In This Issue, see p 1265

Proprotein convertase subtilisin/kexin 9 (PCSK9) is a secreted regulator of cell surface LDL receptor (LDLR) levels, whose function results in elevation of plasma LDL levels. Inhibition of PCSK9 is an active and promising area of therapeutic development for hypercholesterolemia. A major target of these drug development efforts is aimed at reducing levels of PCSK9 by using monoclonal antibodies. We and others have found that PCSK9 is associated with LDL in plasma. As much as 25% of plasma PCSK9 in transgenic mice, and 40% in human subjects, is in the LDL fraction. Various studies have reported a significant correlation between PCSK9 and LDL-C, likely because of PCSK9's effect on cellular LDLR and plasma LDL clearance. It remains to be established whether primary changes in LDL levels affect plasma PCSK9 levels, as can be expected given that significant amounts of PCSK9 are carried by this lipoprotein. PCSK9 circulates in plasma in different molecular forms: (1) a 62 kDa band, representing the full-length circulating protein minus the prodomain; (2) a 55 kDa fragment, product of cleavage of the 62 kDa protein by the protease.
furin\textsuperscript{18,19}, and (3) higher-molecular-weight forms, likely PCSK9 homo- or heteromultimers.\textsuperscript{10,12} The physiological role of the smaller and larger molecular weight PCSK9 forms is not clear.

To test the direct effect of modulating LDL levels by LA on PCSK9 plasma levels, we analyzed plasma from patients with FH before and after removal of apoB-containing lipoproteins via LA and also measured PCSK9 in the apheresis column eluate. We show that LA reduces PCSK9 levels by >50%, via column trapping of both LDL-bound and apoB-free PCSK9.

**Methods**

An expanded Methods section is available in the Online Data Supplement.

**Patients**

Six subjects with severe FH (according to Simone Broome criteria)\textsuperscript{20} and history of CAD undergoing LA every 2 weeks at Vanderbilt University Medical Center (VUMC) were studied. Control subjects were not taking lipid-lowering agents. The study protocol was approved by VUMC’s institutional review board (IRB 101615). All participants gave informed consent.

**Experimental Dextran Sulfate Column**

One milliliter of dextran sulfate cellulose beads (from an unused Liposorber column) was packed into vertical columns and 6 mL of plasma were loaded on the column in each experiment.

**Recombinant PCSK9 With Glutathione S-Transferase Affinity Tag**

Using the Mammalian Transfection System purchased from Promega, HEK293T cells were transfected with pcDNA-PCSK9-GST and purified from culture media.

**Plasma Lipoprotein Separation**

Lipoproteins from pre- and post-apheresis plasma were isolated by ultracentrifugation using natural gradient media (Optiprep) and OptiSeal tubes spun at 90000 rpm for 2.5 hours in a TLN100 rotor.

**Results**

**LA Reduces Plasma PCSK9 Levels**

Because PCSK9 binds to LDL,\textsuperscript{10–13} we predicted that plasma PCSK9 would also be removed by LA. We studied 6 patients undergoing routine LA with dextrose sulfate columns on 3 consecutive treatment cycles and found a significant reduction (52±5%) in plasma PCSK9 after treatment (Figure 1A). The reduction in PCSK9 was higher than predicted by LDL reduction alone (≈80% of LDL removed with ≈40% of PCSK9 associated with LDL should result in a 32% reduction in total PCSK9). No differences were seen in plasma levels of control parameters, such as albumin, creatinine, and CK-MB. Mean changes in plasma lipids and proteins for each patient are summarized in Table 1. PCSK9 levels returned to pretreatment values between each cycle (2-week intervals) in all 6 patients (Figure 1B). As shown in Figure 1C, there was a significant correlation between LDL and PCSK9 decreases (\(P=0.0322; \ r^2=0.26\)). No correlation was found between PCSK9 reduction and triglyceride or high-density lipoprotein changes after treatment (Online Figure IA and IB).

**LA Removes Both LDL-Bound and apoB-Free PCSK9**

As PCSK9 reduction was greater than predicted, we set out to analyze the degree of PCSK9 reduction in different plasma fractions and the quantitative recovery of PCSK9 from the column. We show that 81±11% and 48±14% of PCSK9 was removed from the LDL-bound and apoB-free fraction of the plasma, respectively (Figure 2A). The combined reduction in both fractions explains >80% of PCSK9 removal from the circulation. Additionally, in the column eluate we were able to recover 82±11% of the total PCSK9 removed from the circulation (not shown). Similar to previous reports in mice,\textsuperscript{10–12} western blot analysis of PCSK9 in plasma from apheresis patients showed no PCSK9 bound to the VLDL (Figure 2B).

