Contemporary Aspects of the Biology and Therapeutic Regulation of the Microsomal Triglyceride Transfer Protein

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Abstract: The microsomal triglyceride transfer protein (MTP), the product of the MTTP gene, is essential for the assembly and secretion of apolipoprotein B–containing lipoproteins, but when defective causes abetalipoproteinemia. Abetalipoproteinemia is a rare autosomal recessive disorder characterized by the inability to produce chylomicrons or very low-density lipoproteins, with the absence of apolipoprotein B–containing lipoproteins in the circulation. Knowledge of the molecular basis for abetalipoproteinemia has led to the development of therapies for dyslipidemia that inhibit MTP. Partial MTP inhibition using small molecule inhibitors, such as lomitapide, can effectively lower plasma low-density lipoprotein–cholesterol and apolipoprotein B levels, but is associated with gastrointestinal side effects and hepatic steatosis, whose long-term sequelae remain unclear; lomitapide has accordingly only been approved as a treatment for homozygous familial hypercholesterolemia. Intestine-specific inhibitors of MTP decrease chylomicron biogenesis and improve insulin sensitivity in experimental animals and, while overcoming hepatic steatosis, may have significant gastrointestinal side effects that could limit their use in humans. We review contemporary aspects of the biology and therapeutic regulation of MTP and their significance for lipid metabolism and cardiovascular disease. (Circ Res. 2015;116:193-205. DOI: 10.1161/CIRCRESAHA.116.304637.)

Key Words: abetalipoproteinemia ■ familial hypercholesterolemia ■ LDL-cholesterol ■ lomitapide ■ microsomal triglyceride transfer protein

A polipoprotein (apo) B plays a central role in lipoprotein metabolism. The human apoB gene (APOB) is located on chromosome 2 and produces, via a unique mRNA editing process, 2 physiological isoforms in circulating lipoproteins, namely apoB-48 and apoB-100.1 ApoB-48, a truncated form of apoB-100, is synthesized in the intestine and is essential for the formation and secretion of chylomicrons. ApoB-100 is synthesized in the liver and is a fundamental structural component of very low-density lipoprotein (VLDL), and its metabolic products, intermediate-density lipoprotein and low-density lipoprotein (LDL), and is also a ligand for the LDL-receptor (LDLR). Increased plasma concentration of apoB, a direct measure of the number of circulating atherogenic lipoproteins, is an important risk factor for atherosclerotic cardiovascular disease (ASCVD), whereas a low level is cardioprotective.

A pentapartite model for human apoB-100 has been proposed, which depicts a 5 superdomain structure composed of alternating amphipathic α helices and amphipathic β strands, namely βα1-α2-β2-α2-β3. Several lines of evidence indicate that the amino-terminal βα1 domain of apoB is important for lipoprotein assembly and stability. ApoB segments lacking the βα1 domain are either unable to be secreted or are secreted poorly by experimental cell lines.3,4 The sequence elements involved in the physical interaction between apoB and its molecular chaperone the microsomal triglyceride transfer protein (MTP), a heterodimeric lipid transfer protein, have been located to the βα1 superdomain.5

MTP, a product of the MTTP gene, is essential for the assembly and secretion of apoB-containing lipoproteins, but when defective causes abetalipoproteinemia (OMIM 200100).6,7 Abetalipoproteinemia is a rare autosomal recessive disorder, which is characterized by the absence of MTP expression or activity; this results in the inability to produce chylomicrons or VLDL, with the absence of
apoB-containing lipoproteins in the circulation and an associated decreased likelihood of ASCVD. Knowledge of the molecular bases for abetalipoproteinemia and homozygous familial hypobetalipoproteinemia, a phenotypically similar condition to abetalipoproteinemia due to APOB gene mutations, has led to the development of new antilipemic therapies that inhibit the activity of MTP and the production of apoB-100, respectively. Partial inhibition of MTP has clear potential as a pharmacological strategy to lower LDL-cholesterol and apoB levels in high-risk subjects with familial hypercholesterolemia (FH). This review focuses on contemporary aspects of the biology and therapeutic regulation of MTP and their implications for lipid and lipoprotein metabolism and the prevention of ASCVD.

### MTP Structure and Function

MTP was first described in 1984 by Wetterau and Zilversmit, who isolated a protein from bovine liver microsomes that accelerated the transfer of triglyceride, cholesteryl ester, and phospholipids, between biological membranes. MTP was soon found to consist of 2 subunits. The first is the unique MTP subunit, which in humans is 894 amino acids (97 kDa) and expressed primarily in hepatocytes and enterocytes. The second subunit is the ubiquitously expressed multifunctional protein disulfide isomerase (PDI; 55 kDa). The isomerase activity of PDI is not necessary for MTP’s function. Although it has no lipid transfer activity per se, PDI seems to be important for maintaining the activity and solubility of the complex. Without PDI the MTP subunit forms insoluble aggregates.

MTP is a member of the large lipid transfer protein family, which includes apoB, insect apolipophorin II/I, and vitellogenin, the egg yolk precursor protein. Members of this family have similar amino-terminal regions consisting of a β-barrel and an α-helical domain, with divergent carboxyl-terminal lipid-binding domains reflecting the different quantities and types of lipids bound. MTP may represent the ancestral lipid transfer protein, evolved to transfer lipids, whereas the other members of this protein family may have diverged to carry lipids rather than shuttle them intracellularly. MTP consists of 3 structural regions, an amino-terminal β-barrel domain (amino acids 22–297), central α-helical region (298–603), and carboxyl-terminal domain (604–894; Figure 1). Evidence suggests that while both the amino-terminal and central regions interact with apoB, PDI binding occurs in the central region and lipid binding and transfer occur in the carboxyl-terminal domain.

