NPC1L1: Evolution From Pharmacological Target to Physiological Sterol Transporter

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Abstract—Niemann-Pick C1-like 1 protein (NPC1L1) was recently shown to be the molecular target of the cholesterol absorption inhibitor class of drugs, of which ezetimibe is the first widely used member. Since its discovery, NPC1L1 has also been shown to play a focal physiological role in intestinal absorption of sterols, including plant sterols and cholesterol. Evidence in support of this new metabolic pathway has been garnered not only through human, animal, and cell studies of function but also through the use of human genetics as an approach to study the association of NPC1L1 sequence variation with metabolic and drug-response phenotypes. The example of NPC1L1 shows how the elucidation of a pharmacological target can serve as a means to gain understanding of a key physiological pathway. (Arterioscler Thromb Vasc Biol. 2006;26:000-000.)

Key Words: cholesterol ■ enterocyte ■ intestine ■ lipoproteins ■ low-density lipoprotein ■ pharmacogenetics ■ sterol

Pharmacological inhibition of intestinal cholesterol absorption is proving to be a useful strategy for treating patients with dyslipidemia, especially those with elevated plasma low-density lipoprotein (LDL) cholesterol. Ezetimibe is the first and so far only cholesterol absorption inhibitor to achieve widespread clinical use. Interestingly, ezetimibe was initially identified in an acyl-coenzyme A (CoA): cholesterol acyltransferase (ACAT) inhibitor discovery program with the hypothesis that disruption of intracellular cholesterol esterification within macrophages would have a beneficial influence on the development of arterial wall plaques. However, ezetimibe’s activity on that enzymatic target was underwhelming compared with some other members of the class, but proved to be a potent inhibitor of cholesterol absorption.1 Subsequent animal and later human studies showed that it could effectively and safely lower plasma LDL cholesterol.1 Also, the combination of ezetimibe with statin drugs had an additive effect on LDL-lowering compared with statins alone, suggesting that ezetimibe possessed a distinctive mechanism of action.1 Although ezetimibe and its metabolites were detected in many tissues, which contrasted starkly with the fairly ubiquitous tissue expression of NPC1, Davies et al,7 however, found human NPC1 mRNA to be predominantly expressed in the liver, with small intestine detection levels at 10% of intestinal expression and was barely detectable in many tissues, which contrasted starkly with the fairly ubiquitous tissue expression of NPC1. Davies et al,7 however, found human NPC1 mRNA to be predominantly expressed in the liver, with small intestine detection levels at <5% of the liver expression levels. The role of this protein in human liver biology is still unknown. Further analysis of the duodenal–ileal axis of rat small intestine demonstrated that peak expression of Npc1 mRNA and Npc1 protein occurred in the proximal jejunum, which was also the predominant site for sterol absorption.5 Furthermore, the protein appeared to be discretely localized to the epithelial layer of enterocyte.

Identification of NPC1L1 Through Genomics and Bioinformatics

A major advance in the understanding of ezetimibe’s mechanism of action occurred in 2004 when Altmann, Davis, and colleagues in the research laboratories of Schering-Plough evaluated sequence data from human, rat, and mouse gastrointestinal cDNA libraries to identify proteins with features, such as transmembrane domains and known cholesterol sensing motifs, that would be expected to be seen in a putative cholesterol transporter.3 One credible candidate emerged from this search, namely Niemann-Pick C1-like 1 protein, whose gene is designated as Npc1l1 in mouse or NPC1L1 in human. NPC1L1 was first described in 2000;1,4,5 its name was derived from the fact that it shared 42% amino acid identity with Niemann-Pick type C1 protein (NPC1), which encodes a protein involved in intracellular cholesterol transport and is also the causative gene for Niemann-Pick disease type C1.5 In mouse, rat, and human, the small intestine showed the highest level of NPC1L1 mRNA expression.2,3 With the exception of human liver, which showed similar levels of expression as the intestine, NPC1L1 expression in all other tissues was <10% of intestinal expression and was barely detectable in many tissues, which contrasted starkly with the fairly ubiquitous tissue expression of NPC1. Davies et al,7 however, found human NPC1 mRNA to be predominantly expressed in the liver, with small intestine detection levels at <5% of the liver expression levels. The role of this protein in human liver biology is still unknown. Further analysis of the duodenal–ileal axis of rat small intestine demonstrated that peak expression of Npc1l1 mRNA and Npc1l1 protein occurred in the proximal jejunum, which was also the predominant site for sterol absorption.5 Furthermore, the protein appeared to be discretely localized to the epithelial layer of enterocyte.