Purity of each fraction is shown in Online Figure II. PCSK9 bound to LDL was exclusively in the 62 kDa monomeric

---

**Figure 1.** Lipoprotein apheresis (LA) reduces plasma proprotein convertase subtilisin/kexin 9 (PCSK9) levels. A, Pre- and postapheresis plasma PCSK9 levels in 6 patients with familial hypercholesterolemia (FH). Insert: Representative PCSK9 immunoblot from pre- and post-apheresis plasma. B, Pre- and post-apheresis plasma PCSK9 levels during 3 consecutive treatments in 6 FH patients. C, Correlation between low-density lipoprotein (LDL) reduction and PCSK9 reduction after LA. ***\(P<0.001\).
active form (Figure 2B), whereas the apoB-free fraction showed different molecular forms of PCSK9, mainly the smaller 55 kDa band product of furin cleavage and also low levels of higher molecular weight bands likely due to homo- or hetero-polymerization (Figure 2B).

### Quantification Studies Using a Scaled-Down LA Column

To study PCSK9 removal from each fraction directly, we used a commercial grade, scaled-down dextrose sulfate column with cellulose beads (Liposorber). Using plasma, 61±4% of cholesterol (mainly LDL) and 51±7% of PCSK9 were removed. Using the purified LDL fraction, 68±16% of cholesterol and 61±5% of PCSK9 were removed (Figure 3A and 3B). To test whether purified PCSK9 directly binds the column, we used GST-tag PCSK9 (62 kDa) produced in transfected HEK293T cells (Figure 3B, inset).

Figure 3B shows that the scaled-down dextran sulfate column did not remove the purified GST-tag PCSK9 (62 kDa) from the saline solution (pH=7.4). To determine whether the ability to remove both LDL and PCSK9 from plasma is unique to dextran sulfate, we also used polyethylene glycol 8000 (20%) precipitation, a known method to precipitate apoB particles and other proteins from plasma. Polyethylene glycol precipitation almost completely removed plasma LDL (97±1.6%) and PCSK9 (95±0.2%; not shown).

### Discussion

We were the first to describe the association of PCSK9 with LDL in murine plasma; we and others have recently reported that more than one third of circulating PCSK9 is associated with plasma LDL in humans. Here, we tested the effect of direct LDL removal via apheresis on plasma PCSK9 levels. Using pre- and post-apheresis plasma from patients with severe hypercholesterolemia and CAD, we show that PCSK9 is removed from the circulation during the LA through both LDL-dependent and LDL-independent mechanisms.

FH is mainly caused by mutations in the LDLR and less commonly by mutations in apoB or gain-of-function mutations in PCSK9. Certain LDLR mutations (eg, receptor-negative) may also result in increased plasma PCSK9 levels and lack of responsiveness to anti-PCSK9 therapy. LA is used to treat hypercholesterolemia in patients with FH by acutely lowering levels of apoB-containing particles and other cardiovascular risk factors.

Our goal was to investigate the direct effect of LA on plasma PCSK9. Here, we show that LA with dextran sulfate cellulose beads decreases plasma PCSK9 levels by more than 50%, and that >80% of PCSK9 lost from plasma is recovered from the column eluate. The decreases in plasma PCSK9 levels caused by LA are similar to those attained in bi-weekly injections of low-dose anti-PCSK9 antibody therapy, which resulted in an average LDL drop of 24%. This means that the PCSK9-lowering effect of LA should explain a portion of the maintenance of low LDL levels after each apheresis session and that LDL levels would more rapidly return to baseline without the drop in PCSK9. After LA, plasma LDL
levels progressively increase and return to baseline after 10 to 14 days.26,27 Similarly, in our study, PCSK9 levels returned to pretreatment values between treatment cycles. The reduction in PCSK9 during apheresis significantly correlated ($r^2=0.26$) with LDL reduction. These results imply that the correlation between PCSK9 and LDL-C or apoB levels14,19,16 reported in the literature is not only due to the known effect of PCSK9 on LDLR, but also due to the physical association between PCSK9 and LDL.