High levels of expression of MTP are found within hepatocytes and within epithelial cells of the small intestine—the 2 major sites of the synthesis and secretion of triglyceride-rich lipoproteins. MTP is expressed to a lesser extent in other tissues, including renal tubular epithelial cells, cardiac myocytes, placenta, retina, and immune cells. Cardiac expression of MTP facilitates the secretion of apoB-containing lipoproteins and likely serves to prevent lipid accumulation in the heart. MTP colocalizes with PDI and apoB in the endoplasmic reticulum (ER) and Golgi apparatus, acts as a chaperone, stabilizing the nascent apoB polypeptide and facilitating neutral lipid transfer from the ER membrane to apoB by a shuttle mechanism. Binding of MTP to apoB and lipid transfer occur independently of each other. Although studies of truncated apoB forms show that the first 1000 amino acids of apoB can be secreted independent of MTP, the lipid transfer activity of MTP is essential for the secretion of apoB-48 and apoB-100; if MTP is absent then these underlipidated apoB peptides are targeted for proteasomal degradation (Figure 2).

### Regulation of MTP

The regulation of MTP has been the subject of a comprehensive review by Hussain et al. The promoter region of MTTP contains cis-elements to which several transcription factors involved in the regulation of MTP expression bind. Fox and hepatic nuclear factors hepatocyte nuclear factor 1 and hepatocyte nuclear factor 4 are positive regulatory elements, whereas the sterol and insulin response elements may be negative; in cultured hepatoma cells insulin suppresses MTP via the sterol and insulin response elements. In cells that do not express MTP, nuclear receptors NR2F1 or NR2F2 bind to this element; in cells that do express MTP, retinoid X receptor-α binds. In the liver, MTP expression increases with a peroxisome proliferator–activated receptor-α agonist. MTP expression is also regulated by microRNA (miR)-30c. Inositol-requiring enzyme 1β, an ER stress protein, reduces intestinal MTP mRNA levels via increased post-transcriptional degradation.

Diet affects MTP expression; a high-fat diet increases MTP expression in the liver and intestine, potentially through decreased binding of sterol regulatory element-binding proteins to the MTP promoter. MTP is negatively regulated by bile acids via the nuclear receptor hepatocyte nuclear factor 4. Reduced leptin, through a mechanism not yet understood, decreases intestinal MTP expression. MTP exhibits a diurnal rhythm, regulated by light and food and mediated by the circadian clock. Rodent studies showed that MTP gene transcription was high at night and low during the day; these variations might contribute to daily variation in plasma lipid and lipoprotein concentrations.
affect hepatic cholesterol content, which in turn may relate to diurnal variation of hepatic cholesterol synthesis and proprotein convertase subtilisin kexin type 9 (PCSK9). Animal studies have also demonstrated that ethanol can substantially lower hepatic and intestinal MTTP mRNA levels.

**MTP and Hepatitis C**

The hepatitis C virus (HCV) life cycle is closely linked to MTP. The formation and maturation of virions depends on MTP activity and apoB, mirroring the production of VLDL particles. Circulating HCV is found in the apoB-containing lipoproteins. In chronic HCV, hepatic steatosis is common and associated with low total cholesterol levels and hypobetalipoproteinemia. This could be because of the inhibition of MTP activity by the HCV core protein. MTP mRNA levels in chronic HCV inversely correlate with the degree of hepatic steatosis. The intracellular lipid accumulation caused by the virus-mediated inhibition of MTP is postulated to provide a means for HCV retention and persistence.

**MTTP Gene Variants and Lipid and Lipoprotein Metabolism**

Microsatellite analysis across the genome identified MTTP as 1 of 2 gene regions containing quantitative trait loci influencing cholesterol concentrations in small LDL particles. Three common polymorphisms of MTTP have been described that are in almost complete linkage disequilibrium: −493G>T (rs1800591), −164T>C (rs1800804), and Ile128Thr (rs3816873). The minor T allele at position −493 has been shown in vitro to be associated with a doubling in MTTP transcription compared with the wild-type G allele, as well as a shift in VLDL subfraction composition. However, conflicting observations on the effect of the −493 promoter variant on plasma cholesterol concentrations have been reported in population studies. Ledmyr et al report an association of the minor T allele with increased coronary heart disease risk, despite a small reduction in total cholesterol, whereas in young black men from the CARDIA cohort the T/T genotype was associated with higher total and LDL-cholesterol. Other population studies, including the Framingham Offspring Study, did not find a significant association between the −493 promoter variant and any lipid measurement.

**Figure 1.** Model of the 97 kDa subunit of the microsomal triglyceride transfer protein complex (M subunit) based on lamprey lipovitellin. Ribbon diagram colored to show the different domains. N terminus, blue; β-barrel domain, blue-cyan; helical domain, green; C-sheet, green–yellow; and A-sheet, yellow–red. Image courtesy of Professor C. James McKnight (Boston University).

