia and increased risk of cardiovascular disease (CVD)[4] *(1, 2)*. Hypertriglyceridemia attributable to increased plasma concentrations of VLDL apolipoprotein (apo) B-100 and chylomicron apoB-48 is the most consistent lipid disorder in obesity *(3, 4)*. The precise underlying mechanism for this lipid abnormality remains unclear but may relate to oversecretion, reduced hydrolysis, and/or impaired clearance of triglyceride-rich lipoproteins (TRLs) *(3, 5)*. We have previously shown that obesity in men is associated with increased hepatic secretion and delayed catabolism of TRLs and that these kinetic defects are in part related to accumulation of abdominal fat and insulin resistance *(3, 5)*. We also demonstrated

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[4] Nonstandard abbreviations: CVD, cardiovascular disease; apo, apolipoprotein; TRL, triglyceride-rich lipoprotein; RLP, remnant-like particle; IL-6, interleukin-6; TNF-α, tumor necrosis factor-α; MRI, magnetic resonance imaging; HOMA, homeostasis assessment; BMI, body mass index; ATM, adipose tissue mass; FFM, fat-free mass; SAATM, subcutaneous abdominal adipose tissue mass; IPATM, intraperitoneal adipose tissue mass; RPATM, retroperitoneal adipose tissue mass; NEFA, nonesterified fatty acid; and SDS-PAGE, sodium dodecyl sulfate–polyacrylamide gel electrophoresis.

that obese individuals have insulin resistance and increased concentrations of markers of TRL metabolism, including apoB-48, apoC-III, remnant-like particle (RLP)-cholesterol, non-HDL cholesterol, and triglycerides *(3)*.

The precise relationships between dyslipoproteinemia, adiposity, and insulin resistance are complex and undefined *(2, 4, 6)*. Adipose tissue has recently been shown to secrete a variety of bioactive peptides, called adipocytokines, that can potentially impact on glucose and lipid metabolism *(7–9)*. These adipocytokines include adiponectin, leptin, resistin, interleukin-6 (IL-6), and tumor necrosis factor-α (TNF-α). Adiponectin, also known as adipocyte complement-related protein of 30 kDa (ACRP30), adipoQ, and gelatin-binding protein of 28 kDa (GBP28), is a protein present at relatively high concentrations in the circulation *(9)*. Unlike other adipocytokines, plasma adiponectin concentrations are decreased in obese and insulin-resistant individuals, including those with type 2 diabetes *(10, 11)*. Experimental and clinical evidence suggests that other adipocytokines may exert their effects on insulin sensitivity by influencing adipocyte expression and secretion of adiponectin *(12)*. Hypertriglyceridemia, low HDL-cholesterol concentrations, and decreased LDL particle size have recently been shown in humans to be correlated with low plasma adiponectin concentrations independent of the amount of intraabdominal fat and degree of insulin resistance *(13, 14)*. Moreover, a recent intervention trial reported that changes in adiponectin concentrations after weight loss are correlated with improvements in plasma lipid concentrations independent of changes in adiposity and insulin sensitivity *(13)*. However, the association between plasma adiponectin and specific markers of TRLs in relation to insulin resistance and body fat distribution has not been investigated previously.

In the present study, we hypothesized that, in men, adiponectin would be the adipocytokine most closely associated with changes in TRLs, namely apoB-48 and RLP-cholesterol, and that this association would be independent of body fat compartments and insulin resistance. Our principal aims were (*a*) to examine the association of markers of TRL metabolism, as reflected by plasma concentrations of apoB-48, apoC-III, and RLP-cholesterol, with plasma adiponectin, leptin, resistin, TNF-α, and IL-6 concentrations; and (*b*) to explain these associations in relation to variations in body fat compartments and insulin resistance, measured by magnetic resonance imaging (MRI) and homeostasis assessment (HOMA) score, respectively.

Materials and Methods

STUDY POPULATION

We studied 41 Caucasian men with a body mass index (BMI) ranging from 22 to 35 kg/m^2 and no history of familial dyslipidemia, intercurrent illness, or use of medications affecting lipid metabolism. All were nonsmokers and were consuming ad libitum weight-maintenance diets, as described previously *(15)*. Participants were selected from the community. The study was approved by the Royal Perth Hospital Ethics Committee.