We show that LA results in removal of both LDL-bound and apoB-free PCSK9, and that LDL-bound and apoB-free PCSK9 are different with nonoverlapping molecular forms. We show for the first time that the 62 kDa band, which is the intact and functional form of PCSK9, is only present on the LDL fraction of these patients. This observation was previously described by us and others only in transgenic mice expressing human PCSK9.10–12 This suggests either that only intact PCSK9 has affinity for LDL or that the association with the LDL particle protects PCSK9 from cleavage and multimerization. We also show that both the furin-cleaved 55 kDa form and the low levels of higher-molecular-weight forms (likely homo- or hetero-multimers)28 of PCSK9 are found exclusively in the apoB-free fraction of the plasma. These observations imply that: (1) If intact PCSK9 is the functional protein, then current ELISA methods that test for total plasma PCSK9 levels should be replaced with more specific methods to quantify the 62 kDa form. (2) Because the 62 kDa form is exclusively carried by the LDL particle, then the catabolic destiny of PCSK9 and its effect on LDLR are both driven by the canonical ligand for this receptor. (3) Immune complexes between therapeutic antibodies and target PCSK9 should form on the LDL particle and may be removed via LDL-dependent mechanisms.

Using a Web-based tool (http://isoelectric.ovh.org/),29 we predicted that PCSK9 is negatively charged at plasma pH (full length protein pl=6.6; furin-cleaved fragment pl=7.02) and, as such, not likely to bind the dextran sulfate apheresis column directly, which is also negatively charged. Using purified GST-tagged PCSK9, we show that the intact PCSK9 protein is not removed by the dextran sulfate column, which suggests that the significant loss of plasma PCSK9 we see during LA is mediated by interacting partner protein(s).

Anti-PCSK9 antibodies are seen by most as likely to achieve Food and Drug Administration approval for cholesterol control in patients with less severe hypercholesterolemia than that required for LA qualification.30 More recently, anti-PCSK9 antibodies have been shown to cause significant LDL lowering even in homozygous FH subjects, a group of patients that is currently treated mainly by LA.24 Because the reduction in PCSK9 could contribute to the long-term LDL control caused by LA therapy, anti-PCSK9 therapies may reduce the frequency of LA in patients currently approved for therapy, and LA and anti-PCSK9 therapies may be used synergistically to reduce treatment burden.

Limitation of the Study
This study is based on data from only 6 patients undergoing LA. Therefore, there was limited statistical power to study...
associations between PCSK9 loss and patient characteristics. PCSK9 was measured only in pre- and post-apheresis plasma, and recovery rate of PCSK9 was not studied. In addition, all patients were treated with the most common LA method in the United States (Liposorber, dextran sulfate cellulose beads). It remains to be determined whether other LA interventions such as heparin-induced extracorporeal LDL precipitation or direct adsorption of lipids have similar effects on plasma PCSK9.

Acknowledgments

We thank Dr Patricia Yancey for insightful discussion and advice, and Kimberly Campbell for performing the lipid analyses.

Sources of Funding

This study was supported by National Institutes of Health (NIH–NHLBI) grants R01-HL106845 to S.F. and R01-HL111945 to M.F.L. We acknowledge support from the Atherosclerosis Core of Vanderbilt’s Mouse Metabolic Phenotyping Center (NIH grant DK59637).

Disclosures

None.

References

27. Gordon BR, Kelsey SF, Bilheimer DW, Brown DC, Dau PC, G롯트 AM Jr, Illingworth DR, Jones PH, Leitman SF, Prihoda JS. Treatment of refractory familial hypercholesterolemia by low-density lipoprotein


What Is Known?

- Low-density lipoprotein (LDL) cholesterol lowering is the most common treatment to reduce the risk of atherosclerotic cardiovascular disease, and statins are the drug of choice for many to achieve the desired level.
- PCSK9 circulates in plasma and is responsible for post-transcriptional reduction of hepatic surface LDL receptor.
- Anti-PCSK9 antibodies are proving to be safe and effective in reducing LDL cholesterol levels and are moving toward Food and Drug Administration approval.
- LDL-apheresis (LA) is currently used in patients with familial hypercholesterolemia when LDL >200 mg/dL (>300 if no cardiovascular disease).
- An association of plasma PCSK9 with the LDL particle has been reported.

What New Information Does This Article Contribute?

- We show for the first time that LDLA reduces plasma PCSK9 levels, by >50%.
- The loss of PCSK9 is in excess of that predicted by the extent of association between PCSK9 and LDL.
- Reduction in plasma PCSK9 levels correlated to reduction in LDL cholesterol levels.
- In plasma, the active PCSK9 (62 kDa) is only present on the LDL.
- A significant portion of PCSK9 not associated with LDL is also removed by LA.
- PCSK9 does not directly bind to the apheresis column.
- The loss of LDL-bound PCSK9 is because of the removal of LDL, whereas the loss of LDL-free PCSK9 is likely because of the presence of interacting partner proteins.