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Evidence for an Absorptive Role for NPC1L1 From Animal Models

An in vivo role was characterized by the creation of mice in which the Npc1l1 gene had been deleted by homologous recombination. Intestinal expression of Npc1l1 in the homozygous knockout mice was completely absent. Plasma cholesterol and triglycerides were not different among wild-type Npc1l1+/+ mice and homozygous Npc1l1−/− mice. After oral administration of radiolabeled cholesterol, the Npc1l1+/+ and Npc1l1−/− mice absorbed ≈50% of the administered dose of cholesterol, whereas cholesterol absorption was decreased by ≈70% in the Npc1l1−/− mice. Ezetimibe caused no further reduction in cholesterol absorption in Npc1l1−/− mice, indicating an essential role for Npc1l1 in the ezetimibe-sensitive cholesterol absorption pathway.9

Plant sterol absorption, specifically of radiolabeled sitosterol, was also significantly reduced in Npc1l1−/− mice compared with Npc1l1+/+ mice. Liver sitosterol was decreased by ≈70% and sitosterol uptake into the proximal third of the small intestine was decreased by ≈50% in Npc1l1−/− mice. Ezetimibe treatment of Npc1l1+/+ mice substantially decreased sitosterol uptake into the liver and the proximal small intestine to levels comparable to those in Npc1l1−/− mice. In ezetimibe treated chow-fed mice, plasma sitosterol and campesterol were decreased by >80%. These findings supported the concept that Npc1l1 plays an essential role in the ezetimibe-sensitive pathway of plant sterol absorption.8

Administration of a diet enriched in cholesterol and cholate to Npc1l1+/+ mice increased plasma cholesterol 2-fold and liver cholesterol ester 6-fold. These increases were reduced by 90% in Npc1l1−/− mice and were completely attenuated in Npc1l1−/− mice. Ezetimibe treatment of cholesterol-fed Npc1l1+/+ mice decreased plasma and liver cholesterol to levels similar to those observed in Npc1l1−/− mice. Thus, the absence of Npc1l1 prevented the elevation in plasma and liver cholesterol seen with increasing dietary cholesterol.6

Npc1l1 expression was apparent in the proximal jejunum of Npc1l1+/+ and Npc1l1−/− mice, but was undetectable in Npc1l1−/− mice. Furthermore, a diet enriched in cholesterol and cholate reduced Npc1l1 expression by 75% compared with chow-fed animals of the same genotype, demonstrating that its expression was sensitive to intestinal cholesterol uptake, although this result has not been conclusively established.8,10 Studies of other sterol-sensitive genes had comparable results. For instance, Hmgcs1 encodes 3-hydroxy-3-methylglutaryl (HMG) CoA-synthase, a rate-limiting enzyme in cholesterol biosynthesis. Decreased intestinal cholesterol uptake in chow-fed Npc1l1−/− mice resulted in a 3.5-fold increase in expression of Hmgcs1 and this remained upregulated in cholesterol-fed Npc1l1−/− mice, indicating that absence of absorbed cholesterol failed to downregulate this sterol-sensitive gene. In addition, Abcg5 encodes a transporter that participates in the efflux of plant sterols and cholesterol from the enterocyte back into the intestinal lumen, and is sensitive to cholesterol through activation of the liver X receptor (LXR). Abcg5 expression increased with cholesterol feeding in wild-type mice and this was attenuated in Npc1l1−/− mice. Therefore, in the absence of Npc1l1, levels of genes regulated by sterol-sensitive transcription factors (SREBPs and LXRs) suggested that intra-enterocyte sterol levels were diminished.8