CLINICAL PROTOCOLS

Clinical tests. Body weight, height, and waist and hip circumference were recorded as described previously *(15)*; BMI and waist-to-hip ratio were calculated. Blood pressure was recorded semiautomatically by use of a Dinamap recorder (Critilzon). Body composition was estimated, with participants at rest in the supine position after emptying their bladders, by use of a Holtain Body Composition Analyser (Holtain Ltd.) from which total adipose tissue mass (ATM), fat mass, and fat-free mass (FFM) were derived; FFM was calculated by use of the formula of Lukaski et al. *(16)*: FFM = $(0.85 \times H^2/Z) + 3.04$, where H is the height (cm) of the individual and Z is impedance. For this measure, participants were also asked to refrain from alcoholic beverages for 24 h; they were then studied in the morning, 15 min after emptying their bladder and in a temperature-controlled room. The technical error for FFM was <3%.

Dietary and energy expenditure records. Participants completed a 7-day food intake diary that recorded all dietary, alcohol, and energy intake; data were analyzed by use of DIET4 Nutrient Calculation Software (Xyris Software) based on the Australian Food Composition Database (NUTTAB 95; Australian Government Nutrient Database).

MRI. MRI of eight transaxial segments (field of view, 40–48 cm; 10-mm thickness) at intervertebral disc positions from T11 to S1 was carried out with a 1.0-Tesla Picker MR scanner (Picker International) and a T1-weighted fast-spin-echo sequence with a high fat-to-water signal ratio. Subcutaneous abdominal ATM (SAATM), intraperitoneal ATM (IPATM), and retroperitoneal ATM (RPATM) areas were calculated by summing the relevant adipose tissue pixel units with purpose-designed software, as used previously *(15)*. Fat anterior to the posterior peritoneum and anterior abdominal wall was defined as IPATM, and fat posterior to the posterior peritoneum was defined as RPATM. Anterior and posterior subcutaneous abdominal compartments was separated by drawing a perpendicular line at the midpoint of the anterior–posterior line passing through midpoints of the vertebral bodies in the MRI images. Anterior SAATM was obtained by subtracting posterior SAATM from total SAATM. The imaging protocol has a technical error of <10% and is highly correlated (R^2 = 99%) with measurements obtained from imaging of the abdominal region by contiguous transaxial slices. On the basis of phantom studies using oil/water emulsions, the accuracy of our method for delineating regional adipose tissue was 100.1 (0.01)%. The reproducibility of duplicate in vivo measures of

IPATM and SAATM had a CV <3.5%. Further details are described elsewhere *(15)*.

BIOCHEMICAL ANALYSES

Fasting plasma cholesterol, triglycerides, and HDL-cholesterol were determined by standard enzymatic methods (interassay CVs <3%). LDL-cholesterol was calculated by use of the Friedewald equation. Non-HDL cholesterol was derived as total cholesterol minus HDL-cholesterol. The VLDL fraction was isolated from 3 mL of plasma by ultracentrifugation (Kontron Instruments) at 147 000*g* for 16 h at 4 °C, and the triglyceride concentration was measured as described above. VLDL-apoB concentrations were determined by a modified Lowry method (interassay CV <5%) *(5)*. Plasma nonesterified fatty acids (NEFAs) and glucose were measured by enzymatic methods and insulin by an immunosorbent assay. Insulin resistance was estimated by the HOMA score *(17)*. Plasma apoB-48 concentrations were measured by a sandwich ELISA using anti-human apoB-48 monoclonal antibodies (designated B-48-151) as reported previously (interassay CV <5%) *(18)*. This direct ELISA measurement of apoB-48 in plasma was highly correlated with the traditional method using sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS-PAGE) coupled with immunoblotting and enhanced chemiluminescence in frozen plasma samples (n = 30; $r = 0.805$; $P < 0.001$) with a wide range of triglyceride concentrations (0.4–5.0 mmol/L) *(19)*. Values were 0.3–17.7 mg/L [mean (SD), 5.5 (4.8) mg/L] for the ELISA method and 9.51–54.40 mg/L [52.3 (11.6) mg/L] for the SDS-PAGE method. Plasma apoC-III was measured by immunoturbidimetric assay (Daiichi). Plasma RLP-cholesterol was determined with a JIMRO-II (Japan Immunoresearch Laboratories) assay using an immunoseparation technique (interassay CV <5%) *(20)*. Plasma adiponectin, leptin, IL-6, TNF-α, and resistin concentrations were measured by enzyme immunoassays (R & D Systems and Phoenix Pharmaceuticals); the interassay CV for these methods were <7%.