Both the existence and the clinical significance of LDL-bound PCSK9 have been a matter of debate. In this study, the physical removal of LDL via LA enabled us to prove definitively that a significant portion of PCSK9 is part of the LDL particle. More importantly, we show that all of the intact and likely most active form of PCSK9 is exclusively associated with LDL. Our study suggests that PCSK9 removal could contribute to LDL lowering of LA. This finding should direct studies on the synergistic effect of LA and anti-PCSK9 therapies and foster investigations on the fate of PCSK9-containing LDL after antibody treatment.
Loss of Plasma Proprotein Convertase Subtilisin/Kexin 9 (PCSK9) After Lipoprotein Apheresis
Hagai Tavori, Ilaria Giunzioni, MacRae F. Linton and Sergio Fazio

Circ Res. 2013;113:1290-1295; originally published online October 11, 2013; doi: 10.1161/CIRCRESAHA.113.302655

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2013 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/113/12/1290

Data Supplement (unedited) at:
http://circres.ahajournals.org/content/suppl/2013/10/11/CIRCRESAHA.113.302655.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org/subscriptions/
Supplemental material

Methods

Reagents - The pcDNA3.1 Directional TOPO Expression Kit, Glutathione-agarose column and precast (4-12%) NuPage™ Bis-Tris gels were purchased from Life Technologies (Grand Island, NY). HEK293T cells were purchased from ATCC (Manassas, VA). Sheep polyclonal antibody toward human PCSK9 was purchased from R&D systems (Minneapolis, MN). Rabbit antibody toward apoB was purchased from Abcam (Cambridge, MA). An ELISA kit for detecting human PCSK9 was purchased from MBL International Corp. (Woburn, MA). OptiPrep (natural gradient solution), Donkey anti-sheep HRP IgG antibody and goat anti-rabbit HRP were purchased from Sigma (St. Louis, MO). The Mammalian Transfection System was purchased from Promega (Madison, WI). OptiSeal tubes were purchased from Beckman-Coulter (Brea, CA). Commercial-grade dextran-sulfate cellulose beads (from an unused Liposorber® column) were a kind gift from Kaneka Pharma (New York, NY).

Collection of pre- and post-LDL apheresis plasma samples - Plasma from pre- and post-LDL-A treatments was used to measure lipids and proteins. In the apheresis procedure, the patient’s blood is drawn via venous access to flow in the plasma separator. As blood flows through the hollow fibers of the plasma separator, the plasma (pre-apheresis) is separated and pumped into one of two LDL absorption columns, where the apoB-containing lipoproteins are selectively absorbed by the dextran-sulfate cellulose beads. The LDL-depleted plasma (post-apheresis) exits the column and is recombined with the blood cells exiting the separator, all of which is returned to the patient via a separate venous access. Once one column is full the system automatically moves to the second column, while the first column is washed and then eluted into a waste bag using lactated Ringer’s solution (0.6% Sodium chloride, 0.31% sodium lactate, 0.03% potassium chloride and 0.02% calcium chloride) and 5% NaCl (column eluate).

Western Blotting - Samples were loaded onto NuPage™ 4–12% Bis-Tris precast gels for electrophoresis. The size-separated proteins were then transferred to nitrocellulose membranes. The indicated primary antibodies and HRP-conjugated secondary antibodies were used to detect target PCSK9 and apoB. Signal was detected by enhanced chemoluminescence
(ECL) using a mixture of luminol, p-coumaric acid and hydrogen peroxide in 100 mM Tris pH 8.5.

**Experimental dextran sulfate column** - Using commercial-grade dextran-sulfate cellulose beads (from an unused Liposorber® column), we gravity-packed 1 mL of beads into a vertical column for 30 minutes, followed by washing with 5 volumes of 0.9% NaCl. Six mL of plasma were loaded on the column at 0.2 mL/minute; 6 mL of plasma eluate were collected. Sequentially, using 2 volumes of Ringer's solution, 2 volumes of 5% NaCl and 2 volumes of Ringer's solution (total volume of 6 mL) were used to elute LDL and proteins from the column.

**Plasma PCSK9 levels** - The levels of human PCSK9 in pre- and post-apheresis plasma, column eluate, ultracentrifuge fractions and purified GST-tag protein were determined by ELISA kits as recommended by the manufacturer (MBL-International).

