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Reversible Thrombocytopenia of Functional Platelets after Nose-Horned Viper Envenomation Is Induced by a Snaclec

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Abstract

Profound and transient thrombocytopenia of functional platelets without bleeding was observed in patients envenomed by *Vipera a. ammodytes* (*Vaa*). This condition was rapidly reversed by administration of F(ab)$_2$ fragments of immunoglobulin G targeting the whole venom, leaving platelets fully functional. To investigate the potential role of snake venom C-type lectin-like proteins (snaclecs) in this process, *Vaa*-snaclecs were isolated from the crude venom using different liquid chromatographies. The purity of the isolated proteins was confirmed by Edman sequencing and mass spectrometry. The antithrombotic effect was investigated by platelet agglutination and aggregation assays and blood coagulation tests. Using flow cytometry, the platelet activation and binding of *Vaa*-snaclecs to various platelet receptors was analyzed. Antithrombotic efficacy was tested in vivo using a mouse model of vascular injury. Two *Vaa*-snaclecs were purified from the venom. One of them, *Vaa*-snaclec-3/2, inhibited ristocetin-induced platelet agglutination. It is a covalent heterodimer of *Vaa*-snaclec-3 (α-subunit) and *Vaa*-snaclec-2 (β-subunit). Our results suggest that *Vaa*-snaclec-3/2 induces platelet agglutination and consequently thrombocytopenia by binding to the platelet receptor glycoprotein Ib. Essentially, no platelet activation was observed in this process. In vivo, *Vaa*-snaclec-3/2 was able to protect the mouse from ferric chloride-induced carotid artery thrombosis, revealing its applicative potential in interventional angiology and cardiology.

Keywords
- snake venom
- reversible thrombocytopenia
- snaclecs
- arterial occlusion
- mice
- interventional cardiology
- antithrombotic

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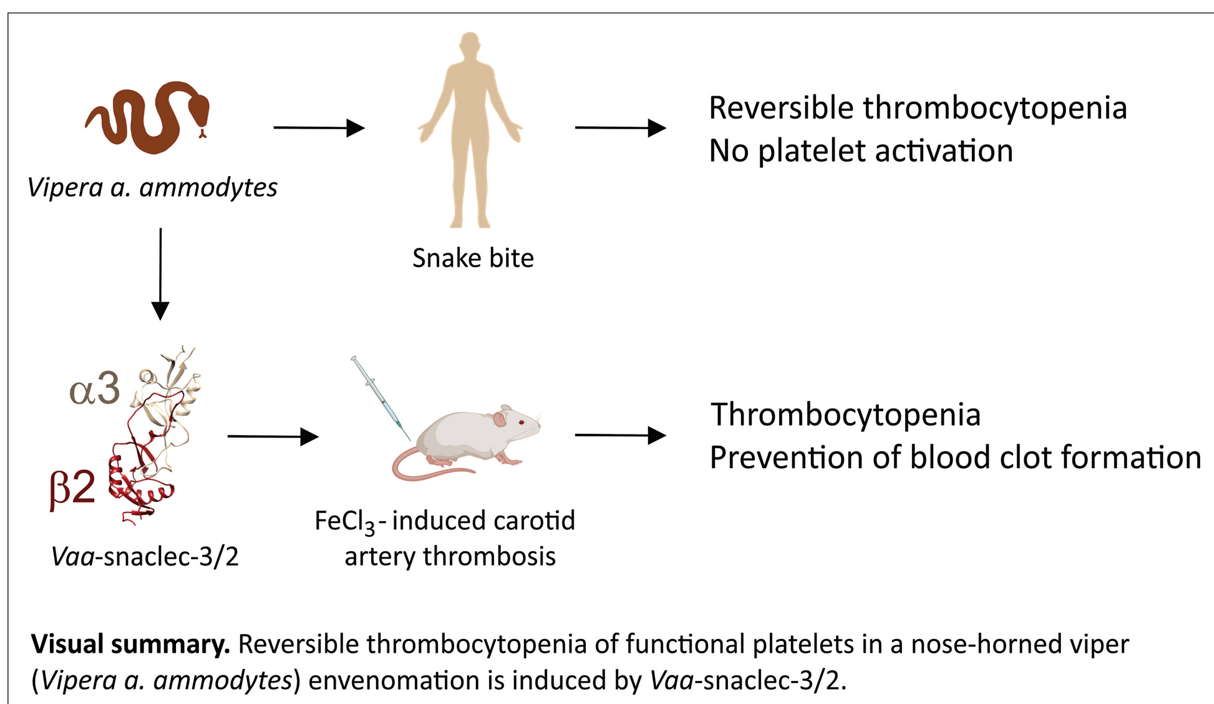

Visual summary. Reversible thrombocytopenia of functional platelets in a nose-horned viper (*Vipera a. ammodytes*) envenomation is induced by *Vaa*-snaclec-3/2.

