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Lipid nanoparticles and siRNA targeting plasminogen provide lasting inhibition of fibrinolysis in mouse and dog models of hemophilia A

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Supplementary Materials
This PDF file includes:
Figs. S1 to S4
Other Supplementary Material for this manuscript includes the following:
Data file S1
MDAR Reproducibility Checklist

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Abstract

Antifibrinolytic drugs are used extensively for on-demand treatment of severe acute bleeding. Controlling fibrinolysis may also be an effective strategy to prevent or lessen chronic recurring bleeding in bleeding disorders such as hemophilia A (HA), but current antifibrinolytics have unfavorable pharmacokinetic profiles. Here, we developed a long-lasting antifibrinolytic using small interfering RNA (siRNA) targeting plasminogen packaged in clinically used lipid nanoparticles (LNPs) and tested it to determine whether reducing plasmin activity in animal models of HA could decrease bleeding frequency and severity. Treatment with the siRNA-carrying LNPs reduced circulating plasminogen and suppressed fibrinolysis in wild-type and HA mice and dogs. In HA mice, hemostatic efficacy depended on the injury model; plasminogen knockdown improved hemostasis after a saphenous vein injury but not tail vein transection injury, suggesting that saphenous vein injury is a murine bleeding model sensitive to the contribution of fibrinolysis. In dogs with HA, LNPs carrying siRNA targeting plasminogen were as effective at stabilizing clots as tranexamic acid, a clinical antifibrinolytic, and in a pilot study of two dogs with HA, the incidence of spontaneous or excess bleeding was reduced during 4 months of prolonged knockdown. Collectively, these data demonstrate that long-acting antifibrinolytic therapy can be achieved and that it provides hemostatic benefit in animal models of HA.

INTRODUCTION

Fibrinolysis is a proteolytic process that remodels and clears blood clots from the vasculature. The enzymes of the fibrinolytic pathway become activated both during and after clot formation, opposing the growth of the fibrin clot and ultimately restoring blood flow through vessels (1). The generation of plasmin, the protease that cleaves fibrin from its proenzyme plasminogen, is mediated by tissue plasminogen activator (tPA) and urokinase (2). Plasmin generation is suppressed by endogenous antifibrinolytics, such as plasminogen activator inhibitor-1 (PAI-1), and is pharmacologically inhibited by the small-molecule tranexamic acid (TXA) and ε-aminocaproic acid (EACA) (3). Fibrinolysis is also regulated by thrombin generation; thrombin converts fibrinogen to fibrin, which acts as a cofactor for tPA-mediated plasminogen activation. Thrombin also activates thrombin-activated fibrinolysis inhibitor and coagulation factor XIII (FXIII), which modify fibrin to decrease the rate of lysis (3).

Fibrin formation and degradation must be balanced to maintain hemostasis. When coagulation is compromised, fibrinolysis can further impede hemostasis (1). For example, hemophilia A (HA) is caused by a deficiency in FVIII and results in low thrombin generation after vascular injury. This, in turn, leads to clots with abnormal fibrin structure that are more susceptible to lysis, as well as more active fibrinolysis (4–6). Patients with HA suffer from spontaneous bleeding in joints and mucosal tissue and excessive bleeding after injury, caused by a combination of less thrombin activity and higher plasmin activity (7). Patients with bleeding disorders greatly benefit from prophylactic therapeutic regimens to prevent bleeding episodes (8); however, the use of current antifibrinolytics, such as TXA,

is limited to on-demand treatment after bleeding has commenced because their circulating half-lives are 3 hours or less (9).

Gene silencing, such as with small interfering RNA (siRNA), has been used in mice to achieve long-lasting control of proteins involved in hemostasis, including fibrinogen (10), FXI (11), FXII (12), and FXIII (13) and a disintegrin and metalloproteinase with a thrombospondin type 1 motif, member 13 (14), and used in clinical trials for bleeding disorders by knocking down antithrombin (15). Lipid nanoparticles (LNPs) can effectively deliver siRNA to hepatocytes, where plasminogen is synthesized, and have been used in three clinically approved RNA-based therapies (16–18). In this study, we tested the hypothesis that siRNA knockdown of plasminogen can achieve long-lasting suppression of fibrinolysis and can be used as a prophylactic therapy to maintain hemostasis in HA. This work adds to previous studies probing the impact of fibrinolysis in murine hemostasis (2, 19) and tests the efficacy of siRNA delivered with LNPs in canine HA, which is a large animal model of human bleeding disorders (20).

RESULTS

siRNA delivered via LNP depletes circulating plasminogen for weeks after a single administration

