Neutrophil-Derived Matrix Metalloproteinase 9 Triggers Acute Aortic Dissection

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Background—Acute aortic dissection (AAD) is a life-threatening vascular disease without effective pharmaceutical therapy. Matrix metalloproteinases (MMPs) are implicated in the development of chronic vascular diseases including aneurysm, but the key effectors and mechanism of action remain unknown. To define further the role of MMPs in AAD, we screened circulating MMPs in AAD patients, and then generated a novel mouse model for AAD to characterize the mechanism of action.

Methods and Results—MMP9 and angiotensin II were elevated significantly in blood samples from AAD patients than in those from the patients with nonruptured chronic aortic aneurysm or healthy volunteers. Based on the findings, we established a novel AAD model by infusing angiotensin II to immature mice that had been received a lysyl oxidase inhibitor, β-aminopropionitrile monofumarate. AAD was developed successfully in the thoracic aorta by angiotensin II administration to β-aminopropionitrile monofumarate-treated wild-type mice, with an incidence of 20%, 80%, and 100% after 6, 12, and 24 hours, respectively. Neutrophil infiltrations were observed in the intima of the thoracic aorta, and the overexpression of MMP9 in the aorta was demonstrated by reverse transcription polymerase chain reaction, gelatin zymography, and immunohistochemistry. The incidence of AAD was reduced significantly by 40% following the administration of an MMP inhibitor and was almost blocked completely in MMP−/− mice without any influence on neutrophil infiltration. Neutrophil depletion by injection of anti-granulocyte-differentiation antigen-1 (anti-Gr-1) antibody also significantly decreased the incidence of AAD.

Conclusions—These data suggest that AAD is initiated by neutrophils that have infiltrated the aortic intima and released MMP9 in response to angiotensin II. (Circulation. 2012;126:3070-3080.)

Key Words: acute aortic dissection ■ MMP9 ■ leukocytes ■ angiotensin II
they are not suitable for AAD models with regard to predicting the actual onset of the dissection, which is critical for understanding the pathogenesis of the disease.

Clinical Perspective on p 3080

Recent studies have demonstrated that matrix metalloproteinases (MMPs), including MMP1, 2, 3, and 9, are overproduced in a wide range of vascular diseases. Among these MMPs, the importance of MMP9 has been documented in the development of chronic aortic aneurysm formation as a function of its ability to degrade extracellular matrix components directly, such as elastin. The increased expression of MMP9, predominantly from macrophages, has also been implicated in acute vascular crises such as atherosclerotic plaque rupture and abdominal aortic aneurysm. However, little or no information is available for the involvement of MMP9 in the development of AAD.

In the current study, we found significant elevation of MMP9 and angiotensin II (AngII) in human blood samples from AAD patients. Based on these findings, we established a novel mouse model of AAD by AngII infusion following sustained administration of BAPN. Upregulation of MMP9 from neutrophils was noted at the onset of the disease in this model. More important, genetic and pharmaceutical depletion of MMP9 attenuated dramatically the occurrence rate of AAD without impairing neutrophil infiltration. Furthermore, AngII per se induced neutrophil infiltration into aortic lesions, and neutrophil depletion by neutralizing antibody also attenuated AAD incidence. Taken together, our study provides the first evidence that MMP9 released from AngII-stimulated neutrophils initiates AAD in preconditioned aorta.

Methods

Human Blood and Affected Aortic Samples

Between April 2004 and August 2006, 16 patients diagnosed with AAD, 11 patients with acute myocardial infarction (AMI); 12 patients with chronic, nonruptured aortic aneurysm; and 16 healthy volunteers were registered in the study. All the AAD patients were free from connective tissue disorders such as Marfan syndrome, Ehlers-Danlos syndrome, and aortitis diagnosed according to the clinical history and physical examinations. They were composed of Stanford type A (6 patients) and type B (10 patients). The blood samples from AAD and AMI patients were collected within 1 hour after arrival in the hospital emergency room. AAD and AMI patients who arrived 10 hours after onset of clinical symptoms were eliminated from the study. Diagnosis of AAD and AMI was confirmed by Giemsa stain of peripheral blood smears. All studies in mice were approved by the Laboratory Animal Care and Use Committee of School of Medicine, Keio University.