Introduction

In Slovenia, *Vipera b. berus* (*Vbb*) and *Vipera a. ammodytes* (*Vaa*) are the only medically important venomous snakes. Profound and transient thrombocytopenia without bleeding was observed in patients envenomed by *Vaa*.[1–3] Moreover, the thrombocytopenia caused by *Vaa* venom was rapidly reversed within 1 hour by the administration of $F(ab)_2$ fragments of immunoglobulin G (IgGs) prepared against the whole viper venom.[4] However, the most intriguing observation in patients with thrombocytopenia due to *Vaa* venom was that their platelet function was not impaired. Thromboelastometry and aggregometry analyses that provide information on the overall kinetics of hemostasis (clot formation and clot stability) displayed values in the normal range after reversal of the severe thrombocytopenia induced by *Vaa* venom.[4] Moreover, despite thrombocytopenia with a fivefold reduction in platelet count compared with normal, only one percent of the platelets expressed P-selectin, a marker of platelet activation, on their surface, both during thrombocytopenia and after its reversal by $F(ab)_2$ fragments.[4] It is therefore evident that *Vaa* venom contains component(s) that can temporarily reduce the number of platelets without affecting their function. The complete reversal of thrombocytopenia by administration of the antivenom produced against the whole *Vaa* venom, but not by that against the *Vbb* venom, indicated that the effective component was predominantly present in the *Vaa* venom.[3] According to the proteomic studies, the main difference in the composition of the *Vaa* and *Vbb* venoms lies in their content of the snake venom C-type lectin-like proteins (snaclecs). The low amount of snaclecs in the *Vbb* venom compared with almost one-fifth of the total protein content in the *Vaa* venom led us to propose that *Vaa*-snaclecs are the venom components responsible for the thrombocytopenia. Our hypothesis was also supported by the fact that snaclecs from some other snake venoms were known to cause platelet agglutination.[5–7] Thrombocytopenia due to platelet aggregation was considered less likely, as aggregation requires platelet activation, which was not observed in the case of *Vaa* envenomation.[4] Snaclecs are dimers of two different C-type lectin-like subunits.[2,8,9] The heterodimers are formed by the so-called “index finger” loop-swapping and stabilized by a highly conserved interchain disulphide bridge.[5] The complete amino acid sequence of nine distinct *Vaa*-snaclec subunits, five α and four β, has been determined so far.[8] The main aim of this work was to purify and characterize the *Vaa*-snaclecs, first to confirm their role in reversible thrombocytopenia of functional platelets and second to decipher their mode of interaction with platelets.

Reversible thrombocytopenia of functional platelets could be beneficial as it hinders and delays the formation of occlusive thrombi. In an animal model, a reduction in platelet count below 10% of normal was highly protective for occlusive thrombus formation, and even a severe reduction in platelet count to 2.5% of normal did not lead to spontaneous bleeding.[10] It therefore appears that profound thrombocytopenia with a functional platelet count between 2.5 and 10% can provide protection against occlusive thrombi without increasing the risk of bleeding. To evaluate the medical potential of the thrombocytopenic component of the *Vaa* venom, we tested its antithrombotic efficacy in a mouse model of vascular injury.

Materials and Methods

Isolation of *Vaa*-snaclecs from Crude *Vaa* Venom

One gram of crude *Vaa* venom (Institute of Immunology, Zagreb, Croatia) was separated by gel filtration.[11] The B2

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fraction was further separated by cation-exchange chromatography on a SP Sepharose Fast Flow column (GE Healthcare Life-Science, Sweden) in 20 mM MES buffer, 2 mM $CaCl_2$, pH 6 (buffer A). The bound proteins were eluted by a linear NaCl gradient from 0 to 0.5 M in buffer A. This was followed by two consecutive anion-exchange chromatographies on a Q Sepharose Fast Flow column. The first was performed in 20 mM Bis/Tris buffer, 2 mM $CaCl_2$, pH 6 (buffer B) and bound proteins were eluted by a linear NaCl gradient from 0 to 0.2 M in buffer B. The second was performed in 20 mM Bis/Tris buffer, 2 mM $CaCl_2$, 30 mM NaCl, pH 5.5. The unbound fraction contained *Vaa*-snaclec-3/2.

Purity Control and Identification of *Vaa*-snaclec-3/2

The purity of the isolated *Vaa*-snaclec-3/2 was confirmed by reversed-phase high-performance liquid chromatography (RP-HPLC) analysis on a C18 column (BIOshell A400 Protein C18 Column 15 cm × 4.6 mm, 3.4 µm particle size; BIOshell Teoranta, Carrowteige, Ballina, Ireland) in solvent A (0.1% (v/v) trifluoroacetic acid [TFA] in water). The column was eluted with a linear gradient of solvent B (90% (v/v) acetonitrile and 0.1% (v/v) TFA) at 0.8 mL/min: 0–30% (v/v) B in 5 minutes, 30–75% (v/v) B in 15 minutes, and 75–100% (v/v) B in 5 minutes.

N-terminal sequencing and mass spectrometry (MS) analysis were used to identify the HPLC-purified protein.[8] The reduced and alkylated *Vaa*-snaclec-3/2 was digested with trypsin and the resulting peptides were analyzed by MS.[12]

Gel Electrophoresis

Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) of *Vaa*-snaclec-3/2 was performed under reducing and nonreducing conditions on 12.5% (m/v) polyacrylamide gels.[13] Isoelectric focusing was performed using a Phast System (Amersham Pharmacia Biotech, Uppsala, Sweden).[14]

Platelet Agglutination and Aggregation Assays

The effects of the venom fractions (5 µg of total protein) obtained by gel filtration and the purified *Vaa*-snaclecs were investigated on ristocetin-induced agglutination, and collagen-, ADP- and arachidonic acid-induced aggregation of human platelets, using turbidimetric assay as previously described.[15] Final concentrations of ristocetin, collagen, ADP, and arachidonic acid used were 1.25 mg/mL, 3 µg/mL, 2 µM, and 1 mM, respectively. The platelet count of the citrated blood-derived platelet-rich plasma (PRP) was 267×10^9/L, and *Vaa*-snaclec-3/2 was tested at concentrations up to 300 nM. Control values were determined in the absence of *Vaa*-snaclec-3/2 (buffer only) and interpreted as 100% change in the optical density of the assay solution. The data are expressed relative to the control values and are means ± SEM (standard error of the mean) of at least three measurements. One-way analysis of variance was used to detect differences.