STATISTICAL ANALYSES

All analyses were performed with SPSS 11.5 (SPSS). The data are reported as the mean (SD). Skewed data were log-transformed where appropriate. Associations were examined by simple and stepwise linear regression methods. Because we carried out multiple comparisons, we considered that only $P < 0.01$ was of major importance in univariate analysis, but we also considered the conventional $P < 0.05$ as being statistically significant. Multiple regression models were used to determine the variables that best predicted plasma apoB-48, apoC-III, RLP-cholesterol, triglyceride, and VLDL-apoB concentrations. The adipose tissue compartment the most significantly correlated with corresponding dependent variable in stepwise regression analysis was included in the regression models.

Table 1. Anthropometric and ATM characteristics of the 41 men studied.

Characteristics	Mean (SD)	Range
Age, years	47 (9)	25–61
Systolic blood pressure, mmHg	127 (16)	96–164
Diastolic blood pressure, mmHg	76 (10)	53–96
Weight, kg	97 (12)	67–117
BMI, kg/m^2	30 (3)	22–35
Waist-to-hip ratio	1.0 (0.1)	0.9–1.1
FFM, kg	63 (8)	40–83
IPATM, kg	3.7 (1.5)	1.2–8.3
RPATM, kg	0.5 (0.06)	0.1–3.7
SAATM, kg	4.0 (1.4)	1.4–6.9
Anterior SAATM, kg	1.4 (0.6)	0.2–2.9
Posterior SAATM, kg	2.6 (0.9)	0.8–4.4
Total ATM, kg	33 (10)	13–56

Results

The anthropometric and ATM characteristics of the 41 men are shown in Table 1. They were generally middle aged and normotensive. Thirteen were nonobese, and 28 were obese, defined as BMI ≥30 kg/m^2. The mean proportions of total adipose tissue as IPATM, RPATM, and SAATM were 11%, 1.5%, and 12.1%, respectively. Of total SAATM, 35% was in the anterior and 65% in the posterior compartment.

The biochemical characteristics in the individuals studied are shown in Table 2. On average, the group was dyslipidemic, with increased triglycerides and low HDL-cholesterol, and insulin resistant. Four had impaired fasting glucose (6.1–6.9 mmol/L). Mean (SD) dietary intake per day was as follows: energy, 9276 (2030) kJ; total fat, 36 (7)%; carbohydrates, 38 (8)%; protein, 21 (4)%; alco-

Table 2. Biochemical characteristics of the men studied.

Characteristics	Mean (SD)	Range
Cholesterol, mmol/L	5.7 (0.9)	3.8–8.3
Triglycerides, mmol/L	2.7 (1.9)	0.5–8.8
HDL-cholesterol, mmol/L	1.0 (0.3)	0.6–1.8
Non-HDL cholesterol, mmol/L	4.7 (1.0)	3.1–7.4
LDL-cholesterol, mmol/L	3.6 (0.9)	1.5–5.8
RLP-cholesterol, mg/L	367 (34)	52–1670
ApoB-48, mg/L	8.9 (6.1)	1.0–24
ApoC-III, mg/L	163 (98)	29–410
VLDL-triglycerides, mmol/L	1.3 (1.3)	0.1–6.1
VLDL-apoB, mg/L	194 (167)	34–865
VLDL-triglycerides/apoB	13.2 (9.3)	0.36–63.9
NEFAs, mmol/L	0.90 (0.27)	0.45–1.67
Glucose, mmol/L	5.4 (0.6)	4.1–6.9
Insulin, mIU/L	11.7 (8.5)	2.6–41.8
HOMA score	2.9 (2.3)	0.6–10.8
Adiponectin, mg/L	4.4 (2.4)	1.4–11.4
Leptin, μg/L	18 (4)	10–23
Resistin, μg/L	204 (69)	53–366
TNF-α, ng/L	17 (7)	6–39
IL-6, ng/L	12 (5)	4–30

hol, 6 (6)%; and cholesterol, 385 (176) g. Compared with the 13 nonobese men, the 28 obese men had significantly increased plasma glucose, insulin, triglyceride, apoB-48, apoC-III, RLP-cholesterol, non-HDL cholesterol, VLDL-apoB, VLDL-triglycerides, and leptin concentrations and HOMA scores ($P < 0.01$), and significantly lower plasma HDL-cholesterol and adiponectin concentrations ($P < 0.01$), with no significant group differences in plasma resistin, IL-6, or TNF-α concentrations.

