Modulation of the Coagulation Cascade Using Aptamers

Rebecca S. Woodruff, Bruce A. Sullenger

Abstract—As a novel class of therapeutics, aptamers, or nucleic acid ligands, have garnered clinical interest because of the ease of isolating a highly specific aptamer against a wide range of targets, their chemical flexibility and synthesis, and their inherent ability to have their function reversed. The following review details the development and molecular mechanisms of aptamers targeting specific proteases in the coagulation cascade. The ability of these anticoagulant aptamers to bind to and inhibit exosite function rather than binding within the active site highlights the importance of exosites in blocking protein function. As both exosite inhibitors and reversible agents, the use of aptamers is a promising strategy for future therapeutics.

Key Words: anticoagulation ■ aptamer ■ coagulation cascade ■ nucleic acids ■ serine endopeptidases

Aptamers are small, single-stranded oligonucleotides whose linear sequences encode specific 3-dimensional structures that allow them to bind to their target proteins or other molecules with high affinity and specificity. By screening large libraries of single-stranded oligonucleotides in a combinatorial chemistry process termed SELEX, or systematic evolution of ligands by exponential enrichment, scientists can identify the oligonucleotide sequence or sequences responsible for binding to various molecules with high affinity.1–3 This technology has been exploited to isolate aptamer sequences to a growing number of proteins, including growth factors, transcription factors, viral proteins and coagulation factors, many of which are currently in clinical trials and which have been reviewed extensively elsewhere.4–6

Crystal structures of aptamers bound to proteins have shown that aptamers fold into a tertiary structure and present an extended conformational surface that is complementary to the surface of its target, thus binding and burying a large surface area (≈1000 Å2) on the protein.7,8 Because of the numerous specific interactions along the extended binding interface, aptamers often bind their targets with high affinity (dissociation constants in the low nanomolar range) and specificity.

Additionally, because a large part of the target protein is concealed by aptamer binding, aptamers tend to act as antagonists by blocking protein–protein interactions rather than inhibiting active site activity.

A unique benefit of aptamers as anticoagulants is their ability to be therapeutically regulated, either by controlling their circulating half-life or reversing their function with an antidote. Unmodified RNA aptamers are rapidly degraded in biological fluids by endogenous endonucleases, leading to extremely short half-lives. Although DNA aptamers are inherently more stable, RNA is thought to be able to adopt more complex conformations, which may allow for different binding patterns and higher affinities to a target protein. To increase stability of RNA aptamers, chemically modified nucleotides are incorporated in the aptamer sequence during the selection process to prevent endonuclease cleavage.9 Highly modified RNA aptamers are even more resistant to nuclease degradation than DNA aptamers in human blood. In addition, other strategies are used to further increase aptamer stability, such as capping the ends of the aptamer to protect it from exonuclease cleavage.10 Both DNA aptamers and modified RNA aptamers are relatively small (8–15 kDa) and are, therefore, rapidly cleared by the renal system.11 To further increase the circulating half-life of an aptamer, bulky, inert moieties, such as polyethylene glycol (PEG), or lipophilic moieties, such as cholesterol, can be conjugated to the 5′ end of an aptamer to increase its molecular weight and, thereby, decrease the renal clearance rate. In this way, the bioavailability of an aptamer can be manipulated depending on its eventual use, with cholesterol conjugation of an aptamer typically increasing the half-life to several hours12 and PEG conjugation extending the half-life to days or even weeks, depending on the mode of administration.6,13

Although the use of an unmodified or rapidly cleared aptamer would require a large amount of compound to produce an effect over a given amount of time, antidote administration to control a long-circulating aptamer formulation allows for the use of lower amounts of active compound. Two types of antidotes have been developed that can rapidly reverse the activity of the aptamer while leaving the target protein intact and functionally available. An oligonucleotide-based antidote recognizes and binds to the primary sequence of the aptamer by Watson–Crick base pairing, resulting in a disrupted aptamer structure that can no longer bind to its target.

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protein. A universal antidote can bind to the backbone of any aptamer in a sequence-independent manner to sequester any aptamer and subsequently reverse its effects. Both types of antidotes would allow clinicians to respond immediately to an urgent clinical need by titrating in the amount of antidote needed. For anticoagulation, this aptamer–antidote system has received significant attention for its ability to control anticoagulation, and therefore bleeding, to the degree required.