Blood Coagulation Assays

Prothrombin time (PT), activated partial thromboplastin time (aPTT), and thrombin time (TT) were measured in human pooled plasma ("Pool Norm" from Diagnostica Stago, Asnieres, France) exposed to 1 µM *Vaa*-snaclec-3/2, essentially as described.[9] The HemosIL reagents (Instrumentation Laboratory, Bedford, Massachusetts, United States), i.e., ReadiPlasTin and SynthASil, were used for PT and aPTT measurements, respectively. The effect of *Vaa*-snaclec-3/2 was assessed using a BCT system (Dade Behring, Marburg, Germany). Results are expressed as a mean ± SEM of duplicate determinations of a relative shift from the control value in %.

Platelet Receptor Binding Assays

Binding of *Vaa*-snaclec-3/2 to platelet receptors (glycoprotein [GP] Ib, GPIIb, GPIIIa, GPIX, GPVI) was tested by flow cytometry (Navios, Beckman Coulter, Brea, California, United States) as previously described.[14] In short, PRP was obtained and the platelet count was adjusted to 15×10^9/L by adding phosphate-buffered saline. *Vaa*-snaclec-3/2 or buffer (negative control) was added to 20 µL of the platelet suspension and incubated for 10 minutes. Subsequently, 5 µL of a corresponding platelet receptor antibody was added and incubated for 25 minutes in the dark at room temperature. Fluorescein-5-isothiocyanate (FITC)-conjugated antibody against CD42b (GPIb, clone SZ2), CD41 (GPIIb, clone P2), CD42a (GPIX, clone SZ1) or CD62P (P-selectin, clone CLB-Throm/6) (Immunotech, Beckman Coulter, Marseille, France), or phycoerythrin (PE)-conjugated antibody against CD61 (GPIIIa, clone SZ21) (Immunotech, Beckman Coulter, Marseille, France) or GPVI (clone HY101) (Becton Dickinson, Franklin Lakes, New Jersey, United States) were added. Before measurement, we added 500 µL of phosphate-buffered saline to each sample. The effect of *Vaa*-snaclec-3/2 was evaluated by comparing the mean fluorescence intensity (MFI) of the control sample with the MFI of the *Vaa*-snaclec-3/2-containing sample. The fluorescence intensity threshold was set using appropriate isotype controls (FITC or PE-conjugated mouse IgG isotype controls).

We tested the following concentrations of *Vaa*-snaclec-3/2 on the platelet receptor GPIb: 0.16, 1.6, 16, 160, 320, 500, 600, 700, 800, 1,000, 1,300, 1,600, and 2,000 nM. The expression of P-selectin (CD62P) was analyzed on the platelet surface after exposure to *Vaa*-snaclec-3/2 at 1 µM concentration.

Microscopic Analysis of the Platelets

Whole blood was collected into the EDTA-containing tubes and incubated with buffer (control) or *Vaa*-snaclec-3/2 (1 µM) for 30 minutes at room temperature. After incubation, the smears were prepared and stained with May-Grünwald Giemsa (Merck, Darmstadt, Germany). Platelets were examined under an optical microscope (Nikon Eclipse Ci-L plus, Tokyo, Japan).

Antithrombotic Evaluation in a Mouse Carotid Artery Thrombosis In Vivo Model

The effect of *Vaa*-snaclec-3/2 was tested in a mouse model of ferric chloride ($FeCl_3$)-induced carotid artery thrombosis. Young adult male Balb/C mice, 12 to 24 weeks of age, obtained from Envigo (Italy), were acclimatized for 14 days in the animal breeding facility of the Veterinary Faculty, University of Ljubljana. All experiments were conducted according to the ethical standards and were approved by the

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Administration of the Republic of Slovenia for Food Safety, Veterinary Sector and Plant Protection (permit no. U34401–9/2021/4). Animals were anesthetized by intraperitoneal administration of ketamine, acepromazine, and xylazine.[16] The left carotid artery was surgically exposed and the MA0.5VB Doppler perivascular flow probe was placed around the artery and connected to the corresponding T420 perivascular flowmeter (Transonic Europe B.V. Elsloo, The Netherlands).

A dose of 50 µg *Vaa*-snaclec-3/2 per kg body mass (BM) of the mouse was administered into the tail vein. The compound solution and saline were injected intravenously in a volume of 100 µL. Heparin (B. Braun Melsungen AG, Melsungen, Germany) was injected as a positive control (200 IU/kg BM).[17,18] Negative controls were injected with saline (0.9% (m/v) NaCl). Four BALB/c mice were used per group of positive or negative controls and for the 50 µg/kg BM dose of *Vaa*-snaclec-3/2. $FeCl_3$-soaked filter paper (approximately 1 × 2 mm, soaked in 3.5% (m/v) $FeCl_3$ solution) was placed on the carotid artery wall for 3 minutes to induce thrombus formation. Vascular flow was monitored for 30 minutes, then a blood sample (200 µL) was taken from the orbital sinus to determine the platelet count. The mice were then sacrificed. Data were statistically analyzed using Sigma Plot for Windows version 12.5 (Systat Software Inc., San Jose, California, United States). The statistical significance of the differences between the platelet counts was evaluated by the analysis of variance and the Bonferroni post-hoc test for multiple-group comparisons. A p-value ≤ 0.05 was considered statistically significant.