siRNA was designed to specifically knock down plasminogen (siPlg) in mice or dogs. siPlg encapsulated in ionizable cationic LNPs was administered to all mice at a dose of 1 mg of siRNA per kilogram of body weight (in milligrams per kilogram). Three days after the first administration to wild-type (WT) C57BL/6 mice, *Plg* mRNA was knocked down by 95 ± 0.67%, and plasminogen protein was correspondingly depleted from plasma, compared with control mice treated with siRNA targeting luciferase (siLuc) (Fig. 1, A and B). WT mice administered a single dose of siPlg exhibited plasminogen knockdown for more than 4 weeks, whereas those that received siLuc exhibited only standard variation of baseline plasminogen expression (Fig. 1C) (21,22). In healthy WT dogs of hound background, the extent and duration of plasminogen knockdown was dependent on the dose of siRNA-LNPs (Fig. 1D). A single dose of 0.54 mg/kg in one dog resulted in more than 6 weeks of plasminogen knockdown. A 10-fold lower dose in the same dog and an additional dog, 0.054 mg/kg, depleted 75 to 85% of plasminogen protein from plasma for 4 weeks, whereas 0.027 mg/kg achieved only modest depression of protein expression in the same two dogs and another (Fig. 1, D and E). No changes in the behavior or appetite of the dogs treated with LNPs were observed. However, the 0.54-mg/kg dose increased liver enzymes transiently over 10 days, which was reduced at lower doses and was independent of plasminogen knockdown (fig. S1, A and B). Alanine transaminase (ALT) and aspartate transaminase (AST) were most elevated after the first exposure to LNPs and waned with subsequent doses (fig. S1, C and D); C-reactive protein was below 5 mg/liter at every measurement.

Prolonged siRNA-mediated plasminogen knockdown in mice does not induce phenotypes associated with complete plasminogen deficiency

Repeated siRNA administration to healthy C57BL/6 mice at 3-week intervals maintained circulating plasminogen below 25% of baseline for 9 months. Whereas mice with genetic

plasminogen knockout (*Plg*$^{-/-}$) are prone to wasting disease, leading to weight loss over time (23), prolonged siPlg treatment did not affect mouse weight compared to siLuc treatment (Fig. 2A). *Plg*$^{-/-}$ mice also demonstrate gastrointestinal and mucosal immunopathology, including periodontitis, and fibrin deposition, resulting in spontaneous extravascular fibrin-rich lesions (liver, stomach, and lungs) at 5 to 12 weeks of age (24, 25). In this study, histopathological assessments after 9 months of siRNA-mediated plasminogen depletion demonstrated no signs of periodontal bone loss (Fig. 2B), nor did the processes that contribute to immunopathology in plasminogen deficiency, such as interleukin-mediated inflammation (Fig. 2, C to F). There were no elevations in hepatic expression of interleukin-6 (*Il6*) or systemic tumor necrosis factor–α (TNF-α) or IL-6 protein; however, hepatic expression of *Tnf* was elevated in both siLuc- and siPlg-treated mice compared with untreated age-matched controls (Fig. 2, C to F). Mice exhibited mild elevations of interleukins (IL-6, IL-5, IL-10, and IL-1β), proinflammatory markers TNF-α and keratinocyte chemoattractant (KC)/growth-regulated oncogenes (GROs), and liver enzymes ALT and AST immediately after their first exposure to siRNA-LNPs, but none of these was elevated after 9 months of repeated dosing (fig. S2).

After 9 months of plasminogen knockdown, there were no signs of fibrin deposition in the liver of treated mice (Fig. 2G and fig. S3, A and B), and in a separate cohort of mice administered siPlg biweekly for 5 months, there were no obvious differences in lung morphology or evidence of fibrin deposition in the lung (fig. S3, C and D). In whole-blood clots formed ex vivo, there were no obvious differences in fibrin structure between siLuc and siPlg treatment groups (Fig. 2H).

Plasminogen knockdown promotes hemostasis in HA mice after SVP but not TVT

The potential hemostatic benefits of antifibrinolysis in different types of bleeds in HA were evaluated in different models of induced bleeding in *FVIII*$^{-/-}$ mice (Fig. 3A). HA mice were treated with siPlg (1 mg/kg) 2 weeks before the injury, resulting in 96% plasminogen protein depletion compared with untreated *FVIII*$^{-/-}$ mice (Fig. 3B). After tail vein transection (TVT), siPlg-treated HA mice exhibited no difference in blood loss compared to untreated HA mice; both treated and untreated HA groups lost significantly more blood than WT controls ($P = 0.013$ and $P = 0.0061$, respectively) (Fig. 3C). Mean bleed time after TVT in siPlg-treated HA mice was 26.0 ± 8.6 min, compared with 41.8 ± 3.7 min in untreated HA mice, and 3.3 ± 0.5 min in WT controls, but the difference between untreated HA mice and siPlg-treated HA mice was nonsignificant (Fig. 3D). In contrast, in a saphenous vein puncture (SVP) model, both blood loss and bleeding time were reduced in HA mice treated with siPlg 2 weeks before injury, similar to WT controls (Fig. 3, E and F).

siRNA targeting plasminogen reduces bleeding events in HA dogs and stabilizes clots similar to clinical antifibrinolytics

In HA dogs with FVIII deficiency, clot stability was measured using thromboelastography in plasma samples collected at baseline, 4 hours after administration of TXA [10 mg/kg intravenously (iv)], and/or 1 week after siPlg administration (0.054 mg/kg iv). Plasma clot lysis with exogenous tPA was delayed in samples collected within 4 hours of TXA administration or 1 week after siPlg administration compared with baseline samples (Fig.

4, A and B). Clot stability was not additionally enhanced when TXA was administered to dogs already treated with siPlg (Fig. 4, A and B). Other clot parameters, such as clot strength (maximum amplitude) and clotting time (α angle and R-time), were not changed, and prothrombin time, fibrinogen concentration, antithrombin activity, and D-dimer concentrations all remained within or close to normal range in the HA dogs (fig. S4). Thrombin and plasmin generation were reduced in plasma from HA dogs compared with WT dogs (Fig. 4, C to F). In plasma samples collected from siPlg-treated animals, residual plasminogen concentration did not significantly correlate with peak thrombin generation ($P = 0.246$) (Fig. 4D) but did significantly correlate with peak plasmin generation ($P = 0.001$) (Fig. 4F).