**Figure 2.** Mechanism of action of microsomal triglyceride transfer protein (MTP) inhibitors. These compounds inhibit MTP in the enterocyte or hepatocyte to reduce the secretion of chylomicrons and VLDL particles, respectively. ASOs indicates antisense oligonucleotides; A-I, apolipoprotein A-I; B-48, apolipoprotein B-48; B-100, apolipoprotein B-100; C-II, apolipoprotein C-II; C-III, apolipoprotein C-III; and E, apolipoprotein E (Illustration credit: Ben Smith).
MTP and Cluster of Differentiation 1

The role of MTP extends beyond the assembly of the apoB-containing lipoproteins. cluster of differentiation 1d (CD1d)-restricted T cells acquire glycolipid antigens during assembly within the ER, in part from the function of lipid transfer proteins called saposins.55 These glycolipid antigens are presented to T cells expressing natural killer receptors and an invariant T-cell receptor–α chain (natural killer T cells). In 2004, it was shown that MTP also associates with CD1d within the ER and, like its role in apoB assembly, facilitates the lipidation and maturation of CD1d.57 This process uses MTP’s phospholipid transfer activity rather than triglyceride transfer activity.56 MTP was later shown to also regulate other CD1 molecules, namely CD1a, CD1b, and CD1c, and despite its ER localization was able to regulate endogenous, as well as exogenous lipid antigen presentation.57 In MTP deficiency, although CD1d biosynthesis, glycosylation, maturation, and internalization from the cell surface were unaffected, the recycling from lysosome to plasma membrane was impaired.58 This phenomenon is yet to be fully understood. However, it could relate to altered membrane lipid composition or structural defects in CD1d as a consequence of deficient lipid loading during biosynthesis that results in degradation, rather than recycling, of these molecules.57,58

MTP is expressed in antigen-presenting cells, including monocytes, B cells and bone marrow and monocyte-derived dendritic cells and its lipid transfer activity can be detected within lysates of these cells.56 Interestingly, mice with a conditional deletion of the Mttp gene are unable to activate natural killer T cells and are resistant to invariant natural killer T-cell–mediated hepatitis and colitis.57 Recent studies of the immune systems in patients with abetalipoproteinemia demonstrated that CD1d was unable to load antigens and as a result natural killer T-cell numbers were reduced and their activation impaired.59 Owing to the small numbers of patients available, it is difficult to ascertain the clinical consequences of these subtle immunologic defects in abetalipoproteinemia.

Abetalipoproteinemia

Abetalipoproteinemia is a rare disorder of lipoprotein metabolism affecting <1 per million people. The absence of MTP expression or activity and the inability to produce chylomicrons or VLDL is associated with a variety of clinical manifestations, which affect multiple organ systems. The disorder serves as a classic model of the effects of complete inhibition of MTP in humans.

Biochemical and Clinical Findings

In 1992, the connection was made between abetalipoproteinemia and the absence of MTP activity in intestinal biopsies.60 The following year, pathogenic mutations of MTP causing abetalipoproteinemia were described.61,62 The absence of MTP activity leads to triglyceride accumulation within enterocytes and hepatocytes and absent circulating apoB-containing lipoproteins; after a fat load, chylomicrons do not appear in plasma.

Overall, the clinical presentation of abetalipoproteinemia is heterogeneous. Although atypical or mild cases of abetalipoproteinemia may present late and with minimal symptoms, patients usually present in childhood with failure to thrive, growth failure, and malabsorption of fat.62 Plasma total cholesterol and triglyceride concentrations are low, whereas vitamin E, LDL-cholesterol, and apoB are typically undetectable. Although homozygous familial hypobetalipoproteinemia because of APOB mutations cannot be differentiated from abetalipoproteinemia based on clinical symptoms, they have different inheritance patterns. Obligate heterozygous parents carrying an APOB mutation will have levels of apoB and LDL-cholesterol less than half of normal, whereas parents of a patient with abetalipoproteinemia, a recessive disorder, usually have normal plasma lipid, and lipoprotein concentrations.63

Hematologic manifestations of abetalipoproteinemia include acanthocytosis, which could be a result of either vitamin E deficiency or an altered membrane lipid composition.64 Other findings include low erythrocyte sedimentation rates, decreased red cell survival,65 anemia, hyperbilirubinemia and hemolysis,66 and increased international normalized ratio as a result of vitamin K deficiency.67 Fat malabsorption is a central feature of abetalipoproteinemia. The severity of gastrointestinal symptoms, chiefly steatorrhea, relates to the dietary fat content, and usually decreases with improved adherence to a low-fat diet.64 Hepatic manifestations include hepatomegaly, steatosis, and abnormal plasma aminotransferases.64 Hepatic steatosis is present in about one third of abetalipoproteinemia cases, with 4 of 58 published probands having severe fibrosis.68 Progression to cirrhosis can also occur.69 Neuromuscular manifestations are secondary the effects of vitamin E deficiency on both the central and peripheral nervous system.70 Ophthalmological manifestations are variable, the most prominent being atypical pigmentation of the retina and night and/or color vision may be lost.71

Molecular Diagnosis

Sequencing of the 18 exons and intron–exon boundaries will detect mutations of MTP associated with abetalipoproteinemia. The majority of mutations either lead to premature stop codons or affect splicing, but several missense mutations have also been described and studied in vitro. The first, Arg540His, was shown to result in defective interaction with PDI, with the mutant MTP remaining as an insoluble aggregate.72 Other mutations in the central α-helical region of MTP, Leu435His, Tyr528His, Arg540Cys, and Ser590Ile, exhibit negligible lipid transfer activity.73–75

A 30 amino acid carboxyl-terminal truncation of MTP, Gly865*, was found to disrupt binding with PDI, suggesting that these 30 amino acids are required for the interaction of MTP with the PDI subunit.76 Gly746Glu and Asn780Tyr, also at the carboxyl terminus, are able to interact with PDI, but cannot transfer lipids.74–77 The discovery and characterization of further missense mutations will help to elucidate the structure–function relationships of MTP.

