Adult-onset deficiency of acyl CoA:monoacylglycerol acyltransferase 2 protects mice from diet-induced obesity and glucose intolerance

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Abstract  Acyl-CoA:monoacylglycerol acyltransferase (MGAT) 2 catalyzes triacylglycerol (TAG) synthesis, required in intestinal fat absorption. We previously demonstrated that mice without a functional MGAT2-coding gene (Mogat2<sup>−/−</sup>) exhibit increased energy expenditure and resistance to obesity induced by excess calories. One critical question raised is whether lacking MGAT2 during early development is required for the metabolic phenotypes in adult mice. In this study, we found that Mogat2<sup>−/−</sup> pups grew slower than wild-type littersmates during the suckling period. To determine whether inactivating MGAT2 in adult mice is sufficient to confer resistance to diet-induced obesity, we generated mice with an inducible Mogat2-inactivating mutation. Mice with adult-onset MGAT2 deficiency (Mogat2<sup>cko</sup>) exhibited a transient decrease in food intake like Mogat2<sup>−/−</sup> mice when fed a high-fat diet and a moderate increase in energy expenditure after acclimatization. They gained less weight than littersmate but the difference was smaller than that between wild-type and Mogat2<sup>−/−</sup> mice. The moderate reduction in weight gain was associated with reduced hepatic TAG and improved glucose tolerance. Similar protective effects were also observed in mice that had gained weight on a high-fat diet before inactivating MGAT2<sup>−/−</sup>. These findings suggest that adult-onset MGAT2 deficiency mitigates metabolic disorders induced by high-fat feeding and that MGAT2 modulates early postnatal nutrition and may program metabolism later in life.—Banh, T., D. W. Nelson, Y. Gao, T-N. Huang, M-I. Yen, and C-L. E. Yen. Adult-onset deficiency of acyl CoA:monoacylglycerol acyltransferase 2 protects mice from diet-induced obesity and glucose intolerance. J. Lipid Res. 2015. 56: 379–389.

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Triacylglycerol (TAG) synthesis is crucial for many physiological processes involving storage or delivery of fatty acids and metabolic energy. TAG synthesis in most cells starts with acylation of glycerol-3-phosphate, followed by two additional acylation steps, whereas in some cells it uses monoacylglycerol (MAG) as the initial acyl acceptor. Acyl-CoA: monoacylglycerol acyltransferase (MGAT) catalyzes the latter pathway and generates diacylglycerol for the final acylation step (1). As MAG is mostly a degradation product of TAG, the MGAT pathway is thought to be important for recycling of TAG. Indeed, the best-characterized MGAT function is in the absorption of dietary fat. During the process, dietary TAG is hydrolyzed in the intestinal lumen to MAG and fatty acids. After uptake, the hydrolysis products are resynthesized to TAG in enterocytes for the assembly of chylomicron, which in turn delivers dietary lipids to peripheral tissues (2).

Among three identified genes encoding MGAT enzymes, Mogat2 is highly expressed in the intestine of both rodents and humans (3–6). Supporting the role of MGAT2 as an intestinal MGAT mediating fat absorption, constitutive global inactivation of the enzyme, through germ-line transmission of a null mutation in Mogat2, greatly reduces intestinal MGAT activity and delays fat absorption (7). Interestingly, these Mogat2<sup>−/−</sup> mice absorb a normal quantity of fat but are protected from obesity and other metabolic disorders induced by high-fat feeding. The underlying physiological mechanisms involve a transient decrease in food intake and a persistent increase in energy expenditure (7, 8). Unexpectedly, the increase in energy expenditure does not require high-fat feeding, and MGAT2 deficiency also protects Agouti mice from excess weight gain (9). Findings from both gain- and loss-of-function mouse models indicate that MGAT2 in the intestine is a major contributor but incompletely accounts for the

Abbreviations:  AUC, area under the curve; dpc, day postcoitus; MAG, monoacylglycerol; MGAT, monoacylglycerol acyltransferase; TAG, triacylglycerol.

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<sup>4</sup>The online version of this article (available at http://www.jlr.org) contains supplementary data in the form of one figure.
differences in body weight (8, 10), suggesting complex mechanisms underlying the role of MGAT2 in the regulation of systemic energy balance.

MGAT2 in mice is expressed in embryos as early as 7 days postcoitus (dpc) and in the liver and intestine during the perinatal period [NCBI UniGeneID:307396, Gene Expression Omnibus GDS3764, and (11, 12)], suggesting a potential role of MGAT2 during early development. Several lines of evidence in both human and rodent studies support the concept that nutritional status during early development, including embryonic and fetal as well as early postnatal periods, programs metabolism and propensity to gain weight later in life (13–19). For example, in a historical cohort study, exposure to the Dutch famine of 1944–1945 during the first half of pregnancy is associated with increased obesity rates in early adulthood, while exposure during the last trimester and the first months of life is associated with reduced obesity rates (20). In mice, early postnatal undernutrition limits adiposity induced by high-fat diet in adulthood (21). Thus, we question whether MGAT2 determines metabolic efficiency during early development and, more importantly, whether lacking MGAT2 during those critical periods is required for the protective effects against metabolic disorders seen in adult Mogat2−/− mice.