Current anticoagulation strategies have been hampered by nonselective agents, agents with narrow therapeutic windows, and agents with no dosing flexibility or the ability to be reversed. The application of the aptamer platform to anticoagulation has the ability to fill this void. Aptamers targeting several members of the coagulation pathway have been developed and progressed into clinical trials, and the first aptamer–antidote system, targeting factor IXa (FIXa), advanced to phase 3 clinical trials. Overall, this system exhibited a rapid and reproducible onset of anticoagulation in a readily measurable manner, with the ability to be predictably controlled with antidote administration. Although this aptamer–antidote system has paved the way for the translation of other aptamer-based antithrombotics, this review will detail the development of several aptamer-based inhibitors against members of the coagulation cascade (Table 1 and Figure).

### Prothrombin/Thrombin Aptamers

Thrombin is the final step in the blood coagulation pathway and mediates many important features of coagulation, including cleaving fibrinogen into fibrin, activating platelets, and amplifying the coagulation cascade. Thrombin has 3 functionally important binding sites: the catalytic active site and 2 anionic binding sites, exosite I and II, which are located on opposite sides of the protein. Pro-exosite I is present on both prothrombin and thrombin and binds to fibrinogen, factor V (FV), factor VIII (FVIII), thrombomodulin, and platelet protease-activated receptor (PAR) receptors. In this way, pro-exosite I mediates fibrinogen cleavage, feedback activation of clotting cofactors, and platelet activation. The other anion-binding site, exosite II, is only present on thrombin and binds to heparin, FV, FVIII, and the platelet receptor GP Ibα. Therefore, exosite II also mediates platelet activation, as well as inhibition by heparin. Thus, inhibitors targeting different sites on thrombin have different modes of action, and combining inhibitors to both exosites can result in a potent inhibition of thrombin activity.

Because of thrombin’s central role in coagulation, this well-characterized protein has been the target for some of the first in vitro aptamer selections. The first aptamer to be isolated to thrombin was also the first aptamer isolated to a non-nucleic acid–binding protein. This aptamer, termed HD1 (also known as ARC183), is an unmodified 15 nucleotide single-stranded DNA aptamer that forms a stable G-quadruplex and binds to pro-exosite I on both prothrombin and thrombin. This aptamer inhibits pro-exosite I functions, including fibrinogen and FV cleavage, and competes with FVa for prothrombin binding, thus inhibiting prothrombinase function. In addition, HD1 blocks platelet PAR interactions with pro-exosite I to inhibit thrombin-mediated platelet activation and aggregation. Unlike heparin, which inhibited only 35% of clot-bound thrombin at clinically relevant doses, HD1 inhibited >80% of clot-bound thrombin in ex vivo studies. Because of its anticoagulant activity in human plasma, this aptamer was explored in several animal models as a cardiopulmonary bypass agent. In cynomolgous monkeys, HD1 has a short half-life (108 seconds) and rapid clearance by the body (2–4 minutes); therefore, a continuous infusion was needed to achieve efficacious anticoagulation as monitored by an increase in a prothrombin time assay. Once administration was halted, coagulation values returned to baseline in ≈10 minutes, abolishing the need for a reversal antidote. Similar studies in canines determined that the aptamer compound was well tolerated and exhibited similar anticoagulant profiles as in monkeys with continual infusion of compound. Although preliminary human studies were commenced, the large quantities of aptamer required for continual administration for anticoagulation resulted in a suboptimal dosing profile, and the human clinical trials were ended. Moreover, the variation in renal function of patients undergoing cardiopulmonary bypass makes dosing and monitoring of such rapidly clearing anticoagulant agents challenging.

