Factor XII Regulates the Pathological Process of Thrombus Formation on Ruptured Plaques

Marijke J.E. Kuijpers, Paola E.J. van der Meijden, Marion A.H. Feijge, Nadine J.A. Mattheij, Frauke May, José Govers-Riemslag, Joost C.M. Meijers, Johan W.M. Heemskerk, Thomas Renné, Judith M.E.M. Cosemans

Objective—Atherothrombosis is the main cause of myocardial infarction and ischemic stroke. Although the extrinsic (tissue factor–factor VIIa [FVIIa]) pathway is considered as a major trigger of coagulation in atherothrombosis, the role of the intrinsic coagulation pathway via coagulation FXII herein is unknown. Here, we studied the roles of the extrinsic and intrinsic coagulation pathways in thrombus formation on atherosclerotic plaques both in vivo and ex vivo.

Approach and Results—Plaque rupture after ultrasound treatment evoked immediate formation of subocclusive thrombi in the carotid arteries of Apoe<sup>−/−</sup> mice, which became unstable in the presence of structurally different FXIIa inhibitors. In contrast, inhibition of FVIIa reduced thrombus size at a more initial stage without affecting embolization. Genetic deficiency in FXII (human and mouse) or FXI (mouse) reduced ex vivo whole-blood thrombus and fibrin formation on immobilized plaque homogenates. Localization studies by confocal microscopy indicated that FXIIa bound to thrombi and fibrin particularly in luminal-exposed thrombus areas.

Conclusions—The FVIIa- and FXIIa-triggered coagulation pathways have distinct but complementary roles in atherothrombus formation. The tissue factor–FVIIa pathway contributes to initial thrombus buildup, whereas FXIIa bound to thrombi ensures thrombus stability. (Arterioscler Thromb Vasc Biol. 2014;34:1674-1680.)

Key Words: blood coagulation ⋅ blood platelets ⋅ factor XII ⋅ fibrin ⋅ plaque rupture ⋅ thrombus ⋅ tissue factor

Atherothrombosis, characterized by atherosclerotic lesion disruption with superimposed thrombus formation, is the major cause of acute coronary syndromes and cardiovascular death. Predominantly, platelet-rich (white) thrombi are formed at the ruptured area, because platelet recruitment preferentially occurs at regions of high shear rate and disturbed flow, whereas maximal fibrin generation occurs in regions of low flow. Activated platelets support the tissue factor (TF) pathway of blood coagulation by binding various (anti)coagulation factors. There is emerging evidence that platelets also support the intrinsic coagulation pathway mediated by factors XII (FXII) and XI (FXI), for example, by releasing polyphosphates, although the exact mechanism is still unclear. Better understanding of these multifaceted roles of platelets in coagulation stimulation can lead to new approaches to selectively inhibit the pathways most relevant in atherothrombosis.

See accompanying editorial on page 1607

Collagen type I is not only the most potent platelet activating component in atherosclerotic plaques by binding and activating the glycoprotein VI receptor, but has also been shown to bind to and activate FXII. Several mouse studies using nonatherosclerotic vessels point to a consolidating role of the FXII pathway in arterial thrombus formation and thrombus stabilization, as concluded from experiments with genetic ablation or pharmacological inhibition of FXII. Interestingly, deficiency in FXII in man or mouse is not accompanied by abnormal bleeding. On the contrary, individuals with partly reduced FXII levels have an increased risk of cardiovascular disease (reviewed in Renné et al and Woodruff et al), which indicates that the clinical consequences of (partial) FXII deficiency are more complex than the reported antithrombotic effects of FXII ablation in mice.

To date, no experimental data exist on a role of the intrinsic coagulation pathway in pathological thrombus formation after atherosclerotic plaque rupture. A recent report studying plaque-induced thrombin generation in vitro suggested that the intrinsic FXII pathway may not play a key role in this process, such in contrast to a predominant role for plaque-derived TF triggering the extrinsic pathway. In the present article, we therefore compared the roles of both the extrinsic and intrinsic coagulation pathways in thrombus formation on atherosclerotic plaques in vivo and ex vivo.
Materials and Methods
Materials and methods are available in the online-only Supplement.