Evidence for Direct Interaction of NPC1L1 With Ezetimibe

Additional evidence has come from in vitro binding assays that tested directly the interaction between the drug and NPC1L1. Garcia-Calvo, with Davis, Thornbury, and colleagues,11 developed a binding assay and showed that labeled ezetimibe glucuronide bound specifically to a single site in intestinal epithelial brush border membranes and in embryonic kidney cells engineered to express NPC1L1. Furthermore, the binding affinities of ezetimibe and its analogs to recombinant NPC1L1 were indistinguishable from those observed for native enterocyte membranes. Values for the dissociation constant of ezetimibe glucuronide for NPC1L1 were evaluated in intestinal enterocyte membranes and human embryonic kidney cells engineered to express NPC1L1 from various species. Binding affinities were highest for rhesus monkey compared with more moderate values for rat and human, with the lowest values reported for mouse, which also correlates well with the in vivo potency observed for ezetimibe across species. Also, ezetimibe failed to bind to membranes collected from Npc1l1−/− null mice compared with wild-type mice. These results directly established NPC1L1 as ezetimibe’s target.

Regulation of NPC1L1 Expression and Subcellular Location of NPC1L1

The regulation of NPC1L1 expression has not been completely defined. Davis et al reported that intestinal Npc1l1...
mRNA expression was downregulated in wild-type and Npc1l1/H11001/H11002 mice fed a cholesterol/cholate diet. This is consistent with sterol-regulated elements (SRE) within the Npc1l1 promoter, suggesting that its expression is regulated like many other genes coding for proteins involved in cholesterol metabolism. Repa et al reported that Npc1l1 expression was lower in the intestine of wild-type mice fed a cholesterol-enriched diet compared with those on chow alone and fell even further in ACAT2 null mice fed a cholesterol-enriched diet compared with those on chow alone. In contrast, intestinal Npc1l1 expression in hamsters was much less sensitive to a cholesterol-enriched diet. In preliminary studies, Npc1l1 expression was increased in both the jejunum and liver in pigs treated with ezetimibe. The enhanced expression correlated with cholesterol depletion in both tissues, consistent with transcriptional regulation by sterols via an SRE.

The subcellular location of NPC1L1 within enterocytes was primarily in the plasma membrane. Using rat hepatoma cells over-expressing human NPC1L1, Yu et al recently reported that NPC1L1 was present simultaneously in both intracellular compartments and the cell membrane. Furthermore, its subcellular distribution was regulated by cholesterol availability. Cholesterol depletion induced translocation of NPC1L1 to the cell surface, preferentially to an apical domain, resulting in an increased uptake of free cholesterol through NPC1L1. Whether a similar pattern of cholesterol-regulated translocation of endogenous NPC1L1 occurs in human hepatocytes remains to be determined.

In contrast to mice and rats, human liver also expresses NPC1L1. The apical location of NPC1L1 in hepatoma cells predicted a canalicular distribution of NPC1L1 in vivo, which has been confirmed in monkey liver. Whether a similar pattern of cholesterol-regulated translocation of endogenous NPC1L1 occurs in human hepatocytes remains to be determined.

Figure 1. NPC1L1 function. Schematic showing NPC1L1 (circled) localized to the brush border of the enterocyte, acting as the gatekeeper for absorption of cholesterol and plant sterols from the lumen of the small intestine and also as the molecular target of ezetimibe. Cholesterol (chol) and plant sterols that have entered the enterocyte can be resecreted into the lumen via the ABCG5/G8 heterodimer. Absorbed cholesterol contributes to the free cholesterol pool, as does the cholesterol from the endogenous biosynthetic pathway for which hydroxyethyl glutaryl coenzyme A reductase (HMGGCoA R) is the rate-limiting step; this activity is pharmacologically inhibited by statin drugs. AcylCoA:cholesterol acyl transferase (ACAT) then esterifies the free cholesterol, which is packaged into chylomicrons and secreted into the lymphatics. After processing in the peripheral circulation, chylomicron remnants are taken up by hepatocytes, contributing to the hepatic pool of cholesterol. Depletion of this pool results in decreased secretion of very low-density lipoproteins (VLDL) and increased catabolism of low-density lipoprotein (LDL) by LDL receptors. Kinetic studies of ezetimibe-treated patients and animals indicated that reduction of plasma apolipoprotein (apo) B was a consequence of both a moderate decrease in the secretion of apoB-containing lipoproteins (LDL and VLDL), and a markedly increased catabolic rate, probably via the LDL receptor. Thus, just as statin drugs reduce the hepatic cholesterol pool by inhibiting cholesterol biosynthesis, ezetimibe ultimately contributes to a decreased hepatic cholesterol pool, albeit via a different mechanism; namely a decreased supply of chylomicron remnant-derived cholesterol to the liver. The diagram does not show the possibility that ezetimibe might also interact with NPC1L1 expressed in human liver, as discussed in the text.
sequently, ezetimibe might also predispose some individuals to gallstone formation by increasing cholesterol saturation of bile, although extensive clinical trial experience would indicate that this is not a major concern.