Another DNA aptamer, Nu172, was developed by Archemix/Nuvelo to be a more potent, short-acting thrombin aptamer than ARC183. Modeled after ARC183, this 26-nucleotide aptamer produced a dose-dependent increase of clinical coagulation assays during phase I testing in healthy male volunteers. Because this aptamer has a short half-life, after terminating infusion of Nu172, coagulation values quickly returned to baseline without requiring the use of an antidote. HD22 is another thrombin-binding unmodified DNA aptamer that is 29 nucleotides long and also forms a G-quadruplex. This aptamer, however, binds to exosite II on thrombin to inhibit thrombin-mediated activation of platelets and FV/FVIII activation, but has minimal effects on fibrinogen cleavage. A potent DNA aptamer was made by designing a hybrid aptamer joining both HD1 and HD22 with a poly-dA linker. HD1-22 thus binds to both exosites and exhibits tighter binding and more efficacious anticoagulation than either of the 2 aptamers alone.

Although many of the first thrombin aptamers were DNA, several RNA aptamers targeting thrombin have since been developed. Although unmodified DNA has a short half-life in the body, RNA can be modified to be resistant to endonuclease cleavage and greatly increase an aptamer’s plasma stability. A 25-nucleotide 2’-fluoropyrimidine RNA aptamer, Tog25, was selected against thrombin using a toggle SELEX method where the selection was toggled back and forth each round with human and porcine thrombin to promote species cross-reactivity. Tog25 binds to exosite II of thrombin, thus inhibiting thrombin-mediated platelet activation, but having a minimal effect on fibrinogen cleavage. In contrast to the G-quadruplex architecture of the DNA aptamers, Tog25 has a traditional stem-loop structure with an internal bulge. A crystal structure of Tog25 in complex with human thrombin shows that the RNA forms an elaborate 3-dimensional
structure to present an extended molecular surface complementary to the protein. Several key interactions, including an A-Arg zipper, which involves many adenine–arginine stacking interactions, as well as hydrogen bonds and van der Waals interactions, contribute to the intricate folding that allows Tog25 to tightly interact with thrombin. Although Tog25 is not a potent anticoagulant, dual administration with the pro-exosite I-binding DNA aptamer, HD-1, results in synergistic anticoagulation, similar to the bivalent DNA aptamer described earlier. An aptamer, 11F7t, was isolated that binds tightly to FX and allows Tog25 to tightly interact with thrombin. Although this aptamer binds to the same exosite as the aptamer that binds to thrombin was described, R9d14t is 58 bases long with the pro-exosite I–binding DNA aptamer, HD-1, results in synergistic anticoagulation, similar to the bivalent DNA aptamer described earlier.

Recently, another 2′-fluoropyrimidine-modified RNA aptamer that binds to thrombin was described. R9d14t is 58 nucleotides and binds to both prothrombin and thrombin at pro-exosite I, thus inhibiting fibrin clot formation, FV feedback activity, and platelet activation mediated by the PAR receptors. In addition, because the aptamer binds to pro-exosite I on prothrombin, it inhibits thrombin generation by the prothrombinase complex of factor Xa (FXa)/FVa. This aptamer is a dose-dependent, potent inhibitor of coagulation in clinical clotting assays, and an oligonucleotide antidote was developed to rapidly and stably reverse this anticoagulation. Although this aptamer binds to the same exosite as the DNA aptamer HD-1, R9d14t is a more potent inhibitor of thrombin because of its increased stability and higher binding affinity.

**FXa Aptamer**

FXa combines with its cofactor, FVas, on the surface of a platelet to cleave prothrombin to thrombin. Although FXa has some protease activity itself, the formation of the prothrombinase complex yields a marked increase in thrombin generation. Biochemically, 11F7t binds to FXa and competes for binding with FVa. Therefore, in the presence of aptamer, the prothrombinase complex cannot form, resulting in a decreased amount of thrombin able to be produced (Figure B). Albeit it’s potent anticoagulant effect, the aptamer does not affect the ability of FX to bind to a phospholipid membrane surface, bind to its catalytic site activity, or influence substrate binding. In addition, the aptamer 11F7t blocks the ability of FX to be activated by the FVIIIa/FIXa complex, but does not have an effect on FX activation by the FVIIa/tissue factor (TF) complex. On the other hand, the aptamer blocks tissue factor pathway inhibitor (TFPI) from inhibiting FXa. Thus, the aptamer biochemically exhibits both procoagulant and anticoagulant effects, and this emphasizes the importance of the net effect of the interactions with which the aptamer interferes to exhibit its anticoagulant effect.