Results
Distinct Roles of Murine FXII and FVII Pathways in Arterial Thrombus Formation on Ruptured Atherosclerotic Plaques

In mouse models, the role of FXII in thrombus formation has only been investigated on damage of healthy arteries. Here, we studied the contribution of FXII to the thrombotic process after acute rupture of an atherosclerotic plaque, using a recently established model of acute plaque rupture in the carotid bifurcation of Apoe−/− mice. In control Apoe−/− mice, ultrasound treatment of the plaque shoulder provoked rapid thrombus formation at the site of rupture (Figure 1A; Movie 1 in the online-only Data Supplement). The formed thrombi remained subocclusive and reduced in size because of platelet contraction and limited embolization during the first 10 minutes after rupture, but then became stable for at least several hours, as observed before. In mice injected with one of the FXII inhibitors, corn trypsin inhibitor (CTI; 4 mg/kg) or recombinant infestin-4 human albumin fusion protein (30 mg/kg), thrombus formation tended to be reduced, an effect that became significant 1 to 2 minutes after plaque rupture (Figure 1A–1C). In addition, either inhibitor caused a significant increase in shedding of discernable emboli from the initial thrombus (Figure 1D; Movie II in the online-only Data Supplement).

Nonstandard Abbreviations and Acronyms

<table>
<thead>
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<th>Abbreviation</th>
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<tr>
<td>CTI</td>
<td>corn trypsin inhibitor</td>
</tr>
<tr>
<td>FVIIai</td>
<td>active-site inactivated factor VIIa</td>
</tr>
<tr>
<td>FXI</td>
<td>factor XI</td>
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<tr>
<td>FXII</td>
<td>factor XII</td>
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<td>PRP</td>
<td>platelet-rich plasma</td>
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<td>TF</td>
<td>tissue factor</td>
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Figure 1. Distinct roles for factor XIIa (FXIIa) and FVIIa in arterial thrombus formation after acute plaque rupture in vivo. Apoe−/− mice were injected with saline (control), corn trypsin inhibitor (CTI; 4 mg/kg), recombinant infestin-4 human albumin fusion protein (rHA-infestin-4; 30 mg/kg), active-site inactivated FVIIa (FVIIai; 1 mg/kg), or CTI (4 mg/kg) and FVIIai (1 mg/kg). Carotid plaques were ruptured by ultrasound after which thrombus formation was quantified from preinjected CFSE-labeled platelets. A, Bright-field images of carotid plaque (p) and threshold masked fluorescence images of thrombi before and after ultrasound treatment. Dotted lines indicate contours of carotid artery and plaque (bars, 200 μm). B, Time courses of integrated carboxyfluorescein diacetate succinimidyl ester (CFSE) fluorescence (FL) intensity above background of thrombi formed (arbitrary units [AU]). Fluctuations in fluorescence intensity indicate thrombi formation and shedding. C, Quantification of thrombus size at various time points after ultrasound treatment (integrated fluorescence intensities from threshold masked images). D, Numbers of fluorescent emboli shed during 3 minutes after plaque rupture. Data are means±SE (n=7–11); *P<0.05 and #P=0.051 compared with control.
whereas embolization was not affected (Figure 1; Movie III in the online-only Data Supplement). In mice treated with FVIIai and CTI, thrombus formation at later, but not at early, time points was even further reduced (P values of 0.210, 0.074, 0.015, and 0.031 at \( t = 0.5, 1, 2, \) and 10 minutes, respectively). Taken together, this pointed to distinct but complementary roles of the FVIIa- and FXIIa-triggered coagulation pathways in the thrombotic process after plaque rupture. Herein, TF–FVIIa interaction seems to be needed for initial thrombus formation, whereas FXII ensures thrombus stability.

