Effects of Thrombin Inhibitor on Thrombin-Related Signal Transduction and Cerebral Vasospasm in the Rabbit Subarachnoid Hemorrhage Model

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Background and Purpose—Thrombin is activated in the cerebrospinal fluid (CSF) after a subarachnoid hemorrhage (SAH). However, the relationship between thrombin and cerebral vasospasm has not yet been fully established. The aim of this study was to investigate the possibility of thrombin as a causative factor for cerebral vasospasm and to delineate the signal transduction mechanism that results in thrombin-inducing sustained vasoconstriction in cerebral vasospasm.

Methods—In the SAH group, SAH was simulated by the 2-hemorrhage rabbit model. In the treatment group, antithrombin III (AT-III) was injected into the cisterna magna just before production of the SAH. CSF samples were obtained serially to measure d-dimer with latex photometric immunoassay. On day 4, the basilar artery was excised after perfusion-fixation. The degree of cerebral vasospasm was evaluated by measuring the cross-sectional area of each basilar arterial lumen, and the expression of mitogen-activated protein kinase (MAPK) in the vascular wall was examined with an immunohistochemical technique.

Results—In the treatment group, the value of d-dimer on day 4 was 0.83±0.07 µg/mL, which was statistically significantly lower than that in the nontreated SAH group (2.49±0.09 µg/mL, P<0.01). The cross-sectional area of the arterial lumen in the treatment group was 3.67×10²±1.58×10³ square pixels, which was statistically significantly larger than that in the nontreated SAH group (2.60×10²±2.29×10³ square pixels; P<0.01). MAPK was detected diffusely in the vascular smooth muscle cell layer in the nontreated SAH group, but it was absent in the treatment group.

Conclusions—Inhibition of thrombin activity leads to amelioration of cerebral vasospasm and suppression of MAPK diphosphorylation. This suggests that thrombin and its related signal transduction, including the MAPK cascade, appear to play an important role in the pathogenesis of cerebral vasospasm after SAH. (Stroke. 2003;34:1497-1500.)

Key Words: subarachnoid hemorrhage • thrombin • vasospasm • rabbits

Cerebral vasospasm after an aneurysmal subarachnoid hemorrhage (SAH) is characterized by the prolonged and reversible contraction of the cerebral arteries.¹,² This vasospasm is 1 of the most important factors affecting the functional prognosis of patients. Although various spasmogens and origins have been studied, the pathogenesis of vasospasm remains unclear.³ Recently, it has been suggested that thrombin may play an important role in the pathogenesis of vasospasm because several clinical studies have revealed that thrombin activity in the cerebrospinal fluid (CSF) after SAH is significantly elevated in patients with symptomatic vasospasm.⁴ However, details of how thrombin is associated with the pathogenesis of vasospasm have not been fully established, although a single study has revealed that argatroban, a synthetic and specific thrombin inhibitor, could prevent cerebral vasospasm in a rabbit SAH model.⁵ Although several in vitro studies have shown that thrombin induces a sustained contraction through some intracellular signaling pathway,⁶ the detailed mechanisms of this thrombin-induced sustained contraction have not been clarified in vivo, especially as it relates to cerebral vasospasm.

The aims of this study were to investigate, through the use of the double-hemorrhage rabbit model,⁷,⁸ the possibility that thrombin plays a role in vasospasm as a spasmogen and to delineate the mechanism of the signal transduction that causes the sustained vasoconstriction in cerebral vasospasm. Antithrombin III (AT-III) was injected into the cisterna magna to inhibit thrombin activity. The prevention of cerebral vasospasm by AT-III and associated changes in the regulation of mitogen-activated protein kinase (MAPK) as a marker of the signaling pathway were examined.

Materials and Methods
All experimental protocols were approved by the Hirosaki University Animal Research Committee. Twenty Japanese white rabbits weighing 2.8 to 3.3 kg were used. All animals were randomly assigned to 4 groups: group 1 (SAH), SAH was produced and animals were given an intracisternal injection of vehicle (distilled water); group 2...
(SAH-AT-III), SAH was produced and the animals were given an intracisternal injection of AT-III; group 3 (untreated controls), animals served as an untreated normal control; and group 4 (treated control), animals were subjected to an intracisternal injection of AT-III without the production of SAH to serve as a treated control.

**Production of SAH**
In groups 1 and 2, SAH was produced according to the double-hemorrhage method. With a 27-gauge butterfly needle, pentobarbital (30 mg/kg) was injected into the central ear vein over 1 to 2 minutes. After anesthesia, under spontaneous breathing, a 23-gauge butterfly needle was percutaneously placed in the cisterna magna, and CSF (1.0 to 1.8 mL) was aspirated under aseptic technique before each blood injection. The central ear artery was cannulated to obtain autologous arterial blood. Autologous nonheparinized arterial blood was injected into the cisterna magna over 1 to 2 minutes. Then, the animals were placed in a 30° head-down tilted position for 15 minutes to ensure that the blood spread into the basal cistern. Forty-eight hours after the first SAH, a second one was produced in the same manner as the first. In group 4, an intracisternal injection of AT-III was given twice (same procedure as used in group 2) but without the production of SAH so that this group could serve as a treated control.