**Factor VII Aptamer**

The principal activator of the extrinsic pathway, and also the major activator in vivo, is the TF/factor VIIa (FVIIa) complex. On TF exposure, FVIIa binds to TF, allowing FVIIa to then cleave FIX and FX to their active proteases and thus initiate thrombin generation at the site of injury. An inhibitor against FVIIa would therefore shut down the initiation of thrombin generation. A 2′-aminopyrimidine RNA aptamer, termed 16.3, was generated that binds to FVII/FVIIa with a dissociation constant of 10 nM. This aptamer inhibits the TF/FVIIa-mediated activation of FX, at least in part by preventing this complex to form. In a prothrombin time assay, this aptamer could dose-dependently prolong the clotting time. Unfortunately, the folding of aptamer 16.3 is temperature-sensitive and, at 37°C, has decreased binding affinity for FVIIa. Therefore, this aptamer was not further developed clinically. Subsequently, FVII-binding aptamers were isolated using a convergent SELEX approach, where 5 rounds of selection against the GLA (γ-carboxyglutamic acid) proteome was performed followed by 2 rounds of selection against purified FVII. Two 2′-fluoropyrimidine

### Table 1. Characteristics of Aptamers Targeting the Coagulation Cascade

<table>
<thead>
<tr>
<th>Name</th>
<th>Target</th>
<th>Oligonucleotide</th>
<th>Binding Affinity</th>
<th>Mechanism of Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC183/HD1</td>
<td>FIIa</td>
<td>DNA</td>
<td>7.1 nM</td>
<td>Inhibits pro-exosite I</td>
</tr>
<tr>
<td>HD22</td>
<td>FIIa</td>
<td>DNA</td>
<td>2.4 nM</td>
<td>Inhibits exosite II</td>
</tr>
<tr>
<td>HD1-22</td>
<td>FIIa</td>
<td>DNA</td>
<td>0.65 nM</td>
<td>Inhibits pro-exosite I and exosite II</td>
</tr>
<tr>
<td>Tog25</td>
<td>FII</td>
<td>RNA</td>
<td>3 nM</td>
<td>Inhibits exosite II</td>
</tr>
<tr>
<td>R9d14t</td>
<td>FXa/FII</td>
<td>RNA</td>
<td>10 nM/1 nM</td>
<td>Blocks FXa/FVa assembly</td>
</tr>
<tr>
<td>11F7t</td>
<td>FXa</td>
<td>RNA</td>
<td>1.1 nM</td>
<td>Inhibits pro-exosite I</td>
</tr>
<tr>
<td>16.3</td>
<td>FVIIa</td>
<td>RNA</td>
<td>11.3 nM</td>
<td>Inhibits TF/FVIIa assembly</td>
</tr>
<tr>
<td>7S-1/7S-2</td>
<td>FVII</td>
<td>RNA</td>
<td>65.7 nM/59.2 nM</td>
<td>Unknown</td>
</tr>
<tr>
<td>9.3t</td>
<td>FXa</td>
<td>RNA</td>
<td>0.58 nM</td>
<td>Inhibits FXa-mediated activation of FX without affecting FIXa/FVIIa complex assembly</td>
</tr>
<tr>
<td>R4cXII-1</td>
<td>FXII/FXIIa</td>
<td>RNA</td>
<td>8.9 nM/0.5 nM</td>
<td>Inhibits autoactivation of FXII- and FXIIa-mediated activation of FX</td>
</tr>
</tbody>
</table>

FII indicates factor II; FVII, factor VII; FIX, factor IX; FX, factor X; and FXII, factor XII.
RNA aptamers were identified that bound to FVII at 37°C with similar dissociation constants of ≈60 nM, but differed in their anticoagulant potency in a prothrombin time assay. 23