**Role of Murine FXII in Flow-Dependent Thrombus Formation on Atherosclerotic Plaque Material**

To study the role of murine FXII in plaque-induced thrombus formation in more detail, flow experiments were performed where blood from wild-type or factor-deficient mice was perfused at moderately high shear rate under coagulant conditions (mmol/L Ca\(^{2+}/Mg^{2+}\)) over a surface coated with murine plaque material. With blood from wild-type mice, platelets rapidly adhered to the plaque and formed large thrombi. These thrombi contracted after several minutes, stained positively for exposed phosphatidylserine, and had fibrin fibers originating from them (Figure 2A). When using blood from \( F12^{-/-} \) mice, initial platelet adhesion to the plaque surface was unchanged, but ensuing thrombus formation and phosphatidylserine exposure (quantified as surface area coverage) were markedly diminished and no formed fibrin could visually be observed (Figure 2). Importantly, the defective thrombus formation was almost fully restored after supplementation with purified human FXII.

The main downstream effector protein of FXII is FXI which, however, can also be activated independently of FXII via a feedback loop of thrombin.\(^{19,20} \) To study the role of FXI in plaque-induced thrombus formation, flow experiments were performed with blood from \( F11^{-/-} \) and \( F11^{-/-}/F12^{-/-} \) mice. In either case, the thrombus-forming process was similarly impaired as with \( F12^{-/-} \) blood (Figure 2A, 2C, and 2D). Together, these data demonstrate a key role of murine FXII in thrombus and fibrin formation during whole-blood perfusion over a murine plaque surface mediated through the classical FXII–FXI reaction cascade.

**Role of Human FXII in Flow-Dependent Thrombus Formation on Atherosclerotic Plaque Material**

Having established the role of murine FXII in plaque-induced thrombus formation, we investigated the function of FXII also in the human system. Blood from control subjects and an FXII-deficient subject (FXII level <1%) was perfused over immobilized human plaque material under coagulation-promoting conditions. With the FXII-deficient blood, initial platelet adhesion to the plaque surface was comparable with that of control blood samples. However, after 10 minutes of perfusion, the surface area covered by thrombi, the amount of fibrin(ogen) binding, and the platelet procoagulant...
activity (phosphatidylserine exposure) were strongly reduced (Figure 3A–3C). Notably, addition of purified human FXII fully restored the defective thrombus formation and platelet procoagulant activity. Control measurements performed with Phe-Pro-Arg chloromethylketone-anticoagulated blood showed that thrombus formation on plaque material was highly similar with blood from control and FXII-deficient subjects at these thrombin-inhibiting/noncoagulating conditions (not shown).

To substantiate these findings, thrombus formation was assessed under coagulant conditions in control blood samples by pharmacological inhibition of FXIIa with CTI (50 μg/mL) or recombinant infestin-4 human albumin fusion protein (250 μg/mL). Either inhibitor caused a 50% reduction in surface area coverage and procoagulant activity of platelets (Figure 4). 

Role of Human FXII in Plaque-Mediated Thrombin Generation and Clotting in Platelet-Rich Plasma

To confirm the effects of FXII inhibition and blockage of TF–FVIIa interaction on platelet- and plaque-dependent coagulation, clotting times were measured in recalculated human platelet-rich plasma (PRP). Addition of plaque homogenate reduced the time to Ca²⁺-triggered clot formation, which effect was partly antagonized with either CTI or FVIIai and fully antagonized by application of both inhibitors (Table I in the online-only Data Supplement). In control PRP, plaque material and collagen triggered a slow-onset, low thrombin generation, whereas the addition of purified FXII normalized this process (Figure 5B). Thus, we concluded that FXII plays a key stimulating role in plaque-induced and platelet-dependent thrombin generation.