Development of AAD Model in Mice

Wild-type (WT) and MMP9−/− mice on FVB background were purchased from Jackson Laboratory (Bar Harbor, ME). Three-week-old male mice were fed on a regular diet and administered BAPN (Sigma-Aldrich, St. Louis, MO) dissolved in drinking water (1 g/kg per day) for 4 weeks. At 7 weeks of age, osmotic mini pumps (Alzet, Cupertino, CA) filled with 1 µg/kg per minute AngII (Sigma-Aldrich) or 1.3 µg/kg per minute norepinephrine (NE) (kindly provided by Daichi-Sankyo Co. Ltd., Tokyo, Japan) were implanted subcutaneously as described previously, and the mice were euthanized 24 hours after implantation. Blood pressure was measured using the tail-cuff method before and after implantation, and prior to sacrifice. Mice were scanned by a microcomputed tomographic system (GE Healthcare, Tokyo, Japan) for imaging of aortas. Mouse aortas were enhanced by in situ infusion of the contrast agent, and the 3-dimensional images were reconstructed. For pharmacological depletion of MMP9, BAPN-fed mice were administered by gastric lavage with a broad-spectrum MMP inhibitor, ONO-4817 (300 mg/kg per day), which was kindly provided by Ono Pharmaceutical Co. Ltd (Tokyo, Japan) daily for 2 days before AngII administration until sacrifice. Dose of ONO-4817 (300 mg/kg per day) was determined according to information from previous studies on the pharmacokinetics and in vivo experiments. For neutrophil depletion experiments, BAPN-fed mice received daily intraperitoneal injections of 200 µg anti-granulocyte-differentiation antigen-1 (anti-Gr-1) neutralizing antibody (R&D Systems, Minneapolis, MN) or control immunoglobulin G from 2 days before the AngII infusion until sacrifice. The depletion of neutrophils was confirmed by Giemsa stain of peripheral blood smears. All studies in mice were approved by the Laboratory Animal Care and Use Committee of School of Medicine, Keio University.

Additional Methods

The expanded Methods section in the online-only Data Supplement contains information on ELISA, histology and immunohistochemistry, reverse transcription polymerase chain reaction, gelatin zymography, film in situ zymography, and in situ detection of superoxide.

Statistics

Human blood sample data were analyzed with 2-sample t-tests, and the occurrence rate of mouse AAD was analyzed with Fisher’s exact test. P value less than 0.05 was regarded as significant. P value was adjusted with Bonferroni method for pairwise comparisons in some experiments.

Results

Elevated Levels of MMP9 and AngII in Blood Samples From AAD Patients

We first screened the circulating levels of MMP1, MMP2, MMP3, MMP9, and metallopeptidase inhibitor 1 (TIMP1) in blood samples from healthy control volunteers and patients with nonruptured, chronic aortic aneurysm; AMI; or AAD. There were no significant differences in average age, ratio of men to women, or prevalence of major risk factors among these groups (Table). As shown in Figure 1, the AAD group exhibited significantly higher levels of MMP9 than the control, nonruptured aneurysm, or AMI groups, whereas the levels of MMP1, MMP2, MMP3, and TIMP1 did not differ among the groups.

AngII is one of the representative vasopressors implicated in the pathogenesis of many vascular diseases, including...
aneurysm formation. In addition, AngII is known to promote neutrophil infiltration into vascular walls, and to induce MMP9 expression in cell types such as vascular smooth muscle cells. Thus, we also measured the AngII levels in serum samples of the control, nonruptured aneurysm, AMI, and AAD groups, and found that the circulating AngII level was significantly higher in the AAD and AMI groups relative to the other groups studied (Figure 1).

**Immunolocalization of MMP9 in Aortic Lesions From AAD Patients**

Immunohistochemistry of patient samples indicated that the AAD tissues contain abundant MMP9-positive cells located mainly in the medial layer of dissected aorta, with smaller numbers of MMP9-positive cells scattered in the aortic tissues of the nonruptured aneurysm, predominantly localized to areas of the media displaying severe atherosclerotic changes (Figure 2A and 2B). Of note, neutrophils accumulated to much higher levels in the dissected aorta from the AAD patients relative to the nonruptured aneurysm (Figure 2A and 2B). Morphometric analysis of MMP9 immunoreactive cells in the aortic tissues showed a statistically significant increase in the aorta from the AAD patients (171.8±97.2 cells/mm²) compared with that from patients with nonruptured aneurysm (47.2±40.6 cells/mm²; P<0.05). Because the MMP9 staining pattern in the AAD aorta was similar to that of antineutrophil elastase (Figure 2A), these data suggested infiltrating neutrophils as the most likely source of MMP9 in the AAD aortas. Thus, we carried out double immunostaining of MMP9 and neutrophil elastase in the AAD aortic tissues and demonstrated that both proteinases colocalize in the cells (Figure 2C).