In this study, to determine whether MGAT2 plays a role in overall energy balance during the intrauterine and the suckling period, we examined body weights of fetuses at late gestation and of pups before weaning. In addition, to determine whether adult-onset MGAT2 deficiency is sufficient to modulate the responses to high-fat feeding, we developed inducible knockout mice in which MGAT2 could be ablated at specific developmental stages and examined their metabolic phenotypes in response to high-fat feeding.

MATERIALS AND METHODS

Mice

Germ-line MGAT2 knockout (Mogat2−/−) mice with constitutive and global MGAT2 deficiency were produced as described (7). To enable inactivation of Mogat2 in adult mice, a line of inducible MGAT2 knockout mice was generated using the Cre-loxP system with a ubiquitously expressed Cre recombinase that remains inactive until induction by tamoxifen treatment (22). Mogat2+/− mice carrying both copies of “floxed” Mogat2 alleles with exon 2 flanked by Cre-recombinase target sites (loxP) (8) were crossed with a line of transgenic mice ubiquitously expressing a tamoxifen-inducible Cre recombinase (23). Cre activity is inducible by tamoxifen but not estrogen (23), which in turn mediates the precise excision of exon 2 of the Mogat2 gene flanked by two loxP sites, switching off the functional gene. Through crossing-breeding, inducible mutant (Mogat2−/+ ) mice carrying “floxed” Mogat2 alleles and one copy of the inducible Cre recombinase and their Mogat2−/− littermate controls were produced.

Upon treatment with the estrogen analog tamoxifen, Cre tranlates to the nucleus and excises exon 2 of the Mogat2 gene in Mogat2−/− mice, resulting in inactivation of MGAT2 (Mogat2 AKO mice).

Mice were housed on a 12 h light/dark cycle. Weighing of mice and changes of diets and cages were performed between 3 PM and 6 PM. All animal procedures were approved by the University of Wisconsin–Madison Animal Care and Use Committee and were conducted in conformity with the Public Health Service Policy on Humane Care and Use of Laboratory Animals.

Tamoxifen treatment to inactivate MGAT2

To inactivate MGAT2, adult Mogat2−/− and Mogat2+/− control mice were intragastrically administered a daily dose of tamoxifen (MP Biomedicals; 200 mg/kg body weight/day; 20 mg/ml in corn oil) for 5 days either at 4 months of age (prior to high-fat feeding) or at 5 months of age (after 7 weeks of high-fat feeding). Because tamoxifen treatment causes a transient decrease in body weight (data not shown), we allowed mice to recover for 1 month before performing energy balance experiments. Tamoxifen-induced weight loss was also observed in diet-induced obese mice.

Genotyping

Genotypes of mice were determined by PCR. To determine the presence of the Cre-recombinase transgene, the following four primers were used: Cre forward, 5′-CCCGGCAAAACAGG-TAGTTA-3′; Cre reverse, 5′-TGCCAGAGATCGGTTAG-3′; Positive control forward, 5′-CCCTTGACCTGGTCAGCCA-3′; and Positive control reverse, 5′-CAGGAAAGCCTTTGATCCCTTC-3′. This reaction produces a 194 bp amplicon and a 381 bp amplicon from the transgene and the internal control gene, respectively. To determine the presence of the wild-type or floxed Mogat2 allele, the following two primers were used: Mogat2 forward, 5′-GTATGGGACCTGTGTA-3′; and Mogat2 reverse, 5′-AGGTCTTACAGTACAG-3′. This reaction produces a 478 bp amplicon and a 512 bp amplicon from the wild-type allele and the allele with the addition of a 34 bp loxP site, respectively. To confirm Cre-recombinase-mediated deletion of Mogat2 following tamoxifen treatment we regenotyped mice using the same Mogat2 primers plus an additional primer, Target forward, 5′-GAACCTCCGAGATAACTCTGC-3′, specific for a region upstream of the floxed allele. This reaction produces 512 and 1,089 bp amplicons prior to excision, and a 191 bp amplicon after excision.

Diets

Mice were fed a complete, fixed-formula chow (#8604; Teklad, Madison, WI). A series of semipurified (defined) diets containing 10, 45, or 60% calories from fat (D12450B, D12451, and D12492; Research Diets, New Brunswick, NJ) were used to examine the effect of dietary fat on food intake and energy expenditure, as indicated. These defined diets contained 20% calories from protein (casein) and fixed amounts of micronutrients and fiber per calorie, but they varied in metabolizable energy (3.8, 4.7, or 5.2 kcal/g), corresponding to the fat content.

