YopM of *Yersinia enterocolitica* specifically interacts with α1-antitrypsin without affecting the anti-protease activity

Gerhard Heusipp,† Katrin Spekker,† Sabine Brast, Stefan Fälker and M. Alexander Schmidt

Institut für Infektiologie, Zentrum für Molekularbiologie der Entzündung, Universitätsklinikum Münster, von-Esmarch-Str. 56, 48149 Münster, Germany

It was previously shown that α1-antitrypsin (AAT) interacts with the type III secreted (T3S) EspB and EspD proteins of enteropathogenic *Escherichia coli* (EPEC), resulting in reduced functionality of the proteins. To determine if AAT is also able to interact with T3S proteins of other pathogens, the binding of AAT to Yop proteins of *Yersinia enterocolitica* was analysed. AAT did not interact with YopB or YopD, which have functions in type III translocation similar to EspB and EspD in EPEC, but specifically interacts with YopM, a member of the leucine-rich repeat (LRR) family of proteins, in overlay and pull-down assays. To determine regions of YopM involved in AAT binding, various N- and C-terminally truncated versions of YopM were recombinantly expressed, and their ability to interact with AAT analysed. All versions tested were able to bind AAT, indicating that at least eight LRR of YopM are sufficient for AAT interaction. The main physiological role of AAT is to inhibit neutrophil elastase; however, elastase was efficiently inhibited by AAT in the presence and absence of YopM, indicating that YopM does not interfere with the anti-protease inhibition activity of AAT, and that the domain of AAT interacting with YopM is not identical to AAT’s protease interaction domain. Furthermore, it was shown that elastase efficiently degrades YopM and other Yop proteins. The data suggest that AAT has additional functions in the host response against bacterial infections that are not related to its anti-protease activity.

INTRODUCTION

The genus *Yersinia* consists of three species pathogenic to humans, *Yersinia enterocolitica*, *Yersinia pseudotuberculosis* and *Yersinia pestis*. Although they differ in their route of infection, all pathogenic *Yersinia* species show a tropism for lymphoid tissues. While *Y. pestis* is transmitted to the bloodstream of the host via a fleabite, *Y. pseudotuberculosis* and *Y. enterocolitica* are food-borne pathogens, and cross the intestinal epithelium at Peyer’s patches. All *Yersinia* species are able to survive and replicate extracellularly in lymphoid tissues. This is made possible by a virulence plasmid-encoded type III secretion system (T3SS) that translocates effector proteins through the bacterial and host membranes directly into the host cell cytosol, where the effectors have anti-phagocytic and anti-inflammatory effects (Cornelis, 2002). T3SSs have been described in various Gram-negative human, animal and plant-pathogenic bacteria, and are devoted to establishing and maintaining a successful infection (Hueck, 1998). The plasmid-encoded *Yersinia* Ysc T3SS has been exceptionally well characterized. The secreted proteins include the two translocators, YopB and YopD, that insert into the host membrane, and six effector Yop proteins (YopE, YopT, YopO/YpkA, YopM, YopP/YopJ, YopH) that interfere with host signalling cascades resulting in the inhibition of phagocytosis, down-regulation of the immune response, and induction of apoptosis (Cornelis, 2002). A biochemical function for each of the effector Yop proteins has been established, although thus far the role in pathogenesis has not been elucidated sufficiently for all of them (reviewed by Viboud & Bliska, 2005). The effectors YopE, YopT and YopO interact with Rho GTPases and thereby disrupt the actin cytoskeleton to prevent phagocytosis. YopH has a similar function, but acts by targeting signalling pathways activated by phagocytic mechanisms. The role of YopP during infection is to suppress cytokine production and induce apoptosis. YopP is a protease that inhibits MAPK and NF-κB signalling by interfering with ubiquitination.

Although YopM has an important role in pathogenesis, its function has until now not been determined satisfactorily (Leung et al., 1990; Mulder et al., 1989). YopM belongs to a

†These authors contributed equally to this work.

**Abbreviations:** AAT, α1-antitrypsin; EPEC, enteropathogenic *Escherichia coli*; LRR, leucine-rich repeat; Ni-NTA, nickel-nitrilotriacetate; SAAAPNA, N-succinyl-Ala-Ala-Ala-p-nitroanilide; T3SS, type III secreted; T3S, type III secretion system.