Results and Discussion

Isolation and Biochemical Characterization of *Vaa*-snaclec-3/2

To test the role of *Vaa*-snaclecs in reversible thrombocytopenia of functional platelets, we purified a protein from crude *Vaa* venom that was able to inhibit ristocetin-induced platelet agglutination (►**Fig. 2**).[19–21] The venom was first separated by size-exclusion chromatography, followed by three ion-exchange chromatographies (►**Fig. 1**). N-terminal Edman sequence analysis and MS showed that we purified a heterodimer consisting of *Vaa*-snaclec-3 (UniProt ID: A0A1I9KNN1_VIPAA available at: https://www.uniprot.org/uniprotkb/A0A1I9KNN1/entry) as the α-subunit and *Vaa*-snaclec-2 (UniProt ID: A0A1I9KNS2 _VIPAA available at: https://www.uniprot.org/uniprotkb/A0A1I9KNS2/entry) as the β-subunit. We named it *Vaa*-snaclec-3/2. As the most likely candidate venom protein causing thrombocytopenia of functional platelets, we have focused on its detailed characterization.

Under nonreducing (NR) conditions on an SDS-PAGE, the apparent molecular mass of *Vaa*-snaclec-3/2 was 24 kDa, but under reducing conditions (R) the protein appeared in two bands, at 18 and 15 kDa, the first corresponding to the α-subunit and the second to the β-subunit (*Vaa*-snaclec-3 and *Vaa*-snaclec-2, respectively, in ►**Fig. 2**). The isoelectric point of *Vaa*-snaclec-3/2 was 5.61.

Ex Vivo Effects of *Vaa*-snaclec-3/2 and Its Binding to Platelet Receptors

One µM *Vaa*-snaclec-3/2 induced thrombocytopenia (average value: 35 × 10^9/L; range: 18–56 × 10^9/L) in the whole blood but had no measurable effect on coagulation parameters, such as PT, aPTT, and TT. Under an optical microscope, agglutinates of two to three platelets were observed in whole blood after exposure to *Vaa*-snaclec-3/2 (►**Fig. 3A**). Platelet aggregation/agglutination assays by turbidometry using PRP showed that *Vaa*-snaclec-3/2 has a dose-dependent inhibitory effect on ristocetin-induced platelet agglutination (►**Fig. 3B**), indicating its interaction with the GPIb platelet receptor. *Vaa*-snaclec-3/2 had no effect on platelet aggregation induced by collagen, ADP, or arachidonic acid (►**Fig. 3C–E**).

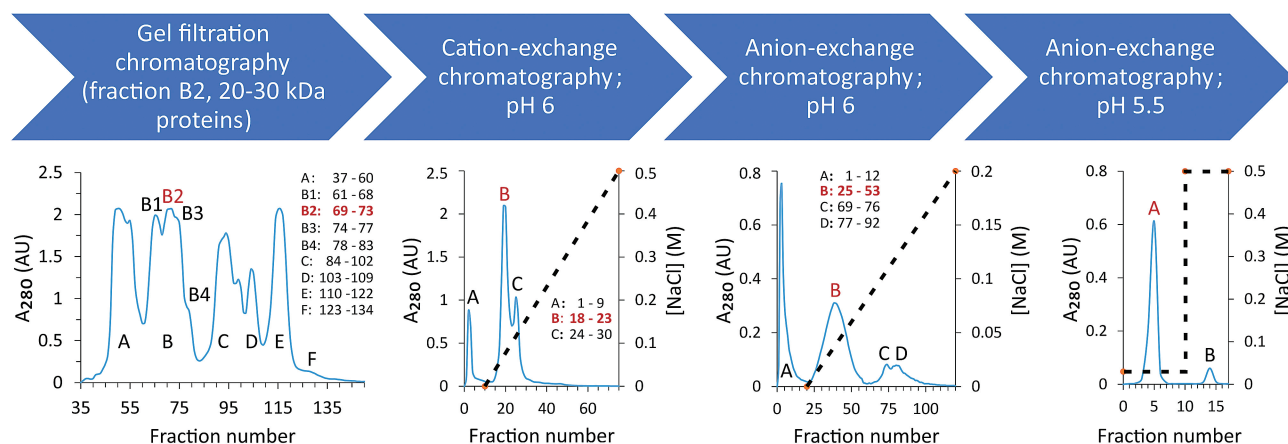

Fig. 1 Purification of *Vaa*-snaclec-3/2 from the venom. Size-exclusion chromatography of the crude *Vaa* venom was performed on a column filled with Sephacryl S-200 superfine. Fraction B2, which inhibited ristocetin-induced platelet agglutination (traced activity), was submitted to cation-exchange chromatography on an SP Sepharose Fast Flow column. The traced activity was concentrated in fraction B, which was further analyzed by two consecutive Q-SFF anion-exchange chromatographies. Fraction A after the second Q-SFF column contained a homogeneous protein sample expressing the traced activity. Structural characterization revealed the purified protein as *Vaa*-snaclec-3/2. Experimental details can be found in the Materials and Methods section.