Cardiovascular Consequences

In abetalipoproteinemia, there is life-long reduction in LDL-cholesterol and apoB and, by implication, protection against ASCVD. APOB and PCSK9 (loss-of-function) mutation carriers, who similarly have life-long low plasma LDL-cholesterol...
levels, clearly exhibit longevity. For example, PCSK9 nonsense mutations lower plasma LDL-cholesterol by 28% and the relative risk of coronary artery disease by 88% and missense mutations lower LDL-cholesterol by 14% and coronary artery disease risk by 47%.78-80 In abetalipoproteinemia, where LDL apoB is virtually absent, the risk of ASCVD is expected to be even lower. Owing to the rarity of the severe form of the condition and premature death from other complications, there are no good data on the incidence of ASCVD; registries are recommended for longitudinal studies. Autopsy data of isolated cases testify to protection against atherosclerosis.81 Beyond virtually absence of apoB-containing lipoproteins, reduced coagulation because of vitamin K depletion secondary to lipid malabsorption may further lower cardiovascular risk in abetalipoproteinemia.54 However, risk may be offset by increased platelet aggregation because of dysfunctional high-density lipoprotein (HDL) that is in turn related to vitamin E depletion and increased oxidizability of these particles.82 Whether this also affects endothelial function remains unclear. Although no studies of arterial structure and function have been reported in abetalipoproteinemia, in the related condition familial hypobetalipoproteinemia there is case–control evidence for a reduction in carotid artery wall stiffness, even in the presence of nonlipid cardiovascular risk factors.83 Both the apoB and MTP are expressed in the myocardium,18 but autopsy studies have not provided clear evidence of an infiltrative cardiomyopathy; further studies of the myocardial consequences of abetalipoproteinemia are recommended.

Lipid and Lipoprotein Metabolism

By contrast to familial hypobetalipoproteinemia, plasma lipid and lipoprotein concentrations are normal in the majority of obligate heterozygotes for abetalipoproteinemia; these subjects also do not develop hepatic steatosis. It is, therefore, possible that the normal MTP allele can compensate for the defective one in heterozygous abetalipoproteinemia or that one MTP allele is sufficient to control plasma lipids. However, a lesser proportion of cases have been described with elevated or low plasma lipid levels, pointing to an effect of other gene variants. Further investigation of the genetic variability in the plasma lipid phenotype in obligate heterozygotes for abetalipoproteinemia could elucidate the interindividual variation in the therapeutic response to MTP inhibitors.

In the absence of chylomicrons and lipoproteins of the VLDL cascade, plasma cholesterol and triglyceride levels are markedly reduced in abetalipoproteinemia. After a fat-containing meal, plasma triglyceride concentrations generally do not increase. Although total body turnover of cholesterol from the VLDL and LDL density intervals have a cuboidal restriction in dietary fat and reduction in chylomicron formation.83 Despite the defective hepatic assembly of apoB-100 in abetalipoproteinemia, small amounts of uncomplexed apo(a) may be detected in plasma,86,87 implying that apo(a) may be secreted by the liver into the circulation without previous intrahepatic coupling with apoB-100, with implications for furthering our understanding of the metabolic regulation of lipoprotein (a) (Lp(a)). The findings also suggest that MTP inhibitors may lower plasma Lp(a) by decreasing the intrahepatic assembly of Lp(a), but that the effect on plasma Lp(a) may be offset by independent secretion of apo(a) and its coupling with LDL apoB outside the hepatocyte membrane. Further kinetic studies of Lp(a) metabolism in subjects with abetalipoproteinemia and familial hypobetalipoproteinemia are warranted.

HDL is the major lipoprotein in plasma in abetalipoproteinemia. The plasma concentration of HDL is on average decreased by 50%, with reduced HDL3, and HDL2 present at normal concentrations.54,55 HDL is enriched in apoE and is able to deliver cholesterol to tissues via the LDLR pathway.56 Low plasma lecithin-cholesterol acyltransferase activity in abetalipoproteinemia is considered secondary to reduction in acceptor lipoproteins in plasma and not of major significance.97 The low circulating levels of apoA-I may result from either reduced synthesis or a combination of reduced production and increased fractional catabolic rate.98 Reduction in apoA-I secretion in abetalipoproteinemia could be because of decreased formation of chylomicrons, noting that the plasma concentrations of other enterocyte-derived apolipoproteins (apoA-IV, C-I, and C-II) are similarly low; another possibility is reduction in cholesterol substrate availability in the liver that decreases the expression of apoA-I, although the rate of whole body cholesterol turnover is apparently normal in abetalipoproteinemia. The accelerated catabolism of apoA-I, chiefly in LpAI:AII particles, is most likely related to alteration in the HDL particle morphology referred to earlier, noting that the increase in HDL size in abetalipoproteinemia is likely to delay particle catabolism. The maintenance of HDL–apoA-I turnover is critical for delivering cholesterol to cells and is closely related to the turnover of apoE in abetalipoproteinemia, and underscores in general the tighter metabolic coupling between the apoA and apoE systems than between the apoA and apoB systems. Whether the reduction in HDL-cholesterol noted with MTP inhibitors involves similar mechanisms to those in abetalipoproteinemia has not been reported and warrants further investigation.