Received 18 November 2005
Revised 24 January 2006
Accepted 6 February 2006
family of proteins containing leucine-rich repeat (LRR) motifs that have been described as participating in protein–
protein interactions (Kobe & Kajava, 2001). Determination of the crystal structure revealed that YopM is a horseshoe-
shaped protein and that four YopM monomers interact to form a hollow cylinder (Evdokimov et al., 2001). In earlier
experiments it was shown that YopM of Y. pestis interacts with x-thrombin and inhibits platelet aggregation, but these properties are dispensable for virulence (Hines et al., 2001; Leung et al., 1990; Nemeth & Straley, 1997; Reisner & Straley, 1992). As for the other effector proteins, YopM is trans-
located into the cytoplasm of the host cell, but interestingly can also be found in the nucleus of infected cells (Skrzypek et al., 1998). More recently, transcriptional analysis of mouse macrophages after infection with Y. enterocolitica indicated a putative role for YopM in the control of cell cycle and cell growth (Sauvonnet et al., 2002), while in another study no effect of YopM on host cell transcription could be detected (Hoffmann et al., 2004). Using a different approach, McDonald et al. (2003) identified the kinases PRK2 and RSK1 as intracellular targets of YopM, but again the biolog-
ical significance of this interaction remains to be determined. The most recent data indicated that YopM targets the innate immune system, as it was required for depletion of NK cells after intravenous infection of mice with Y. pestis (Kerschen et al., 2004). Interestingly, in contrast to all other Yop proteins, an enzymic activity could not be identified for YopM (Viboud & Bliska, 2005).

In a recent study we identified the acute-phase protein α1-antitrypsin (AAT) as a binding partner for the type III
secreted (T3S) EspB and EspD proteins of enteropathogenic Escherichia coli (EPEC). This interaction resulted in reduced virulence of EPEC as analysed by EspB/EspD-dependent haemolysis of red blood cells and pedestal formation on infected HeLa cells (Knappstein et al., 2004). AAT is the most abundant circulating serine protease inhibitor in human serum. Its main role is to protect the upper respira-
tory tract from destruction by neutrophil elastase. It is synthesized primarily in the liver, but also is expressed in,
and secreted by, extra-hepatic tissues, intestinal enterocytes, macrophages and monocytes (Molmenti et al., 1993; Perlmutter et al., 1985). To analyse if AAT is able to interact with T3S effector proteins of other human pathogens besides EPEC, we analysed the interaction of AAT with Yop proteins of Y. enterocolitica. We show that AAT binds specif-
ically to YopM in overlay and pull-down assays, and that the AAT–YopM interaction does not interfere with AAT’s activity to inhibit elastase. It can be inferred from our data that there is a novel role for AAT in host defence that is not related to its anti-protease activity.

METHODS

Bacterial strains, tissue culture cell lines and culture con-
ditions. We used the Y. enterocolitica O8 strain JB580v as the wild-
type strain (Kinder et al., 1993). Unless otherwise indicated, all strains were grown in Luria–Bertani (LB) broth or on agar plates, at 26°C for Y. enterocolitica or 37°C for E. coli. The following antibiotics were used at the final concentrations indicated: for Y. enterocolitica, nalidixic acid (20 μg ml−1), chloramphenicol (12.5 μg ml−1); for E. coli, kanamycin (50 μg ml−1), chloramphenicol (25 μg ml−1). For the induction of type III secretion, an overnight culture of Y. enterocolitica grown in brain–heart infusion (BHI) medium was diluted to an OD600 0.1 in fresh BHI medium supplemented with 20 mM MgCl2 and 20 mM sodium oxalate (BHI-MOX) to deplete Ca2+ from the medium, grown at 26°C for 2 h and then shifted to 37°C for an additional 4 h. Yop proteins were precipitated by the addition of trichloroacetic acid (TCA) to a final concentration of 10% (v/v) to bacteria-free supernatants, washed with acetone and analysed by SDS-PAGE.