**FIXa Aptamer**

Although a member of the intrinsic pathway, FIX can be activated by both FXIa and the TF/FVIIa complex and is thus involved in both pathways. FIXa then forms a complex with its cofactor, FVIIIa, to activate a large amount of FX on the platelet surface, leading to stable fibrin clot formation. A 35-nucleotide, 2′-fluoropyrimidine-modified RNA aptamer termed 9.3t was isolated that binds to both FIX and FIXa. Biochemical studies indicate that 9.3t blocks an extended substrate-binding site so as to inhibit FIX-mediated activation of FX, but it does not inhibit FVIIa/FIXa complex formation (Figure C).24 Saturating doses of this aptamer can inhibit >99% of FIXa activity and results in prolonged in vitro plasma clotting times. In addition, several short 2′-O-methyl–modified RNA antidote oligonucleotides complementary to different portions of the aptamer sequence were identified that could bind to the FIXa aptamer and rapidly reverse all aptamer activity.14 The most potent of these antidotes was able to reverse anticoagulation within 10 minutes in human plasma, and this effect was stable over 5 hours.14

The FIXa-binding aptamer was also effective in several animal models. In a murine ferric chloride injury model, a cholesterol-modified version of 9.3t protected mice from occlusive thrombus formation.12 Additionally, administration of the aptamer–antidote pair in swine exhibited reproducible anticoagulation and subsequent reversal, with the antidote neutralizing >95% of anticoagulant effects within 10 minutes.12 Use of the aptamer–antidote system in a 1-hour, neonatal porcine cardiopulmonary bypass surgery model was as effective as using heparin and protamine for reversible anticoagulation.41 Overall, these preclinical studies established the FIXa aptamer–antidote pair to be a predictable and non-toxic reversible anticoagulation system, and the 2 compounds (aptamer and antidote) were optimized for clinical studies as the REG1 Anticoagulation System (Regado Biosciences, Durham, NC).37

Phase I clinical studies established REG1 as a safe, effective, and reproducible anticoagulation system in healthy patients or patients with stable coronary artery disease on antiplatelet therapy (Table 2).13,16,51 Bolus or weight-adjusted administration of RB006, the optimized version of the FIXa aptamer 9.3t conjugated to a 40-kDa PEG carrier, resulted in a dose-dependent increase in clinical clotting assays over a 24-hour period.13 Subsequent administration of RB007, the 2′-O-methyl–modified 15-nucleotide RNA antidote, led to reversal of anticoagulant activity within 1 to 2 minutes in both patient populations.16 No rebound anticoagulation was seen over 72 hours, indicating that the aptamer–antidote complex was stable with irreversible binding of aptamer to antidote. Although clearance of the free RB006 aptamer involves mainly intravascular and some renal mechanisms, clearance of the antidote RB007, which is not formulated with a PEG, is achieved by rapid renal filtration, allowing for the readministration of aptamer with immediate restoration of anticoagulant effects.16 Across these phase I studies, no major bleeding events or serious adverse side effects were seen with REG1 use. Importantly, drug reversal could be closely controlled by titrating in antidote as needed to either fully or partially neutralize the anticoagulant effects of the aptamer to the necessary degree intended.51 These initial studies were highly significant because they were the first reported clinical studies on any aptamer administered systemically.

Because of the success of the phase I studies, REG1 was next compared with unfractionated heparin as the anticoagulant for elective percutaneous coronary intervention (PCI)
in patients with stable coronary artery disease in the phase 2a pilot study REVERSAL-PCI (NCT00715455; Table 2).17 Patients received the antiplatelet drugs aspirin and clopidogrel, as well as an appropriate dose of the aptamer RB006, to inhibit >99% of FIXa activity. Anticoagulation could be predictably controlled with either full or partial aptamer reversal with the antidote RB007, and overall, the REG1 system exhibited low patient-to-patient variability with stable anticoagulation and reversal.17 A larger phase 2b study termed RADAR (a randomized, partially blinded, multicenter, active-controlled, dose-ranging study assessing the safety, efficacy, and pharmacodynamics of the REG1 anticoagulation system in patients with acute coronary syndrome; NCT00932100) was designed to assess the degree of reversal required to prevent thrombosis and control bleeding in planned cardiac catheterization.42 A total of 640 patients with acute coronary syndrome were randomly assigned to one of 4 REG1 treatment arms, all receiving a weight-adjusted dose of the FIX aptamer RB006 (now termed pegnivacogin) with 4 increasing levels of antidote RB007 (now termed anivamersen) to achieve 25% to 100% reversal.43 Overall, the REG1 system effectively anticoagulated patients undergoing invasive cardiac procedures while preventing thrombotic and bleeding events in patients receiving at least 50% reversal. Moreover, a trend toward reduced ischemic events and bleeding was observed in patients receiving REG1.44 Although the incidence of adverse events was similar with REG1 and heparin, enrollment in RADAR was halted after 3 allergic events, albeit with sufficient clinical data from a total of 640 patients enrolled.43 Despite the 3 adverse events, a phase 3, 13,000 patient clinical trial, REGULATE-PCI, was initiated to test the REG1 system compared in PCI compared with bivalirudin (a study to determine the efficacy and safety of the trial’s data and safety monitoring board, purportedly concerning rare, severe allergic reactions, although data from the trial has yet to be published (Regado Biosciences, Inc, now Tobira Therapeutics). It has not been reported to date the frequency or what elicited such allergic reactions, but because the event occurred before antidote administration, it has been speculated that the allergic reactions must be because of recognition of either the aptamer or PEG portion (the high molecular weight modification that was appended to the end of the