**Establishment of an AAD Model by AngII Infusion to BAPN-Treated Mice**

Based on the finding that both MMP9 and AngII are upregulated in human AAD, we sought to define their roles in AAD in vivo by developing a relevant mouse model. Because previous studies have shown that sustained administration of a lysyl oxidase inhibitor, BAPN, to premature rodents induces medial degeneration of aorta and results in aneurysm formation by disrupting the structural integrity of the aortic wall as a consequence of inhibiting collagen and elastin cross-linking, we administered BAPN to 3-week-old WT mice for 4 weeks. Under these conditions, apparent aneurysm formation was observed secondary to the medial degeneration (Figure 3A). However, BAPN alone was not sufficient to trigger AAD (Figure 3A and 3B). Because blood pressure elevation is considered to be a major inducer of AAD, we modified our protocol by infusing vasopressive-equivalent doses of AngII or NE to BAPN-treated WT mice for up to 48 hours. Blood pressure elevated equivalently from 96.3±4.6 mm Hg to 119.4±13.7 mmHg (P<0.05) and 111.9±5.13 mm Hg (P<0.05) 1 hour after the infusion of AngII or NE, respectively (data not shown). More important, 24 hours after the infusion was initiated, AngII led to AAD in all the mice examined. Furthermore, 30% of the mice died as a result of aortic rupture and subsequent hemothorax, whereas AAD was obtained in only 10% of the mice treated with NE.
infusion or BAPN treatment alone (Figure 3B). Enhanced computed tomographic scanning and histological examination demonstrated AAD in the descending thoracic aorta of the BAPN/AngII-treated mice (Figure 3A). Time course examination of AAD formation in the BAPN/AngII-treated mice demonstrated that AAD is initiated as early as 6 hours after AngII infusion, with 100% of the mice developing AAD by 24 hours (Figure 3C). Because NE infusion in BAPN-treated mice failed to induce AAD despite changes in blood pressure similar to those observed with AngII, the singular effects of AngII on triggering AAD onset are independent of blood pressure change alone.

Figure 2. Dissected aortic media from AAD patients is infiltrated by numerous MMP9-positive neutrophils. Aortic tissues obtained from the patients with AAD (A) or nonruptured aneurysm (B) were subjected to histological and immunohistochemical studies for MMP9 and neutrophil elastase (Neutrophil) on serial paraffin sections. High-power view of the rectangular areas is shown in the lower rows in each panel. Asterisks indicate false lumen of the dissected aorta; red arrowheads, positively immunostained cells. Note that, in AAD samples, MMP9 is expressed by the cells mainly in the media, and the distribution of MMP9-positive cells and neutrophil elastase-positive cells is closely related. Scale bars on the upper and lower panels, 200 μm and 50 μm, respectively. C. Double immunostaining of MMP9 and neutrophil elastase on paraffin sections of the AAD aortic tissue. Inset shows high-power view of a double immunostained cells. Red arrowheads indicate MMP9 and neutrophil elastase-double positive cells. Scale bar, 50 μm. AAD indicates acute aortic dissection; MMP9, matrix metalloproteinase 9; Adv, adventitia; Med, media; Int, intima; H&E, hematoxylin and eosin stain; and Nonimmune, nonimmune immunoglobulin G.
Involvement of MMP9 in an AAD Model

When MMP9 expression levels were examined by reverse transcription polymerase chain reaction in the mouse aortic tissues 24 hours after the infusion of AngII, high levels were detected in the aortas from the BAPN/AngII-treated mice whereas aortas from the other groups showed weak or negligible expression (Figure 4A). Gelatin zymography showed gelatinolytic bands of 92 kDa and 87 kDa, which correspond to the latent and active forms of MMP9, respectively, but only in aortas from the BAPN/AngII-induced AAD mice, and not in aortas from the other groups (Figure 4B). Histological and immunohistochemical study showed that the accumulation of MMP9-positive cells, which also immunostained with antineutrophil antibody, localized to the media of the dissected aortas of BAPN/AngII-treated mice (Figure 4C). Film in situ zymography on the aortic tissues demonstrated that gelatinolytic activity was generated in the dissected area of the aortas from BAPN/AngII-treated mice, whereas the digestion was abrogated in gelatin film treated with 1,10-phenanthroline, and the nondissected aortas from control mice showed negligible activity (Figure 4D). These data indicate that metalloproteinases exist within the dissected aortic tissue. Although the experimental methods used were not specific to detect MMP9 activity, our findings including the zymographical data in the presence of an active MMP9 form suggest the possibility that pro-MMP9 derived from neutrophils infiltrated in the aortic media is activated within the tissue. To study the location of superoxide production within the aortic tissues, we used staining with dihydroethidium, which is specific for superoxide. As shown in Figure 4D, strong fluorescence was detected in the dissected aortic tissue from the AAD mice, whereas control aortic tissue showed only a low-intensity fluorescence. More important, the infiltration of MMP9-positive neutrophils was demonstrated not only in the dissected media, but also in the intima of nondissected lesions of BAPN/AngII-induced AAD.
thoracic aortas (Figure 5). In control mice treated with BAPN alone or BAPN and NE, immunostaining of MMP9 and neutrophils was only rarely observed in the tissues (Figure 5). These findings suggest that the increased levels of MMP9 detected in the AAD aortas are derived primarily from neutrophils that infiltrate both the aortic intima and media.