The univariate associations of plasma lipid and lipoprotein concentrations with plasma adipocytokine concentrations, measures of insulin resistance, and adipose tissue compartments are shown in Table 3. Plasma adiponectin concentration was significantly and negatively correlated with plasma apoB-48, apoC-III, RLP-cholesterol, triglyceride, total cholesterol, non-HDL cholesterol, VLDL-apoB, and VLDL-triglyceride concentrations and positively with HDL-cholesterol ($P < 0.05$ for both). By contrast, plasma leptin concentration was positively associated with plasma apoB-48, apoC-III, RLP-cholesterol, triglyceride, non-HDL cholesterol, VLDL-apoB, and VLDL-triglyceride concentrations and inversely with HDL-cholesterol (both $P < 0.05$). Plasma VLDL-apoB concentration was significantly and positively correlated with triglyceride ($r = 0.799$; $P < 0.001$), cholesterol ($r = 0.447$; $P < 0.01$), and non-HDL cholesterol ($r = 0.534$; $P < 0.001$) concentrations and negatively with HDL-cholesterol ($r = 0.402$; $P < 0.01$) concentration. The associations of apoB-48, apoC-III, RLP-cholesterol, and triglycerides with plasma adiponectin and leptin are shown in Figs. 1 and 2, respectively. Plasma resistin, IL-6, and TNF-α concentrations were not significantly associated with any of these lipid and lipoprotein variables except for a direct correlation between apoC-III and IL-6 ($r = 0.321$; $P < 0.05$). Plasma apoB-48, apoC-III, RLP-cholesterol, triglyceride, VLDL-apoB, and VLDL-triglyceride concentrations were positively associated with insulin, HOMA score, and the masses of all adipose tissue compartments except for total ATM in the case of VLDL-triglycerides. Plasma apoB-48 concentrations were also highly significant associated (both $P < 0.01$) with plasma concentrations of triglycerides ($r = 0.826$), RLP-cholesterol ($r = 0.732$), non-HDL cholesterol ($r = 0.517$), and VLDL-apoB ($r = 0.829$). Moreover, plasma adiponectin and leptin concentrations were significantly associated with insulin concentrations, HOMA score, and the masses of all adipose tissue compartments except for RPATM. Plasma resistin, IL-6, and TNF-α were not significantly associated with insulin concentration, HOMA score, and the masses of all adipose tissue compartments except for IPATM in the case of IL-6 and TNF-α (data not shown).

As shown in Table 4, plasma adiponectin concentration was a significant independent predictor of plasma apoB-48, apoC-III, RLP-cholesterol, and triglyceride concentrations ($P < 0.05$) in regression models including HOMA score, adipose tissue compartment, age, and NEFAs. Plasma adiponectin concentration was also a significant independent predictor of plasma VLDL-apoB (β coefficient = -0.377; $P = 0.016$) and VLDL-triglyceride (β coefficient = -0.364; $P = 0.042$) concentrations. In these models, IPATM was also an independent predictor of plasma apoC-III and VLDL-apoB concentrations, whereas total SAATM was an independent predictor of plasma triglyceride concentrations (Table 4). In contrast to adiponectin, plasma leptin was not an independent predictor of plasma apoB-48, apoC-III, RLP-cholesterol, and triglyceride concentrations in the same regression models (Table 4). In these models, total SAATM was an independent predictor of plasma apoB-48 and triglyceride concentrations, whereas HOMA score was an indepen-

Table 3. Associations (Pearson correlation coefficients) of plasma lipid and lipoprotein concentrations with plasma adipocytokine concentrations, measures of insulin resistance, and adipose tissue compartments.

