Genome Editing to Delete PCSK9 and Control Hypercholesterolemia in a Single Shot

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Cholesterol management is the centerpiece of cardiovascular risk reduction. The most commonly used tool for cholesterol control is a daily statin, and the recent American Heart Association/American College of Cardiology guidelines have sanctified this approach by endorsing widespread use of statins in large groups of patients, including those with cardiovascular disease, hypercholesterolemia, diabetes mellitus, and elevated cardiovascular disease risk. Challenges to the notion of a daily medication for cholesterol control have been introduced with the discovery of proprotein convertase subtilisin/kexin 9 (PCSK9), a secreted serine protease that binds the low-density lipoprotein (LDL) receptor (LDL-R) and targets it for lysosomal destruction. Thus, a hyperactive (gain-of-function mutant) PCSK9 causes hypercholesterolemia, whereas a dysfunctional (loss-of-function mutant) PCSK9 causes lifelong low LDL-cholesterol (LDL-C) levels and protection against cardiovascular disease. The basic mechanism of PCSK9 action and its crystal structure made it clear early on that it would be difficult to develop a small molecule inhibitor for this protein. However, because PCSK9 is a secreted protein, it can be targeted with inhibitory antibodies, a modality that would change the paradigm of cholesterol treatment from oral to injectable and from daily to once or twice monthly dosing. A large number of clinical studies with the 2 leading antibodies have shown great efficacy and no safety signals, with LDL-C reductions in the range of 55% to 70% (even without concomitant use of statin) and no reports of myalgia (even in subjects with history of statin intolerance caused by myalgia), transaminase elevations, or alterations in glucose metabolism. In addition to neutralizing circulating PCSK9 via antibodies or adnectins, current drug development strategies also include genetic modalities, such as antisense RNA or RNA interference, to block PCSK9 synthesis. Given the likelihood that PCSK9 inhibitors will gain regulatory approval in the near future, it is appropriate to look into a plausible, more distant future of cholesterol management where the intervention is not biweekly or monthly, but rather it is a one-time injection that permanently and selectively modifies the genome to inactivate a target gene whose function is undesirable. PCSK9 is a dream target for such strategy because humans without circulating PCSK9 have been identified and shown to be healthy, fertile, and enjoying ultra-low LDL-C levels and absence of cardiovascular disease. The article by Ding et al in this issue of the journal gives us a sense of where the technology stands at this point for genome editing in vivo in an adult mouse model and of how feasible and effective such approach may be for human subjects affected by hypercholesterolemia as a way to correct the metabolic problem permanently.

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Genome engineering technologies based on the RNA-guided Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)/CRISPR-associated protein 9 (Cas9) system allow for the permanent alteration of the mammalian genome in a living organism. The CRISPR/Cas9 system has been used for silencing, enhancing, or changing specific genes in mice and in primates. The CRISPR system is an exploitation of an immune mechanism used by some bacteria to defend themselves against viruses and based on the production of small RNAs matching portions of the invading viral DNA and of a nuclease (Cas9) that will cleave the foreign genome at targeted sites. The technology is handy and only relies on 2 short pieces of RNA, one that matches the targeted DNA region and another that binds to Cas9, which can be combined into a single-guide RNA molecule that both targets a specific DNA sequence and recruits Cas9 nuclease. The therapeutic potential of this technology has 2 major applications: (1) targeted genome editing to correct genetic disorders by single-base repair or promoter activation and (2) genome disruption or gene repression. Again, and at the cost of beating a dead horse, this technology can be applied to introduce permanent changes in the genome of adult animals of any species, including humans. It is apparent that this technological platform may be exploited to provide a cure for several monogenic and complex diseases, from anemia to Alzheimer’s disease to autism.