Real-time quantitative PCR analysis

The levels of Mogat2 mRNA in tissues collected from fetuses of embryonic day 19 or mice fed the 60 kcal% fat diet for 10 weeks were assessed as previously described (8). Cyclophilin B (Cypb) expression was used as an internal control. The primer sequences of the Cypb gene were 5′-TGCCGGAGATCGAGAATGAT-3′ (forward) and 5′-TGGAGAAGACCCAGACAGACAG-3′ (reverse). The primers to
detect Mogat2 mRNAs were located on exon 1 and exon 2, respectively; the forward primer sequence was 5′- TGGGAGCGGAGGTTACAGA-3′, and the reserve primer sequence was 5′- CAGGTGCGCATCAGGACAGA-3′. The qRT-PCR method was used to calculate the fold change in gene expression (24).

**In vitro MGAT assays**

MGAT activity assays were performed with total tissue homogenates as previously described (10). Reactions were started by adding total tissue homogenates to the assay mixture and were stopped by adding chloroform-methanol (2:1, v/v). The lipids were extracted, dried, and separated by TLC on silica gel G-60 TLC plates with hexane-diethyl ether-acetic acid (80:20:1, v/v/v). Lipid bands were visualized with iodine vapor, and products were identified by comparison with the migration of lipid standards. The incorporation of radioactive substrates into lipid products was also visualized by an imaging scanner (Typhoon FLA 7000; GE Healthcare Life Sciences, Piscataway, NJ) followed by band scraping and counting in a scintillation counter analyzer (Packard Tri-Carb 2200 CA Liquid Scintillation Counter Analyzer; PerkinElmer, Santa Clara, CA).

**Metabolic phenotyping studies**

To assess phenotypes related to acute energy balance, mice were housed in a metabolic phenotyping system with housing and wood chip bedding similar to the home cage environment (LabMaster modular animal monitoring system; TSE, Chesterfield, MO). Adult male mice were acclimated to individual housing and metabolic cages for 1 week before experiments and were fed indicated diets sequentially for 3 days each. Data collection and analysis were performed as previously reported (9, 10).

**Body weight response to chow or high-fat feeding**

We monitored weight gains daily before weaning and weekly afterward to assess long-term energy balance. To examine long-term body weight responses to low-fat chow and high-fat diet, male mice were fed a regular mixed meal chow at weaning (3 weeks) and then switched to a 60% diet at 4 months of age and for an additional 10 weeks. To investigate the effect of MGAT2 inactivation in diet-induced obese mice, male mice were switched to the 60 kcal% fat diet at 2–3 months of age, prior to inactivation of MGAT2.

**Biochemical assays**

Plasma lipids were assayed using enzymatic kits (InfiniTM Tri-glycerides Lipid Stable Reagent, Thermo Fisher; Cholesterol E, Non Esterified Fatty Acid assay, Wako Diagnostics). Hepatic and fecal lipids were extracted in chloroform-methanol (2:1, v/v) following homogenization in PBS. Blood samples were collected from the orbital plexus, and plasma was separated by centrifugation. Hepatic TAG and glycogen were measured as described previously (8). Protein concentration was measured by Pierce BCA Protein Assay Kit (Thermo, Rockford, IL). To examine glucose metabolism following high-fat feeding, mice were fed 60 kcal% fat diet for ~8 weeks, then a glucose tolerance test was performed. Briefly, male mice were fasted for 6 h beginning at 7 AM and then injected with glucose (1 g/kg bodyweight, ip, 10% glucose in PBS). Blood glucose was measured immediately before and at defined intervals after glucose injection using a handheld glucose monitor (OneTouch Ultra; LifeScan Inc., Milpitas, CA). Plasma insulin was measured by ELISA (Crystal Chem Inc., Downers Grove, IL).

**Statistical analyses**

All data are presented as mean ± SEM. *P* < 0.05 was considered statistically significant. Each experiment was performed with independent samples at least twice to confirm reproducibility of the results. For comparisons between two groups, Student’s *t*-tests were used. Differences measured over time were compared using repeated-measures two-way ANOVA to determine main effects of, and interactions between, time and genotype. To identify group differences, Bonferroni’s posttests were performed. Analyses were conducted using GraphPad Prism statistical analysis software (version 5.01; GraphPad Software, La Jolla, CA).