Reduction of AAD Incidence by Pharmaceutical and Genetic Depletion of MMP9 or by Neutrophil Depletion

To determine whether MMP9 plays a direct role in the AAD mouse model, BAPN/AngII-treated mice were treated with synthetic MMP inhibitor ONO-4817. As shown in Figure 6A, when ONO-4817 was administered orally on daily basis to BAPN-treated WT mice from 48 hours prior to AngII infusion until sacrifice, the incidence of AAD decreased significantly from 100% to 60%, and spontaneous death caused by aortic rupture was blocked completely. Consistent with these observations, when MMP9−/− mice were treated with BAPN/AngII, AAD incidence was attenuated remarkably to basal levels (10% of the MMP9−/− mice) whereas BAPN alone induced thoracic aneurysm formation at a frequency comparable with that observed in WT mice (Figure 6A and 6B). Hence, these findings support a direct role for MMP9 in the development of AAD.

Although multiple cell populations are capable of expressing MMP9 (eg, macrophages, endothelial cells, and vascular smooth muscle cells), neutrophil infiltrates dominated the affected tissues. As such, we depleted neutrophils during aneurysm formation by treating the mice with anti-Gr-1

Figure 4. AAD in BAPN/AngII-treated wild type (WT) mice is accompanied by enhanced MMP9 expression, neutrophil infiltration, and superoxide production. A, Analysis of MMP9 mRNA expression by reverse transcription polymerase chain reaction in aortic tissues from the WT mice treated with vehicle (control), BAPN, BAPN/AngII (BAPN + AngII), or BAPN/NE (BAPN + NE). Polymerase chain reaction products of 3 independent samples from each group are shown. B, Gelatinolytic activity of the aortic tissue homogenates was assessed by gelatin zymography. BAPN/AngII-treated WT aorta shows gelatinolytic bands of 92 kDa and 87 kDa, corresponding to pro-MMP9 and active MMP9, respectively. C, Serial paraffin sections of dissected thoracic aorta of BAPN/AngII-treated WT mice were stained with H&E and immunostained with anti-MMP9 antibody, antineutrophil antibody, or control immunoglobulin G. Note the infiltration of MMP9-positive neutrophils in the media of the dissected lesion. D, Film in situ zymography and dihydroethidium staining of aortic tissues from BAPN/AngII-treated or control vehicle-treated WT mice. Serial frozen sections were made and stained with H&E or subjected to film in situ zymography using gelatin films coated with or without 1,10-phenanthroline. Frozen sections were also stained with dihydroethidium. Scale bars, 200 μm. AAD indicates acute aortic dissection; BAPN, β-aminopropionitrile monofumarate; AngII, angiotensin II; WT, wild type; MMP9, matrix metalloproteinase 9; NE, norepinephrine; H&E, hematoxylin and eosin stain; FIZ, film in situ zymography; GAPDH, glyceraldehyde 3-phosphate dehydrogenase; and DHE, dihydroethidium.

Figure 5. Infiltration of MMP9-positive neutrophils in the intima of nondissected lesions of BAPN/AngII-induced AAD thoracic aortas. MMP9 expression and neutrophil infiltration were examined by histology and immunohistochemistry in the aortas of untreated wild type mice (control) or wild type mice treated with BAPN alone, BAPN + AngII, and BAPN + NE. Note the accumulated MMP9-positive neutrophils in the intima of nondissected aorta from BAPN/AngII-treated mice. Inlets in the BAPN + AngII group show a higher-power view of the rectangular areas. Scale bar, 200 μm. MMP9 indicates matrix metalloproteinase 9; H&E, hematoxylin and eosin stain; BAPN, β-aminopropionitrile monofumarate; AngII, angiotensin II; AAD, acute aortic dissection; and NE, norepinephrine.
neutralizing antibody. The number of circulating neutrophils was reduced to 20% of control levels by intraperitoneal injection of the antibody for 48 hours prior to AngII infusion (data not shown), and, as expected, neutrophil depletion attenuated AAD incidence significantly (Figure 6A).