Localization of FXII in Human Thrombi Formed on Atherosclerotic Plaque Material

In whole-blood perfusion experiments over collagen ex vivo, the thrombogenic role of FXII has been explained by activated FXII binding to collagen. This prompted us to determine the detail the contribution of FXII to thrombin generation in PRP triggered by CaCl₂ with(out) plaque material. The thrombin generation curve generated in control PRP in the presence of CaCl₂ was absent in FXII-deficient PRP (Table II in the online-only Data Supplement). In control PRP, plaque material caused a similar acceleration and increase in thrombin generation as collagen (Figure 5A). In contrast, in FXII-deficient PRP, plaque material and collagen triggered a slow-onset, low thrombin generation, whereas the addition of purified FXII normalized this process (Figure 5B).

Figure 3. Deficiency of human factor XII (FXII) impairs thrombus formation under coagulant conditions on plaque material ex vivo. Citrate-anticoagulated blood from an FXII-deficient subject (FXII <1%) or from 3 healthy control (Ctrl) subjects was recalcified with CaCl₂/MgCl₂ and perfused over human plaque material at 500 s⁻¹. Where indicated, patient blood samples were supplemented with human FXII (hFXII; 375 nmol/L). Shown are representative microscopic images and quantitative data of surface area coverage analysis of (A) platelet–fibrin thrombi, (B) AF647–annexin A5 labeling of phosphatidylserine-exposing platelets, and (C) OG488–fibrin(ogen) labeling. Bars, 30 μm. Data are means±SE; *P<0.05 vs Ctrl.

Figure 4. Pharmacological inhibition of factor XII (FXII) suppresses thrombus formation on human plaque material. Blood was perfused over human plaque material, as in Figure 3. Inhibitors corn trypsin inhibitor (CTI; 50 μg/mL) or recombinant infestin-4 human albumin fusion protein (rHA-infestin-4; 250 μg/mL) were present in the collecting tube during blood collection. Incubation with active-site inactivated FVIIa (FVIIai; 10 μg/mL) was for 15 minutes before the experiment. Shown is deposition of all thrombus components on human plaque surface. Data are means±SE (n=5–10); *P<0.05.

Figure 5A). In contrast, in FXII-deficient PRP, plaque material and collagen triggered a slow-onset, low thrombin generation, whereas the addition of purified FXII normalized this process (Figure 5B). Thus, we concluded that FXII plays a key stimulating role in plaque-induced and platelet-dependent thrombin generation.
The FXII-dependent procoagulant effect of plaque material was also observed as an increase in thrombin generation in the presence of platelets. Interestingly, immunologic staining for FXII was also observed as an increase in thrombin generation in the presence of platelets. Moreover, immunologic staining for FXII was also observed as an increase in thrombin generation in the presence of platelets. Interestingly, immunologic staining for FXII was also observed as an increase in thrombin generation in the presence of platelets. Interestingly, immunologic staining for FXII was also observed as an increase in thrombin generation in the presence of platelets. Interestingly, immunologic staining for FXII was also observed as an increase in thrombin generation in the presence of platelets.

**Discussion**

In the present article, we revealed a major role of the FXII-driven intrinsic pathway of coagulation in arterial thrombus formation on atherosclerotic plaques. Evidence for the involvement of FXII came from an in vivo model of acute plaque rupture on atherosclerotic mouse arteries using 2 structurally different pharmacological FXII inhibitors, from ex vivo perfusion experiments using blood of F12−/− mice and blood of a subject with severe deficiency in FXII (FXII level <1%). The FXII-dependent procoagulant effect of plaque material was also observed as an increase in thrombin generation in the presence of platelets. Interestingly, immunologic staining for FXII did not colocalize with AF568–annexin A5 staining indicative for phosphatidylserine-exposing platelets (Pearson, r=0.02), implying that these procoagulant platelets did not bind FXIIa.