**RESULTS**

**Mouse pups with constitutive Mogat2 inactivation gain less weight during the suckling period**

To explore a potential role of MGAT2 during early development, we first assessed if its coding gene Mogat2 is expressed prenatally in fetal tissues collected on embryonic day 19 (dpc) using quantitative PCR. We found high levels of MGAT2 mRNA in intestine, similar to in adult mice. Relatively moderate levels of MGAT2 were also found in yolk sac, liver, and kidney, but not in placenta (Fig. 1A). We next compared body weights of fetuses at a late stage of gestation (19 dpc) from intercrosses of heterozygous mice (Mogat2+/−), bearing a constitutively null Mogat2 allele. We found no difference in intrauterine growth between wild-type, Mogat2+/−, and Mogat2−/− fetuses (Fig. 1B), suggesting that MGAT2 does not play an indispensable role in the regulation of energy balance during the prenatal period. In contrast, after birth, pups with the germ-line null mutation (Mogat2−/−) gained less weight than wild-type littermates throughout the suckling period, when pups nursed on milk rich in fat [~20% by weight (25)] (Fig. 1C). At weaning, their average weight was ~80% that of controls. Consistent with previous reports (7, 9), after weaning onto a standard low-fat chow, these mice exhibited compensatory growth and were able to reach a body weight similar to wild-type littermates by 3 months of age (Fig. 1D). When their feed was switched to a diet containing 60% calories from fat, wild-type mice gained significantly more weight than did Mogat2−/− littermates (Fig. 1E). During 10 weeks of high-fat feeding, wild-type mice gained on average 20.2 ± 1.6 g while Mogat2−/− mice gained only 4.7 ± 0.3 g (Fig. 1E).

**Generation of mice with tamoxifen-inducible Mogat2 inactivation**

To determine whether MGAT2 deficiency during early development is required for the obesity-resistant phenotype seen in Mogat2−/− mice, we developed a mouse model in which Mogat2 can be inactivated in adulthood. Mice carrying a tamoxifen-inducible ubiquitin-Cre recombinase were crossed with mice carrying two loxP sites flanking exon 2 of the Mogat2 gene (8). The offspring were intercrossed to generate mice carrying homozygous “flxed” Mogat2alleles (Mogat2fl/fl), and half of them were also hemizygous, carrying a copy of the transgene expressing the inducible Cre recombinase (Mogat2fl/fl, UBC-Cre). Before induction, these inducible mutants are designated Mogat2im mice.

**Adult-onset MGAT2 deficiency in mice**

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tamoxifen treatment was efficient in activating Cre recombinase and causing Mogat2 ablation in the intestinal stem cells, which normally replace intestinal epithelia every 3–5 days (26).

Mogat2 mRNA levels correlated with MGAT activity in the small intestine. Before tamoxifen treatment, Mogat2 f/f and Mogat2 im mice showed MGAT activity similar to that of wild-type mice (Fig. 2B). Ablation of Mogat2 expression in adulthood by tamoxifen treatment reduced intestinal MGAT activity in Mogat2 AKO mice to levels similar to those in constitutive germ-line Mogat2+/H11002 mice (Fig. 2B). These results indicate that tamoxifen treatment effectively transforms adult inducible mutant Mogat2 im mice into adult-onset MGAT2-deficient Mogat2 AKO mice.

To inactivate Mogat2 in adulthood, we treated Mogat2im mice with tamoxifen at 12 weeks of age. Tamoxifen treatment resulted in deletion of Mogat2 exon 2 in Mogat2im mice, but not in their Mogat2/ littermate controls, as confirmed by PCR using genomic DNA (data not shown). These mice with Mogat2 inactivated in adulthood by tamoxifen-mediated Cre-recombinase induction were designated “adult-onset knockout” (Mogat2AKO). To assess the specificity as well as efficiency of Mogat2 ablation, we measured Mogat2 mRNA expression level in these mice. Before tamoxifen treatment, both Mogat2/ and Mogat2im mice expressed levels of Mogat2 mRNA in small intestine similar to that found in wild-type mice (Fig. 2A). As reported previously (7, 8), Mogat2+/H11002 mice had no detectable Mogat2 mRNA (Fig. 2A). In contrast, following tamoxifen treatment, Mogat2/ mice maintained their Mogat2 mRNA levels while Mogat2AKO mice showed very low levels of expression in the small intestine (Fig. 2A). Similar relative expression levels among genotypes were also found in the kidney and white adipose tissue (supplementary Fig. 1), confirming the efficiency of Mogat2 deletion by the inducible Cre recombinase. Tissues examined were collected from mice after 10 weeks of high-fat feeding. The lasting MGAT2 deficiency indicates that the tamoxifen treatment was efficient in activating Cre recombinase and causing Mogat2 ablation in the intestinal stem cells, which normally replace intestinal epithelia every 3–5 days (26).

Mogat2 mRNA levels correlated with MGAT activity in the small intestine. Before tamoxifen treatment, Mogat2/ and Mogat2im mice showed MGAT activity similar to that of wild-type mice (Fig. 2B). Ablation of MGAT2 expression in adulthood by tamoxifen treatment reduced intestinal MGAT activity in Mogat2AKO mice to levels similar to those in constitutive germ-line Mogat2+/ mice (Fig. 2B). These results indicate that tamoxifen treatment effectively transforms adult inducible mutant Mogat2im mice into adult-onset MGAT2-deficient Mogat2AKO mice.