### AngII-Induced Neutrophil Infiltration to Aortic Intima Independent From MMP9 Expression

Infiltration of neutrophils into the aortic intima was observed in BAPN/AngII-treated WT mice with or without ONO-4817 administration, as well as in BAPN/AngII-treated MMP9−/− mice (Figure 7A). Hence, these data demonstrate that AngII promotes neutrophil infiltration independent of MMP9 expression in our AAD model, but these results do not exclude the possibility that normal rates of neutrophil infiltration are maintained only within the noncross-linked, fragile vessel wall caused by chronic BAPN treatment. Thus, we further assessed the effect of AngII on neutrophil infiltration by infusing AngII in BAPN-untreated WT or MMP9−/− mice wherein vascular structural integrity is intact. As shown in Figure 7B, neutrophil infiltration into the aortic intima was unaffected between the 2 groups, indicating that AngII infusion evokes neutrophil infiltration to the intact aortic wall independent of MMP9 expression.

### Discussion

In the current study, we demonstrated that serum levels of MMP9 and AngII are elevated in AAD patients, but not in patient populations with chronic, nonruptured aneurysms. Furthermore, increased circulating levels of MMP9 correlated with the presence of MMP9-positive neutrophils that accumulated in the aortic tissues of AAD patients. Given these findings from studies of human AAD specimens, we established a novel mouse model that develops AAD unfailingly within 24 hours of AngII infusion. This model was dependent on preconditioning mouse aortas with the lysyl oxidase
inhibitor BAPN to create an aneurysmal, pre-AAD status in immature mice. Collagen and elastin cross-links, which are critical for maintaining vessel wall integrity, are disrupted by BAPN administration, leading to the generation of mechanically fragile aortas that both display medial degeneration and develop aortic aneurysms. This type of aortic aneurysm is typically seen in human connective tissue diseases such as Marfan syndrome, but the histology of cystic medial degeneration is commonly seen in aneurysms that arise secondary to aging and atherosclerosis as well. It is not clearly elucidated whether aortic matrix cross-links are different between normal and aneurysmal aorta; however, several studies from human pathological samples indicate that the composition of the aortic extracellular matrix changes as medial degeneration proceeds with enhanced deposition of proteoglycans and decreased collagen content, coupled with apoptosis of vascular smooth muscle cells. These findings suggest that the aortic media and its matrix components are disorganized as a function of disease progression, thus leading to the generation of an aneurysmal aorta with weakened mechanical properties. As such, our mouse model would appear to recapitulate a similar state in which suitable triggers, such as AngII, precipitate the transition from a preconditioned, chronic aortic aneurysm to AAD.

Previous studies have suggested possible roles for MMP9 in the development of chronic atherosclerosis-derived aneurysms as well as connective tissue disease-related aortic aneurysm. By contrast, our findings demonstrate that AAD formation itself proceeds in an MMP9-dependent fashion that is inhibited significantly by either pharmacological or genetic targeting of MMP9. A previous study by Gough et al has shown that macrophages overexpressing autoactivating MMP9 induce atherosclerotic plaque rupture by disruptions of fibrous cap in apolipoprotein E mice, suggesting the ability of MMP9 to destroy aortic tissue. Altogether, these data support the notion that MMP9 is responsible for triggering aortic dissection from the preconditioned aneurysmal aorta. We have further demonstrated that neutrophil infiltration is observed in the intima of the predissecting aorta as well as in the dissected media, and that neutrophil depletion attenuates AAD incidence significantly. The importance of inflammation in the pathogenesis of vascular diseases is well documented, but until now, it has been difficult to determine whether neutrophil accumulation triggers dissection or occurs as a consequence of the massive vascular damage that develops during dissection. Because MMP9-positive neutrophils were confined to the intima of nondissected lesions while the dissected lesions displayed strong staining for MMP9-positive neutrophils primarily within the media, we posit that neutrophils infiltrate the intima at the initiation of dissection. Despite the importance of neutrophils, we cannot rule out the contribution of other immune effector cells that might be recruited subsequent to the inflammatory responses initiated by infiltrating neutrophils, as depleting neutrophils attenuated AAD, but not to the degree observed with MMP9 targeting. Indeed, the upregulated MMP9 mRNA levels detected in AAD aortic samples 24 hours after AngII infusion could result from nonneutrophil effector cells, because neutrophil MMP9 synthesis is mostly completed at earlier stages of differentiation, with mature neutrophils primarily storing MMP9 in granule compartments. Nevertheless, the rapid induction of aortic dissection in our model as early as 6 hours after AngII infusion, in tandem with the accumulation of MMP9-positive neutrophils, supports the conclusion that infiltrating neutrophils trigger the initiation of dissection directly or indirectly.