HeLa cells (ATCC CCL 2) were routinely grown at 37°C in a 10% CO2 atmosphere in DMEM supplemented with 10% (v/v) fetal calf serum, 1 mM glutamine, penicillin (100 U ml−1) and streptomycin (100 μg ml−1). J774.A1 cells (ATCC TIB-67) were routinely grown at 37°C in a 10% CO2 atmosphere in RPMI medium supplemented with 10% (v/v) fetal calf serum, 1 mM glutamine, penicillin (100 U ml−1) and streptomycin (100 μg ml−1).

Construction of plasmids and protein purification. The primers used for the amplification of yopM fragments by PCR are listed in Table 1. For the recombinant expression of YopM with a C-terminal 6 × His-tag, the yopM coding sequence was amplified by PCR using the primer pair KS-yopM1/KS-yopM2 and Pfu poly-
merase, and ligated into pNdel/Xhol-digested pET24b(+) (Novagen) resulting in plasmid pET-yopM. N- or C-terminally truncated versions of YopM were similarly constructed using primer pairs KS-yopM5/KS-yopM2 (pET-yopM5-77c), KS-yopM7/KS-yopM2 (pET-yopM172c), KS-yopM1/KS-yopM6 (pET-yopM172c-N39) and KS-yopM1/KS-yopM8 (pET-yopM5-286c) (Fig. 3). The plasmids were transferred to E. coli BL21(DE3) (Novagen) by electroporation to allow the induction of expression of the recombinant YopMs. E. coli BL21(DE3) cells carrying the respective expression plasmids were grown to OD600 0.6. After addition of 1 mM IPTG to induce YopM expression, the cultures were incubated for an additional 3 h at 37°C. Subsequently, bacteria were harvested by centrifugation. His-tagged proteins were purified by Ni-nitrilotriacetate (Ni-NTA)–agarose affinity purification under nondenaturing conditions as recommended by the supplier (Qiagen). Proteins were eluted in buffer containing 50 mM Tris pH 8, 150 mM NaCl, 1 mM EDTA, 0.01% (v/v) Triton X-100 and analysed by SDS-PAGE. Protein concentrations were assessed by the Bradford assay (Bradford, 1976).

Construction of a Y. enterocolitica yopM mutant strain. For the construction of the Y. enterocolitica yopM mutant strain GHY189
(yopM::pEP-yopM), an internal fragment of the yopM gene was amplified by PCR using primers KS-yopM3 and KS-yopM4 (Table 1), digested with ClaI/XbaI, and ligated into the ClaI/XbaI-
digested suicide plasmid pEP185.2 (Kinder et al., 1993) resulting in plasmid pEP-yopM. This plasmid was transferred to Y. enterocolitica JB580v by conjugation using E. coli S17-1 Δpir (Miller & Mekalanos, 1988) as donor. The resulting Y. enterocolitica strains resistant to nalidixic acid and chloramphenicol were analysed for proper inser-
tion of the suicide plasmid by Southern blotting, and for the loss of YopM in supernatants after growth under conditions inducing type III secretion of Yop proteins.

Overlay assay, pull-down assay and preparation of cell lysates. To investigate the interaction of Yop proteins with AAT, supernatants of Y. enterocolitica grown at 37°C in BHI-MOX were TCA precipitated, separated by SDS-PAGE and transferred to nitrocellu-
lose membrane by Western blotting. The membrane was incubated with AAT and subsequently probed with AAT-specific antiserum as previously described (Knappstein et al., 2004). Pull-down assays were performed as previously described (Knappstein et al., 2004) with the following exception. Recombinant YopM proteins were
eluted from the Ni-NTA agarose column to determine the amount of protein. After dialysis against Tris-buffered saline, approximately 3 μg recombinant YopM was incubated with Ni-NTA agarose and subsequently incubated with purified AAT (Sigma) or cell lysates as previously described (Knappstein et al., 2004). Eluted proteins were analysed by SDS-PAGE and immunoblotting using AAT- and YopM-specific antibodies.