	ApoB-48	ApoC-III	RLP-C[a]	TG	Cholesterol	HDL-C	Non-HDL C	LDL-C	VLDL-apoB	VLDL-TG
Adiponectin	−0.506[b]	−0.531[b]	−0.557[b]	−0.632[b]	−0.453[b]	0.474[b]	−0.564[b]	−0.172	−0.622[b]	−0.452[b]
Leptin	0.342[c]	0.400[b]	0.423[b]	0.548[b]	0.224	−0.414[b]	0.334[c]	0.050	0.463[b]	0.359[c]
Resistin	−0.113	0.027	−0.073	0.034	0.007	0.120	−0.014	−0.009	−0.010	−0.153
TNF-α	0.057	0.204	0.255	0.198	0.197	−0.105	0.227	0.119	0.187	0.197
IL-6	0.067	0.321[c]	0.166	0.169	0.132	−0.060	0.133	0.149	0.167	0.110
NEFAs	−0.207	−0.156	−0.200	−0.197	−0.078	0.163	−0.111	−0.063	−0.167	−0.042
Glucose	0.241	0.364[c]	0.387[c]	0.401[b]	0.016	−0.370[c]	0.108	−0.135	0.367[c]	0.335[c]
Insulin	0.483[b]	0.511[b]	0.613[b]	0.660[b]	0.423[b]	−0.439[b]	0.525[b]	0.119	0.572[b]	0.386[c]
HOMA score	0.343[c]	0.411[b]	0.512[b]	0.671[b]	0.395[b]	−0.459[b]	0.509[b]	0.092	0.440[b]	0.319[c]
IPATM	0.440[b]	0.508[b]	0.490[b]	0.565[b]	0.266	−0.366[c]	0.360[c]	0.022	0.553[b]	0.347[c]
RPATM	0.335[c]	0.382[c]	0.398[c]	0.438[b]	0.206	−0.285	0.280	0.025	0.310[c]	0.337[c]
Total SAATM	0.491[b]	0.401[b]	0.435[b]	0.591[b]	0.317[c]	−0.433[b]	0.431[b]	0.132	0.517[b]	0.417[c]
Anterior SAATM	0.458[b]	0.385[c]	0.386[c]	0.546[b]	0.255	−0.340[b]	0.342[c]	0.018	0.452[b]	0.420[c]
Posterior SAATM	0.462[b]	0.369[c]	0.424[b]	0.560[b]	0.328[c]	−0.453[b]	0.450[b]	0.195	0.508[b]	0.371[c]
Total ATM	0.386[c]	0.367[c]	0.396[c]	0.468[b]	0.301	−0.309[c]	0.381[c]	0.173	0.490[b]	0.254

[a] RLP-C, remnant-like particle-cholesterol; TG, triglycerides; HDL-C, HDL-cholesterol; Non-HDL C, non-HDL cholesterol; LDL-C, LDL-cholesterol.
[b,c] Significant at [b]$P < 0.01$; [c]$P < 0.05$.