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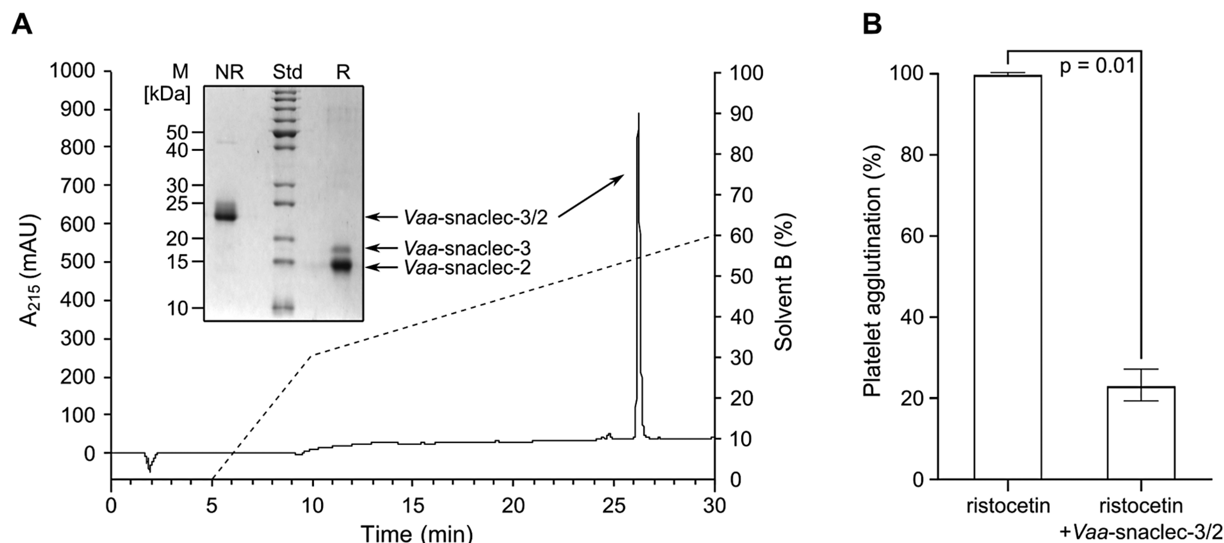

Fig. 2 Characterization of *Vaa*-snaclec-3/2. (**A**) RP-HPLC analysis of the purified *Vaa*-snaclec-3/2 on a C18 column revealed only one sharp peak. SDS-PAGE analysis of this peak (inset) under nonreducing conditions (NR) revealed a single protein with an apparent molecular mass of 24 kDa. Under reducing conditions (R), the band split into two bands. As structural characterization disclosed, these bands corresponded to α and β subunit of *Vaa*-snaclec-3/2, *Vaa*-snaclec-3, and *Vaa*-snaclec-2, respectively. (**B**) Inhibition of ristocetin-induced platelet agglutination by 50 nM of *Vaa*-snaclec-3/2.

Using flow cytometry and fluorescently-conjugated GP-specific antibodies, we were able to show indirectly that *Vaa*-snaclec-3/2 indeed binds to the GPIb (CD42b) of the von Willebrand factor receptor complex GPIb–IX–V on the surface of human platelets (►**Fig. 3F**). However, this binding, which was dose-dependent, did not trigger platelet activation, as no expression of P-selectin (CD62P) could be detected on the surface of platelets (►**Fig. 3G**). In agreement with the aggregation assays, *Vaa*-snaclec-3/2 did not bind to the fibrinogen-binding site of the receptor complex GPIIb–IIIa (CD41 and CD61) or to the collagen-binding site of the receptor GPVI.

In Vivo Effects of *Vaa*-snaclec-3/2 and Its Potential Clinical Implications

The antithrombotic activity of *Vaa*-snaclec-3/2 was tested in vivo in the mouse model of $FeCl_3$-induced carotid artery thrombosis. The protein showed antithrombotic activity as it successfully prevented complete occlusion of the artery as detected by Doppler flow measurements with the probe connected to the perivascular flowmeter. Intravenous administration of 50 µg/kg *Vaa*-snaclec-3/2 ($n = 4$) resulted in prevention of carotid artery occlusion in all animals tested, mirroring the result observed with heparin ($n = 4$) as a positive control. Conversely, in the negative control group treated with 0.9% NaCl ($n = 4$), thrombus formation leading to complete arterial occlusion was observed in all experimental animals (►**Fig. 4B**).

At a dose of 50 µg/kg of *Vaa*-snaclec-3/2, a reduction in platelet count of up to 98% was observed. The platelet count decreased from $884 \pm 247 \times 10^9$/L in the group of mice treated with 0.9% NaCl (negative control, i.e., baseline count) to $19 \pm 8 \times 10^9$/L ($p = 0.01$). The platelet count of the positive control group of heparin-treated mice was $796 \pm 132 \times 10^9$/L (►**Fig. 4A**). The in vivo experiment thus clearly showed that *Vaa*-snaclec-3/2 both induces thrombocytopenia and inhibits thrombus formation.