**Elastase activity assay.** The activity of elastase (from human leukocytes; Sigma) was analysed with the chromogenic substrate N-succinyl-Ala-Ala-Ala-p-nitroanilide (SAAAPNA; Sigma). Briefly, 1 mM SAAAPNA was incubated with 0-008 U elastase in buffer containing 50 mM Tris pH 8-0, 100 mM NaCl, 0-5% (v/v) Triton X-100, for various time points at 37°C in a microtitre plate. Substrate conversion was measured in a microplate reader as the increase in absorbance at a wavelength of 405 nm. Inhibition of elastase was achieved by the addition of 10 μM AAT (final concentration). To analyse the effect of YopM on AAT’s ability to inhibit elastase, the elastase activity assay was performed in the presence or absence of various concentrations of recombinant YopM. To analyse the effect of elastase on YopM, recombinant YopM or the supernatant of Y. enterocolitica grown at 37°C in BHIMOX was incubated with elastase (0-008 U) in the presence or absence of inhibitory concentrations of AAT (10 μM) at 37°C for 2 h. Samples were mixed with SDS-PAGE sample buffer, and analysed by Western blotting and YopM-specific antibodies, or Coomassie staining of SDS-polyacrylamide gels.

### RESULTS

**AAT interacts with YopM in an overlay assay**

In a previous study we identified AAT as a binding partner for the T3S translocator proteins EspB and EspD of EPEC. As the translocators have a central conserved role in T3SSs of forming a pore in the host cell membrane through which effector proteins are translocated into the host cytosol, we hypothesized that AAT might also be able to interact with translocator proteins from other pathogens employing T3SSs. Therefore, we analysed supernatants of Y. enterocolitica grown under conditions inducing the secretion of Yop proteins (37°C, BHIMOX) in an overlay assay with AAT. As shown in Fig. 1, a specific interaction occurred with a protein with an approximately 50 kDa molecular mass. Comparison with the molecular masses of all T3S proteins of Y. enterocolitica we assumed that the protein interacting with AAT might be YopM. This was confirmed by using Yop supernatant from a yopM mutant strain (GYH189) and recombinant YopM with a C-terminal His-tag in an overlay assay. These experiments clearly showed an interaction of AAT with recombinant YopM and YopM from supernatants of wild-type Y. enterocolitica, while no interaction of AAT with proteins from the yopM mutant strain could be detected (Fig. 1). These data show that AAT specifically interacts with YopM of Y. enterocolitica, while it does not interact with the translocation pore-forming proteins YopB and YopD as might be expected from data obtained with EPEC.

**AAT interacts with YopM in a pull-down assay**

To analyse if AAT is also able to bind YopM in solution, we performed pull-down assays with recombinant YopM and purified AAT. His-tagged YopM was bound to Ni-NTA agarose matrix, incubated with AAT, washed, eluted from the matrix and analysed by SDS-PAGE and immunoblotting using AAT-specific antibodies. Fig. 2 shows that YopM is able to bind to AAT in solution; binding of AAT to the matrix in the absence of YopM was not detected. To further show that the interaction of YopM with AAT is specific, we performed pull-down assays with recombinant YopM and cell lysates from HeLa cells and J774.A1 macrophage-like cell lines.

### Table 1. Primers

<table>
<thead>
<tr>
<th>Primer</th>
<th>Sequence (5’→3’) (restriction site is underlined)</th>
<th>Recognition site</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS-yopM1</td>
<td>CTCGAGCTGATTATCTCTGACATCAAGTTT</td>
<td></td>
</tr>
<tr>
<td>KS-yopM2</td>
<td>CTAGCTAGCTGATTATCTCTGACATCAAGTTT</td>
<td></td>
</tr>
<tr>
<td>KS-yopM3</td>
<td>CCATCGATCGACAAAGCCCATGAGCTAGAA</td>
<td></td>
</tr>
<tr>
<td>KS-yopM4</td>
<td>CTAGCTGATTATCTCTGACATCAAGTTT</td>
<td></td>
</tr>
<tr>
<td>KS-yopM5</td>
<td>CTAGCTAGCTGATTATCTCTGACATCAAGTTT</td>
<td></td>
</tr>
<tr>
<td>KS-yopM6</td>
<td>CTAGCTGATTATCTCTGACATCAAGTTT</td>
<td></td>
</tr>
<tr>
<td>KS-yopM7</td>
<td>CTAGCTGATTATCTCTGACATCAAGTTT</td>
<td></td>
</tr>
<tr>
<td>KS-yopM8</td>
<td>CTAGCTGATTATCTCTGACATCAAGTTT</td>
<td></td>
</tr>
<tr>
<td>KS-yopM1</td>
<td>CTAGCTGATTATCTCTGACATCAAGTTT</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1.** AAT specifically interacts with YopM in an overlay assay. Supernatants of Y. enterocolitica JB580oV (lane 1) or of yopM mutant strain GYH189 (lane 2) grown at 37°C in BHIMOX to induce Yop protein secretion were separated by SDS-PAGE, transferred to nitrocellulose and incubated with AAT. As a control, recombinant His-tagged YopM was included (lane 3). Binding of AAT to YopM was detected with anti-AAT antiserum. Molecular masses of standard proteins are indicated in kDa (lane M).
cells. *Y. enterocolitica* interacts with both cell types during an infection, and Yop proteins specifically target macrophages in the host. As shown in Fig. 2, AAT can be detected after a pull-down assay with YopM and cellular lysates, indicating that YopM interacts not only with purified AAT, but also with AAT from HeLa and J774.A1 cell lysates in a pull-down assay.