FXIIa of thrombi containing platelets and fibrin pointed to an accumulation of FXIIa in the luminal-exposed regions of the thrombus. This likely is relevant, because these top regions are subjected to high shear gradients and hence most prone to embolization.22 The present findings significantly extend earlier data, using purified or plasma systems, demonstrating that FXIIa can interact with fibrin to modulate clot structure.21 Taken together, this suggests that local, FXIIa-initiated thrombin and fibrin generation provides stabilization to the regions of a thrombus distant from the vascular TF. Recent studies in which anti-FXIIa and anti-FXIIa antibodies were found to reduce fibrin formation in an ex vivo perfusion system with human blood provide additional support for this idea.13,23 Although the binding sites of FXIIa on platelets have not been elucidated, our confocal microscopic studies indicate that FXIIa does not bind to phosphatidylserine-exposing platelets. This is of interest, because the majority of coagulation factors (FII, FV, FVII, FVIII, FIX, and FX) have been shown to bind to this population of activated platelets.2 In addition, we and others have shown that both collagen and polyphosphates are able to activate FXII,24 although it needs to be noted that the chain length of platelet-derived polyphosphates is relatively short for optimal FXII activation.24 Together with the present findings, this would advocate for a combined role of collagen, platelets, and fibrin in activation of the FXII pathway.

Our data indicate that the formation of platelet–fibrin thrombi on immobilized plaque material is similarly affected in blood from F12−/−, F11−/−, or F11−/−F12−/− mice, thus suggesting that the role of FXII in promoting atherothrombosis is
mediated via activation of FXI. This is in line with several in vivo studies pointing to corresponding roles of FXII and FXI in thrombus formation in artificially damaged nonatherosclerotic mouse vessels.\textsuperscript{3,5,10} Consistent with an FXI-dependent role of FXII in arterial thrombosis, an anti-FXI monoclonal antibody that specifically targets FXIIa-mediated FXI activation has been shown to suppress thrombus formation in mice and baboons.\textsuperscript{3,25}

Studies by our group and others have elucidated a coagulation-initiating role of atherosclerotic plaques via localized activity of TF, whereas the contact activation pathway was not investigated here.\textsuperscript{6,7,26–28} In the present study, inhibitor experiments using FVIIa similarly pointed to a role of TF in the initiation of thrombus formation after plaque rupture in vivo, whereas FXII may be more important at later stages of this process. It is tentative to relate this early effect of the TF–FVIIa pathway and later contribution of the FXII pathway with the fact that FVII deficiency in man is accompanied by severe bleeding, whereas deficiency in FXII is not.\textsuperscript{3,14} Notably, our findings contrast to a recently published article showing a lack of effect of CTI on plaque-induced platelet aggregation and thrombin generation in vitro.\textsuperscript{8} Differences in methodology and procedures could explain this discrepancy. Of note, in our experiments, FXIIa inhibitors were always added directly during blood taking, and a CTI batch with high enzymatic activity (1.5 U/mL) was used. This procedure was followed to prevent residual ongoing FXIIa activity in the anticoagulated blood samples.

Whereas FXII in man or mouse is not required for normal hemostasis,\textsuperscript{3,14} we here demonstrate a promoting role for FXII in pathological thrombus formation after plaque rupture. This is in accordance with clinical evidence that elevated levels of FXII(a) positively associate with arterial thrombosis, ischemic stroke, and coronary heart disease.\textsuperscript{29–31} On the contrary, conflicting evidence exists on whether individuals with partly reduced FXII levels have an increased risk of cardiovascular disease (reviewed in Renné et al\textsuperscript{15} and Woodruff et al\textsuperscript{16}). In this regard, the thrombus-stabilizing effect observed under conditions of reduced FXII activity needs more attention. Patients with a stroke or myocardial infarction mostly have thrombosis of the carotid or coronary artery and may present with symptomatic emboli that potentially give rise to (semi) occlusive thrombi downstream in the vasculature. However, many patients also develop clinically asymptomatic embolization,\textsuperscript{32} which remain for the major part without pathological consequences.\textsuperscript{33} The latter is in line with the emerging notion that limited instability may be considered as a natural phenomenon in arterial thrombus formation.\textsuperscript{22}