<table>
<thead>
<tr>
<th>Aptamer (Sponsor), Target</th>
<th>Condition</th>
<th>Trial Phase</th>
<th>ClinicalTrials.gov Identifier and References</th>
</tr>
</thead>
<tbody>
<tr>
<td>NU172 (ARCA Biopharma, Inc.), Thrombin</td>
<td>Heart disease</td>
<td>Phase 2 (REVERSAL-PCI)</td>
<td>Recruitment Status Unknown (June 2011) NCT00808964</td>
</tr>
<tr>
<td>REG1 (Regado Biosciences, Inc.), FIX/FIXa aptamer/antidote system</td>
<td>Healthy</td>
<td>Phase 1 Completed (Oct 2005)</td>
<td>NCT00113997</td>
</tr>
<tr>
<td></td>
<td>Coronary artery disease</td>
<td>Phase 2 (REVERSAL-PCI) Completed (Oct 2008)</td>
<td>NCT00715455</td>
</tr>
<tr>
<td></td>
<td>Acute coronary syndrome</td>
<td>Phase 2 (RADAR) Completed (Jan 2011)</td>
<td>NCT00932100</td>
</tr>
<tr>
<td></td>
<td>Coronary artery disease</td>
<td>Phase 3 (REGULATE-PCI) Terminated (Oct 2014)</td>
<td>NCT01848106</td>
</tr>
<tr>
<td>REG2 (Regado Biosciences, Inc.), FIX/FIXa aptamer/antidote system</td>
<td>Healthy (subcutaneous delivery)</td>
<td>Phase 1 Completed (Dec 2009)</td>
<td>NCT01872572</td>
</tr>
<tr>
<td>ARC1779 (Archemix Corp.), Von Willebrand Factor</td>
<td>Thrombosis</td>
<td>Phase 1 Completed (March 2007)</td>
<td>NCT00432770</td>
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<tr>
<td></td>
<td>TTP, WVD-Type 2B</td>
<td>Phase 2 Completed (Dec 2008)</td>
<td>NCT00632242</td>
</tr>
<tr>
<td></td>
<td>Acute myocardial infarction</td>
<td>Phase 2 Terminated (Jan 2009)</td>
<td>NCT00507338</td>
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<tr>
<td></td>
<td>VWD</td>
<td>Phase 2 Withdrawn (Aug 2009)</td>
<td>NCT00694785</td>
</tr>
<tr>
<td></td>
<td>Thrombotic microangiopathy, TTP</td>
<td>Phase 2 Terminated (Nov 2009)</td>
<td>NCT00726544</td>
</tr>
<tr>
<td></td>
<td>Intracranial embolism, cerebral thromboembolism, carotid stenosis</td>
<td>Phase 2 Terminated (Jan 2010)</td>
<td>NCT00742612</td>
</tr>
<tr>
<td>ARC19499 (Baxalta US Inc.), TFPI</td>
<td>Hemophilia</td>
<td>Phase 1 Terminated (Dec 2011)</td>
<td>NCT01191372</td>
</tr>
</tbody>
</table>

