THROMBOSIS AND HEMOSTASIS

Differential contribution of FXa and thrombin to vascular inflammation in a mouse model of sickle cell disease

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Key Points

- Inhibition of FXa or thrombin might be considered to reduce thrombotic complications and vascular inflammation in sickle cell patients.
- PAR-2 could be a potential target to inhibit vascular pathology associated with sickle cell disease.

Introduction

Sickle cell disease (SCD) is a hematologic disorder caused by a single nucleotide mutation in the β-globin gene. Under hypoxic conditions, the mutation leads to abnormal polymerization of hemoglobin tetramers. Aggregation of abnormally large hemoglobin polymers results in the formation of sickle red blood cells that are susceptible to hemolysis, adhere to the endothelium, and form aggregates with leukocytes and platelets.1 These processes result in the 2 primary pathologies of SCD: hemolytic anemia and vaso-occlusive crises.2,3 Furthermore, SCD is also associated with a chronic activation of coagulation and vascular inflammation.

Despite the well-documented hypercoagulable state of SCD, little is known about the contribution of coagulation to the pathology of the disease. Clinical studies investigating the use of warfarin,4 acenocoumarol,5 and heparin6 in acute pain crises in sickle cell patients were inconclusive; however, these studies were performed on a small number of patients, lacked placebo controls, and used pain crises as the only clinical end point.7 Notably, the only adequately powered and placebo-controlled study to examine the effect of the low-molecular-weight heparin tinzaparin demonstrated a significant reduction in the duration of a painful crisis and hospital stay,8 suggesting that anticoagulants might be beneficial in SCD.

In SCD, increased expression of tissue factor (TF) has been demonstrated in both leukocytes and endothelial cells (ECs).9,10 We and others recently demonstrated that inhibition of TF inhibited activation of coagulation and attenuated the enhanced thrombosis in cerebral microvessels in sickle mice.11,12 Importantly, we demonstrated that inhibition of TF also reduced plasma levels of interleukin-6 (IL-6) and soluble vascular cell adhesion molecule-1 (sVCAM-1) as well as reduced local lung inflammation measured by tissue levels of myeloperoxidase (MPO). These data indicate that TF not only promotes activation of coagulation but also contributes to chronic vascular inflammation in a mouse model of SCD.11 Moreover, we have shown that EC-specific deletion of the TF gene significantly reduced plasma levels of IL-6 without affecting activation of coagulation,11 suggesting that EC TF contributes to the expression of IL-6 independent of thrombin generation.

Coagulation proteases, such as FXa and thrombin, can induce multiple cellular effects via activation of protease activated receptors (PARs). PARs are the family of G-protein-coupled receptors that are

Activation of coagulation and vascular inflammation are prominent features of sickle cell disease (SCD). Previously, we have shown that inhibition of tissue factor (TF) attenuates activation of coagulation and vascular inflammation in mouse models of SCD. In this study, we examined the mechanism by which coagulation proteases enhance vascular inflammation in sickle BERK mice. To specifically investigate the contribution of FXa and thrombin, mice were fed chow containing either rivaroxaban or dabigatran, respectively. In addition, we used bone marrow transplantation to generate sickle mice deficient in either protease activated receptor-1 (PAR-1) or protease activated receptor-2 (PAR-2) on nonhematopoietic cells. FXa inhibition and PAR-2 deficiency in nonhematopoietic cells attenuated systemic inflammation, measured by plasma levels of interleukin-6 (IL-6). In contrast, neither thrombin inhibition nor PAR-1 deficiency in nonhematopoietic cells affected plasma levels of IL-6 in sickle mice. However, thrombin did contribute to neutrophil infiltration in the lung, independently of PAR-1 expressed by nonhematopoietic cells. Furthermore, the TF-dependent increase in plasma levels of soluble vascular cell adhesion molecule-1 in sickle mice was not mediated by FXa or thrombin. Our data indicate that TF, FXa, and thrombin differentially contribute to vascular inflammation in a mouse model of SCD. (Blood. 2014;123(11):1747-1756)
activated by proteolytic cleavage. PAR-1 is activated by various proteases, including FXa and thrombin, whereas PAR-2 is activated by the TF/FVIIa complex, FXa, and other proteases. It has been demonstrated that coagulation protease-dependent activation of PARs contributes to inflammation in many vascular disorders.