hepatic secretion of VLDL apoB and subsequent production of LDL apoB, with accelerated catabolism of VLDL.99,100 The former mechanism is likely to be shared with the effect of both lomitapide (an MTP inhibitor) and mipomersen (an antisense oligonucleotide [ASO] directed against apoB-100), although detailed mechanistic studies have not been hitherto reported with either of this agents in humans. That plasma PCSK9 levels are normal in familial hypobetalipoproteinemia suggests that in this condition, and by implication in abetalipoproteinemia, there is no change in the catabolism of LDL particles.91

In homozygous familial hypobetalipoproteinemia, marked acceleration in the catabolism of VLDL particles results in a low conversion rate to LDL, but this requires confirmation.92 In classical abetalipoproteinemia, plasma lipases are significantly decreased, consistent with enzyme downregulation because of restriction in dietary fat and reduction in chylomicron formation.93 Despite the defective hepatic assembly of apoB-100 in abetalipoproteinemia, small amounts of uncomplexed apo(a) may be detected in plasma,86,94 implying that apo(a) may be secreted by the liver into the circulation without previous intrahepatic coupling with apoB-100, with implications for furthering our understanding of the metabolic regulation of lipoprotein (a) (Lp(a)). The findings also suggest that MTP inhibitors may lower plasma Lp(a) by decreasing the intrahepatic assembly of Lp(a), but that the effect on plasma Lp(a) may be offset by independent secretion of apo(a) and its coupling with LDL apoB outside the hepatocyte membrane. Further kinetic studies of Lp(a) metabolism in subjects with abetalipoproteinemia and familial hypobetalipoproteinemia are warranted.
Treatment
Regular follow-up to monitor growth in children and gastrointestinal, hepatic and neurological complications is recommended in all patients with abetalipoproteinemia.63 A low-fat diet, with total fat <30% of caloric intake and minimal consumption of long-chain fatty acids, eliminates steatorrhea. Medium chain triglycerides, which are not packed into chylomicrons, have been suggested as a form of delivering calories, but their use and safety have not been established.63,82 Early treatment with high oral doses of vitamins E and A can mitigate neuropathy and retinopathy,7,100–103 As vitamin E transport strongly relies on apoB-containing lipoproteins, high doses of vitamin E (100–300 mg/kg per day orally) are required to circumvent the chylomicron pathway, perhaps by incorporation into HDL.54,63,64 Erythrocyte and platelet vitamin E levels provide the best assessment of tissue vitamin E status.104 Supplementation with vitamins A, D, and K are also recommended.

Murine Models
Knockout of the Mttp gene in mice is lethal to the embryo, whereas heterozygous knockout is associated with reduced LDL-cholesterol, a 28% reduction in apoB-100, and cytosolic fat accumulation in the liver of adult animals.105 Liver-specific inactivation of MTP ablates the synthesis and secretion of VLDL and the subsequent production of LDL–apoB-100.106,107 The mice develop moderate hepatic steatosis, with VLDL-sized lipid-staining particles observed within the ER and Golgi apparatus.107 Pulse-chase experiments confirm inhibition of apoB secretion from hepatocytes.108

Mice with a conditional Mttp deletion in villus enterocytes manifested steatorrhea, growth arrest, and reduced cholesterol absorption, consistent with the human abetalipoproteinemia phenotype.108 Chylomicron secretion was reduced with an 80% decrease in apoB-48 secretion from primary enterocytes. Mice with the intestine-specific knockout of Mttp had increased hepatic lipogenesis and VLDL secretion presumably to compensate for the defective secretion of chylomicrons.

In a cardiac-specific Mttp knockout, triglyceride stores in the heart were elevated.109 It is not known whether cardiac lipid stores are increased either in human patients with abetalipoproteinemia or by the use of synthetic MTP inhibitors. A recent study in Ldlr−/− mice fed a chow diet showed that an MTP inhibitor (BMS 212122) decreased the development of atherosclerotic plaques over a period of 2 weeks, with significantly decreased cholesterol content in monocyte-derived cells and reduction in inflammation, as well as increased collagen deposition in the arterial wall.110

MTP as a Therapeutic Target
Given that a genetic mutation, or experimental disruption, of MTP results in reduction or ablation of the secretion of apoB-containing lipoproteins, pharmacological inhibition of MTP may be a useful therapeutic option for the treatment of hyperlipidemia and mitigation in the associated risk of ASCVD (Figure 2). In 1998, Wetterer et al111 described a small molecule inhibitor of MTP that could effectively inhibit secretion of apoB-containing lipoproteins in rodents and normalize hypercholesterolemia in the Watanabe-heritable hyperlipidemic rabbits, an experimental model for LDLR defective homozygous FH (hoFH). However, it was noted that hamsters treated with the compound showed reversible hepatic fat accumulation, as well as fat accumulation in enterocytes. These observations foreshadowed the side effects that have plagued human clinical trials of MTP inhibitors. Despite this, MTP inhibitors may still play a role in the treatment of severe forms of hyperlipidemia.