The canine HA model demonstrates similarities in bleeding phenotype and treatment to human HA (20). To assess the prophylactic potential of siPlg, two HA dogs were administered siPlg (0.054 mg/kg) every 3 weeks for 15 weeks. Plasma plasminogen was maintained at <50% of baseline values (Fig. 5A). Annualized bleeding rates were reduced on siPlg treatment compared with a 10-month observation period before initiation of siPlg, when bleed rates were similar to what has been previously reported (Fig. 5B) (26). Whereas in the 10 months before treatment, one dog had experienced five hematomas or joint bleeds and the other dog experienced one, neither dog experienced a joint bleed or hematoma during the siPlg treatment period. During the 4 months of treatment with siPlg, one dog experienced two instances of mouth bleeds and one instance of excess bleeding from an intravenous puncture site. No clinical evidence of overt thromboembolic disease was observed during siPlg treatment.

DISCUSSION

Antifibrinolytics such as TXA and EACA are used to reduce bleeding in diverse clinical scenarios including postpartum hemorrhage, prehospital trauma, surgical hemorrhage, and bleeding disorders (27–33). Mortality in trauma and postpartum hemorrhage may be reduced by TXA, but only if administered within hours of the onset of bleeding (34, 35); this suggests that fibrinolysis contributes early in bleeding, and a prophylactic antifibrinolytic approach may be beneficial for preventing major bleeding episodes and restoring hemostasis. However, the short half-life of current antifibrinolytics preclude their usage for prophylaxis. Here, we evaluated siRNA-LNPs as a strategy to inhibit hepatic plasminogen expression. This resulted in sustained plasma plasminogen depletion and reduced fibrinolytic activity. siRNA-LNPs achieved a dose-dependent knockdown of plasminogen, consistent with previous studies knocking down other hepatic proteins (36–38). In mice and dogs, at doses of 1 and 0.054 mg/kg, respectively, siPlg caused plasminogen protein depletion of >75% for multiple weeks after a single administration, and knockdown could be sustained for months by repeat administration at 3-week intervals.

Dogs with FVIII deficiency are a translationally relevant model with the types, size, and duration of bleeds similar to humans with HA. In dogs with HA, siPlg stabilized clots equally to therapeutic TXA, a commonly used antifibrinolytic in dogs. Consistent with previous studies, plasminogen knockdown did not affect thrombin peak (39, 40), although TXA did appear to reduce thrombin generation through an unknown mechanism. During

a 4-month period of sustained plasminogen knockdown, the number of bleeding events experienced by two HA dogs was reduced compared with pretreatment. The role of fibrinolysis in hemostasis appears to be weaker in mice compared with that in humans or canines. For example, previous studies showed that mice deficient in PAI-1 or α2-antiplasmin do not exhibit overt bleeding, despite these deficiencies being associated with spontaneous bleeding in humans (2). Previous studies also showed no hemostatic benefit after a TVT model of injury in mice with combined plasminogen and FVIII genetic knockout (19, 41). Although we did not directly compare bleeding between mice with complete plasminogen knockout versus knockdown, we confirmed that this result held true with siRNA knockdown of plasminogen. However, in a different injury model, the SVP, plasminogen knockdown reduced blood loss and bleeding time. We hypothesize that this difference is due to the type of injury, which may be more sensitive to changes in clot fibrinolysis. Saphenous vein injury models are less severe, are less dependent on the action of platelets, and exhibit greater sensitivity to factors seen in hemophilia conditions, such as low plasma FVIII concentrations (42, 43). Further differences may include the amount of tissue damage, the blood flow shear rate, the inflammation resulting from the injury models, and the availability of tissue matrix to hold unstable clots at the site of injury, although these require further detailed study.

Although plasminogen deficiency is not associated with an elevated risk of thrombosis (44–48), both humans and mice exhibit other adverse effects, including ligneous conjunctivitis, periodontal bone loss, and fibrin deposition in various tissues (25, 49–52). Ligneous conjunctivitis has also been induced by continuous TXA administration, which is reversed on stopping TXA treatment (53). If these symptoms were to occur with siPlg, they might be reversed by a combination of stopping treatment and replacing plasminogen with transfusion of plasma or purified protein or plasminogen-containing eyedrops, as is done in cases of plasminogen deficiency. The absence of adverse phenotypes associated with plasminogen deficiency after prolonged plasminogen knockdown by siPlg was likely due to the low residual plasminogen expression. This is supported by the fact that heterozygous $Plg^{+/-}$ mice do not display the spontaneous pathologies seen in plasminogen knockout mice (24, 25). This study suggests that less than 25% of baseline plasminogen is required to avoid these pathologies. By achieving substantial plasminogen knockdown for weeks after a single administration while avoiding the $Plg^{-/-}$-associated disease state, siPlg may enable long-term studies of antifibrinolytic therapy in disease models where plasminogen has been implicated as a potential therapeutic target, such as asthma, multiple sclerosis, and many bleeding disorders (54, 55).

A mild response to the introduction of siRNA-LNPs was observed in the acute phase, but prolonged and repeated exposure was not associated with chronic systemic inflammation. The response appeared to be independent of plasminogen knockdown but may have been induced by the siRNA component, because mild elevation of AST was observed after exposure to LNPs containing siRNA compared with empty LNPs. Toxicity to other tissues is not expected because previous studies have suggested that 90% of LNPs localize to the liver (38).