Ding et al used the CRISPR/Cas9 system in a small, proof-of-concept study to disrupt the PCSK9 gene in adult mice via introduction of insertion and deletion mutations specifically in the liver via adenoviral infection. The adenovirus targets both Cas9 and the CRISPR guide RNA to the liver, which is the main site of both PCSK9 expression and function. Using the CRISPR/Cas9 system, the authors were able to mutate the PCSK9 gene in the liver, achieving an exceptionally high reduction in plasma PCSK9 levels (>90%) that cannot be explained solely by the mutagenesis rate (just >50%). It is be
kept in mind that hepatic LDLR is not only the main target of PCSK9 action but also the main regulator of circulating PCSK9 levels because PCSK9 uses LDLR for its own plasma clearance.14 In this case, reduced production of PCSK9 leads to high hepatic LDLR levels, which in turn further remove pre-existing PCSK9 from the circulation, leading to extremely low PCSK9 levels, above what would be expected simply from the mutagenesis rate. In this scenario, the altered balance between LDLR and PCSK9 (increased LDLR levels because of reduced PCSK9 production) creates a cycle of events leading to a new homeostatic balance between PCSK9 and LDLR (reduced PCSK9 levels due to increased LDLR-dependent clearance), caused by the well-characterized reciprocal regulation between these 2 proteins.14,15 The biology of PCSK9–LDLR interaction outside of the liver is much less defined, as there are tissues, such as the adrenal glands, where PCSK9 knockout or overexpression do not have an effect on LDLR levels.1 Because PCSK9’s effect on cholesterol metabolism is through its extra-cellular interaction with membrane LDLR, serum PCSK9 levels may be used as marker for PCSK9 activity. Indeed, PCSK9 and LDL-C levels are highly correlated not only because they are both cleared by the LDLR but also because the active form of PCSK9 (≤40% of total serum PCSK9) is physically associated with the LDL particle.16,17 It is important to mention that the ELISA assays currently used to evaluate serum PCSK9 levels, including the one used by the authors of this study, do not distinguish between active (LDL-associated) and inactive forms (not associated with LDL), and thus do not capture the specific information that adds insight on PCSK9 activity.

The CRISPR/Cas9 system has been used in adult mice to correct the fumaryl-acetoacetase hydrolyase mutation in a model of the human disease type I tyrosinemia, a rare and severe autosomal recessive condition.12 In this case, the objective was to express functional fumaryl-acetoacetase hydrolyase protein. Ding et al10 used a different strategy, exploiting the unwanted consequences of PCSK9 action on cholesterol metabolism, thus targeting the gene for deletion. Using the CRISPR/Cas9 system, the authors were able to induce a mutagenesis of the PCSK9 gene in the liver, followed by impressive increases in hepatic LDLR levels, decreases in total cholesterol levels from 35% to 40% (due to decreases in both LDL-C and high-density lipoprotein-C levels), and no changes in control analytes, such as plasma triglyceride and transaminase levels.10 Earlier studies showed similar effects from the removal of endogenous PCSK9 in the mouse system via standard gene deletion approaches.18

It is important to note that there are differences between the mouse and the human system in how PCSK9 affects serum lipids. These include (1) modulation of high-density lipoprotein levels in mice but not in humans, (2) modulation of intestinal de novo lipogenesis of human but not of murine PCSK919, and (3) effects on triglyceride and lipoprotein(a) levels in humans but not in mice.18 Thus, targeted PCSK9 perturbation in humans may have additional effects of lipid metabolism beyond LDL-C reduction.

As a note of caution for the applicability of the current study to human disease management, the authors used an adeno-virus to carry out the delivery of the CRISPR/Cas9 system to the liver, a method not applicable for human treatment because it triggers a host immune response. Other appealing nonviral approaches for the delivery of the CRISPR/Cas9 construct include (1) lipid nanoparticles,20 (2) hydrodynamic tail injection,12 and (3) ultrasound microbubbles.21

Another theoretical limitation of the CRISPR/Cas9 system is the possibility of off-target mutagenesis. In the small-scale experiment presented by Ding et al,18 no off-site mutagenesis was detected in a list of 10 selected genes that were most likely to be affected based on the CRISPR guiding sequence and similarities to the target gene. To turn the CRISPR/Cas9 into a valid therapeutic application, methods to detect and minimize off-target mutagenesis at the level of the whole genome are needed. More importantly, as this method involves permanent alteration of the genome, which unlike a drug cannot be undone, the safety and tolerability of lifelong gene deletion must be confirmed for each target. Although beneficial loss-of-function mutations are rare, permanent partial disruptions of gene expression may have several other therapeutic applications, such as to gain protection against malaria via introduction of the sickle cell trait, or protection against HIV infection via deletion of CCR5.22 Equally intriguing is the possibility of using permanent gene perturbation in adult animal models for basic research purposes. Current techniques to modulate gene expression in vivo include RNA inhibition, with the limitation of looking only at acute and transient effects, and gene knockout or overexpression, with the limitation of heavy financial burden and long periods required to generate, breed, and maintain animals. The use of the CRISPR/Cas9 system as an efficient, tissue-specific delivery strategy with minimal to no off-target effects has the potential to become a new standard for introducing genomic changes in mice and with the tremendous advantage of being equally applicable to any other experimental model.

In conclusion, this study should serve as an introduction to our field of a revolutionary technology that holds the enormous promise to change the face of modern medicine. The study itself simply shows that PCSK9 is targetable with this novel approach, leading to all the expected and desirable consequences of PCSK9 inhibition or loss. The larger point is that one day we may be able to correct hypercholesterolemia permanently with a one-time injection of a biological agent. The nearer future likely will show a massive adoption of this new technology in the basic sciences.

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Disclosures
None.

References


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