In this study, we investigated the mechanism by which 2 coagulation proteases, FXa and thrombin, contribute to the vascular inflammation in sickle cell mice. We treated mice with either the direct FXa inhibitor rivaroxaban or the direct thrombin inhibitor dabigatran. We also determined the role of nonhematopoietic PAR-1 and PAR-2 by transplanting bone marrow (BM) from sickle mice into PAR-1−/− or PAR-2−/− deficient mice. Our results demonstrate that FXa and thrombin differentially contribute to the vascular inflammation in a mouse model of SCD.

### Methods

#### Mice

We used the Berkeley (BERK) mouse model of SCD. BERK mice have a transgene (Tg) containing normal human α−, γ−, δ-globins and sickle β-globin and targeted deletion of murine α− and β-globins (α−/−, β−/−, Tg). We generated these mice by intercrossing α−/−, β−/−, Tg males with α−/−, β−/−, Tg females. As a control, we used wild-type (WT) mice that have no human transgenes (α+1+/+, β+1+/+) on the similar mixed genetic background. These mice were used as a BM donor for experiments investigating the role of PAR-1 and PAR-2. Generation of PAR-1−/− and PAR-2−/− mice was previously described. They were backcrossed to a C57Bl/6J background for 10 generations, and experimental animals were generated by intercrossing PAR-1−/− or PAR-2−/− mice. For dabigatran and rivaroxaban experiments, we used BERKAA and BERKSS mice containing double copies of the transgenes.

#### BM transplantation

PAR-1−/−, PAR-1−/−, PAR-2−/−, and PAR-2−/− mice (8 weeks old) were lethally irradiated with 14 Gy (2 doses of 7 Gy 4 hours apart) with a 137Cs irradiator (Mark I Irradiator, L. J. Shepherd & Associates). Recipient mice were injected via the retro-orbital sinus with BM cells (4×10^6 nucleated cells) from BERK or WT control mice that do not express any human transgenes on the same mixed genetic background. These mice are referred to as BERKBM or WTBM. Mice were used for experiment 4 months later and samples were collected as described below. Reconstitution of BM was confirmed by electrophoretic analysis of the different forms of hemoglobin.

#### Optimizing the doses of dabigatran and rivaroxaban

NMRI mice were fed with chow containing dabigatran (Boehringer Ingelheim, Biberach, Germany) at various concentrations (0.75, 5, 10, and 15 mg/g chow) or matching placebo for 4 days. Blood was collected in the morning, and the concentration of dabigatran (the active compound) was assessed by liquid chromatography mass spectrometry. In similar studies, C57Bl/6J mice were fed with placebo or rivaroxaban (Janssen Pharmaceuticals, Bayer AG) at 0.0125, 0.2, or 0.4 mg/g chow (Dyets, Bethlehem, PA) for 10 days. Blood was collected in the morning, and prothrombin time (PT) was assessed in plasma as described below. To measure the plasma concentration of rivaroxaban in mice, the PT was compared with a standard curve generated by measuring the PT of normal mouse plasma containing known concentrations of rivaroxaban. We assumed that plasma concentrations of dabigatran and rivaroxaban would be at the peak in the morning because mice are nocturnal.

### Saphenous vein bleeding model

Eight-week-old male C57Bl/6J mice were fed chow containing placebo, dabigatran (10 mg/g chow), or rivaroxaban (0.4 mg/g chow) for 5 days. On the morning of the last day of treatment, the level of anticoagulation was determined using the saphenous vein bleeding model as previously described.

### Analysis of hematologic profile, PT, aPTT, TAT, sVCAM-1, and IL-6

Blood cell count and hematologic profile were determined using the automatic HEMAVET system (Drew Scientific, Inc.). PT was determined by a 1-stage clotting assay with a Start 4 Clotting Machine (Diagnostica Stago, Parsippany, NJ) using Thromboplastin D reagent (Thermo Scientific). Activated partial thromboplastin time (aPTT) of plasma samples was analyzed with TrinClot aPTT reagents (Diagnostica Stago). The plasma level of thrombin-antithrombin complex (TAT; Siemens Healthcare Diagnostics, IL-6, and sVCAM-1 (R&D Systems) was determined by enzyme-linked immunosorbent assay.