Before inactivation of MGAT2, inducible mutant mice exhibit normal energy balance and gain weight like controls

Before tamoxifen treatment, the inducible mutant Mogat2im pups gained weight normally during the suckling period like their Mogat2/ littermates (Fig. 3A). After weaning, when mice were fed a low-fat chow, these mice continued to grow at a similar rate as control mice did into
adulthood (Fig. 3B). To further confirm that the inducible Cre recombinase does not affect energy metabolism prior to induction, we characterized acute energy balance of these mice in response to a regular low-fat chow diet and three semipurified diets containing 10, 45, or 60% of calories from fat sequentially by indirect calorimetry. Both food intake and energy expenditure, reflected by oxygen consumption (VO₂), were similar between groups (Fig. 4A, C). The differences in body weights increased throughout the following 10 weeks of high-fat feeding (Fig. 5A). Mogat2AKO mice gained only 65% as much as Mogat2f/f controls (12 g vs. 19 g, respectively). The differences were largely due to differences in fat mass. White and brown adipose tissues were significantly smaller in Mogat2AKO mice compared with Mogat2f/f controls (both ~70% of controls; Fig. 5B). Lean mass, represented by calf and heart, was not different across genotypes (Fig. 5B).

**Adult-onset MGAT2 deficiency protects mice from diet-induced hepatic steatosis and glucose intolerance**

Constitutive MGAT2 deficiency protects Mogat2−/− mice from several metabolic disorders induced by high-fat feeding (7). Thus, we next examined whether inactivation of MGAT2 in adulthood was sufficient to protect Mogat2AKO mice from comorbidities associated with obesity. After 10 weeks of high-fat feeding, Mogat2AKO mice had similar levels of TAG and free fatty acids but a moderately lower level of total cholesterol in fasting plasma, compared with Mogat2f/f mice (Fig. 6A–C). Like wild-type mice, after longer-term high-fat feeding, Mogat2f/f mice developed hepatic steatosis and glucose intolerance.

**Adult-onset MGAT2 deficiency modulates energy balance and protects mice against diet-induced weight gain**

We next determined the effect of MGAT2 inactivation in adulthood on acute energy balance in response to the same four diets. Mogat2AKO mice were produced by treating 3-month-old chow-fed Mogat2f/f mice with tamoxifen to induce Mogat2 deletion. As controls, their Mogat2f/f littermates were also subjected to the same treatment. Indirect calorimetry was performed 1 month after treatment to allow for recovery of stable body weight. When fed chow or the semipurified diet containing 10 kcal% fat, Mogat2AKO mice exhibited levels of food intake, respiratory exchange ratio (RER), and energy expenditure similar to those of Mogat2f/f controls (Fig. 4A–C). Though all levels trended higher in Mogat2AKO mice, the differences did not reach statistical significance. When first exposed to high-fat diets (45 kcal% and 60 kcal% fat for 3 days each), Mogat2AKO mice reduced food intake significantly as compared with Mogat2f/f controls (Fig. 4A). The difference disappeared after 1 week of high-fat feeding (Fig. 4A), similar to that reported in mice with constitutive global MGAT2 deficiency as well as those with intestine-specific deficiency (8, 9). Associated with decreases in food intake, Mogat2AKO mice exhibited a lower RER than Mogat2f/f controls when first exposed to high-fat feeding (Fig. 4B), suggesting an increase in fat oxidation and/or a decrease in fat accretion. Mogat2AKO mice did not exhibit significant elevations in energy expenditure until they were acclimated to high-fat feeding. They showed a significant 13% increase in 24 h energy expenditure compared with Mogat2f/f mice when food intake was similar between groups (Fig. 4A, C).

Mogat2AKO and Mogat2f/f mice did not differ in energy balance, as indicated by similar body weights when fed chow or the 10% fat diet (Fig. 4D). When fed the high-fat diets, Mogat2AKO mice maintained their body weight, while Mogat2f/f mice gained weight during the metabolic chamber studies (Fig. 4D). After acclimatization to high-fat feeding, Mogat2AKO mice absorbed similar amounts of dietary fat as Mogat2f/f mice did, as indicated by similar levels of fecal output and fecal fat (Fig. 4E).