Additional Evidence of the Centrality of NPC1L1 in Sterol Absorption

LXRs function as nuclear cholesterol sensors that become activated in response to elevated intracellular cholesterol and then induce the expression of numerous genes involved in cholesterol absorption, efflux transport, and excretion. Duval et al showed that LXR activation with a synthetic agonist downregulated intestinal expression of NPC1L1, supporting a crucial role for both LXR and NPC1L1 in intestinal cholesterol homeostasis. Npc1l1 repression was also associated with protection against a Western diet in another transgenic model, perhaps mediated by bile acid responsive genes. These findings further emphasized the sterol-sensitivity of Npc1l1 and its central position in intestinal sterol absorption. The final word on the regulation of NPC1L1 expression is still, however, largely unknown, with mixed results from several labs for the regulation of NPC1L1 by LXR agonists.

Inhibition of NPC1L1 by Ezetimibe Decreases LDL Cholesterol

Apolipoprotein B100 (apoB) kinetic studies in men with primary hypercholesterolemia revealed that ezetimibe decreased LDL cholesterol, primarily through enhanced catabolic rates of very-low-density lipoprotein (VLDL), intermediate-density lipoprotein, and LDL, which is consistent with an upregulation of hepatic LDL receptor activity.

In the pig model, apoB kinetic analyses demonstrated that the combination of ezetimibe plus simvastatin decreased VLDL and LDL apoB concentrations. Ezetimibe inhibited cholesterol absorption and simvastatin blocked the compensatory increase in cholesterol synthesis observed with ezetimibe monotherapy, resulting in a significant reduction in hepatic cholesterol and a marked synergistic increase in hepatic LDL receptor expression. Plasma apoB was significantly decreased by a modest reduction in VLDL apoB production and a greatly enhanced LDL receptor-mediated LDL apoB clearance, both of which are attributed to the reduction in hepatic cholesterol (Figure 1). The efficacy of ezetimibe for lowering plasma LDL cholesterol both in patients with homozygous familial hypercholesterolemia and in Ldlr-deficient mice further support a role for this agent in reducing hepatic VLDL production. Therefore, inhibition of NPC1L1 by ezetimibe enhances LDL cholesterol-lowering compared with statins alone, through a distinct yet complementary mechanism of action.

Human Genetic Studies

Human genetic studies from 2004 provided some of the earliest evidence in favor of NPC1L1 as the target of ezetimibe. The rationale for these studies was as follows: if NPC1L1 is ezetimibe’s target, then naturally occurring coding mutations in the NPC1L1 gene might affect response to the drug among individuals who carried such mutations. Thus, Wang et al selected 8 individuals from a lipid clinic who exhibited no plasma LDL cholesterol response to ezetimibe treatment and determined the genomic sequence of the coding regions and intron–exon boundaries of NPC1L1 in these patients. This strategy found a compound heterozygous subject among the ezetimibe nonresponders: an elderly European man who had 2 rare nonsynonymous mutations of the NPC1L1 gene, namely V55L and I1233N (Figure 2) on different chromosomes. This provided indirect evidence that NPC1L1 was the ezetimibe target, albeit in the absence of direct functional data.