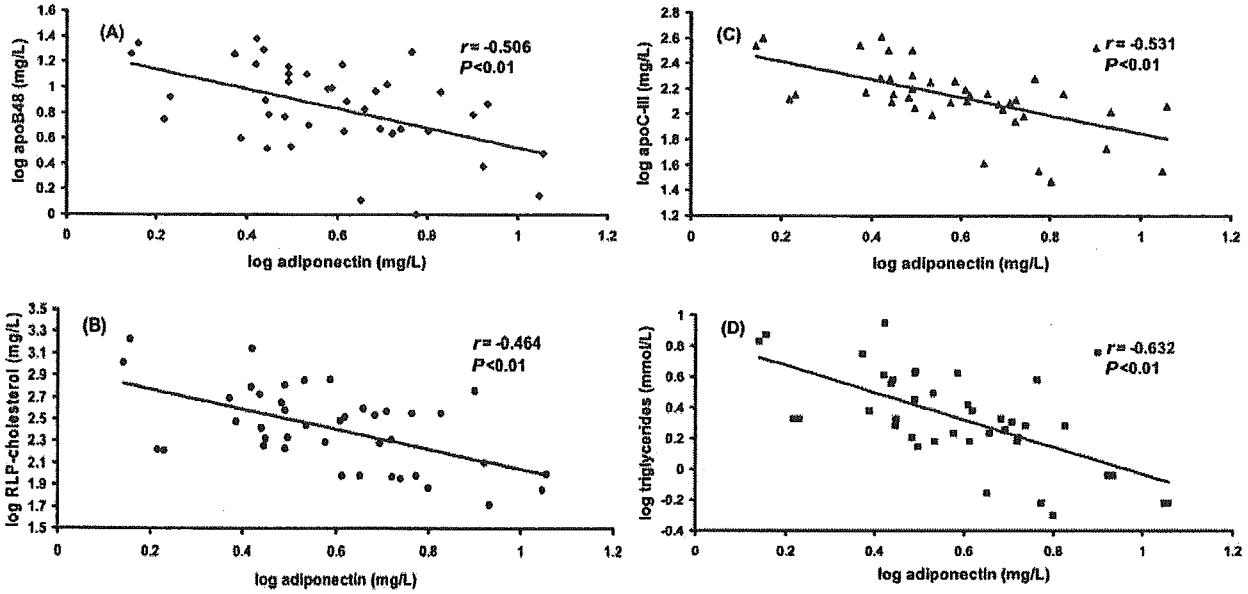

Fig. 1. Associations of plasma adiponectin concentrations with apoB-48 (*A*), apoC-III (*B*), RLP-cholesterol (*C*), and triglyceride (*D*) concentrations.

dent predictor of plasma RLP-cholesterol and triglyceride concentrations. Plasma IL-6 concentration was not an independent predictor of plasma apoC-III in the regression models including HOMA, age, NEFAs, and IPATM (data not shown).

Discussion

We report on the relationships between a wide spectrum of plasma adipocytokines and markers of TRL metabolism in humans. Our principal result was that low plasma adiponectin concentrations were highly predictive of increased plasma apoB-48, apoC-III, RLP-cholesterol, and triglyceride concentrations and that this was independent of both insulin resistance and size of adipose tissue compartments. Another new finding was that, in these men, other adipocytokines (resistin, IL-6, and TNF-α) were not significantly associated with these markers except for a direct association between plasma apoC-III and IL-6 concentrations. In the case of leptin, significant associations were not independent of body fat compartments and insulin resistance. We also showed good agreement across a wide range of plasma triglyceride concentrations