Improved LNP formulations that have decreased toxicity and enable the use of lower doses of siRNA are expected to alleviate this response. Dogs are sensitive to LNPs, exhibiting a diverse set of reactions (56); this has limited their use as a model for investigating LNP-based therapies. Here, we show that after the first exposure to siRNA-LNPs, a 0.054-mg/kg dose enabled potent knockdown in dogs without severe toxicity or systemic inflammation; this dose is approximately 10-fold lower than the equivalent dose of the clinically approved siRNA-LNP drug, Onpattro, 0.3 mg/kg, converted using body surface area ratios from the US Food and Drug Administration guidelines (36, 57).

A limitation of this work was the inclusion of only a single LNP formulation for the delivery of this siRNA. Although formulations containing the ionizable lipid DLin-MC3-DMA are the clinical standard for hepatic delivery, recent advances in the potency of LNP for RNA therapies would likely enable improved hepatotoxicity and inflammatory profiles. Furthermore, whereas the results in the canine model of HA were consistent with those in mice, the interanimal variability in the canine model is relatively large (26), and this study was limited by a small sample size. Further exploration in a larger cohort of FVIII-deficient dogs or dogs with other bleeding disorders is required to validate a difference in annualized bleeding rate. Although we foresee this being an effective strategy for bleeding disorders of various causes, this study was limited to only testing the impact in models of FVIII deficiency. Future studies should consider the use of this strategy in the many indications where TXA is effective.

The efficacy of siPlg is similar to TXA but lasts for weeks rather than hours after administration. TXA is effective for reducing blood loss in many scenarios and in patients with increased risk of bleeding due to diverse etiologies; thus, siPlg may be useful in the same scenarios if translated to humans. Although further study is needed, we envisage that this agent may be useful in other contexts of high fibrinolysis, such as in bleeding in mucosal tissues, or disorders such as α2-antiplasmin deficiency, PAI-1 deficiency, or Quebec platelet disorder (3, 58).

MATERIALS AND METHODS

Study design

The aim of this study was to develop a long-lasting antifibrinolytic, using LNP-delivered siRNA that targets plasminogen, and to evaluate the efficacy of this strategy to decrease bleeding in animal models of HA. First, plasminogen knockdown was assessed by measuring mRNA and protein in liver tissue and blood circulation, respectively. Once knockdown was established, markers of toxicity were evaluated, fibrinolysis was visualized in blood samples ex vivo, and bleeding tendency was compared with or without treatment in FVIII-deficient mice and dogs. Treatments were randomly assigned. Investigators were not blinded to treatment groups. Replicates varied depending on the experiment according to SD and power analysis. Quantification of plasminogen was done in technical triplicate in mice ($n = 3$ per time point) and dogs [$n = 1$ (0.54 mg/kg), 2 (0.054 mg/kg), or 3 (0.027 mg/kg)]. After long-term repeat dosing of siRNA-LNPs in mice, periodontal bone loss was measured at six predetermined sites ($n = 6$ or 7); body weight, inflammatory markers, and fibrin deposition were also assessed ($n = 6$ to 10). Analysis of acute hepatotoxicity and

inflammation 4 hours after administration of siRNA-LNPs was done in WT C57BL/6 mice (n = 5). Bleeding challenges were performed in WT and FVIII-deficient mice using SVP (n = 5 to 7) and TVT (n = 7 to 10) models. Fibrinolysis and impacts on spontaneous bleeding were evaluated in dogs of Irish setter background with FVIII deficiency (n = 2).

siRNA-LNP preparation

2′O-methylated siRNA against murine plasminogen (sense: GCAAAACCUCUGCUUACUAAAGCUT, antisense: AAGCUUUAGUAAGCAGAGGUUUUGCUC) and canine plasminogen (sense: AAGCAAGAACUUGAAGAUGAAUUAC, antisense: GUAAUUCAUCUUCAAGUUCUUGCUUGG), obtained commercially (Integrated DNA Technologies), was dissolved in 25 mM sodium acetate (pH 4) buffer at an amine-to-phosphate (N/P) ratio of 3. Lipids (6Z,9Z,28Z,31Z)-heptatriaconta-6,9,28,31-tetraen-19-yl 4-(dimethylamino)butanoate (DLin-MC3-DMA), disterarolyphosphatidychloline (DSPC), cholesterol, and 1,2-dimyristoyl-rac-glycero-3-methoxypolyethylene glycol-2000 (PEG-DMG) were dissolved in ethanol at a molar ratio of 50/10/38.5/1.5 mol%, respectively, to achieve a final concentration of 20 mM total lipid. The two solutions were mixed using a T-junction mixer as described previously (59). The resulting LNPs were dialyzed against 1000-fold v/v phosphate-buffered saline (pH 7.4). Cholesterol content was measured using the Cholesterol E Assay Kit (Wako Chemicals), from which total lipid concentration was extrapolated. Nucleic acid entrapment was determined using a RiboGreen assay (60).

siRNA-LNP administration and subsequent blood draws

Animal studies were performed in accordance with the protocols approved by the University of British Columbia, Queen’s University, Medical College of Wisconsin, and University of North Carolina. Mouse strains were of C57BL/6J, B6129SF2/J, and B6;129S-F8tm1Kaz/J (the Jackson Laboratory, stock nos. 000664, 101045, and 004424). All studies in mice, except that reported in fig. S3 (A and B), used a dose of 1 mg of siRNA per kilogram of body weight administered via tail vein or retro-orbital venous sinus injection. Blood samples used to assess plasma protein were collected via SVP into heparinized capillaries or via retro-orbital bleeds, no more frequently than once every 2 weeks. Blood was drawn for coagulation assays from isoflurane-anesthetized mice by cardiac puncture using a 23-gauge needle containing sodium citrate (109 mM) to a final v/v concentration of 10% in whole blood. To collect plasma, whole blood was spun at 800g for 10 min.