### Table 1. Hematologic parameters of BERKAA and BERKSS mice treated with dabigatran (10 mg/g chow) or placebo

<table>
<thead>
<tr>
<th>Variable</th>
<th>AA/Con</th>
<th>AA/Dab</th>
<th>SS/Con</th>
<th>SS/Dab</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBC (10^6/μL)</td>
<td>8.9 ± 0.1</td>
<td>9.2 ± 0.3</td>
<td>6.0 ± 0.3**</td>
<td>6.2 ± 0.5***</td>
</tr>
<tr>
<td>Hematocrit (%)</td>
<td>37.0 ± 0.6</td>
<td>37.1 ± 1.1</td>
<td>27.7 ± 1.5**</td>
<td>28.5 ± 2.1***</td>
</tr>
<tr>
<td>RDW (%)</td>
<td>18.6 ± 0.5</td>
<td>18.1 ± 0.3</td>
<td>28.1 ± 0.8</td>
<td>27.9 ± 1.4</td>
</tr>
<tr>
<td>WBC (10^9/L)</td>
<td>2.9 ± 0.4</td>
<td>3.5 ± 0.7</td>
<td>283 ± 5.5**</td>
<td>236 ± 4.4***</td>
</tr>
<tr>
<td>Neutrophil (10^3/μL)</td>
<td>0.8 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td>2.75 ± 0.5**</td>
<td>2.3 ± 0.4**</td>
</tr>
<tr>
<td>Lymphocyte (10^3/μL)</td>
<td>2.1 ± 0.2</td>
<td>2.7 ± 0.6</td>
<td>24.0 ± 4.9***</td>
<td>20.3 ± 3.9**</td>
</tr>
<tr>
<td>Monocyte (10^3/μL)</td>
<td>0.1 ± 0.01</td>
<td>0.1 ± 0.04</td>
<td>1.4 ± 0.3***</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>Platelet (10^3/μL)</td>
<td>566 ± 19</td>
<td>564 ± 17</td>
<td>568 ± 34</td>
<td>537 ± 43</td>
</tr>
</tbody>
</table>

Asterisks indicate statistical significance compared with BERKAA mice within the same treatment (*P < .05, **P < .01, and ***P < .001). There were no statistically significant differences in any parameters between dabigatran and control within BERKAA or BERKSS mice.

### Table 2. Hematologic parameters from BERKAA and BERKSS mice treated with rivaroxaban (0.4 mg/g chow) or placebo chow

<table>
<thead>
<tr>
<th>Variable</th>
<th>AA/Con</th>
<th>AA/Riv</th>
<th>SS/Con</th>
<th>SS/Riv</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBC (10^6/μL)</td>
<td>8.0 ± 0.7</td>
<td>8.2 ± 0.9</td>
<td>5.1 ± 0.7***</td>
<td>4.7 ± 0.8***</td>
</tr>
<tr>
<td>Hematocrit (%)</td>
<td>32.7 ± 3.1</td>
<td>33.1 ± 3.7</td>
<td>22.5 ± 3.8**</td>
<td>20.2 ± 3.7***</td>
</tr>
<tr>
<td>RDW (%)</td>
<td>18.3 ± 1.0</td>
<td>18.7 ± 2.1</td>
<td>28.6 ± 2.3**</td>
<td>29.1 ± 2.8***</td>
</tr>
<tr>
<td>WBC (10^9/L)</td>
<td>4.1 ± 2.1</td>
<td>3.92 ± 1.1</td>
<td>39.1 ± 10.7***</td>
<td>39.3 ± 13.1***</td>
</tr>
<tr>
<td>Neutrophil (10^3/μL)</td>
<td>0.9 ± 0.7</td>
<td>0.9 ± 0.4</td>
<td>3.9 ± 2.1***</td>
<td>3.5 ± 2.3***</td>
</tr>
<tr>
<td>Lymphocyte (10^3/μL)</td>
<td>3.0 ± 1.8</td>
<td>2.9 ± 0.9</td>
<td>33.1 ± 8.6**</td>
<td>33.6 ± 10.1***</td>
</tr>
<tr>
<td>Monocyte (10^3/μL)</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>2.0 ± 0.7***</td>
<td>2.2 ± 1.2***</td>
</tr>
<tr>
<td>Platelet (10^3/μL)</td>
<td>652 ± 85</td>
<td>626 ± 117</td>
<td>709 ± 144</td>
<td>688 ± 150</td>
</tr>
</tbody>
</table>

Asterisks indicate significant difference compared with BERKAA mice within the same treatment (**P < .001). There were no statistically significant differences in any parameters between Riv and Con within BERKAA or BERKSS mice.