Also, in patients with FVII deficiency, thrombotic episodes, particularly deep venous thrombosis, have been reported with an incidence of 3% to 4%.\textsuperscript{34} Although the underlying mechanism is unclear, it seems that these are mostly related to surgery and the use of replacement therapy with FVIIa or prothrombin complex concentrate.\textsuperscript{34}

In summary, the present results indicate that the coagulation pathways triggered by TF–FVIIa and FXIIa have distinct but complementary roles in atherothrombus formation. The TF–FVIIa pathway contributes to initial thrombus build-up, whereas FXIIa bound to thrombi ensures stability of the thrombus in later phases.

Acknowledgments
We acknowledge Dr S. Heeneman (CARIM, Maastricht, The Netherlands) for providing patient material, M.W. Nolte, PhD (CSL Behring GmbH, Marburg, Germany) for providing recombinant infestin-4 human albumin fusion protein, and L. Pelmans, MSc (CARIM, Maastricht, The Netherlands) for performing initial experiments.

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Disclosures
F. May is an employee of CSL Behring GmbH, Marburg, Germany. The other authors report no conflicts.

References
12. Revenko AS, Gao D, Crosby JR, Bhattacharjee G, Zhao C, May C, Gailani D, Monia BP, MacLeod AR. Selective depletion of plasma prekallikrein or


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Material and Methods

Materials. Monoclonal mouse anti-FXIIa antibody was generated as described (United States Patent Application 20090304685, D. Pritchard). Recombinant infestin-4 human albumin fusion protein (r-HA-Infestin-4) was provided by M.W. Nolte, PhD (CSL Behring GmbH, Marburg, Germany). Fluorescein isothiocyanate (FITC) labeled goat-anti-mouse IgG was from Santa-Cruz Biotechnologies (Santa Cruz, CA, USA), carboxyfluorescein diacetate succinimidyl ester (CFSE) was from Molecular Probes (Leiden, the Netherlands). Sources of other materials as described.1

Animals. Apoe<sup>-/-</sup> mice with C57BL/6 background (4 weeks old) were obtained from Charles River (Sulzfeld, Germany). The Apoe<sup>-/-</sup> mice were fed a Western-type diet with 0.25% cholesterol for 18-20 weeks, at which time plaques had developed in the carotid arteries near the bifurcation.2 Mice homozygous for null mutations in the FXI (F11<sup>-/-</sup>) or FXII gene (F12<sup>-/-</sup>) were generated and then crossed to generate F12<sup>-/-</sup>/F11<sup>-/-</sup>-double deficient mice as described.3 Age-and sex-matched wildtype C57BL/6 mice (Charles River) were used as controls. Animal experiments were approved by the research ethics committees of the universities of Maastricht (The Netherlands) and Stockholm (Sweden).

In vivo rupture of atherosclerotic plaques by targeted ultrasound treatment. Acute rupture of plaques in the carotid arteries was provoked by targeted ultrasound treatment, as described.2, 4 Fifteen min prior to rupture, the mice were injected with 100 µL of either saline solution (control), CTI (4 mg/kg), rHA-Infestin-4 (30 mg/kg) or FVIIai (1 mg/kg). In wildtype C57BL/6 mice, these treatments have been shown to specifically block the FXIIa<sup>5</sup> or FVIIa<sup>6</sup> pathways of coagulation.

Blood collection. Blood was obtained from control subjects and a FXII deficient (FXII < 1%) after full informed consent according to the Helsinki declaration. Blood was taken by venipuncture via a non-vacuum system, allowing the blood to drip into a polypropylene collecting tube that contained 12.9 mM trisodium citrate with(out) CTI (50 µg/mL) or rHA-Infestin-4 (250 µg/mL). FVIIai (10 µg/mL) was added 15 minutes prior to experimentation. Mice were anesthetized by a subcutaneous injection of 0.1 mg/g body weight ketamine and 0.02 mg/g body weight xylazine and bled retro-orbitally.