Data from www.clinicaltrials.gov. FIX indicates factor IX; RADAR, A Study Assessing the REG1 Anticoagulation System Compared Heparin in Subjects With Acute Coronary Syndrome; REGULATE PCI, A Randomized, Open-Label, Multi-Center, Active-Controlled, Parallel Group Study To Determine the Efficacy and Safety of the REG1 Anticoagulation System Compared to Bivalirudin in Patients Undergoing Percutaneous Coronary Intervention; REVERSAL-PCI, Phase 2a, Multi-Center, Open Label, Randomized, Feasibility/Safety Study Comparing REG1 Anticoagulation System With Unfractionated Heparin in Subjects Undergoing Elective PCI After Pretreatment With Clopidogrel and Aspirin; TFPI, tissue factor pathway inhibitor; TTP, thrombotic thrombocytopenic purpura; and VWD, von Willebrand Disease.
aptamer to increase circulating half-life) of pegnivacogin. To this end, no immune reactions or complement activation because of any aptamer administration have been reported in preclinical or clinical trials. However, antibodies to PEG have been detected both in animal studies and in humans. In addition, there is some evidence that PEGylated compounds can induce complement activation, leading to hypersensitivity reactions and anaphylactic shock, although the mechanism involved is not determined. It is not clear whether a response to PEG or preexisting PEG antibodies could have caused the adverse reactions seen in the clinical trials, and we await the publication of the REGULATE-PCI data to shed light on this question. Overall, REG1 is the first aptamer–antidote pair to be tested in humans, and aside from rare, adverse reactions in later clinical trials, this system has been shown to be a successful anticoagulant strategy with extreme and rapid control over drug activity in many hundreds of patients. Although the REG1 system was administered intravenously in these studies, a phase I clinical trial of a subcutaneous administration of the system (termed REG2) was able to increase the duration of anticoagulation to a half-life of 6 days (Table 2). Subsequent antidote administration successfully reversed anticoagulation, but did not inhibit further absorption of aptamer into the bloodstream. No adverse reactions were reported during the trial. As the first subcutaneously administered aptamer, it is unclear whether this mode of administration will affect the adverse reactions seen during intravenous application in the REGULATE-PCI trial, but could offer an additional strategy for long-term anticoagulation.

Factor XII Aptamer
Factor XII (FXII) is the initiating member of the contact pathway and is activated when exposed to a negatively charged surface, including substances such as collagen, extracellular nucleic acids, or polyphosphates, that are present in the bloodstream at the site of a growing thrombus. Once activated, FXIIa then cleaves FXI to initiate the coagulation cascade, leading to thrombin generation and fibrin clot formation. FXIIa also activates kallikrein, leading to bradykinin-induced proinflammatory signaling. Activation of the contact pathway has been implicated in thrombus formation either on the surface of a foreign material, such as a catheter, or during inflammatory events, such as plaque rupture in atherosclerosis. However, members of the contact pathway are not considered essential in hemostasis because patients deficient in FXII or kallikrein do not present with a bleeding phenotype, and some patients deficient in FXI may have a mild hemophilia. Inhibition or deficiency of FXII has been effective at limiting thrombosis without interrupting hemostasis in several animal models. Recently, a 2′-fluoropyrimidine-modified RNA aptamer inhibitor of FXII has been isolated. This aptamer, R4cXII-1, binds to both FXII and FXIIa, but has no effect on active site activity. Although the aptamer itself does not induce the activation of FXII, it does block the ability of other negatively charged reagents, such as kaolin or ellagic acid, from activating FXII. In addition, R4cXII-1 blocks the ability of FXII to activate FXI to decrease thrombin generation and thus increase the clotting time in plasma-based assays activated through the intrinsic pathway. This aptamer, however, is specific for inhibition of the coagulation cascade because it does not block the ability of FXIIa to activate kallikrein.