Several synthetic MTP inhibitors (BMS-201038, CP-346086, and BAY-13-9953) were shown to dose-dependently lower plasma LDL-cholesterol and apoB in experimental animals and humans, but development programs were discontinued because of gastrointestinal side effects and hepatic steatosis; we have reviewed these early trials elsewhere.112 The remainder of this section focuses on lomitapide, a small molecule MTP inhibitor that has been approved by the US Food and Drug Administration and European Medicines Agency as adjunctive therapy to diet and statins for patients with hoFH aged ≥18 years. In this rare, but serious autosomal dominant condition, patients have deficient or defective hepatic LDLRs and plasma LDL-cholesterol concentrations typically ranging from 10 to 25 mmol/L and develop premature onset coronary heart disease in childhood, almost none achieve plasma LDL-cholesterol targets (<2.0 mmol/L) on conventional cholesterol–lowering therapy, and many require lipoprotein apheresis.113

Lomitapide (Juxtapid, Lojuxta)
FH and Primary Hypercholesterolemia
Lomitapide (BMS-201038 at that time) was initially evaluated open-label in 6 patients with hoFH (5 receptor-negative and 1 receptor-defective) on a low-fat diet and reported to reduce plasma LDL-cholesterol by 50.9% (mean LDL-cholesterol at baseline 15.9 mmol/L) and apoB of 55.6% at the highest dose tested (1.0 mg/kg body weight per day) after 4 weeks; there was a significant increase in plasma aminotransferase levels and hepatic fat content, but these returned to normal in all patients 14 weeks after cessation of therapy.114

In a subsequent randomized, double-blind trial, the effect of lomitapide (AEGR-733 at that time; dose 5, 7.5, and 10 mg/d) alone and in combination with ezetimibe (10 mg/d) was studied over 12 weeks in 85 patients with primary hypercholesterolemia (mean baseline LDL-cholesterol 4.4 mmol/L) on a low-fat diet.115 There was a dose-dependent reduction in LDL-cholesterol and apoB with lomitapide, which at the highest dose averaged 30% and 24% from baseline, respectively, increasing significantly to 46% and 37% with the addition of ezetimibe; plasma triglyceride, HDL-cholesterol and Lp(a) levels fell by 10%, 6%, and 17% with lomitapide, with no statistically significant changes in combination with ezetimibe. Twenty percent of patients either stopped or were taken off lomitapide, mainly because of elevation in hepatic aminotransferase levels, which returned to normal 2 weeks after cessation of therapy; gastrointestinal symptoms were frequent, but mild.

Most recently, lomitapide was studied in an open-label phase 3 trial, using a dose-ranging regimen (maximum 60 mg/d over 26 weeks), in 29 patients with hoFH (defined genetically or phenotypically; mean LDL-cholesterol 8.7 mmol/L) on best standard of care, including lipoprotein apheresis.116 Plasma LDL-cholesterol, apoB, and triglyceride levels fell by 50%, 49%, and 45% from baseline at week 26 on a median dose of
lomitapide of 40 mg/d. Twenty-three subjects completed a 78-week safety phase, with LDL-cholesterol, apoB, and triglycerides remaining 30%, 43%, and 31% below baseline; 55% and 33% of subjects attained LDL-cholesterol treatment goals <2.6 and <1.8 mmol/L, respectively. Lp(a) levels fell significantly by 19% at week 26, but returned to baseline levels by week 78. Plasma HDL-cholesterol and apoA-I levels also dropped significantly by 12% and 14%, respectively, after 26 weeks, but approached baseline levels by week 78. Of 18 subjects treated with lipoprotein apheresis, 3 stopped this treatment due to increased from 1.0% at baseline to 8.6% (0–33.6%) at week 26, remaining stable to 78 weeks (8.3%, 0%–19%). The efficacy and safety finding of the above investigation have been confirmed in 19 patients who continue to participate in a long-term extension study, published only in abstract form. The long-term effect of hepatic steatosis on insulin resistance and cellular injury remains unclear, but other data suggest that it may be more closely related to hepatic accumulation of toxic saturated fatty acids rather than triglycerides120,123 and may depend on the fatty acid partitioning enzyme, stearyl-Coenzyme A desaturase-1;120 the effect of MTP inhibition on hepatic fatty acid metabolism, insulin resistance, and stearyl-Coenzyme A desaturase-1 activity merits further research. One human study has suggested that lomitapide decreases plasma triglycerides less than LDL-cholesterol, but used lower drug doses and did not investigate postprandial triglycerides that are more responsive than fasting levels to MTP inhibition.124 However, whether low dose of lomitapide has an inhibitory effect on the direct hepatic secretion of LDL apoB remains unclear. The significant fall in plasma HDL-cholesterol with lomitapide was sustained in the recently reported long-term study, and, as in abetalipoproteinemia, could be because of decreased secretion of apoA-I by the enterocyte and liver or to increased catabolism of apoA-I; the therapeutic low-fat diet aimed at decreasing chylomicron biogenesis can also decrease the expression and secretion of apoA-I.125 Whether MTP inhibition affects the turnover of apoE and its coupling with apoA-I remains to be investigated, as does the effect on apoA-IV, apoC-II, and apoC-III kinetics.