**Recombinant PCSK9 with Glutathione S-transferase (GST) affinity tag** - We previously generated a pcDNA-PCSK9-GST construct in which a GST tag was placed in the C-terminal region of the protein1. Using the Mammalian Transfection System purchased from Promega (Madison, WI), HEK293T cells were transfected with pcDNA-PCSK9-GST as previously described1. The full-length PCSK9 protein with a C-terminal GST tag was purified from the culture medium of transfected HEK293T cells using a glutathione-agarose column and protein concentrations were then determined.

**Plasma lipoprotein separation** - Plasma lipoproteins from pre- and post-apheresis plasma were isolated by natural gradient media (Optiprep) using a TLN100 rotor and OptiSeal tubes at 90,000 rpm for 2.5 hours, as previously described2.

**Statistical Analyses** - GraphPad Prism 4 software was used to carry out statistical analyses. Pairwise t-test was used to compare pre- and post-apheresis values. Student's paired t-test was used to compare the means of two groups. Results are presented as means ± SD or as percent ± CV. (*p<0.05, **p<0.01, ***p<0.001).
References:


Online Figure I: (A) Correlation between HDL-C reduction and PCSK9 reduction after LDL-apheresis treatment (B) Correlation between triglyceride reduction and PCSK9 reduction after LDL-apheresis treatment. (NS = Not Significant).
Online Figure II: Representative immunoblot of apoB in pre-apheresis plasma fractions isolated by ultracentrifugation, lane 1=VLDL, lane 2=LDL, lane 3=apoB-free.
### Online Table I: Patients characteristic of the six subjects with Familial Hypercholesterolemia (FH) included in the study.

<table>
<thead>
<tr>
<th>Patient #1</th>
<th>Age</th>
<th>Sex</th>
<th>Height (cm)</th>
<th>Weight (Kg)</th>
<th>BMI</th>
<th>Race</th>
<th>List of Medication</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 Male</td>
<td>183</td>
<td>63.5</td>
<td>19.0</td>
<td>Caucasian</td>
<td>Zetia, Metoprolol succinate, Aspirin, Crestor, Niaspan, Cozaar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patient #2</td>
<td>61 Female</td>
<td>170</td>
<td>90.2</td>
<td>31.2</td>
<td>Caucasian</td>
<td>Aspirin , Plavix, Atenolol, Furosemide , Advair Diskus, Cetirizine, Fluticasone, Potassium chloride, Prevacid, Cyanocobalamin, Alamast Ophthalmic Soln, Medtronic insulin pump, INSPRA, Gabapentin, Ketoconazole, Diclofenac sodium, Amlodipine, Lunesta, Humalog, Fish Oil, Astepro, Docusate sodium.</td>
<td></td>
</tr>
<tr>
<td>Patient #3</td>
<td>62 Female</td>
<td>145</td>
<td>69.4</td>
<td>33.0</td>
<td>Caucasian</td>
<td>Ambien, Sertraline, Hydrocodone-acetaminophen, Buspirone, Amlodipine, Livalo.</td>
<td></td>
</tr>
<tr>
<td>Patient #4</td>
<td>21 Female</td>
<td>160</td>
<td>99.3</td>
<td>38.8</td>
<td>Caucasian</td>
<td>Lopressor, Niaspan, WelChol, Zetia, Amlodipine, Aspirin, Claritin, Crestor, Mirena, Senna, Warfarin</td>
<td></td>
</tr>
<tr>
<td>Patient #5</td>
<td>56 Female</td>
<td>157</td>
<td>42.1</td>
<td>17.1</td>
<td>Caucasian</td>
<td>Premarin patch, Aspirin, Atorvastatin, Hyoscyamine sulfate, Lactobacillus acidoph &amp; bulgar, Lactulose, Levofloxacin, Levothyroxine, Lisinopril, Metoprolol tartrate, Nitroglycerin, Nystatin, Omeprazole, Sennosides, Simethicone, Warfarin, Zolpidem, Plavix, Protonix, Donnatal TID, Zetia, Crestor, Carvedilol.</td>
<td></td>
</tr>
<tr>
<td>Patient #6</td>
<td>57 Male</td>
<td>168</td>
<td>114.8</td>
<td>40.7</td>
<td>Caucasian</td>
<td>Endocet, Patanol, Fluticasone, Flovent HFA, Vimovo, Miralax, Diazepam, Nexium, Metoprolol tartrate, Crestor, Simethicone, Aspirin, Soma, Nitroglycerin.</td>
<td></td>
</tr>
</tbody>
</table>