Collection and characterization of human and mouse plaques. Human atherosclerotic plaques, collected from the carotid artery at autopsy, were obtained from the Maastricht Pathology Tissue Collection. Collection, storage and use of tissue and patient data were performed in agreement with the Code for Proper Secondary Use of Human Tissue in the Netherlands. After resection, one segment of the atherosclerotic specimens was used for histological analysis. Staining of the plaque material for hematoxylin, eosin, Sirius red, collagen type I, collagen type III, TF and FXII was performed as before.7 Collagen type I and III showed a disperse spongiform distribution in the atherosclerotic plaques. Staining of TF was mainly confined to macrophages in the lesions (not shown). In the remaining segments, the tunica intima was anatomically separated from the media layer and isolated for experimental use. Murine atherosclerotic plaques were anatomically separated from the isolated aortic arches of Apoe<sup>-/-</sup> mice.

Isolated human and mouse atherosclerotic specimens were homogenized in
phosphate-buffered saline and pooled at a concentration of 165 mg wet tissue weight/mL, corresponding to protein concentrations of 26.1 (human) and 13.1 (mouse) mg/mL, respectively. Collagen content of pooled human and mouse plaques was determined at 48 and 54 µg collagen/mg protein, respectively (Sircol collagen assay). Activity of TF in the homogenates was ≈ 10 pmol/mg protein, i.e. similarly as described earlier.

**Blood perfusion experiments.** Whole blood samples were perfused through a flow chamber over a coverslip coated with plaque material, as described. Coagulation of human blood was introduced by co-perfusion with 0.1 volume of CaCl₂ (75 mM), MgCl₂ (37.5 mM) in Hapes buffer A (136 mM NaCl, 5 mM Hapes, 2.7 mM KCl, 1 mg/mL glucose, 1 mg/mL BSA, pH 7.45) at 500 s⁻¹ for 10 minutes. Mouse blood was co-perfused with 0.5 volume of CaCl₂ (15 mM), MgCl₂ (7.5 mM) in Hapes buffer A supplemented with 0.42 mM Na₂H₂PO₄ at 1000 s⁻¹ for 6 minutes. After blood perfusion, thrombi on coverslips were rinsed with Hapes buffer supplemented with 2 mM CaCl₂, 2 mM MgCl₂, heparin (1 U/mL) and FITC-annexin A5 (0.5 µg/mL) for 2 minutes after which phase-contrast and fluorescence images were captured and analyzed as described.

**Thrombin generation.** Thrombin generation was measured in platelet-rich plasma (PRP) (1×10⁸ platelets/mL), as described. Coagulation was started with CaCl₂ by adding 1 volume of buffer C (2.5 mM Z-GGR-AMC, 20 mM Hapes, 140 mM NaCl, 100 mM CaCl₂ and 6% bovine serum albumin).

**Confocal microscopy.** Thrombi generated in flow chambers were blocked with goat serum (10%), rinsed and incubated with mouse anti-FXIIa monoclonal antibody (100 µg/mL). Alexa Fluor 647 (AF647)-labeled goat anti-mouse IgG (1:200) was used for staining. Alexa Fluor 488-labeled (AF488) annexin A5 was added to detect procoagulant platelets. Confocal overlays of differential interference contrast images with fluorescence images were recorded with a Plan-Apochromat 63x/1.40 oil differential interference contrast immersion objective on a Zeiss LSM Live7 microscope system (Zeiss, Jena, Germany).

**Statistical analysis.** Data are presented as means ± SE. Groups were compared using the non-parametric Mann-Whitney U test using the statistical package for social sciences (SPSS 15.0, Chicago, IL, USA). Size distribution of platelet aggregates was evaluated by χ² analysis. P<0.05 was considered significant.