MMP9 is a multifunctional proteinase endowed with the ability to degrade multiple extracellular matrix macromolecules, including types III, IV, and V collagens; denatured histological and immunohistochemical analyses of MMP9 expression and neutrophil infiltration in the aortic intima of WT mice treated with BAPN and AngII (BAPN + AngII) and those in the intima of the MMP9−/− mice treated with BAPN and AngII (BAPN + AngII) (n = 10 for each group). Note that neutrophil infiltration is independent of MMP9 expression. Scale bar, 200 μm. Figure 7. AngII-induced neutrophil infiltration in aortic intima is independent of MMP9 expression or BAPN treatment. A, Histological and immunohistochemical analyses of MMP9 expression and neutrophil infiltration in the aortic intima of the WT mice treated with BAPN and AngII (BAPN + AngII); BAPN, AngII, and ONO-4817 (BAPN + AngII + ONO-4817); or BAPN, AngII, and anti-Gr-1 antibody (BAPN + AngII + Gr-1); and those in the intima of the MMP9−/− mice treated with BAPN and AngII (BAPN + AngII) (n = 10 for each group). Note that neutrophil infiltration is independent of MMP9 expression. Scale bar, 200 μm. B, Histological and immunohistochemical analyses of MMP9 expression and neutrophil infiltration in the aortic tissues of BAPN-untreated WT and MMP9−/− mice 24 hours after AngII infusion. Note that neutrophil infiltration is independent of BAPN treatment. Scale bar, 200 μm. AngII indicates angiotensin II; WT, wild type; MMP9, matrix metalloproteinase 9; H&E, hematoxylin and eosin stain; BAPN, N-α-aminopropionitrile monofumarate; and anti-Gr-1, anti-granulocyte-differentiation antigen-1.
collagens (ie, gelatin); and elastin. Furthermore, MMP9 can modulate inflammatory responses by hydrolyzing a variety of cytokines and chemokines. For example, MMP9 can activate prointerleukin-1, increase the bioactivity of interleukin 8, and promote interleukin 13-induced pulmonary inflammation, while inactivating neutrophil chemokines such as growth-regulated oncogene and mature interleukin 1.

A recent clinical trial has shown that the treatment of aortic abdominal aneurysms with doxycycline, a nonspecific MMP inhibitor, reduced neutrophil and cytotoxic T-cell infiltration into the aneurysmal wall in association with decreased production of MMP9 and inflammatory cytokines. MMP9 has also been reported to affect neutrophil chemotactic activity in lung injury models. In the current study, however, we detected no differences in neutrophil infiltration within the aortic tissues of OND-4817-treated mice or between WT and MMP9 mice in our AAD model. Furthermore, in contrast to malignant cells, with MMP-dependent invasive activity that is affected by collagen cross-links, our study showed that neutrophils infiltrate aortic tissues similarly in both BAPN-treated and -untreated mice. Together, these data suggest that neutrophil infiltration proceeds independently of MMP9 activity or collagen cross-links in this model system.

A detailed mechanism regarding how MMP9 contributes to the induction of AAD remains to be defined. In recent studies using Fibrillin1 mice, which develop AAD spontaneously secondary to connective tissue defect, the elevation of transforming growth factor levels and its downstream signaling cascade contribute to the pathogenesis of aortic aneurysm and dissection. In this model, MMP2 and MMP9 were both upregulated, and doxycycline attenuated disease progression. Because MMP9 is a potent activator of latent transforming growth factor, it is interesting to speculate that upregulated MMP9 activity may trigger AAD by in situ activation of transforming growth factor in the affected aortic media of the mice.