**Injection of AT-III or Vehicle**
In group 2, AT-III was administered before each blood injection to inhibit thrombin activity in the CSF. We dissolved 25 U AT-III in distilled water (total volume, 0.5 mL) and injected it into the cisterna magna over 1 to 2 minutes. In group 1, instead of injecting AT-III, we injected 0.5 mL distilled water into the cisterna magna in the same manner as in group 1 before each blood injection.

In group 4, an intracisternal injection of AT-III was given twice (same procedure as used in group 2) but without the production of SAH so that this group could serve as a treated control.

**Biochemical Evaluation**
For the purpose of evaluating thrombin activity, we measured the levels of D-dimer in the CSF 3 times in groups 1, 2, and 4. CSF samples were obtained from the cisterna magna just before the injection of AT-III or vehicle on days 0 and 2. A CSF sample was also obtained from the cisterna magna just before the animals were killed on day 4. In group 3, CSF was taken once, and the animal was killed. All samples were immediately stored at -80°C until analysis. D-Dimer was assayed with latex photometric immunoassay.

**Histological Evaluation**
In groups 1, 2, and 4, perfusion-fixation was performed on day 4 after the CSF was sampled for the evaluation of D-dimer. Animals were then anesthesia deeply with 100 mg/kg pentobarbital, the thorax was opened, and a cannula was immediately inserted into the ascending aorta via the left ventricle. Perfusion was performed at 75 mm Hg with 300 mL heparinized physiological saline (5000 U/500 mL), followed by 500 mL of phosphate-buffered 4% paraformaldehyde (pH 7.4). Finally, the brain was carefully removed so as not to stretch and injure the basilar artery. Group 3 underwent perfusion-fixation without any previous operation except for the injection of AT-III in distilled water (total volume, 0.5 mL) and injected it into the cisterna magna via the left ventricle. Perfusion was performed at 75 mm Hg with 300 mL heparinized physiological saline (5000 U/500 mL). A total of 100 mL autologous arterial blood. Autologous nonheparinized arterial blood was injected into the cisterna magna over 1 to 2 minutes. Then, the animals were placed in a 30° head-down tilted position for 15 minutes to ensure that the blood spread into the basal cistern. Forty-eight hours after the first SAH, a second one was produced in the same manner as the first. In group 4, an intracisternal injection of AT-III was given twice (same procedure as used in group 2) but without the production of SAH so that this group could serve as a treated control.

**Thrombin Activity (D-Dimer)**
The cutoff value of D-dimer in the CSF is 0.5 μg/mL, and values >0.5 μg/mL can be detected. D-Dimer was not detected in the CSF taken on day 0 in groups 1, 2, and 4 and at the time just before death in group 3. On day 4, there was a significant difference between groups 1 and 2 (P<0.01).

**Statistical Analysis**
The Mann-Whitney U test was used to compare the intensity score among the groups. To compare 2 unpaired groups, the t test was used. Multiple comparisons of the data were analyzed by analysis of variance (ANOVA, Bonferroni’s method).

**Results**

**Thrombin Activity (D-Dimer)**
The cisternal CSF D-dimer levels were 0.5 μg/mL on days 0, 2, and 4. Values are presented as mean±SEM. D-Dimer was not detected in the CSF taken on day 0 in groups 1, 2, and 4 and at the time just before death in group 3. On day 4, there was a significant difference between groups 1 and 2 (P<0.01).

**Evaluation of Cerebral Vasospasm**
The mean basilar artery cross-sectional area was 4.56×10^4±0.76×10^4 μm^2 in group 3 and 4.61×10^3±0.47×10^3 μm^2 in group 4 (P=NS). Thus, the mean basilar artery cross-sectional area was not affected by the injection of AT-III without SAH production. The average cross-sectional...
The change in lumen cross-sectional area was \( \approx 25\% \) (with a 12% reduction in vessel diameter) for groups 1 and 2 compared with group 3. In addition, there was a statistically significant difference in the mean cross-sectional area between groups 1 and 2 (\( P < 0.01 \)). Marked corrugation of the internal elastic lamina around the wall, with thickening of the vascular smooth muscle layer, was seen in group 1 (Figure 3A). In contrast, the corrugation was much less remarkable in group 2 (Figure 3B). Therefore, in this study, the histological findings reflected the cross-sectional area measurements, with larger luminal cross-sectional areas corresponding to less corrugation of the internal elastic lamina.