For dogs, siRNA-LNPs were diluted up to 20 ml in saline and administered intravenously directly after administration of dexamethasone (5 mg/kg iv), diphenhydramine [intramuscularly (im), 1 mg/kg], and famotidine (0.5 mg/kg im); dogs were also administered prednisone [per os (po), 5 mg/kg], diphenhydramine (2.2 mg/kg po), and famotidine (0.5 mg/kg po) each morning and evening before siRNA-LNP infusion. After testing three doses in WT dogs of hound background (0.54, 0.054, and 0.027 mg/kg), two HA dogs (ages 6 and 7, from an Irish setter background) were administered siPlg at 0.054 mg/kg.

mRNA quantification

Livers were surgically removed from anesthetized mice, and tissue was homogenized in TRIzol (Thermo Fisher Scientific, Waltham, MA). Nucleic acid was isolated after phenol-chloroform extraction. DNA was digested by incubating the sample with TURBO deoxyribonuclease (DNase) (Thermo Fisher Scientific) at 37°C for 1 hour. DNase was removed by repeating the TRIzol-chloroform extraction. Reverse transcription was performed using the iScript cDNA Synthesis Kit (Bio-Rad) followed by quantitative polymerase chain reaction (qPCR) with SYBR Green Master Mix (Thermo Fisher Scientific) and DNA primers (Integrated DNA Technologies) against *Plg* (forward: TTCTTGGGGTCTTGGCTGTG, reverse: AGAGGTTTTGCTCGGCCTTC) and *Ppia* (forward: GCGTCTCCTTCGAGCTGTT, reverse: TGTAAAGTCACCACCCTGGC) or TaqMan probes (Thermo Fisher Scientific) against *Plg, Tnfa*, *Adgre1*, and *Il6.*

Western blotting

Samples were reduced, boiled, and separated on 4 to 15% acrylamide gradient gels (Bio-Rad). After electrophoresis, the samples were transferred to a nitrocellulose membrane (GE Healthcare) and blocked with Odyssey blocking buffer (LI-COR). The membranes were treated with a primary antibody against plasminogen (1:1000; SAPG-AP; confirmed cross-reactivity: human, rat, mouse, rabbit, canine, and pig; Affinity Biologicals), washed, and treated with horseradish peroxidase–labeled anti-host secondary antibody (1:15,000; Abcam). Specific bands were imaged using Clarity ECL (enhanced chemiluminescence; Bio-Rad) on film (Mandel). Quantification of Western blots was done using ImageJ (National Institutes of Health) to measure band intensity relative to background and loading controls.

Histopathology

To measure periodontal bone loss in mice, samples were defleshed and stained with methylene blue, and then the distance between the cementoenamel junction and alveolar bone crest was measured at six predetermined sites as previously described (24). To measure fibrin deposition, mouse liver and lung tissue samples were fixed in neutral buffered formalin solution (Sigma-Aldrich) immediately after sacrifice. Tissues were then embedded in paraffin, sectioned, and stained via standard procedure with hematoxylin and eosin stain and immune labeling against fibrinogen (antimurine fibrinogen antibody, R-4025; made in-house). To visualize fibrin structure within clots, whole blood was collected from treated mice, clotted ex vivo for 2 hours, then fixed, embedded, sectioned, and stained, as described above.

Plasma multiplex cytokine analysis

Ten proinflammatory biomarkers (IFN-γ, IL-1β, IL-2, IL-4, IL-5, IL-6, IL-10, IL-12p70, KC/GRO, and TNF-α) were measured in plasma collected from mice 4 hours after the first administration of siRNA-LNPs or after 9 months of repeated dosing, using an electrochemiluminescence-based enzyme-linked immunosorbent assay (K15048D; Meso Scale Discovery).

Thromboelastography

Shear elastic moduli were evaluated at 37°C using a TEG hemostasis analyzer system 5000 (Haemoscope Corp). Citrated mouse whole blood or canine plasma was combined with $CaCl_2$ (10 mM), thrombin (0.03 nM Innovin, MedCorp), and tPA (3.8 nM) over 3 hours.

Murine bleeding models

Two weeks after siPlg administration, mice were anesthetized with 10 to 15% isoflurane. For SVP, mice were placed supine on a heating pad, and inner leg fur was removed. The saphenous vein was visualized under a ×20 magnification stereoscope and isolated from artery, nerve, and connective tissue. After an approximately 5-min rest period, to negate the impact of any venous constriction during isolation, a puncture wound was made using the bevel of a 28-gauge needle. Blood was absorbed into preweighed filter paper, and blood loss was measured from net weight.

Assessment of bleeding after tail tip injuries was performed using TVT as described previously (61). Bleeding was induced 2 weeks after siPlg administration, and blood loss was quantified by measurement of hemoglobin concentrations. Mice were weighed before bleeding challenge.