### Analysis of AAT interaction with N- and C-terminally truncated versions of YopM

The main function of AAT is to interact with serine proteases and to inhibit their activity. However, in this and a previous study (Knappstein *et al.*, 2004) we could show that AAT also interacts with non-proteolytic bacterial T3S proteins. We were, therefore, interested in determining if a specific binding domain exists in YopM that mediates interaction with AAT. The YopM protein is heterogeneous between different *Yersinia* strains, and variants differing in the amount of LRR have been reported (Boland *et al.*, 1998). The YopM protein of *Y. enterocolitica* O8 strain JB580v used in our study contains 13 LRR. An additional characteristic structural feature of YopM is its N-terminal tandem pair of α-helices (Evdokimov *et al.*, 2001). Different recombinant YopM versions were constructed, which were truncated at the N- or the C-terminus and expressed in *E. coli* with a C-terminal His-tag. After purification of the proteins by affinity chromatography, we analysed their interaction with AAT in overlay and pull-down experiments (Figs 3 and 4). The recombinant YopM87-C protein is missing the N-terminal α-helices and the first half of LRR1. As this protein is still able to bind AAT, we conclude that the α-helices are not involved in AAT interaction. Further N-terminal deletion up to LRR6 (YopM172-C) did not abolish AAT binding, although nearly half of the protein is deleted,
indicating that the N-terminus of YopM is not necessary for AAT binding. Similar results were obtained with the C-terminal deletions YopMN-239 and YopMN-286, showing that, in addition, no specific C-terminal motif necessary for AAT interaction exists. All YopM variants tested were able to bind AAT in overlay as well as in pull-down assays (Fig. 4b, c). The weak signals from YopM87-C and YopM172-C in the overlay assay (Fig. 4a, b) are not due to inefficient AAT binding, but to the instability of these variants, resulting in only small amounts of protein in the assay. Attempts to further concentrate both proteins were not successful. However, YopM87-C as well as YopM172-C bound AAT with efficiencies comparable to the other YopM versions in pull-down experiments (Fig. 4c). The shortest YopM variants used in our study still contained eight LRRs (YopMN-239 and YopM172-C), indicating that the LRRs are involved in AAT–YopM interaction and that eight LRRs from the N- or the C-terminus of YopM are sufficient for interaction with AAT. Our results might indicate either that AAT is able to interact with any LRR irrespective of its location in YopM, or that LRRs 6–8, which are included in all the truncated versions, constitute a binding motif.