Con, control placebo; Riv, rivaroxaban; WBC, white blood cell.
Table 3. Hematologic parameters from PAR-1+/− or PAR-1−/− mice transplanted with bone marrow from WT or sickle BERK (SS) mice

<table>
<thead>
<tr>
<th>Variable</th>
<th>WT/PAR-1+/−</th>
<th>WT/PAR-1−/−</th>
<th>SS/PAR-1+/−</th>
<th>SS/PAR-1−/−</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBC (10^12 μL)</td>
<td>7.4 ± 0.1</td>
<td>8.1 ± 0.3</td>
<td>4.9 ± 0.3**</td>
<td>4.0 ± 0.3***</td>
</tr>
<tr>
<td>Hematocrit (%)</td>
<td>35.3 ± 0.3</td>
<td>37.0 ± 0.6</td>
<td>26.4 ± 0.6***</td>
<td>24.6 ± 0.7***</td>
</tr>
<tr>
<td>RDW (%)</td>
<td>17.1 ± 0.8</td>
<td>16.2 ± 0.1</td>
<td>30.4 ± 0.5***</td>
<td>28.2 ± 0.4***</td>
</tr>
<tr>
<td>WBC (10^9 μL)</td>
<td>7.4 ± 1.9</td>
<td>10.9 ± 1.4</td>
<td>18.7 ± 1.5***</td>
<td>18.8 ± 1.9***</td>
</tr>
<tr>
<td>Neutrophil (10^9 μL)</td>
<td>1.4 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>3.9 ± 0.4*</td>
<td>4.6 ± 0.9**</td>
</tr>
<tr>
<td>Lymphocyte (10^9 μL)</td>
<td>5.7 ± 1.8</td>
<td>8.9 ± 1.4</td>
<td>13.5 ± 1.0***</td>
<td>12.9 ± 1.0</td>
</tr>
<tr>
<td>Monocyte (10^9 μL)</td>
<td>0.3 ± 0.04</td>
<td>0.5 ± 0.08</td>
<td>1.3 ± 0.2***</td>
<td>1.2 ± 0.1***</td>
</tr>
<tr>
<td>Platelet (10^11 μL)</td>
<td>699 ± 23</td>
<td>687 ± 21</td>
<td>690 ± 29</td>
<td>687 ± 43</td>
</tr>
</tbody>
</table>

Asterisks indicate statistical significance compared with WTBM mice within the same treatment (*P < 0.05, **P < 0.01, and ***P < 0.001). There were no statistically significant differences between PAR1+/− and PAR1−/− mice within WTBM or SSBM.

Analysis of MPO in lung tissue

Protein was isolated from lung as previously described, and total protein concentration was determined by the bicinchoninic acid protein assay (Bio-Rad, Hercules, CA). MPO levels were detected by enzyme-linked immunosorbent assay (Hycult Biotech, Plymouth Meeting, PA).

Table 4. Hematologic parameters from PAR-2+/− or PAR-2−/− mice transplanted with bone marrow from WT or sickle BERK (SS) mice

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>RBC (10^12 μL)</td>
<td>8.2 ± 0.7</td>
<td>8.6 ± 0.36</td>
<td>5.4 ± 0.7***</td>
<td>5.4 ± 0.6***</td>
</tr>
<tr>
<td>Hematocrit (%)</td>
<td>38.3 ± 3.4</td>
<td>40.5 ± 1.6</td>
<td>27.3 ± 5.2***</td>
<td>25.4 ± 3.6***</td>
</tr>
<tr>
<td>RDW (%)</td>
<td>17.0 ± 0.7</td>
<td>16.6 ± 0.3</td>
<td>31.7 ± 2.4***</td>
<td>31.9 ± 4.4***</td>
</tr>
<tr>
<td>WBC (10^9 μL)</td>
<td>12.9 ± 4.7</td>
<td>15.5 ± 4.7</td>
<td>19.4 ± 5.4*</td>
<td>19.1 ± 4.3</td>
</tr>
<tr>
<td>Neutrophil (10^9 μL)</td>
<td>2.2 ± 1.3</td>
<td>1.9 ± 0.8</td>
<td>5.38 ± 4.6</td>
<td>1.96 ± 0.58</td>
</tr>
<tr>
<td>Lymphocyte (10^9 μL)</td>
<td>10.5 ± 3.6</td>
<td>13.3 ± 3.9</td>
<td>13.0 ± 3.7</td>
<td>16.4 ± 4.0</td>
</tr>
<tr>
<td>Monocyte (10^9 μL)</td>
<td>0.31 ± 0.16</td>
<td>0.04 ± 0.05</td>
<td>0.96 ± 0.3***</td>
<td>0.92 ± 0.3***</td>
</tr>
<tr>
<td>Platelet (10^11 μL)</td>
<td>788 ± 84</td>
<td>734 ± 29</td>
<td>894 ± 161</td>
<td>914 ± 141*</td>
</tr>
</tbody>
</table>