Thrombin and plasmin generation assays

Thrombin generation was measured by calibrated automated thrombography similar to methods described previously (62). Briefly, 10 μl of bovine serum albumin (BSA, 5 mg/ml) buffer containing silica/phospholipids [1:300 (v/v) final concentration] or 10 μl of thrombin calibrator (α2-macroglobulin-thrombin) was added to 40 μl of diluted canine plasma (1:2 dilution, 20 μl of plasma:40 μl of HEPES buffered saline).

Plasmin generation was measured on the basis of cleavage of a plasmin-specific fluorogenic substrate (63, 64). To trigger plasmin generation, 10 μl of BSA solution (5 mg/ml) containing silica/phospholipids and rtPA (Alteplase) or 10 μl of plasmin calibrator (α2-macroglobulin-plasmin) was added to 40 μl of diluted canine plasma. Final concentrations were as follows: silica/phospholipids (1:300 dilution), rtPA (0.31 μg/ml), $CaCl_2$ (16.6 mM), and fluorogenic substrate (0.5 mM Boc-Glu-Lys-Lys-AMC). Reactions were initiated by adding 10 μl of substrate/calcium solution and monitored every 20 s with a fluorometer (Fluoroskan Ascent, Thrombinoscope) equipped with a 390/460 filter set (excitation/emission) for 2 hours (65).

Statistical analysis

Statistical analyses were performed using GraphPad Prism 8.0.1. All results presented in graphs are the mean ± SEM. *N* indicates the number of biological replicates. Two-tailed unpaired Student's *t* test was used to compare two datasets. Two-way analysis of variance (ANOVA) was used to compare two datasets over time; one-way ANOVA was used to compare multiple datasets with one variable. Welch's ANOVA was used when variance was not equal (Brown-Forsythe); all data were of normal distribution (Shapiro-Wilk). Significance was designated at *P* values <0.05.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data and materials availability:

All data associated with this study are present in the paper or the Supplementary Materials. siRNA-LNPs described in this work are available under a material transfer agreement with the University of British Columbia and Versiti Blood Research Institute.

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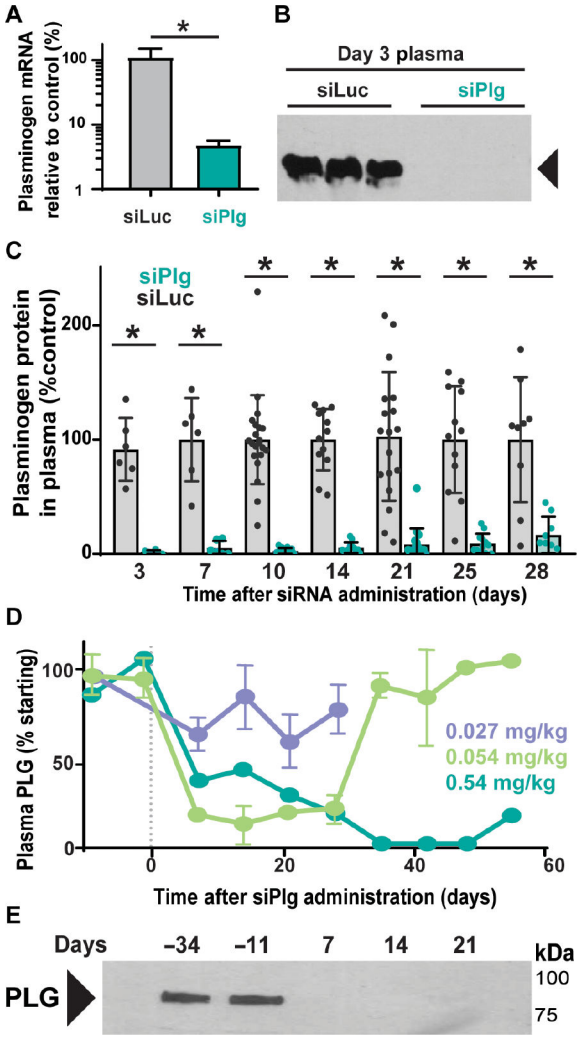

Fig. 1. Plasminogen is depleted for weeks after a single administration of siPlg in mice and dogs.

(**A**) Mice were injected with a single dose of siLuc (gray) or siPlg (teal blue). *Plg* mRNA in liver tissue was measured using qPCR, normalized against the housekeeping gene, *Ppia*. (**B**) Representative Western blot against plasminogen, where each lane contains the plasma from an individual mouse in either treatment group. The triangular marker indicates the expected molecular weight of plasminogen (92 kDa). (**C**) Plasminogen protein in plasma measured in a portion of the mice enrolled at each time point using densitometry, normalized to a loading control, and graphed relative to untreated mice. (**D**) Plasminogen protein in plasma quantified after administration of siPlg to dogs at 0.027 (purple, $n = 3$), 0.054 (green, $n = 2$), or 0.54 (teal blue, $n = 1$) mg siRNA/kg body weight. (**E**) Representative Western blot against plasminogen, where each lane contains plasma collected from a single WT dog at a different time point before or after siPlg administration at 0.054 mg/kg. Data are presented as mean ± SEM and were analyzed by two-tailed unpaired Student's *t* test (A) or by two-way ANOVA (C); $*P < 0.05$.