**AAT interaction with YopM does not interfere with protease inhibition**

The main physiological role of AAT is to inhibit elastase in the lung of humans (Crystal, 1990). However, as AAT is expressed in various human tissues, and cells like enterocytes, monocytes and macrophages, its protease inhibition function is not restricted to the lung epithelium (Perlmutter et al., 1985, 1989). As Y. enterocolitica survives and replicates in lymphatic tissues after infection, it interacts with macrophages and neutrophils that express various proteases. It has been shown that neutrophil elastase specifically cleaves virulence factors of *Shigella*, *Salmonella* and *Yersinia* (Weinrauch et al., 2002). The specific inhibition of proteolytic enzymes by anti-proteases such as AAT is an important mechanism for regulating proteolysis. However, studies suggest that protease inhibitors can be inactivated by different mechanisms involving cellular as well as bacterial factors, leading to microenvironments in which proteolysis is facilitated even in the presence of inhibitors (Owen & Campbell, 1999). Therefore, we hypothesized a role for a YopM-AAT interaction during infection might be the obstruction of AAT’s inhibition activity against proteases like elastase, resulting in, for example, tissue destruction or interference with host signalling. We developed an assay employing human leucocyte elastase and the synthetic substrate SAAAPNA to characterize the effect of YopM on AAT’s ability to inhibit elastase. The results are shown in Fig. 5. Conversion of the substrate by elastase was detected as an increase in absorbance at a wavelength of 405 nm. AAT (10 μM final concentration) efficiently inhibited elastase activity in this assay. When different concentrations of YopM were added to the assay, this did not interfere with elastase inhibition by AAT. However, addition of YopM alone resulted in a reduced conversion of the SAAAPNA substrate. This could be the result of elastase inhibition by YopM; alternatively, YopM could be a competitor for the substrate. From these data we conclude that YopM does not interfere with AAT’s ability to inhibit elastase.
Elastase efficiently degrades YopM and other Yop proteins

As it has been shown that neutrophil elastase is able to degrade T3S virulence factors of *Shigella*, *Salmonella* and *Yersinia* (Weinrauch et al., 2002), and as we observed a decreased conversion of a synthetic substrate by elastase in the presence of YopM, we investigated whether YopM itself might be degraded by elastase. When recombinant YopM or T3S supernatant of *Y. enterocolitica* was incubated with elastase, YopM was efficiently degraded. This degradation was inhibited by the addition of 10 μM AAT (Fig. 6). However, in the presence of other Yop proteins, YopM is degraded less efficiently than recombinant YopM alone. Residual amounts of YopM can still be detected after 2 h incubation with elastase, while a higher amount of recombinant YopM is completely degraded in the same assay. Furthermore, not only YopM, but also other Yop proteins from supernatants were degraded, implicating substrate competition as a possible explanation for the less efficient degradation of YopM from supernatants. The results are in accordance with other observations indicating a role for neutrophil elastase in the specific degradation of bacterial virulence factors (Weinrauch et al., 2002).

**Fig. 5.** YopM does not interfere with AAT’s ability to inhibit elastase. Elastase was incubated with the chromogenic substrate SAAAPNA in the presence (+) or absence (−) of 10 μM AAT, and substrate conversion was detected as increase in absorbance at 405 nm. In addition, various amounts of YopM (black bars, no YopM; white bars, 28 μM YopM; grey bars, 14 μM; hatched bars, 7 μM YopM) were added to analyse the effect on substrate conversion. AAT efficiently inhibits elastase activity irrespective of the presence or absence of YopM in the assay. Addition of YopM in the absence of AAT also resulted in a decreased substrate conversion. Means and SDs of a representative experiment performed in duplicate are shown.

**Fig. 6.** Elastase efficiently degrades Yop proteins. After incubation of recombinant YopM or Yop proteins from supernatants with or without 0.008 U elastase for 2 h at 37 °C, proteins were separated by SDS-PAGE and transferred to nitrocellulose. YopM was detected using specific antibodies (a). Alternatively, proteins were Coomassie stained after SDS-PAGE (b). Recombinant His-tagged YopM (lanes 1–3) as well as YopM from bacterial supernatants (lanes 4–6) is efficiently degraded by elastase in the absence, but not in the presence, of AAT. Lanes 1 and 4, YopM and Yop protein supernatant, respectively, without elastase; lanes 2 and 5, YopM and Yop protein supernatant, respectively, incubated with elastase; lanes 3 and 6, YopM or Yop protein supernatant, respectively, incubated with elastase and 10 μM AAT. Molecular masses of standard proteins are indicated in kDa (lane M).
DISCUSSION

The acute phase protein AAT is a well-characterized anti-protease that inhibits the proteolytic activity of serine proteases. Its main target in humans is neutrophil elastase in the lung, and AAT deficiency may result in emphysema due to tissue destruction by elastase (Crystal, 1990). In a recent study we could show that AAT has an additional function presumably not related to its anti-protease activity: binding to the EPEC proteins EspB and EspD, which reduced the virulence of the bacteria by interfering with type III secretion (Knappstein et al., 2004). As T3SSs are common in bacterial pathogens, we analysed if AAT might be able to interact with T3S proteins of other pathogens. We were able to identify an interaction between YopM of *Y. enterocolitica* and AAT in overlay assays, as well as in pull-down assays. This interaction is probably mediated by the LRR structure of YopM, but does not interfere with AAT’s role as an anti-protease, implying that different domains of AAT are involved in interacting with proteases and with YopM.