Last, our study has validated AngII as a potent inducer of mouse AAD, a result that complements the higher levels of AngII detected in our AAD patient population. Long-term AngII infusion is known to lead to spontaneous aortic dissection in atherosclerosis models using apoE mice. Recent studies have also demonstrated that Losartan, an antagonist of the AngII receptor, AT1, prevents aortic aneurysm development and aortic root dilatation in Marfanoid mice and humans. It is clear that the role of AngII in the induction of AAD is not a result of vasopressor effects alone, because NE failed to trigger AAD in our model despite similar levels of hypertension. One of the significant differences between the aortic lesions observed in BAPN/AngII-treated versus BAPN/NE-treated WT mice was the presence of neutrophil infiltrates in the BAPN/AngII-treated mice, suggesting that AngII acts as a potent stimulus for neutrophil infiltration into the aorta intima. Indeed, recent studies indicate that AngII can induce neutrophil infiltration. In addition, AngII is also able to activate neutrophils and stimulate the nicotinamide adenine dinucleotide phosphate (NADPH) oxidase-dependent production of reactive oxygen metabolites, which may promote the oxidative autoactivation of pro-MMP9. In the current study, we could show the gelatinolytic metalloprotease activity and superoxide production in the neutrophil-infiltrated dissecting aortic tissue from the BAPN/AngII-treated mice. Thus, AngII likely plays a key role in triggering AAD onset not only by attracting neutrophils to the affected sites, but also by stimulating the release and activation of pro-MMP9.

This study has a few limitations. First, we used a mouse model to demonstrate the role of neutrophil-derived MMP9 activity in AAD formation. Because mouse models do not recapitulate human disease progression stringently, the results of our AAD model may be different in humans. In the mouse model, AAD was induced in the descending thoracic aorta by AngII infusion to the young mice treated with BAPN. Preconditioning for the AAD induction (ie, aneurism formation) by BAPN treatment is artificial and may be applicable for AAD in patients with connective tissue disorders but not for commonly observed AAD in humans, such as our patients in the current study. Another limitation of this study is that the activation mechanism of pro-MMP9 within aortic tissues has not been examined in mouse or human AAD. Although our study on the mouse model has suggested possible involvement of reactive oxygen species in the activation, detailed studies regarding whether pro-MMP9 activation and AAD incidence are suppressed by antioxidant therapy, and which reactive oxygen species are required for pro-MMP9 activation in coculture system of neutrophils and smooth muscle cells, will be necessary. Moreover, reactive oxygen species-mediated pro-MMP9 activation in human aortic tissues from AAD patients needs to be investigated by future work.

AAD is a potentially fatal disease, the prompt diagnosis and treatment of which are required for successful intervention. Although the fibrin product, D-dimer, is the only established biomarker for AAD, the differential diagnosis of AMI versus pulmonary embolism, which displays similar symptoms to that of AAD, can be difficult. In this context, MMP9 could serve as a potential biomarker for the diagnosis of AAD. Furthermore, although the dominant treatment for AAD relies on surgical reinforcement of the affected aorta, our data raise the possibility that the preventive administration of AngII receptor blockers or MMP9-specific inhibitors to patients at risk with nonruptured atherosclerotic aneurysm could prove useful as effective therapeutics to reduce AAD incidence.

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Disclosures

None.

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CLINICAL PERSPECTIVE

Acute aortic dissection (AAD) is a potentially fatal vascular disease, and prompt diagnosis and treatment by timely surgery are required for survival of the patients. No efficient biomarkers are available for diagnosis of AAD prior to determination of the disease by computed tomography. Medial degeneration is known as an important risk factor for the development of AAD; however, the emergent nature of the disease and the paucity of animal models prevent us from studying the molecular mechanisms for triggering the disease. We found that matrix metalloproteinase 9 (MMP9) and angiotensin II were increased significantly in blood samples from AAD patients compared with those from normal subjects and the patients with nonruptured aortic aneurysm. This was accompanied by enhanced infiltrations of MMP9-producing neutrophils in the dissected aortas. Based on the data, we established a mouse model of AAD, which was induced by infusion of angiotensin II to mice pretreated with β-aminopropionitrile monofumarate (a lysyl oxidase inhibitor). All mice exhibited AAD within 24 hours after angiotensin II infusion. Aortic tissue from the AAD mice showed enhanced expression and activity of MMP9, and MMP9-immunoreactive neutrophils were infiltrated in both dissected media and intima of nondissected lesions. Genetic deletion or pharmaceutical inhibition of MMP9 and neutrophil ablation attenuated the AAD incidence. These data demonstrate that neutrophil-derived MMP9 is responsible for triggering AAD in this model. Taken together, MMP9 could serve as a potential biomarker for diagnostic screening of AAD, and administration of angiotensin II receptor blockers or MMP9 inhibitors could be effective therapeutic approaches to AAD.
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Neutrophil-Derived Matrix Metalloproteinase 9 Triggers Acute Aortic Dissection