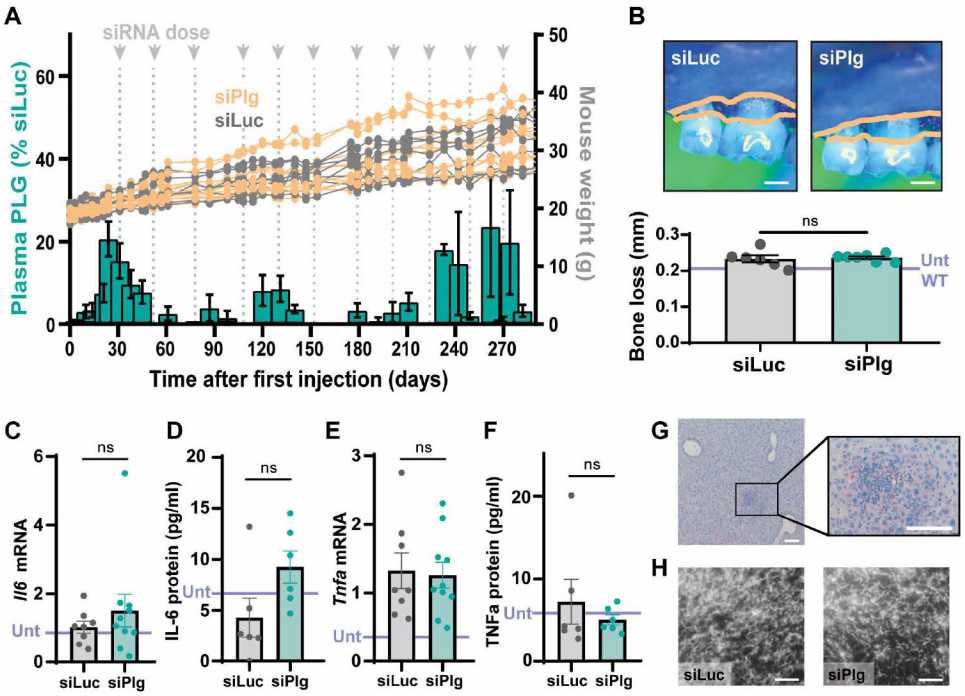

Fig. 2. Long-term knockdown of plasminogen does not lead to pathologies associated with complete plasminogen deficiency.

(**A**) Plasma plasminogen (left *y* axis) quantified during 9 months of repeat administration of siPlg. The weight of mice (right *y* axis) was tracked over this period during administration of siLuc (gray) and siPlg (orange). (**B**) Periodontal bone loss measured by the distance between the cementoenamel junction and the alveolar bone crest (orange lines) in samples stained with methylene blue from mice administered siLuc ($n = 6$) or siPlg ($n = 7$) for 9 months compared to untreated (Unt WT) age-matched WT controls (purple line). Scale bar, 2 mm. (**C** to **F**) Inflammatory markers IL-6 (C and D) and TNF-α (E and F) were measured using qPCR in liver tissue or enzyme-linked immunosorbent assay in plasma from siLuc-treated ($n = 8$) or siPlg-treated ($n = 10$) mice compared to untreated (Unt) controls (purple line). (**G**) Immunohistochemistry against fibrin(ogen) in microscopy images of liver tissue of siPlg-treated mice showed inflammatory infiltrates but no fibrinous lesions. Scale bar, 100 μm. (**H**) Immunohistochemistry against fibrin(ogen) in clots formed ex vivo in whole blood from mice treated with siLuc (left) or siPlg (right). Scale bar, 25 μm. For all graphs, values represent mean ± SEM, ns indicates difference not statistically significant ($P > 0.05$), analyzed by two-tailed unpaired Student's *t* test.

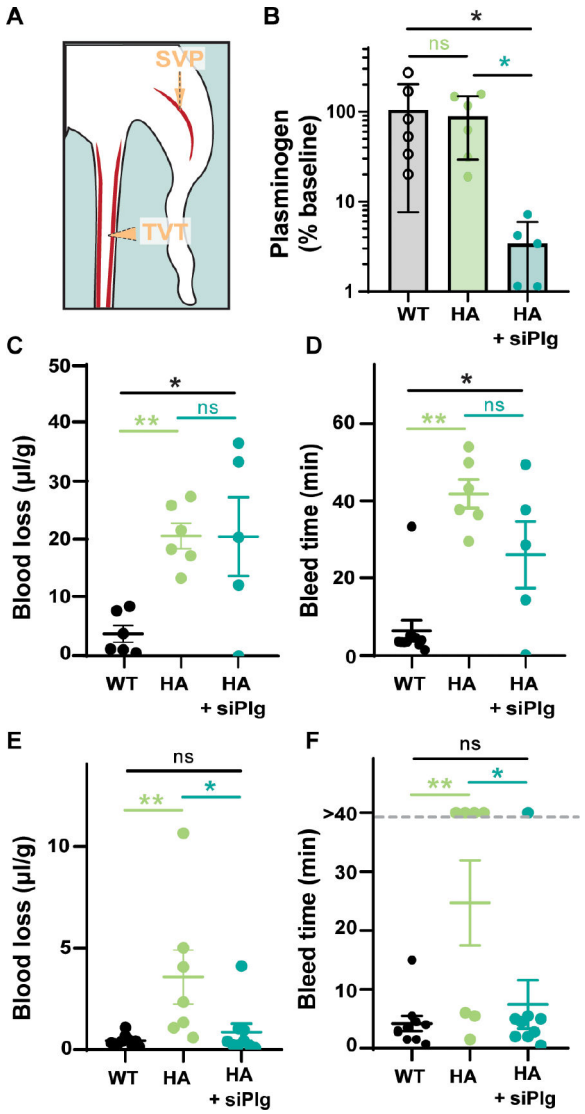

Fig. 3. Plasminogen knockdown enhances hemostasis after SVP but not TVT in a mouse model of HA.