Asterisks indicate statistical difference compared with WTBM within the same genotype (*P < 0.05 and ***P < 0.001). Hash sign indicates statistical difference between SS/PAR-2+/− and SS/PAR-2−/− (#P < 0.05).
mice; dabigatran-treated mice had a significantly longer mean hemostasis time than rivaroxaban-treated mice (Figure 1E). In addition, the number of clots formed during 30 minutes was significantly reduced in mice fed with chow containing rivaroxaban and dabigatran compared with mice fed with control chow, and dabigatran treatment had a significantly stronger effect compared with rivaroxaban treatment (Figure 1F). These data indicate that the dose of dabigatran used for the study had a more potent anticoagulant effect compared with the dose of rivaroxaban.

Effect of thrombin inhibition on vascular inflammation in SCD

BERKSS mice had significantly lower red blood cell (RBC) counts, hemoglobin levels, and hematocrits compared with BERKAA controls; thrombin inhibition with dabigatran had no effect on these parameters, indicating that thrombin inhibition does not affect hemolysis of sickle RBCs (Table 1). There was also a significant increase in white blood cell counts in BERKSS mice that was not affected by thrombin inhibition (Table 1). Dabigatran prolonged aPTT in both BERKAA and BERKSS mice compared with mice on placebo chow (Figure 2A). There was a significant increase in plasma TAT levels in BERKSS mice compared with BERKAA controls that was attenuated with dabigatran treatment (Figure 2B). BERKSS mice had elevated plasma levels of IL-6 and sVCAM-1 compared with BERKAA controls; however, thrombin inhibition had no effect on these parameters (Figure 2C-D). Importantly, thrombin inhibition significantly attenuated the increase in MPO levels (Figure 2E) and the number of neutrophils observed in the lungs of BERKSS mice (Figure 2F-G). These data indicate that TF-dependent thrombin generation has no effect on systemic inflammation but does contribute to local inflammation in the lung via a mechanism involving neutrophil recruitment.

Role of nonhematopoietic cell PAR-1 on vascular inflammation in SCD

To determine if the thrombin-mediated effect in the lung was PAR-1 dependent, we generated sickle cell mice lacking PAR-1 expression on all nonhematopoietic cells. PAR-1+/− and PAR-1−/− mice transplanted with BERKBM had significantly decreased RBC counts and hematocrits compared with mice transplanted with WTBM, indicating that deletion of PAR-1 from nonhematopoietic cells has no effect on anemia in sickle mice (Table 3). We also observed an increase in the total number of white blood cells in BERKBM mice; deletion of PAR-1 from nonhematopoietic cells had no effect on these parameters (Table 3). PAR-1−/− mice transplanted with sickle BM from BERK mice had significantly elevated plasma levels of TAT, sVCAM-1, and IL-6 (Figure 3A-C), indicating that transplantation with sickle cell BM caused coagulation activation, vascular inflammation, and EC activation. PAR-1 deletion from all nonhematopoietic cells did not attenuate any of these parameters (Figure 3A-C). Furthermore, PAR-1+/− mice transplanted with sickle BM had significantly elevated MPO levels and the number of neutrophils in the lungs; however, these parameters were not affected by deletion of PAR-1 from nonhematopoietic cells (Figure 3D-E). These data
suggest that thrombin contributes to local lung inflammation in sickle cell mice independently of PAR-1 activation on nonhematopoietic cells.

**Effect of FXa inhibition on vascular inflammation in SCD**

FXa inhibition had no effect on markers of anemia in BERKSS mice, nor did it affect leukocytosis (Table 2). Rivaroxaban significantly prolonged PT in both BERKAA and BERKSS mice compared with mice on placebo chow (Figure 4A). Furthermore, the increase in plasma TAT levels observed in BERKSS mice was attenuated by rivaroxaban (Figure 4B), whereas increased levels of sVCAM-1 were not affected (Figure 4C). Interestingly, we observed a significant decrease in neutrophil numbers in PAR-2−/− sickle mice compared with sickle PAR-2+/+ controls (Table 4).