The differences in body weights increased throughout the following 10 weeks of high-fat feeding (Fig. 5A). Mogat2AKO mice gained only 65% as much as Mogat2f/f controls (12 g vs. 19 g, respectively). The differences were largely due to differences in fat mass. White and brown adipose tissues were significantly smaller in Mogat2AKO mice compared with Mogat2f/f controls (both ~70% of controls; Fig. 5B). Lean mass, represented by calf and heart, was not different across genotypes (Fig. 5B).
Inactivation of MGAT2 in obese mice reduces body weight and improves glucose tolerance

To examine the effects of inactivating MGAT2 in diet-induced obese mice, we fed 3-month-old adult Mogat2/+/ (M2+/+, blue squares) and Mogat2−/− (M2−/−, green circles) mice a high-fat diet for 7 weeks. Both Mogat2/++ and inducible Mogat2−/− mice gained weight before tamoxifen treatment (Fig. 7A). During the 5-day tamoxifen treatment, both groups of mice lost similar amounts of body weight. Whereas Mogat2/++ mice resumed high-fat diet-induced weight gain within 2 weeks of tamoxifen treatment, Mogat2 AKO mice continued to lose weight for an additional week. Mogat2 AKO mice weighed significantly less than Mogat2/++ littermates, and the difference increased throughout the remainder of the study (Fig. 7A). The reduction in steatosis as indicated by increased liver mass and TAG content (Fig. 6D, E). Meanwhile, Mogat2 AKO mice were protected and had smaller livers and lower TAG content than Mogat2/++ controls. Hepatic glycogen was not different across genotypes (Fig. 6F). In parallel with accumulation of liver TAG, Mogat2 AKO mice developed impaired glucose tolerance, while Mogat2 AKO mice were protected. After 8 weeks of high-fat feeding, Mogat2 AKO mice had lower fasting glucose than Mogat2/++ controls (191 mg/dl vs. 238 mg/dl) and a blunted increase in blood glucose following an intraperitoneal glucose challenge (AUC, 80% of controls; Fig. 6G). Further, Mogat2 AKO mice had lower plasma insulin concentrations right before as well as after glucose challenge (Fig. 6H), which was consistent with greater insulin sensitivity.

Fig. 3. No difference in energy balance before inactivation of MGAT2. Body weight of Mogat2/++ (M2/++, blue squares) and Mogat2−/− (M2−/−, green circles) mice during suckling (A) and chow feeding (B). n = 9–19 mice per group. C–E: Three-month-old mice sequentially fed chow or defined diets containing 10, 45, or 60% calories from fat for 3 days per diet. Cumulative food intake (C) and oxygen consumption rates (D) adjusted for baseline body weights of each mouse at the start of each diet treatment. Data from each mouse were pooled from the same time of the day of the same diet treatment. Graphs represent average days. Gray areas mark dark phase of the light cycle (6 PM to 6 AM). E: Body weight of mice during 12-day metabolic phenotyping experiment. n = 8 per group. F: Body weight of mice during 10 weeks of high-fat feeding. n = 9 or 13.
weight gain was associated with significantly reduced liver and white adipose mass (Fig. 7B). Lean mass (as indicated by calf and heart) was not different between genotypes (Fig. 7B).

After 6 weeks of high-fat feeding, glucose metabolism was impaired in both Mogat2+/+ and Mogat2−/− mice as illustrated by high fasting glucose (219 ± 9 mg/dl vs. 218 ± 12 mg/dl) and insulin levels (1.9 ± 0.4 ng/ml vs. 2.5 ± 0.5 ng/ml), respectively. Response to an oral glucose challenge was similar in both groups of mice (Fig. 7C, left panel). When the same test was administered 3 weeks after Mogat2 inactivation, both levels of fasting blood glucose and insulin were lower in Mogat2−/− than those of controls (Fig. 7C, middle panel; data not shown). In addition, the blood

![Graphs](image)
adulthood is sufficient to decrease metabolic efficiency and the propensity to gain weight upon high-fat feeding. Before inducing the deletion of MGAT2, *Mogat2* im mice exhibited energy balance similar to wild-type mice during the suckling period as well as upon high-fat feeding. After the ablation of MGAT2 in adulthood, *Mogat2 AKO* mice exhibited a transient decrease in food intake when fed a high-fat diet and a persistent increase in energy expenditure after acclimatization to high-fat feeding. These findings indicate that inactivating glucose levels in *Mogat2 AKO* mice did not rise as high as in tamoxifen-treated *Mogat2 f/f* controls (Fig. 7C, middle panel). After adjusting for blood glucose levels right before the challenge, the net AUC in *Mogat2 AKO* mice was 66% of that in controls (Fig. 7C, middle panel, inset). The differences were even more pronounced after prolonged high-fat feeding (10 weeks after *Mogat2* inactivation). Blood glucose levels rose to a lower level and declined faster in *Mogat2 AKO* mice than in *Mogat2 f/f* controls (Fig. 7C, right panel).