The clinical study on *Vaa* envenomation has shown that the *Vaa* venom contains component(s) that can temporarily reduce platelet count without affecting platelet function.[4] In this study, we have identified *Vaa*-snaclec-3/2 as the venom component responsible for this effect. It binds to the platelet receptor GPIb and thus triggers platelet agglutination, which leads to a dose-dependent reduction in the platelet count. It has been suggested that snaclec-mediated platelet agglutination[5] is due to the ability of snaclecs to cross-link GPIb receptors[22] on adjacent platelets. Two other snaclecs, alboaggregin-B from the venom of the white-lipped tree viper (*Trimeresurus albolabris*) and agglucetin from the venom of the Chinese moccasin (*Deinagkistrodon acutus*), also bind to the GPIb–IX–V receptor complex without inducing platelet activation—namely, they neither increased intracellular Ca^{2+} concentration nor triggered platelet degranulation.[5] This is consistent with the clinical study in *Vaa*-envenomed patients[4] and this study, in which no platelet aggregation, i.e., activation, was observed either.

According to our biochemical, ex vivo, in vivo, and clinical studies, the profound and reversible thrombocytopenia of functional platelets after *Vaa* envenomation is caused by the venom component *Vaa*-snaclec-3/2 after its binding to the functional site of the GPIb platelet receptor as evidenced by the dose-dependent reduction in the binding of a fluorescently labeled monoclonal antibody to human platelet GPIb (►**Fig. 3F**) and the inhibition of ristocetin-induced platelet agglutination (►**Fig. 3B**). The reversible thrombocytopenia of functional platelets by *Vaa*-snaclec-3/2, which inhibits thrombus formation, could be beneficial in interventional procedures that require only a temporary reversal of platelet adhesion/aggregation, such as balloon dilation, stent implantation, and embolus aspiration.

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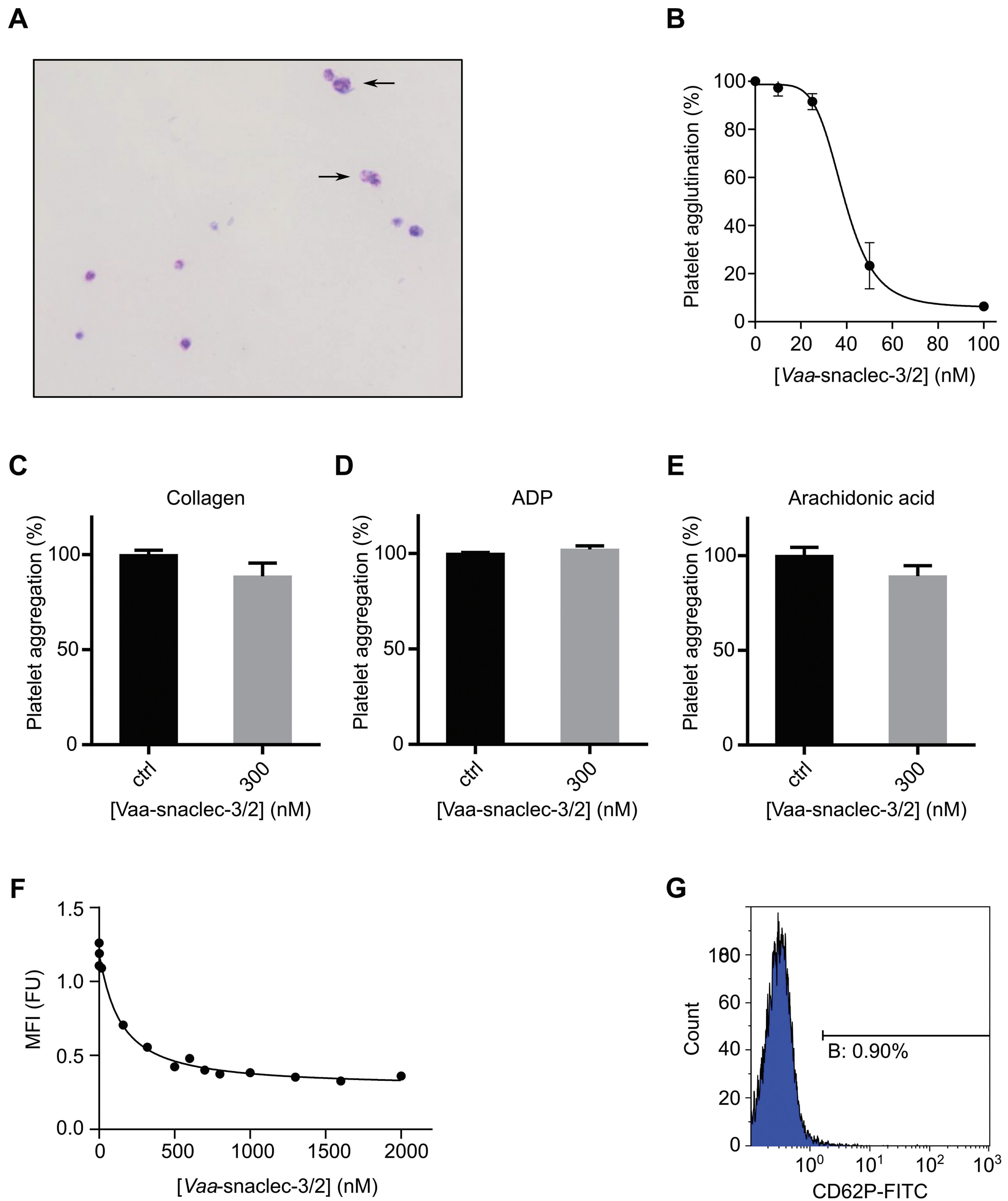