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Supplemental Methods

ELISA
Levels of matrix metalloproteinase1, 2, 3 and 9 (MMP1, MMP2, MMP3 and MMP9), tissue inhibitor of metalloproteinases-1 (TIMP1) and AngII were measured by sandwich ELISA from the blood samples of all the registered patients as previously described.\textsuperscript{1, 2}

Histology and immunohistochemistry
Sections (4 μm thick) were cut from the paraffin-embedded aortic specimens obtained at surgery from the AAD patients or non-ruptured aneurysm patients. The sections were stained with hematoxylin and eosin (H&E) or by elastica Van Gieson (EVG) stain, and immunostained with mouse monoclonal antibodies against human MMP9 (56-2A4; Daiichi Fine Chemicals, Ltd., Takaoka, Japan)\textsuperscript{3} and neutrophil elastase (Santa Cruz Biotechnology, Santa Cruz, CA) or control IgG (Santa Cruz Biotechnology). The degree of MMP9-immunoreactive cell density was evaluated by morphometric analysis of the immunostained tissue sections. In each section, the aortic tissues from the AAD or non-ruptured aneurysm patients was photographed, and the number of immunoreactive cells was calculated by two independent pathologists (M.S. and Y.O.) by observing 5 different fields at magnification of 200×. The average number of positive cells per square millimeter was calculated as MMP9-immunoreactive cell density. For double immunostaining for neutrophil elastase and MMP9, the paraffin sections from the AAD patients were immunostained with anti-neutrophil elastase antibody (Santa Cruz Biotechnology) and then anti-MMP9 antibody (56-2A4;
Daiichi Fine Chemicals, Ltd.) by using the Envision System (Vector Laboratories) and additionally HistoGreen Substrate Kit (AbCys SA, Paris, France) according to the manufacturer’s protocols. The serial sections were stained with H&E or immunostained with control IgG.

Mouse aortic tissues were also stained with H&E and EVG or immunostained with anti-mouse MMP9 antibody (R&D systems), anti-neutrophil antibody as an allotypic mouse neutrophil marker (7/4 clone; Serotec, Oxford, UK) or control IgG. Histology and immunohistochemistry were evaluated by pathologists (M.S. and Y.O.) who were not informed of the results of the experimental treatments.

**RT-PCR**

Total RNA was extracted from mouse aortae, and then RT-PCR was performed as previously described. The primer sequences were as follows; **MMP9** (sense, 5'-TGTACCGCTATGGTTACACCG-3'; antisense, 5'-CGCGACACCAAACCTGGATGAC-3') and **GAPDH** (sense, 5'-GCCAAGGTCATCCATGACAAC-3'; antisense, 5'-GTCCACCACCTGGTGTGCTGTA-3').

**Gelatin zymography, film in situ zymography and in situ detection of superoxide**

Mouse aortae were snap-frozen in liquid nitrogen and gelatin zymography was performed with homogenate supernatants prepared from the tissue samples according to the methods previously described. For film in situ zymography,
fresh mouse aortae were embedded without fixation in Tissue-Tek OCT compound (Miles, Inc., Elkhart, IN), and subjected to in situ zymography.\textsuperscript{1} Frozen sections were made by a cryostat (Miles, Inc.), and mounted onto gelatin films which were prepared by coating a cross-linked gelatin on a polyester base.\textsuperscript{1} Some frozen sections were also placed on the gelatin films coated with 1,10-phenanthroline, a metalloproteinase inhibitor. The films with sections were incubated for 24 h at 37°C and then stained with 1.0% Amido Black 10B (Sigma Aldrich, Saint Louis, MO).\textsuperscript{1} Serial sections were stained with H&E. In situ detection of superoxide in the aortic tissues from the AAD mice and control mice was performed according to the methods previously described.\textsuperscript{6} Briefly, frozen sections of the aortic tissues were incubated with 10 mM dihydroethidium (DHE) in PBS for 30 min at 37°C in a humidified chamber protected from light. Ethidium bromide generated from DHE by oxidation with superoxide within the tissue was detected by confocal microscope using a 543-nm He-Ne laser combined with a 560-nm long-pass filter (Carl Zeiss MicroImaging Inc., Tokyo, Japan).

References