**DISCUSSION**

We have previously reported that constitutive inactivation of MGAT2 through a null mutation in the germ line protects *Mogat2*(/−) mice against obesity and associated metabolic disorders induced by high-fat feeding as well as by the Agouti mutation (7, 9). In this study, we showed that *Mogat2*(/−) mice experience undernutrition during the early postnatal period, as suckling *Mogat2*(/−) pups gained less weight than their wild-type littermates. To determine whether MGAT2 deficiency during early development is essential for the effects on energy balance, we generated mice with adult-onset MGAT2 deficiency. We found that MGAT2 inactivation during adulthood is sufficient to decrease metabolic efficiency and the propensity to gain weight upon high-fat feeding. Before inducing the deletion of MGAT2, *Mogat2*° mice exhibited energy balance similar to wild-type mice during the suckling period as well as upon high-fat feeding. After the ablation of MGAT2 in adulthood, *Mogat2 AKO* mice exhibited a transient decrease in food intake when fed a high-fat diet and a persistent increase in energy expenditure after acclimatization to high-fat feeding. These findings indicate that inactivating
Adult-onset MGAT2 deficiency in mice is sufficient to confer resistance to obesity induced by diet. However, the protection against weight gain observed in Mogat2\(^{AKO}\) mice was to a lesser extent than in Mogat2\(^{−/−}\) mice, raising the possibility that the early postnatal nutrition status may modulate energy balance phenotypes observed in Mogat2\(^{−/−}\) mice later in life.

The expression of Mogat2 in mice has been reported during early development in 7-day embryos [RIKEN full-length enriched library (27); GenBank accession number: AK049560.1]. Its expression in fetal intestine is relatively low 6 days before birth but reaches levels as high as those in adults during perinatal periods (12). In tissues from E19 fetuses, we found a high level of Mogat2 expression in the intestine (Fig. 1A), consistent with a role of MGAT2 in mediating the absorption of milk fat soon after birth. Interestingly, we also found Mogat2 expression in the yolk sac, which plays an important role in supplying nutrients for early embryos (28), analogous to the intestine in postnatal life. However, the null mutation of Mogat2 in the germ line did not lead to apparent intrauterine growth defects, as Mogat2\(^{−/−}\) fetuses appeared normal and had body weights similar to wild-type and heterozygous litters at E19. The role of MGAT2 during embryogenesis, if any, appears dispensable. In contrast, MGAT2 is required for normal growth in early postnatal life. Mogat2\(^{−/−}\) pups grew slower than their wild-type littermates when pups relied on fat-rich mouse milk for calories, consistent with its role in enhancing metabolic efficiency upon high-fat feeding (7, 9).

The effects of nutrition during early postnatal development on long-term energy balance have been demonstrated in several mammalian species (16). Thus, limited weight gain during the suckling period and the compensatory growth after weaning seen in Mogat2\(^{−/−}\) mice could contribute to the obesity-resistance observed later in life. More importantly, from the prospective of designing an

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Fig. 7. Inactivation of MGAT2 in diet-induced obese mice attenuates further weight gain and improves glucose tolerance. A: Body weight of mice during high-fat feeding before and after inactivation of MGAT2. \(n=5\) mice per group. GTT1, GTT2, and GTT3 indicate time of glucose tolerance tests. \(^{\dagger}P<0.05\) by repeated-measures ANOVA after tamoxifen treatment, respectively. \(^{*}P<0.05\) versus littermate controls by Bonferroni test. B: Tissue mass of mice following 10 weeks of post-tamoxifen treatment high-fat feeding. \(^{*}P<0.05\) versus littermate controls. C: Blood glucose before and at indicated times after an intragastric challenge of glucose (200 \(\mu\)l of 10% glucose) in high-fat fed mice before (left panel), 3 weeks after (middle panel), and 10 weeks after (right panel) inactivation of MGAT2. Inset: net AUC. \(n=8–10\) mice per group. \(^{*}P<0.05\) versus littermate controls by \(t\)-test. Color scheme for all panels: Mogat2\(^{+/+}\) (M2\(^{+/+}\), blue), Mogat2\(^{−/−}\) (M2\(^{−/−}\), green), tamoxifen-treated Mogat2\(^{+/+}\) (M2\(^{+/+}\), gray), and tamoxifen-treated Mogat2\(^{−/−}\) (adult-onset knockout, M2\(^{AKO}\), red) mice.
feeding. Protect mice from metabolic disorders induced by high-fat adulthood is sufficient to reduce metabolic efficiency and protect mice from metabolic disorders induced by high-fat feeding.

The energy balance phenotypes of Mogat2AKO mice resembled those of Mogat2−/− mice as well as mice with an intestine-specific MGAT2 deficiency (Mogat2IKO) (7, 8). When fed chow or the semipurified diet containing 10 kcal% fat, these MGAT2-deficient mice tended to show increased energy expenditure as well as food intake. Compared with their respective controls, the increases were less pronounced in Mogat2IKO and Mogat2KO mice than in Mogat2−/− mice; however, all maintained energy balance similar to controls, as reflected by similar body weights during short-term diet challenge in the metabolic chambers. The marked increase in energy expenditure protects Mogat2−/− mice against weight gain-induced by a high-refined carbohydrate diet as well as by the Agouti mutation without high-fat feeding (9). It remains to be determined if adult-onset MGAT2 deficiency also reduces propensity to gain weight independent of fat content in diet.