**References**

are proinflammatory and procoagulant mediators in vivo. *Cell*. 2009;139:1143-1156


SUPPLEMENTAL MATERIAL

Detailed Methods

Animals. Apoe<sup>-/-</sup> mice with C57BL/6 background (4 weeks old) were obtained from Charles River (Sulzfeld, Germany). The Apoe<sup>-/-</sup> mice were fed a Western-type diet with 0.25% cholesterol for 18-20 weeks, at which time plaques had developed in the carotid arteries near the bifurcation. Animal experiments were approved by the research ethics committees of the universities of Maastricht and Stockholm.

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Thrombin generation and coagulation times. Thrombin generation was measured in platelet-rich plasma (PRP) (1×10<sup>8</sup> platelets/mL), as described. Coagulation was started with CaCl<sub>2</sub> by adding 1 volume of buffer C (2.5 mM Z-GGR-AMC, 20 mM Hepes, 140 mM NaCl, 100 mM CaCl<sub>2</sub> and 6% bovine serum albumin). Alternatively, clotting times were measured in PRP (3×10<sup>8</sup> platelets/mL), prepared and recalcified as above, with a KC4 coagulation device.
Suppl. Figure I
Stills of Suppl. videos I-III indicating the outline of the carotid artery (dotted lines), plaque area (“plaque”), platelet thrombi (red circles entitled “thrombus”) and direction of blood flow.

Legend for video files
Real time thrombus formation after ultrasound treatment in Apoe<sup>−/−</sup> mouse (suppl. video I), Apoe<sup>−/−</sup> mouse injected with CTI (suppl. video II) or Apoe<sup>−/−</sup> mouse injected with FVIIai (suppl. video III).
Suppl. Table I. Plaque material enhances platelet-dependent clotting via the intrinsic and extrinsic coagulation pathways. Platelet-rich plasma (PRP, 3 x 10^8 platelets/mL) was obtained in the presence of CTI (50 µg/mL); FVIIa (10 µg/mL) was added. Coagulation in PRP without or supplemented with plaque material (0.14 mg wet tissue weight/mL), was triggered by addition of CaCl_2 (7.5 mM) and MgCl_2 (3.75 mM), and clotting times were recorded up to 16.6 minutes. Mean ± SE (n=6), *p<0.05 compared to plaque material alone.

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<td>Plaque</td>
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<tr>
<td>Plaque + CTI</td>
<td>6.0 ± 0.9*</td>
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<tr>
<td>Plaque + FVIIa</td>
<td>8.0 ± 1.2*</td>
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<td>Plaque + CTI + FVIIa</td>
<td>12.6 ± 2.5*</td>
</tr>
</tbody>
</table>

Suppl. Table II. Human FXII moderates plaque- and collagen-induced thrombin generation in platelet-rich plasma. Thrombin generation was performed with platelet-rich plasma (PRP) from control subjects or a FXII-deficient subject (FXII def), as described for Fig. 5. Quantitative analysis of thrombin generation curves was for the parameters: lag time (minutes) and peak height (nM thrombin). Mean ± SE (n=5-10).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Control</th>
<th>FXII def</th>
<th>FXII def + hFXII</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRP</td>
<td>17.0 ± 1.8</td>
<td>0.0</td>
<td>6.8</td>
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<tr>
<td>+CTI</td>
<td>37.8 ± 4.6</td>
<td>0.0</td>
<td>-</td>
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<tr>
<td>+plaque</td>
<td>7.3 ± 0.5</td>
<td>20.7</td>
<td>4.5</td>
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<tr>
<td>+collagen</td>
<td>5.8 ± 0.4</td>
<td>23.4</td>
<td>3.8</td>
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<table>
<thead>
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<th>FXII def + hFXII</th>
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</thead>
<tbody>
<tr>
<td>PRP</td>
<td>53.9 ± 5.3</td>
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<tr>
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<tr>
<td>+plaque</td>
<td>89.2 ± 8.9</td>
<td>71.7</td>
<td>171.0</td>
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<tr>
<td>+collagen</td>
<td>104.6 ± 9.9</td>
<td>65.2</td>
<td>162.2</td>
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</tbody>
</table>
Supplemental References