### MAPK Activity

In both groups 3 and 4, MAPK was not detected in the smooth muscle cells, which was evaluated as a score of 0. In group 1, MAPK was detected diffusely at the vascular smooth muscle layer (Figure 3C). Immunoreactivity was better visualized compared with the background, and the average score was 1.8. In contrast, all sections of group 2 showed lower MAPK immunoreactivity (Figure 3D), with an average score of 0.2. With the Mann-Whitney \( U \) test, a statistically significant difference in MAPK scores was found between groups 1 and 2 (\( P < 0.01 \); the Table).

### Discussion

Although it is known that prothrombin exists in the CSF, thrombin has not yet been confirmed to be present in normal CSF. Nevertheless, once bleeding into the subarachnoid space occurs, thrombin is activated rapidly and remains at a high level because a firm, persistent fibrin network is produced through activation of the coagulation system in the subarachnoid space. Furthermore, CSF thrombin is only minimally inactivated by the AT-III found in circulating blood and by the thrombomodulin found in vascular endothelial cells. A previous study has shown that post-SAH CSF thrombin activity is correlated with the persistence of blood and development of vasospasm.

After SAH, it has been found that levels of thrombin–AT-III complex and prothrombin fragment F1+2, both molecular markers of CSF thrombin activation, are elevated and that these levels correlate well with both the clinical severity at the onset of SAH and the occurrence of cerebral vasospasm. In the present study, CSF thrombin activity was evaluated by measuring D-dimer. D-Dimer, the decomposition product of fibrin, reflects thrombin activity, as do the thrombin–AT-III complex, prothrombin fragment F1+2, and fibrinopeptide A. After SAH, D-dimer is found in the CSF with a high sensitivity. Results of this study revealed that increased CSF thrombin activity was seen in the SAH plus distilled water (untreated control) group.

To inhibit thrombin activity, we used AT-III. AT-III, with a molecular weight of \( \approx 59,000 \) U, is an endogenous plasma glycoprotein that inhibits a number of serine proteases.
Results of the present study showed that intrathecal administration of AT-III significantly decreased the CSF levels of α-d-dimer compared with the SAH control group. The decrease in α-d-dimer resulting from intrathecal administration of AT-III paralleled the increase in cross-sectional areas, which demonstrated the improvement of the cerebral vasospasm. Therefore, thrombin in the CSF may be involved in the pathogenesis of cerebral vasospasm.

Smooth muscle contraction was thought to be caused by myosin light-chain phosphorylation induced by an increase in intracellular Ca\(^{2+}\) concentration, followed by the sliding of myosin and actin proteins. However, several studies have revealed that myosin light-chain phosphorylation is not up-regulated and that high-energy phosphates decline during cerebral vasospasm. Thus, mechanisms that can cause vasospasm by processes other than that associated with myosin light-chain phosphorylation must be considered. Therefore, various intracellular signal transduction pathways have been investigated in association with cerebral vasospasm.

Recently, the MAPK (ERK1&2) cascade has been thought to play an important role in cerebral vasospasm. MAPK is a family of serine/threonine protein kinases involved in cell growth, transformation, and proliferation through the activation of transcription factors and target genes. It also plays an important role in prolonged smooth muscle contraction by phosphorylating caldesmon, which is a thin filament-associated protein that inhibits α-actin. Zubkov et al\(^3\) revealed that tyrosine kinase and MAPK cascades play a role in hemolysate-induced contraction of rabbit cerebral arteries, a process that is independent of intracellular Ca\(^{2+}\) concentration. The MAPK cascade is thought to be upregulated by tyrosine kinase activated as a result of growth factors such as platelet-derived growth factor\(^1\) and by protein kinase C activation as a result of a G protein-coupled receptor agonist.\(^3\)

An in vitro study using bovine aorta showed that thrombin caused sustained contraction through the activation of the MAPK cascade.\(^6\) However, the role of MAPK cascade activation in thrombin-induced cerebral vasospasm has not been evaluated in vivo.

Previous studies have revealed that in situ distribution of the active, dual phosphorylated form of MAPK (ERK1&2) could be visualized in a wide range of organisms by immunohistochemistry with a specific monoclonal antibody. In the present study, a similar technique was used to evaluate MAPK activity in the arterial wall. Results showed that MAPK detection was markedly increased in the vascular smooth muscle cell layer after SAH production but that it was diminished through the suppression of thrombin activity achieved by the intrathecal administration of AT-III. Therefore, sustained contraction during cerebral vasospasm may be attributed partially to activation of the MAPK cascade induced by thrombin. We propose that triggering of the MAPK cascade results in the phosphorylation of caldesmon, which plays an important role in prolonged smooth muscle contraction. In short, thrombin stimulates tyrosine phosphorylation of growth factor receptors, and the activation of the receptor tyrosine kinases then stimulates the MAPK cascade, which phosphorylates caldesmon and leads to contraction.

Clearly, the detailed mechanism of cerebral vasospasm in association with signal transduction, including the MAPK cascade, should be investigated in the future. Yet, the results of this study suggest that the inhibition of thrombin activity could be a powerful preventive therapy for cerebral vasospasm.

References
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