When switched to the high-fat diets, Mogat2AKO mice, like Mogat2KO and Mogat2−/− mice, were able to adjust to the high caloric content and reduced food intake, with a pronounced reduction on the first day [Fig. 4A (8) and data not shown]. These findings suggest that MGAT2 in the intestine likely modulates short-term food intake regulation in the hypothalamus. The reduction in food intake of Mogat2KO mice contributed to the immediate differences in the initial weight gain to the same extent as observed in Mogat2IKO and Mogat2−/− mice (8). As control mice acclimated to high-fat feeding and decreased their food intake, the differences in food intake disappeared (Fig. 4A). In the meantime, the increase in energy expenditure of Mogat2KO mice over control littermates became significant and could explain the increasing differences in weight gain over time.

The molecular mechanisms underlying the effects of inactivating MGAT2 in adulthood are not clear. Intestinal MGAT2 is likely a major contributor. Its expression levels determine the rate of MAG uptake and esterification in enterocytes (8, 10). Deficiency of MGAT2 in the intestine leads to changes in temporal and spatial distribution of fat absorption, which may result in blunted postprandial triglyceridemia as seen in both Mogat2−/− and Mogat2KO mice (7, 8, 10). The associated changes in neural and hormonal signals may also contribute to the alterations in food intake, partitioning of energy-yielding nutrients, and systemic energy metabolism. Nonetheless, MGAT2 expressed in other tissues, such as the adipose tissues, may further contribute to the energy balance phenotypes, because both mice expressing MGAT2 and those lacking MGAT2 in an intestine-specific manner exhibit an energy balance phenotypes intermediate between wild-type and global knockout mice (8, 10). These possibilities remain to be tested experimentally.

Interestingly, the difference in energy expenditure between Mogat2KO mice and their littermate controls (Fig. 4C) appeared smaller than the difference between Mogat2−/− and wild-type littermates (8), which was consistent with the observation that Mogat2KO mice were protected from diet-induced weight gain to a lesser extent than were Mogat2−/− mice (Fig. 1E and Fig. 5A). These findings suggest that lacking MGAT2 during early development may have lasting effects later in life, including increases in energy expenditure. The underlying mechanisms might involve the hypothalamic pathways controlling energy balance, as implicated by findings from studies in which mouse pups are raised in varying litter sizes as well as pups nursed by dams fed different fatty acids (15, 29, 30). On the other hand, even though the levels of Mogat2 mRNA and MGAT activity in tissues from Mogat2KO mice examined were reduced to levels similar to tissues from Mogat2−/− mice, we cannot exclude the possibility that some minor population of cells could retain MGAT2 expression and contribute to the decreased phenotypic differences.

Despite an intermediate effect on prevention of diet-induced weight gain, inactivation of Mogat2 in adulthood in mice had robust effects on preventing hepatic TAG accumulation. The moderate reduction in weight gain was also associated with improved glucose homeostasis, as indicated by lower levels of fasting glucose and insulin as well as enhanced glucose tolerance compared with controls (Fig. 6), similar to that seen in Mogat2−/− mice (7, 8). It is unclear if the role of MGAT2 in hepatic lipid metabolism and glucose homeostasis is completely dependent on its effect on systemic energy balance.

Acute inactivation of MGAT2 in mice that had already gained weight on a high-fat diet also diminished their ability to gain more weight and enhanced their glucose tolerance (Fig. 7); their blood glucose peaked at a lower level, and it declined faster than those of controls after being challenged intragastrically with the same dose of glucose. Further, the differences in glucose tolerance were exacerbated over time. In concert with previous findings that Mogat2KO mice have improved glucose homeostasis (8), these findings indicate that acute inactivation of intestinal MGAT2 may enhance glucose homeostasis, similar to intermediate metabolic improvements following some of the bariatric procedures (31).

In summary, our findings indicate that MGAT2 enhances metabolic efficiency and promotes positive energy balance during early development in mice. Nonetheless, inactivation of MGAT2 in adulthood is sufficient to decrease the propensity to gain weight and prevent glucose intolerance when challenged with a calorie-dense diet, even in mice that had already accumulated excess body fat. These findings imply the potential efficacy of MGAT2 as an intervention target for combating obesity and related metabolic diseases caused by chronic caloric surplus. However, the reduction in weight gain is diminished as compared with mice born
without the enzyme, suggesting that MGAT2 can modulate nutritional status in early postnatal life and its deficiency during critical periods may program metabolism later in life.

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