Fig. 3 Effects of *Vaa*-snaclec-3/2 on platelets. (**A**) Agglutinates of two or three platelets (arrows) formed in PRP smears after 30 minute-incubation with *Vaa*-snaclec-3/2. (**B**) *Vaa*-snaclec-3/2 inhibited ristocetin-induced platelet agglutination dose-dependently. The half-maximal inhibitory concentration of *Vaa*-snaclec-3/2 was 39.2 nM. At 300 nM, *Vaa*-snaclec-3/2 did not inhibit collagen-induced platelet agglutination (**C**), ADP-induced platelet agglutination (**D**) nor arachidonic-induced platelet agglutination (**E**). (**F**) As revealed by flow cytometry, *Vaa*-snaclec-3/2 dose-dependently reduced the binding of fluorescently-labeled monoclonal antibody to human platelet CD42b (GPIb). MFI stands for mean fluorescence intensity. (**G**) The expression of P-selectin (CD62P) on the platelet surface was detected by flow cytometry in less than 1% of platelets after exposure of PRP to *Vaa*-snaclec-3/2. For experimental details, refer the Materials and Methods section. PRP, platelet-rich plasma.

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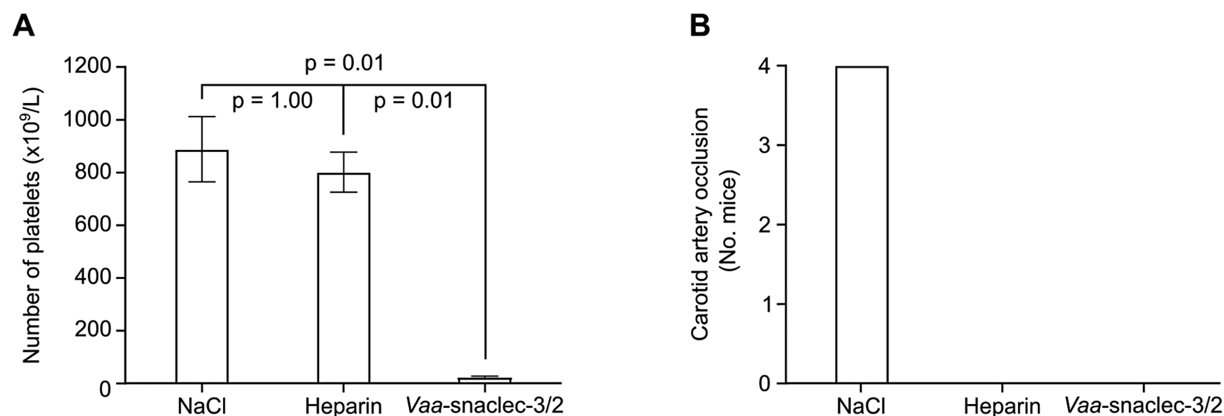

Fig. 4 Antithrombotic effect of *Vaa*-snaclec-3/2 in a mouse model of carotid artery thrombosis. Intravenous administration of 50 µg/kg *Vaa*-snaclec-3/2 in a mouse model (**A**) strongly reduced platelet count (i.e., induced thrombocytopenia) ($p = 0.01$; data represent the mean ± SD) and (**B**) protected the carotid artery from occlusion.

Conclusions

Vaa-snaclec-3/2 induces platelet agglutination by binding to the GPIb platelet receptor as indicated by its inhibition of the monoclonal antibody binding to the functional site of GPIb and of the ristocetin-induced platelet agglutination. In vivo, *Vaa*-snaclec-3/2 causes thrombocytopenia and protects the experimental animals from arterial occlusion.

What is known about this topic?

- Envenomation by *Vipera a. ammodytes* (*Vaa*) venom often leads to severe thrombocytopenia.
- A normal number of fully functional platelets is restored within an hour by treatment of the patient with a specific antivenom.

What does this paper add?

- The reversible thrombocytopenia of functional platelets in *Vaa* envenomation is induced by *Vaa*-snaclec-3/2.
- *Vaa*-snaclec-3/2 most likely agglutinates platelets by binding to the GPIb receptor.
- *Vaa*-snaclec-3/2 protected mice from arterial occlusion demonstrating its antithrombotic potential in interventional cardiology.

Ethical Approval Statement

Study protocol on human blood was reviewed and approved by the Slovenian National Medical Ethics Committee (No. 87/07/15 and No. 0120–546/2017/5). The study was conducted according to the guidelines of the Declaration of Helsinki. All animal experiments were performed in strict accordance with the Slovenian legislation, which was harmonized with the European Communities Council guidelines (Directive 86/609/EGS of November 24, 1986 and recently adopted Directive 2010/63/EU of September 22, 2010). The permission for in vivo experiments was obtained from the Ministry of Agriculture Forestry and Food of the Republic of Slovenia, The Administration of the Republic of Slovenia for Food Safety, Veterinary and Plant Protection, approval number: U34401–9/2021/4. The ARRIVE guidelines have been followed.