PAR-2+/+ mice transplanted with BERKBM had significantly increased plasma TAT, sVCAM-1, and IL-6 levels (Figure 5A-C). Deletion of PAR-2 from nonhematopoietic cells had no effect on TAT or sVCAM-1 but dramatically reduced the increase in plasma levels of IL-6 in sickle mice (Figure 5A-C). These data indicate that PAR-2 contributes to systemic inflammation. Furthermore, PAR-2 deletion from nonhematopoietic cells attenuated the increase in MPO levels (Figure 5D) and the number of neutrophils in the lungs of BERKBM mice (Figure 5E).

**Role of nonhematopoietic cell PAR-2 on vascular inflammation in SCD**

Next, we determined if the proinflammatory effect of FXa in sickle cell mice is due to activation of PAR-2 on nonhematopoietic cells. PAR-2+/+ and PAR-2−/− mice were lethally irradiated and transplanted with WTBM or BERKBM. As expected, reconstitution with BM from BERK mice significantly decreased RBC counts, hemoglobin, and hematocrit in PAR-2+/+ mice, and deletion of PAR-2 from nonhematopoietic cells had no effect on these parameters (Table 4). Interestingly, we observed a significant decrease in neutrophil numbers in PAR-2−/− sickle mice compared with sickle PAR-2+/+ controls (Table 4).
Discussion

The vascular pathology of SCD is characterized by chronic activation of coagulation and inflammation. In our previous study, we demonstrated that inhibition of TF reduced plasma levels of sVCAM-1 and IL-6, as well as MPO, in the lungs of sickle mice, indicating a crosstalk between coagulation and inflammation.11 TF-dependent coagulation activation results in the generation of the downstream coagulation proteases FXa and thrombin, which increase inflammation, in part, by activating PARs.11 In this study, we investigated the role of FXa, thrombin, PAR-1, and PAR-2 in vascular inflammation in a mouse model of SCD.

The hypercoagulable state of SCD is well characterized. Rivaroxaban and dabigatran are new direct inhibitors of FXa and thrombin, respectively, which were recently approved to prevent stroke and venous thromboembolism.26-29 We found that feeding mice dabigatran (10 mg/g chow) or rivaroxaban (0.4 mg/g chow) resulted in plasma levels of the active drugs similar to those seen in human patients receiving 150 mg of dabigatran twice daily30 or rivaroxaban 10 mg once daily.31 Dabigatran and rivaroxaban significantly prolonged the aPTT and PT, respectively, which were recently approved to prevent stroke and venous thromboembolism.26-29 We found that feeding mice dabigatran (10 mg/g chow) or rivaroxaban (0.4 mg/g chow) resulted in plasma levels of the active drugs similar to those seen in human patients receiving 150 mg of dabigatran twice daily30 or rivaroxaban 10 mg once daily.31 Dabigatran and rivaroxaban significantly prolonged the aPTT and PT, respectively, in both BERKAA and BERKSS mice and normalized plasma TAT levels in BERKSS mice without causing spontaneous bleeding. These data indicate that both FXa and thrombin inhibition can anticoagulate sickle cell mice and that treatment with the new oral anticoagulants might reduce thrombotic complications in SCD.

Importantly, inhibition of either FXa or thrombin resulted in a reduction in the elevated MPO levels in the lungs of sickle cell mice similar to that observed in sickle mice treated with anti-TF antibody.11 These results suggest that TF contributes to local lung inflammation in a thrombin-dependent manner. Importantly, dabigatran-treated BERKSS mice also demonstrated reduced number of neutrophils in the lung tissue, indicating that increased levels of MPO observed in the lung of BERKSS mice resulted from thrombin-mediated neutrophil infiltration rather than from thrombin-mediated neutrophil activation. Surprisingly, deletion of PAR-1 from nonhematopoietic cells did not attenuate neutrophil numbers or lung MPO levels in sickle mice, suggesting that PAR-1 activation on nonhematopoietic cells is not essential for thrombin-mediated neutrophil recruitment into the lung. One possibility is that thrombin contributes to neutrophil recruitment via a fibrin- or fibrin degradation product-dependent mechanism. For instance, the E1 fibrin degradation fragment has been shown to facilitate neutrophil-EC interactions and mediates infiltration of neutrophils into inflamed tissue.32 Inhibition of thrombin would reduce formation of the E1 fragment and may explain, in part, the anti-inflammatory effects of dabigatran in the lung. Inhibition of this pathway may also reduce neutrophil infiltration in BERKSS mice treated with rivaroxaban.