After examining the extreme situation of ezetimibe nonresponders, the next hypothesis tested was whether common genetic variation in NPC1L1 would underlie more subtle interindividual differences in plasma LDL cholesterol response to ezetimibe. Three informative common single nucleotide polymorphisms (SNPs) in NPC1L1, namely 1735C>G, L272L, and 25342A>C, were used to build a “3-site haplotype” which was in turn used to genotype 101 subjects who were treated with ezetimibe for primary hypercholesterolemia. For subjects carrying the most common 1735C>25342A>27677T haplotype (termed “haplotype 2”), plasma LDL cholesterol concentration decreased by approximately 24% on ezetimibe treatment. However, 12% of individuals did not carry the common NPC1L1 haplotype 2, and among these individuals plasma LDL cholesterol concentration decreased by approximately 35% in response to ezetimibe, representing a highly significant between-genotype difference. Whereas the study was limited because of small sample size, lack of a replication sample and no direct functional consequence for the SNPs, the statistical association again strongly linked NPC1L1 with ezetimibe in humans.

Simon et al similarly evaluated the hypothesis that genetic variation in NPC1L1 would influence the LDL cholesterol response to ezetimibe in 2 large independent
al26 also responded abnormally to ezetimibe. Further studies
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Nor is it known whether the I1233N nonresponder to ezetimibe reported by Wang et al was also a
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types composed of the variant and surrounding markers were
also significantly associated with variation in LDL cholesterol response. These results added significant weight in favor of
the hypothesis that the effect of NPC1L1 genetic variation is on intestinal cholesterol transporter activity.
Finally, additional genetic proof of a physiological role for
NPC1L1 was provided by the recent report of a significant relationship between sterol absorption and the presence of
multiple rare NPC1L1 sequence variants. In this population-based study, intestinal sterol absorption was estimated by the
ratio of plasma campesterol to lathosterol (Ca:L); campe-
sterol is a plant sterol absorbed only from the diet whereas
lathosterol is a cholesterol precursor that correlates with rates
of endogenous cholesterol synthesis. Screening of the
genomic DNA sequences of NPC1L1 coding regions in
individuals at each extreme of the Ca:L ratio distribution curve showed an excess of sequence variations among the
low absorbers (low Ca:L), with ≈4 times as many nonsyn-
nonymous sequence variants, tending to involve highly con-
served residues (Figure 2), identified in the low absorbers
compared with the high absorbers. Interestingly, the major-
ity of the sequence changes (≈75%) were found among
blacks. The variants also appeared to be associated with lower baseline plasma concentrations of LDL cholesterol. The
I1233N mutation found in 1 subject of the 128 in the high
absorber group (Figure 2) coincidentally had been initially
found in the original ezetimibe non-responder reported by
Wang et al. It is unknown whether the I1233N heterozygous nonresponder to ezetimibe reported by Wang et al was also a
hyperabsorber of sterols. Nor is it known whether the I1233N heterozygote hyperabsorber of sterols reported by Cohen et
al also responded abnormally to ezetimibe. Further studies
might show an overlap between genetic determinants of sterol absorption and ezetimibe response phenotypes.

Until direct functional assessment of any of these common
or rare variants has been performed, no definitive conclusions
can be drawn about the gene mutations and NPC1L1 func-
tion. However, the evidence taken together, including their significant: (1) associations with response to ezetimibe; (2)
association with measures of sterol absorption; and (3) associations with concentrations of plasma LDL cholesterol implicate the NPC1L1 gene product as the target
for ezetimibe and physiological determinant of intestinal sterol absorption in humans.

Conclusion

Thus, in <3 years, NPC1L1 has catapulted from virtually
unknown status to being a key player in normal physiology
and as a determinant of response to a useful cholesterol-
lowering medication, ezetimibe. Ezetimibe has, in effect,
served as a probe to expose a new pathway, to work “backward” from protein function to protein identification. Evidence in support of this new pathway has been garnered
not only through traditional reductionist models and in vitro
binding assays, but also through the use of human genetics as
to study the impact of NPC1L1 sequence variation in
patients and healthy subjects. It is fortuitous that ezetimibe,
which was identified in an ACAT inhibitor discovery pro-
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References
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