Authors' Contribution

Conceptualization: A.L., M.B., and I.K.; data curation: M.D.B., A.L., K.P., K.R., and M.C.Ž.; formal analysis: M.D.B., A.L., K.P., K.R., H.P., A.P., A.T.B., M.C.Ž., R.F., M.B., and I.K.; funding acquisition: K.P., R.F., M.B., and I.K.; investigation: M.D.B., A.L., K.P., K.R., A.P., S.K.B., T.T., and M.C.Ž.; methodology: A.L., H.P., A.T.B., R.F., M.B., and I.K.; project administration: M.B. and I.K.; resources: H.P., A.T.B., R.F., M.B., and I.K.; supervision: A.L., H.P., A.T.B., R.F., M.B., and I.K.; validation: A.L., H.P., A.T.B., R.F., M.B., and I.K.; visualization: M.D.B., K.P., A.L., M.C.Ž., and R.F.; writing—original draft: M.D.B. and K.P.; writing—review and editing: A.L., K.R., H.P., A.P., A.T.B., M.C.Ž., R.F., M.B., and I.K.

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Conflict of Interest

None declared.

References

1 Dobaja Borak M, Babić Ž, Caganova B, et al. Viper envenomation in Central and Southeastern Europe: a multicentre study. Clin Toxicol (Phila) 2023;61(09):656–664

2 Kurtović T, Karabuva S, Grenc D, et al. Intravenous *Vipera berus* venom-specific Fab fragments and intramuscular *Vipera ammodytes* venom-specific F(ab')$_2$ fragments in *Vipera ammodytes*-envenomed patients. Toxins (Basel) 2021;13(04):279

3 Brvar M, Kurtović T, Grenc D, Lang Balija M, Križaj I, Halassy B. *Vipera ammodytes* bites treated with antivenom ViperaTAb: a case series with pharmacokinetic evaluation. Clin Toxicol (Phila) 2017;55(04):241–248

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4 Dobaja Borak M, Grenc D, Reberšek K, et al. Reversible and transient thrombocytopenia of functional platelets induced by nose-horned viper venom. Thromb Res 2023;229:152–154
5 Eble JA. Structurally robust and functionally highly versatile-C-type lectin (-related) proteins in snake venoms. Toxins (Basel) 2019;11(03):136
6 Herrera C, Rucavado A, Warrell DA, Gutiérrez JM. Systemic effects induced by the venom of the snake *Bothrops caribbaeus* in a murine model. Toxicon 2013;63:19–31
7 Nashimoto Y, Matsushita F, Dijkstra JM, et al. Bitiscetin-3, a novel C-type lectin-like protein cloned from the venom gland of the viper *Bitis arietans*, induces platelet agglutination and inhibits binding of von Willebrand factor to collagen. Toxins (Basel) 2022; 14(04):236
8 Leonardi A, Sajevic T, Pungerčar J, Križaj I. Comprehensive study of the proteome and transcriptome of the venom of the most venomous European viper: discovery of a new subclass of ancestral snake venom metalloproteinase precursor-derived proteins. J Proteome Res 2019;18(05):2287–2309
9 Latinović Z, Leonardi A, Šribar J, et al. Venomics of *Vipera berus berus* to explain differences in pathology elicited by *Vipera ammodytes ammodytes* envenomation: therapeutic implications. J Proteomics 2016;146:34–47
10 Morowski M, Vögtle T, Kraft P, Kleinschnitz C, Stoll G, Nieswandt B. Only severe thrombocytopenia results in bleeding and defective thrombus formation in mice. Blood 2013;121(24): 4938–4947
11 Karabuva S, Brizić I, Latinović Z, Leonardi A, Križaj I, Lukšić B Cardiotoxic effects of the *Vipera ammodytes ammodytes* venom fractions in the isolated perfused rat heart. Toxicon 2016; 121:98–104
12 Premrov Bajuk B, Zrimšek P, Kotnik T, Leonardi A, Križaj I, Jakovac Strajn B. Insect protein-based diet as potential risk of allergy in dogs. Animals (Basel) 2021;11(07):1942
13 Laemmli UK. Cleavage of structural proteins during the assembly of the head of bacteriophage T4. Nature 1970;227(5259):680–685
14 Požek K, Leonardi A, Pungerčar J, et al. Genomic confirmation of the P-IIIe subclass of snake venom metalloproteinases and characterisation of its first member, a disintegrin-like/cysteine-rich protein. Toxins (Basel) 2022;14(04):232
15 Sajevic T, Leonardi A, Kovačič L, et al. VaH3, one of the principal hemorrhagins in *Vipera ammodytes ammodytes* venom, is a homodimeric P-IIIc metalloproteinase. Biochimie 2013;95(06): 1158–1170
16 Ogrizek M, Grgurevič N, Snoj T, Majdič G Injections to pregnant mice produce prenatal stress that affects aggressive behavior in their adult male offspring. Horm Behav 2018;106:35–43
17 Wang X, Xu L. An optimized murine model of ferric chloride-induced arterial thrombosis for thrombosis research. Thromb Res 2005;115(1–2):95–100
18 Wang X, Cheng Q, Xu L, et al. Effects of factor IX or factor XI deficiency on ferric chloride-induced carotid artery occlusion in mice. J Thromb Haemost 2005;3(04):695–702
19 Lu Q, Clemetson JM, Clemetson KJ. Snake venom C-type lectins interacting with platelet receptors. Toxin Rev 2007;26:77–93
20 Kini RM. Toxins in thrombosis and haemostasis: potential beyond imagination. J Thromb Haemost 2011;9(Suppl 1):195–208
21 Sajevic T, Leonardi A, Križaj I. Haemostatically active proteins in snake venoms. Toxicon 2011;57(05):627–645
22 Clemetson KJ. Snaclecs (snake C-type lectins) that inhibit or activate platelets by binding to receptors. Toxicon 2010;56(07): 1236–1246

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