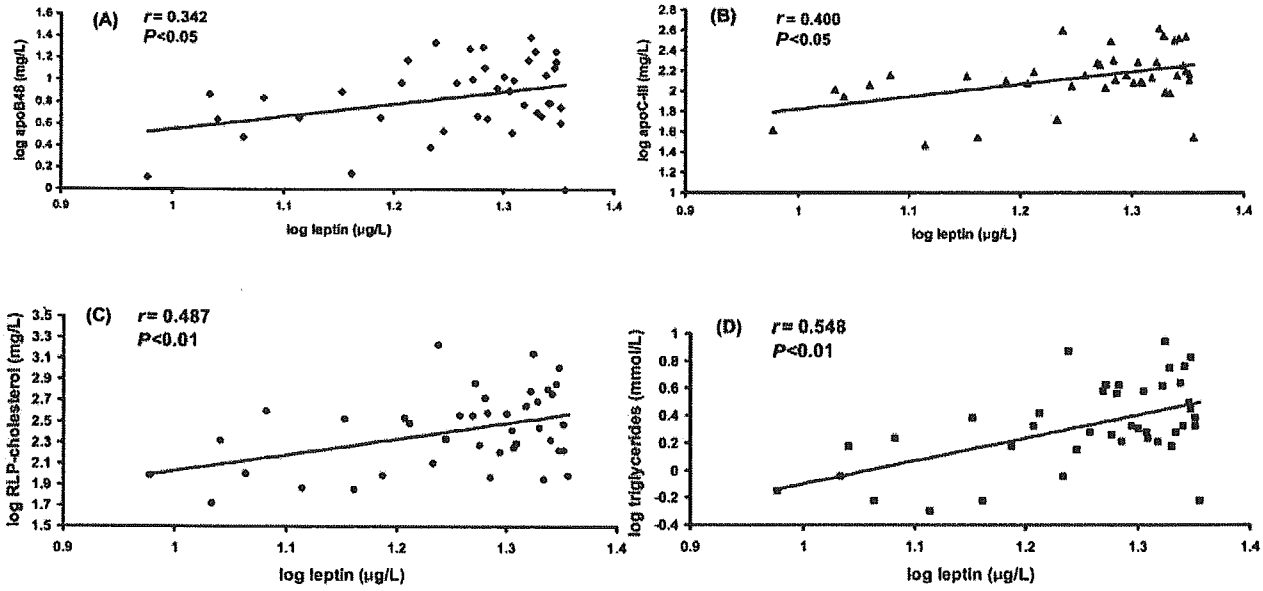

Fig. 2. Associations of plasma leptin concentrations with apoB-48 (*A*), apoC-III (*B*), RLP-cholesterol (*C*), and triglyceride (*D*) concentrations.

Table 4. Multiple regression analyses of the relationships between markers of TRL metabolism, plasma adiponectin or leptin, HOMA, and adipose tissue compartment.[a]

	Predictor	β coefficient	P	Adjusted R^2
ApoB-48	Adiponectin	−0.354	0.044	
	HOMA	0.019	0.909	
	Total SAATM	0.297	0.072	
				28% ($P = 0.005$)
	Leptin	−0.200	0.386	
	HOMA	0.187	0.259	
	Total SAATM	0.576	0.013	
				21% ($P = 0.019$)
ApoC-III	Adiponectin	−0.406	0.012	
	HOMA	0.038	0.820	
	IPATM	0.322	0.047	
				33% ($P = 0.002$)
	Leptin	0.093	0.618	
	HOMA	0.19	0.274	
	IPATM	0.354	0.077	
				20% ($P = 0.025$)
RLP-cholesterol				
	Adiponectin	−0.377	0.016	
	HOMA	0.203	0.219	
	IPATM	0.236	0.130	
				36% ($P = 0.001$)
	Leptin	0.133	0.461	
	HOMA	0.336	0.049	
	IPATM	0.241	0.207	
				26% ($P = 0.008$)
Triglycerides				
	Adiponectin	−0.374	0.013	
	HOMA	0.213	0.129	
	Total SAATM	0.325	0.021	
				49% ($P = 0.001$)
	Leptin	0.099	0.623	
	HOMA	0.335	0.024	
	Total SAATM	0.403	0.044	
				40% ($P = 0.001$)

[a] The adipose tissue compartment most closely correlated with the corresponding dependent variable in stepwise regression analysis was included in the models, and statistical models were also adjusted for age and NEFAs.

between a new direct ELISA for apoB-48 and a previously published method based on SDS-PAGE coupled with immunoblotting and enhanced chemiluminescence *(19)*.

Our data are consistent with previous findings that low adiponectin concentrations are associated with an atherogenic lipid profile, including increased triglycerides and low HDL-cholesterol *(13, 14, 21)*. We have extended these studies by investigating the association of plasma adiponectin concentrations with markers of TRL metabolism as measured by plasma apoB-48, apoC-III, and RLP-cholesterol concentrations and demonstrating that low adiponectin concentrations are most closely correlated with accumulation of TRLs independent of insulin resistance and body fat distribution. We also provide new data, based on comprehensive investigation of body fat compartments by MRI, that plasma concentrations of apoB-48, apoC-III, and RLP-cholesterol are strongly associated with adipose tissue compartments, including IPATM, RPATM, anterior SAATM, posterior SAATM, and total ATM.

Dyslipidemia in obesity and insulin resistance is fundamentally related to expansion in the plasma pool of TRLs *(6, 22)*. Accumulation of adipose fat, particularly in the abdominal region, leads to a markedly increased flux of NEFAs to the liver *(6, 23)*, which stimulates triglyceride synthesis *(24)*. Insulin resistance increases hepatic synthesis of lipid substrates and the secretion of VLDL apoB-100; it also down-regulates LDL receptors *(22, 25)*. These effects potentially increase the plasma concentrations of remnant lipoproteins containing apoB-100 and increase competition for hepatic uptake between chylomicron and VLDL remnants *(26)*. However, the lack of a significant correlation of plasma NEFAs with VLDL-triglyceride and/or total triglyceride concentration in our study suggests that measurement of circulating NEFAs in plasma may not simply reflect portal flow of NEFAs to the liver. We have previously reported that, in obese men, accumulation of TRL remnants is attributable to defective lipolysis and impaired clearance of chylomicron remnants, as reflected by increased apoC-III concentrations and a reduced catabolic rate of a remnant-like emulsion *(3)*. The metabolic differences between obese and nonobese men in this study were consistent with our previous data *(3)*. We also demonstrated that insulin resistance and body fat distribution were strongly and independently predictive of plasma apoB-48, apoC-III, RLP-cholesterol, triglyceride, and VLDL-apoB concentrations.