Reduction in plasma Lp(a) concentration could be because of decreased apoB-100 production and coupling with apo(a) within the hepatocyte. The Lp(a)-lowering effect seems to be lost over time, the reason for which remains unclear, but may be because of a compensatory increase in hepatic secretion of apo(a), a phenomenon that may not be seen with mipomersen126 and requires further research. The postulated mechanism of action of lomitapide on apoB-100 transport differs from statins and ezetimibe, both of which increase the fractional catabolism of apoB-100-containing lipoproteins. This provides a rationale for the additive effects noted above. MTP inhibition is also more likely to lower plasma LDL-cholesterol in hoFH with LDLR deficiency than PCSK9 inhibitors, that a priori accelerate the catabolism of LDL particles. This offers a synergistic mechanism of action for combination therapy in patients with defective LDLRs and requires verification. Lomitapide is, therefore, likely to have a comparable effect on LDL-cholesterol in patients with hoFH on or off lipoprotein apheresis. Future studies should explore how genetic variants and hormonal factors bear on the effect of lomitapide on the wider spectrum of disordered lipoprotein metabolism in FH.
Other Strategies for Inhibiting MTP

Entero-Specific
Intestinal-specific inhibition of MTP aims to decrease the secretion of apoB-48 and, therefore, reduce triglyceride-rich lipoprotein secretion from enterocytes. Theoretically, this approach should not have a direct effect on plasma LDL-cholesterol, but may indirectly reduce cholesterol supply to the liver in chylomicrons with possible upregulation of the LDLR. These mechanisms, as well as the effect on HDL particle turnover, will require investigation. Other potential effects of intestinal MTP inhibition include improved insulin sensitivity and the suppression of food intake. Enteric-specific MTP inhibition therapies are being investigated not only for the treatment of hypercholesterolemia but also severe hypertriglyceridemia and type 2 diabetes mellitus; they may initially have a clinical role for treating primary chylomicronemia and preventing recurrent acute pancreatitis, and eventually also for regulating the postprandial accumulation of atherogenic chylomicron-remnant particles.

JTT-130
JTT-130 (Japan Tobacco) is an orally administered compound that inhibits MTP’s triglyceride transfer activity in enteroctyes, thus avoiding the elevated liver aminotransferases and steatosis seen with hepatic MTP inhibition. In hyperlipidemic hamsters, 2 weeks of treatment with JTT-130 decreased plasma triglyceride and cholesterol and reduced triglyceride content of the liver without causing hepatotoxicity. Studies in Sprague-Dawley rats showed that treatment with JTT-130 reduced food intake and gastric emptying and increased plasma concentrations of gut peptide YY and GLP-1. Triglyceride, free fatty acids, and cholesterol were elevated in the luminal contents of the intestine, which may trigger the suppression of food intake in response to the hydrolysis of triglycerides. Further studies in rats showed that when fed a high-fat (35%) diet, JTT-130 treatment was associated with reduced body weight and plasma glucose and insulin during intraperitoneal glucose tolerance tests compared with controls.

In Zucker diabetic fatty rats, JTT-130 treatment suppressed lipid absorption and food intake, ameliorating impaired glucose and lipid metabolism. Recently, JTT-130 was used in combination with pioglitazone to improve glycemic control, enhance insulin sensitivity, and reduce plasma triglycerides in this rat model, suggesting that this combination therapy could be useful in the treatment of type 2 diabetes mellitus. A phase 2 clinical trial of JTT-130 for the treatment of obese type 2 diabetic subjects has been completed (NCT00929539), but no results have been published.

SLx-4090
Like JTT-130, SLx-4090 (Surface Logix) is an intestine-specific MTP inhibitor. Mice treated with SLx-4090 showed a reduction in serum LDL-cholesterol and triglyceride and increase in HDL-cholesterol concentration, with the evidence of weight loss, despite a high-fat diet. The fall in LDL-cholesterol may be a consequence on reduced hepatic delivery of cholesterol substrate in chylomicrons and requires further mechanistic study. The increase in HDL-cholesterol probably involves reduction in the catabolism of apoA-I because of remodeling of HDL particles as a consequence of fall in plasma triglyceride levels. These data, as well as observations in the Caco-2 cell line, suggest that specific inhibition of chylomicron formation with SLx-4090 has no influence on the enterocytic secretion of apoA-I. In a phase 2a trial in 24 patients with dyslipidemia, SLx-4090 reduced postprandial triglycerides and LDL-cholesterol and, importantly, was well tolerated, with no effect on liver function tests. SLx-4090 is currently in phase 2 trials for the treatment of familial chylomicronemia (NCT01675154).

Dirlotapide
In canines, this MTP inhibitor is specific to intestinal MTP, and has been approved by the Food and Drug Administration for the treatment of obesity in dogs. Over 3 months of treatment with oral doses ranging from 0.15 to 0.5 mg/kg per day, treated dogs lost 19% of body weight, compared with a 10% gain in control animals. This effect is attributed to an anorectic effect and reduced fat absorption. A modified version of dirlotapide with improved gut selectivity, PF-02575799, has advanced into human phase 1 trials for the treatment of obesity.

RNA-Based Therapies

RNAi
miRs are short noncoding RNAs that can negatively regulate gene expression by interacting with mRNA to either prevent protein translation or cause the mRNA to be degraded. Recently, the Hussain laboratory showed that miR-30c interacts with MTP mRNA, leading to a reduction in MTP protein activity and apoB secretion. Transduction of mice with a mir-30c lentivirus led to mainly hepatic expression of miR-30c, with levels ≈4-fold higher than normal. Overexpression of miR-30c reduced plasma non–HDL-cholesterol, whereas an anti–miR-30c increased non–HDL-cholesterol; no effects were seen on fasting plasma triglycerides. Importantly, Apoe knockout mice expressing miR-30c had smaller atherosclerotic plaques compared with controls.