Other Aptamers Targeting Coagulation Proteins
Although this review focuses on aptamers targeting the proteases of the coagulation cascade, several aptamers have been identified against other proteins involved in other aspects of coagulation, such as anticoagulant proteins, platelet receptors, and von Willebrand factor (VWF), that will be briefly mentioned. A panel of single-stranded DNA aptamers was isolated to the anticoagulant protein activated protein C (APC), and these aptamers bind to the main exosite on APC to inhibit cleavage of FVa and FVIIa and, thus, inhibit anticoagulant function. In addition, an aptamer targeting TFPI was developed to treat hemophilia, and this aptamer, ARC19499, interacts with multiple domains on the protein to inhibit its function both in vitro and in vivo. Because of its efficacy as a procoagulant, this aptamer was tested in a phase I clinical trial in hemophilia patients (Table 2). However, the study was prematurely terminated because of increased bleeding events. Mechanistically, this side effect was reported to be because of several reasons, namely that aptamer binding decreased TFPI clearance and thus increased its circulatory half-life, leading to an actual increase in the amount of TFPI and resulting in the increased anticoagulant activity seen in patients. Aptamers have also been developed as antiprotein agents, with an aptamer–antidote system preliminarily described against the collagen platelet receptor glycoprotein VI. Additionally, several aptamers targeting VWF have been developed, and the aptamer ARC1779 advanced in clinical trials for acute coronary syndromes, von Willebrand disease, and thrombotic thrombocytopenic purpura, among other indications (Table 2). The development, mechanisms, and clinical trials of the VWF aptamer aptamer have been reviewed extensively elsewhere and we refer the reader to the cited literature for additional discussion on these aptamers.

Conclusions
As shown in Table 1 and Figure A, anticoagulant aptamers have now been generated against most of the coagulation proteases. These aptamers have been shown to be selective, bind tightly to their target proteins, and act as anticoagulants by interfering with the protein–protein interactions that are central to the coagulation cascade. Thus, aptamers may prove to be valuable tools and analytic reagents for identifying and defining functionally important regions of the coagulation factors. In this regard, aptamers have several advantages over antibodies, including being chemically synthesizable with minimal batch-to-batch variability, having an unlimited shelf life and able to withstand temperature insult, using a relatively quick in vitro system for their isolation, being able to be manipulated with ease, and exhibiting...
binding affinities comparable to antibodies. Unfortunately, to date, the only crystal structures reported in the coagulation field are for aptamers bound to thrombin and VWF, and aptamers as a whole have yet to be universally adopted as reagents. To this end, additional structural and biochemical information is greatly needed to further elucidate the mechanisms aptamers use to bind their target proteins, and this information could yield insight into exosite functions for the entire coagulation system.

As therapeutics, aptamers have received significant attention as rapid onset anticoagulants, with aptamers to thrombin, FIX/FIXa, and VWF evaluated in clinical studies (Table 2). Overall, coagulation aptamers make up 4 out of the 10 aptamers assessed in clinical trials to date. Although the disease states of these other aptamers range from cancer to diabetes mellitus, one aptamer, Macugen (pegaptanib), targeting vascular endothelial growth factor, has been approved for use in age-related macular degeneration since 2004, and another aptamer, Fovista (E10030), targeting platelet-derived growth factor, is rapidly progressing through definitive phase 3 studies for the same indication (NCT01944839). The majority of the other clinically tested aptamers are in phase 2 or awaiting phase 3 clinical trials, highlighting that the field has increasingly excelled at overcoming challenges inherent in defining a new class of drugs. The recent results from the clinical studies of anticoagulant aptamers are encouraging from the perspective of defining a novel class of rapidly reversible anticoagulant agents. Although gains have been made, the recent issues with the unexpected effects of the TFPI aptamer, as well as the rare allergic responses to the FIX/FIXa aptamer pegnivacogin, highlight the need for continued effort, so that additional translation of these promising agents can proceed.

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Disclosures

B.A. Sullenger is a scientific founder of Regado Biosciences, Inc. The other author reports no conflicts.

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Aptamers are a novel, emerging class of therapeutics that distinguish themselves from other classes of drugs for several reasons: their ability to specifically target a wide range of proteins, their ease of isolation, their chemical flexibility and synthesis, and their inherent ability to have their activities reversed with an antidote. This latter property lends itself well to anticoagulation because maintaining a balance between bleeding and thrombosis is critical for patient care. Aptamers have been developed that target many proteases of the coagulation cascade, and studies into the mechanisms of aptamer inhibition determine that this class of drugs mainly mediates anticoagulation by binding to exosites and inhibiting protein–protein interactions. Although these aptamers have been used to probe protein function, several of these anticoagulant aptamers have also been tested in clinical trials.
Modulation of the Coagulation Cascade Using Aptamers
Rebecca S. Woodruff and Bruce A. Sullenger

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