Our previous study showed that EC-specific deletion of the TF gene selectively reduced plasma levels of IL-6 without affecting any other parameters, including TAT.11 These results strongly suggested that in sickle mice, EC TF contributes to the increased expression of IL-6 independently of thrombin generation. Consistent with this notion, our current study demonstrated that neither thrombin inhibition nor deletion of PAR-1 from nonhematopoietic cells reduced plasma levels of IL-6. In contrast, FXa inhibition abolished the increase in plasma levels of IL-6 in BERKSS mice, similar to that observed in sickle mice treated with anti-TF antibody or lacking the TF gene in ECs.11 Because prolongation of the saphenous vein bleeding time was significantly longer in dabigatran-fed mice than in rivaroxaban-fed mice, the absence of an effect on IL-6 levels in...
BERKSS fed with dabigatran cannot be attributed to insufficient anticoagulation. Therefore, we proposed that EC TF contributes to IL-6 expression via a mechanism involving FXa-dependent activation of PAR-2 in nonhematopoietic cells. Whether PAR-2 activation is mediated by the ternary TF:FVIIa:FXa complex assembled on the EC surface or by locally generated FXa remains to be determined.

PAR-2 deletion from nonhematopoietic cells not only reduced plasma levels of IL-6 but also completely attenuated lung MPO levels and the number of neutrophils in the lungs, indicating that activation of PAR-2 in nonhematopoietic cells plays a crucial role in the recruitment/activation of neutrophils in SCD. At this point, we do not know if this PAR-2-mediated effect results from FXa-dependent activation of the receptor. It is possible that other PAR-2 agonists, such as mast cell tryptase, can also contribute to this response. Indeed, elevated levels of mast cell tryptase have been reported in BERKSS mice compared with BERKAA controls. Furthermore, PAR-2 contributed to the neutrophilia, which is commonly observed in both sickle cell patients and animal models of SCD. Sickle cell mice lacking PAR-2 in all nonhematopoietic cells had a significantly reduced number of circulating neutrophils compared with PAR-2–proficient sickle cell mice. Interestingly, neutrophilia was not affected by inhibition of TF or by rivaroxaban or dabigatran treatment, further supporting the concept that in sickle cell mice, PAR-2 can be activated by ligands other than coagulation proteases. In support of this, neutrophilia is attenuated in BERKSS mice lacking mast cells, suggesting that mast cell tryptase-dependent PAR-2 activation might play a role in neutrophilia in SCD.

Deletion of PAR-1 from nonhematopoietic cells had no effect on coagulation, systemic inflammation, or EC activation in BERKBM mice. Although thrombin is the main physiologic ligand for PAR-1, a recent study demonstrated that PAR-1 can be also activated by activated protein C (APC). In contrast to thrombin-mediated activation of PAR-1, APC-dependent cleavage of PAR-1 requires the presence of endothelial protein C receptor and results in antiapoptotic and anti-inflammatory effects. The APC pathway is activated in sickle cell patients, most likely due to the prothrombotic state associated with SCD. Our results from BERKBM, PAR-1−/− mice suggest that endogenous APC:ECPR- PAR-1 signaling pathway does not play a major role in vascular inflammation in SCD. However, both administration of exogenous APC and genetic overexpression of the endothelial protein C receptor protected sickle mice from cerebral microvascular thrombosis, which warrants further studies to investigate both anticoagulant and possibly anti-inflammatory effects of exogenous APC administration.

Pulmonary hypertension (PH) is a common clinical complication of SCD, but the etiology has yet to be defined. Proposed mechanisms include vasconstriction and endothelial dysfunction due to nitric oxide depletion or the hypercoagulable state and chronic inflammation. Indeed, SCD patients with PH have higher levels of coagulation and inflammation biomarkers compared with the sickle cell patients without PH. There is an emerging concept that inflammation is an important proximal mediator in the generation of PH in the general population. Recent studies demonstrated that rivaroxaban treatment, as well as PAR-2 or IL-6 deficiency, attenuates PH in animal models. Also, there is at least 1 case report in which PH

Figure 4. Role of FXa in vascular inflammation in SCD. (A-F) PT (A) and plasma levels of TAT (B), sVCAM-1 (C), IL-6 (D), and MPO (E) in the lungs and average number of neutrophils (F) in lungs of BERKAA (n = 16) and BERKSS (n = 13-15) mice fed with chow containing rivaroxaban (Riv) or placebo control (Con) for 10 days. Asterisks directly above bars indicate statistical significance between BERKSS mice compared with BERKAA mice within the same treatment group (Con or Riv) (*P < .05, **P < .01, ***P < .001).
improved in a patient treated with an IL-6 receptor-blocking antibody. Therefore, our data from PAR-2–deficient mice and rivaroxaban experiments imply that targeting FXa-mediated PAR-2 activation may reduce IL-6 expression and potentially attenuate PH in SCD.