The effect of adiponectin on TRL metabolism may principally involve intrinsic changes in skeletal muscle lipid metabolism and effects on lipoprotein lipase activity in both skeletal muscle and adipocytes *(8, 27, 28)*. Adiponectin may decrease accumulation of triglycerides in skeletal muscle by enhancing fatty acid oxidation through activation of acetyl-CoA oxidase, carnitine palmitoyltransferase-1, and AMP kinase *(27)*. Adiponectin may also stimulate both lipoprotein lipase *(29)*, the lipolytic enzyme that catabolizes VLDL, and apoC-III by increasing the expression of peroxisome proliferator-activated receptor-α in the liver and adipocytes *(30)*. At the hepatic level, adiponectin may decrease the supply of NEFAs to the liver for gluconeogenesis, hence decreasing triglyceride synthesis. Taken together, low circulating adiponectin concentrations could lead to delayed removal of TRLs by the liver and peripheral tissue by increasing competition between chylomicrons and VLDL for LPL lipolysis, and between chylomicron remnants and VLDL remnants for LDL-receptor-mediated clearance *(26)*. Because resistin, IL-6, and TNF-α were not associated with insulin resistance and total body fat in the present study, it was not surprising that we found no significant association of these peptides with markers of TRLs. Our findings also suggest that plasma leptin may not per se have a direct

impact on the metabolism of TRLs and may simply reflect changes in body fat stores *(31)*.

Several methods have been used for the measurement of apoB-48 in plasma *(18, 19, 32)*. The Western blotting method is time-consuming and is less quantitative than the standard ELISA technique; the specificity of polyclonal antibodies in the competitive ELISA is also questionable. In the present study, we used a novel ELISA system that incorporates monoclonal antibodies against apoB-48 to measure apoB-48 in plasma *(18)*. This method enhances the specificity and sensitivity of apoB-48 measurements in plasma without the need for time-consuming isolation of TRLs. Differences in fasting apoB-48 values reported by different methods reflect differences in standardization *(32)*. Despite the analytical shortcomings listed above, we found that the apoB-48 values obtained by our ELISA and the SDS-PAGE methods were well correlated.

We used a surrogate estimate of insulin resistance, the HOMA score, which is well correlated with the hyperinsulinemic, euglycemic clamp technique *(17)*. Measurements of apoB-48 may not differentiate between the nascent chylomicron and its remnant. However, because participants were fasted for at least 12 h to ensure minimal intestinal secretion of nascent chylomicrons, the apoB-48 concentration was probably indicative of small, dense chylomicrons and their remnants. In addition, fasting RLP-cholesterol is not a specific marker of chylomicron and VLDL remnants because it quantifies apoE-rich lipoproteins of intestinal origin as well as some hepatic lipoproteins *(20, 33)*. The association of plasma adipocytokines with apoC-III kinetics also requires further investigation. Future studies should examine the effect of adiponectin genotypes on TRL metabolism *(34, 35)*. In addition, the individual effects of the full-length peptide as well as the low- and high-molecular-weight forms of adiponectin on TRL metabolism also merit further investigation *(36)*.

Several studies have clearly demonstrated the close relationship between the impaired metabolism of TRLs and the development of CVD and type 2 diabetes *(33, 37–39)*. Clinical and experimental data have also recently demonstrated that adiponectin is a strongly protective predictor of CVD, having several antiatherogenic properties *(28, 40, 41)*. Our study therefore suggests that the relationship between low adiponectin concentrations and CVD may in part be mediated by the accumulation of TRLs in plasma. However, definitive evidence of the role of adiponectin in regulating TRL metabolism will require further investigation using adiponectin-knockout animals and recombinant adiponectin replacement therapy *(29)*.

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