(**A**) Schematic showing SVP and TVT injury models. (**B**) Plasminogen in HA mice at the time of TVT bleed. (**C** and **D**) Blood loss in microliters of blood per gram of body weight (C) and bleeding time (D) after TVT in WT, untreated HA, and treated HA mice ($n = 5$ to 7). (**E** and **F**) Blood loss in microliters of blood per gram of body weight (E) and bleeding time (F) to end of observation period at 40 min (gray dashed line) after SVP ($n = 7$ to 10). Values represent mean ± SEM; *$P < 0.05$, **$P < 0.01$, and ns indicates not significant ($P > 0.05$), analyzed by one-way ANOVA.

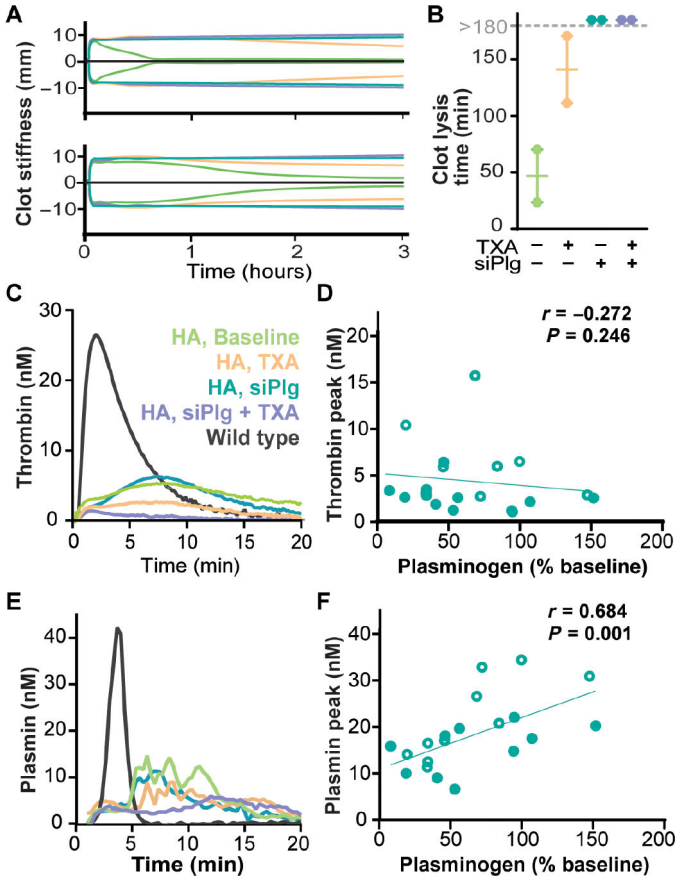

Fig. 4. Plasminogen knockdown stabilizes clots ex vivo in two dogs with HA.

Samples were collected from two HA dogs at baseline (green), within 4 hours of TXA (10 mg/kg iv, orange), within 3 weeks of siPlg administration without TXA (teal), or after administration of both siPlg and TXA (purple). (**A**) Representative TEG curve tracings using plasma from two HA dogs (top and bottom graphs) with added tPA. (**B**) Clot lysis time within 180-min monitoring period, values represent mean, and error bars represent ± SEM. (**C**) Thrombin generation in plasma collected weekly from two HA dogs or pooled plasma from WT dogs (WT, gray). (**D**) Correlation between plasminogen protein in plasma and thrombin generation peak (open and closed markers distinguish the two siPlg-treated dogs). (**E**) Plasmin generation in plasma collected weekly from two HA dogs or pooled plasma from WT dogs. (**F**) Correlation between plasma plasminogen and plasmin generation peak.

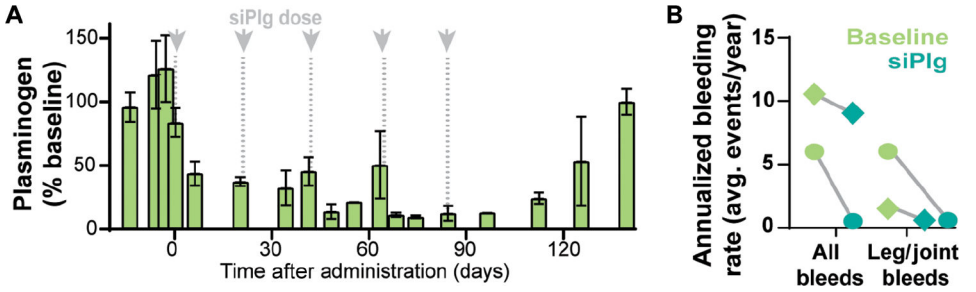

Fig. 5. Plasminogen knockdown decreases bleeding events in two dogs with HA over a 4-month period.

HA dogs were administered five doses of siPlg over 15 weeks. Vertical dashed lines indicate days of an administration. (**A**) Plasminogen in plasma quantified using densitometry of Western blots. Values represent mean ± SEM. (**B**) Annualized bleeding rate extrapolated from 10 months before treatment and the 4-month period of siPlg treatment in two HA dogs (circle and diamond each indicate an individual dog).