A possible advantage to this approach is that miR-30C, in addition to reducing apoB secretion, reduces lipid synthesis independently of MTP by targeting lysophosphatidylglycerol acyltransferase 1 mRNA. Hepatic overexpression of miR-30c, therefore, does not cause fatty liver. However, the administration and delivery vehicle for miR-30c therapy may prove challenging, as to be effective miR-30c expression would likely need to be increased in the small intestine and liver. In addition, miR-30c has a potential tumor suppressor role; down-regulation of its expression has been associated with poorer survival in ovarian and breast cancer, but better survival in malignant mesothelioma. Potential long-term consequences of miR overexpression need to be carefully considered.

ASOs (Hepato-Specific MTP Inhibition)
ASOs can be used for the targeted inhibition of mRNA, and mipomersen, an ASO specific for apoB-100, has been approved by the Food and Drug Administration for the treatment of hoFH. Experiments performed in mice showed that administration of an MTP ASO (ISIS 144477) could reduce hepatic triglyceride secretion and serum lipid concentrations. However, ASOs preferentially distribute to the liver, and hepatic MTP mRNA inhibition also resulted in greater...
accumulation of hepatic triglyceride and elevation in hepatic aminotransferases compared with apoB ASO therapy. This difference seems to be because of a compensatory decrease in hepatic de novo lipogenesis, which occurs with apoB ASO.

Conclusions: Future Therapeutic Perspective
MTP is a key protein necessary for the assembly and secretion of apoB-containing lipoproteins by the liver and small intestine. Absence of MTP activity results in abetalipoproteinemia, a rare, but potentially serious metabolic disorder with absent or very low-LDL-cholesterol often presenting with hepatic steatosis, failure to thrive, and low concentrations of the fat-soluble vitamins; the disorder is considered to protect against the development of ASCVD. The molecular defects in abetalipoproteinemia and familial hypobetalipoproteinemia have informed the development of MTP inhibitors and apoB-100 ASOs, respectively, for the treatment of severe hyperlipidemia. Partial MTP inhibition using small molecule inhibitors, such as lomitapide, can effectively lower plasma cholesterol, but is associated with gastrointestinal side effects and hepatic steatosis; steatosis is mild-to-moderate and stabilizes over time, but its long-term sequelae, such as hepatic insulin resistance, fibrosis, cirrhosis, and cancer, remain to be determined.

In patients with hoFH, who from a young age have a high risk of cardiovascular events and death and in whom diet, statins, and other conventional lipid-regulating drugs are either not effective or partially effective, lomitapide could be a useful additional therapy for achieving target plasma levels of LDL-cholesterol. The most efficacious and safe approach to target hepatic steatosis as a result of lomitapide is lifestyle modifications, including weight loss and exercise. FH is associated with extended metabolic defects in lipoprotein metabolism, such as hepatic oversecretion of VLDL and increased production of LDL, which can be specifically targeted by MTP inhibitors.141-149 This is a unique mechanism of this agent that has hitherto not been confirmed with either mipomersen or PCSK9 monoclonal antibodies. Further mechanistic studies of the integrated effect of lomitapide and entero-specific MTP inhibitors on lipoprotein metabolism in humans are warranted.

Lomitapide has an orphan indication for hoFH. The precise definition of this disorder remains under debate, however, noting recent data testifying to the genetic and clinical heterogeneity of severe forms of FH.113,130 For use in United States via the REMS (Risk Evaluation and Mitigation Strategy) program, a clinical definition is required, without the need for molecular testing. Until the definition of hoFH can be refined and extended, lomitapide will retain orphan drug indication, but its high cost will remain a drawback for payers. It is possible that its indication could be extended to patients with refractory heterozygous FH, as well as in combination with ezetimibe for high-risk hypercholesterolemic patients who cannot tolerate statins.115 Although cardiovascular outcome trials with MTP inhibitors are most unlikely to ever be done, efficacy could be assessed using surrogate cardiovascular end points and prospective cardiovascular outcome data from FH registries.131

The efficacy, use and cost-effectiveness of lomitapide will need to be evaluated if indications are widened to cover these other conditions, but because of its gastrointestinal and hepatic adverse event profile may be superseded by PCSK9 monoclonal antibodies.132 The balance between side effects and benefits makes lomitapide less acceptable to lower risk patients than those with hoFH. Lomitapide is likely to be more acceptable than mipomersen as it is administered orally and not by injection. However, by contrast to mipomersen and PCSK9 monoclonal antibodies, it is metabolized by CYP3A4 and is susceptible to drug interactions, including statins and warfarin. However, lomitapide may lower the need and cost of lipoprotein apheresis in hoFH.133 The lack of a sustained reduction in plasma Lp(a) and the fall in HDL-cholesterol with lomitapide would also favor use of mipomersen or PCSK9 monoclonal antibodies, but whether these small metabolic differences are clinically meaningful remains unclear. Head-to-head comparisons of these new agents are unlikely to be done, but testing the efficacy of combination therapy could be possible in severer forms of FH. Cholesteryl ester transfer protein inhibition may also have a future role in the management of FH, but its efficacy remains to be demonstrated by ongoing clinical trials (NCT01841684 and NCT01524289). The place of lomitapide and other new agents in the management of hoFH was recently reviewed by 2 expert groups.118,174

Further studies are needed to determine the clinical use RNA based and other therapies targeting MTP that could be useful for the treatment of dyslipidemia, diabetes mellitus, or obesity. These alternative strategies may be able to avoid the development of fatty liver by either concomitantly reducing hepatic lipogenesis, or by specifically inhibiting MTP in the intestine, although gastrointestinal side effects may continue to limit clinical use.

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