ECs are chronically activated in SCD, in part due to increased adherence of sickle RBCs and activated leukocytes, as well as high levels of cell-free hemoglobin and heme in the blood. We previously found that inhibition of TF with a rat monoclonal antibody called 1H1 attenuates EC activation in sickle cell mice, as measured by plasma levels of sVCAM-111; however, deletion of TF from ECs11 or low levels of TF in all nonhematopoietic cells (data not shown) had no effect on plasma levels of sVCAM-1. In the present study, neither FXa nor thrombin inhibition had any effect on this marker of EC activation in BERKSS mice. Moreover, nonhematopoietic PAR-1 and PAR-2 also did not affect plasma

Figure 5. Role of PAR-2 in vascular inflammation in SCD. (A-E) Plasma levels of TAT (A), sVCAM-1 (B), IL-6 (C), and MPO (D) and average number of neutrophils (E) in the lung of PAR-2+/+ or PAR-2−/− mice transplanted with bone marrow from WT (n = 8-9) or BERK (n = 8-12) mice. (F) Representative lung sections demonstrating neutrophil infiltration in four different groups of mice. Neutrophils stain as brown. Asterisks directly above the bars indicate statistically significant difference between BERKBM mice compared with WTBm mice within the same PAR-2 genotype (∗P < .05, **P < .01, and ***P < .001).

Figure 6. Proposed role of FXa and thrombin in vascular inflammation in SCD. FSP, fibrin split product.
levels of sVCAM-1 in sickle cell mice. These data suggest that the TF-dependent increase in plasma levels of sVCAM-1 is mediated by TF:FVIIa signaling in hematopoietic cells, which then indirectly results in EC activation. An alternative hypothesis is that alternatively spliced TF (asTF), a truncated, soluble form of TF, might mediate EC activation.\(^\text{52}\) It was recently demonstrated that interaction between human asTF and \(\beta_1\) integrin increases the expression of adhesion molecules, including VCAM-1, on microvascular ECs and modulates monocyte-EC interactions.\(^\text{53}\) However, future studies will have to determine if 1H1 antibody can disrupt asTF- \(\beta_1\) integrin interactions and the possible contribution of asTF to vascular inflammation in SCD.

SCD is one of a few pathological conditions in which TF expression is upregulated not only on leukocytes but also on ECs. Our data indicate that TF expressed by different cell types has specific roles in the pathology of the disease (Figure 6). We propose that EC TF does not contribute to the activation of coagulation in SCD but instead contributes to systemic inflammation mediated by FXa-dependent activation of PAR-2 on ECs. The fact that deletion of TF from ECs\(^\text{13}\) or low levels of TF in nonhematopoietic cells (data not shown) does not affect coagulation activation in sickle cell mice suggests that hematopoietic cells are the major source of TF that is responsible for the activation of coagulation. Indeed, increased TF expression by monocytes strongly correlates with markers of coagulation activation in sickle cell patients.\(^\text{54}\)

In summary, we have demonstrated that FXa and thrombin differentially contribute to the vascular inflammation in a mouse model of SCD. We identified PAR-2 as a potential target to inhibit vascular pathology associated with SCD. We also demonstrated that recently developed oral anticoagulants dabigatran and rivaroxaban might be useful in treating sickle cell patients by reducing thrombotic complications as well as reducing both systemic and local inflammatory responses.

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### Authorship

**Contribution:** E.M.S. and P.C. designed the experiments, performed the experiments, and interpreted the data; N.M., D.M.M., and N.S.K. aided in data interpretation and editing the manuscript; R.P.H. and J.V.R. provided valuable reagents and critically read the manuscript; D.M.M. designed and J.M. performed the hemostasis experiment; and R.P. designed the experiments, interpreted the data, wrote the manuscript, and contributed to the overall design of the study.

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