When we first analysed the interaction of AAT with Yop proteins in overlay assays, we were surprised that we did not detect binding to YopB or YopD. As for EspB and EspD in EPEC, these Yop proteins are involved in the formation of a pore in the eukaryotic host membrane, through which T3S effector proteins are translocated into the host cytosol (Ide *et al.*, 2001; Neyt & Cornelis, 1999). In contrast to our previous results showing interaction of AAT with the EspB and EspD translocator proteins, AAT interacted with the effector protein YopM, indicating that AAT does not recognize a general motif that might be present on translocator proteins of T3SSs. The specificity of the binding of AAT to YopM was confirmed by various complementary approaches. First, AAT did not interact with proteins from supernatants of a *yopM* mutant strain; second, AAT bound to recombinantly expressed and affinity-purified YopM; and third, YopM bound to purified AAT as well as AAT from HeLa and J774.A1 cell lysates in pull-down assays. It was especially important to show binding of YopM to AAT from cellular lysates, as this experiment showed the specificity of the interaction most convincingly. McDonald *et al.* (2003) used a similar approach to identify host proteins binding to YopM. The two protein kinases PRK2 and RSK1 co-immunoprecipitated with, and were activated by, YopM (McDonald *et al.*, 2003). However, the biological function of the interaction remains unknown. In different studies it was shown that YopM of *Y. pestis*, which contains two more LRR compared to YopM of *Y. enterocolitica* O8 used in our study, is able to bind the protease z-thrombin (Leung *et al.*, 1990; Reisner & Straley, 1992). This suggests that YopM is a versatile protein that is able to interact with various host proteins, presumably via its LRR. Depending on the bound substrate, YopM monomers might interact with each other to assemble distinct protein regions into an overall structure capable of binding a specific ligand. This is supported by the crystal structure of the *Y. pestis* YopM protein, where four YopM monomers interact to form a hollow cylinder (Evdokimov *et al.*, 2001). Furthermore, the LRR structure allows the presentation of variable loop regions and might thereby facilitate various protein–protein interactions.

To analyse which regions of YopM were important for AAT binding, we constructed various N- and C-terminally truncated versions of YopM. Our analysis revealed that neither the N- nor the C-terminus is necessary for AAT binding. Even when approximately half of the protein from the N- or the C-terminus is deleted, YopM is still able to bind AAT. This indicates that either the LRR itself, or a motif presented by LRR6–8, is recognized by AAT. Future analysis will be aimed at defining the binding region of YopM, but also of EspB and EspD from EPEC, more closely, to shed more light on the interaction of AAT with virulence proteins. These investigations should, of course, also include analysis of the mechanism by which AAT is able to interact with non-protease proteins, as this interesting new aspect of AAT interaction with pathogen proteins has not been studied until now.

The main questions that remain to be answered are, first, where does the YopM–AAT interaction take place (intracellularly or extracellularly), and second, what is the biological significance of the YopM–AAT interaction in the context of a natural infection? AAT is mainly a secreted protein that is very abundant in human serum, but it is also secreted from macrophages, monocytes and enterocytes (Molmenti *et al.*, 1993; Perlmutter *et al.*, 1985), cells with which *Y. enterocolitica* interacts during infection. YopM is translocated by *Y. enterocolitica* directly into the host cytosol. This might indicate that both proteins interact either intracellularly, before AAT is secreted, or extracellularly, assuming some YopM protein might be secreted. It has been discussed that YopM of *Y. pestis* might have a role in pathogenesis after secretion in addition to a role after translocation, as it interacts with z-thrombin, but this hypothesis could not be proven experimentally (Hines *et al.*, 2001). In addition, there is experimental evidence suggesting that YopM and possibly other Yop effectors might not only be translocated, but also be secreted during an infection. For example, Cheng & Schneewind (2000) quantified the amount of apolarly secreted YopM during an infection of HeLa cells to be approximately 7%. A different study shows that there is a strong humoral immune response of mice infected with *Y. pestis* to YopM, but not to, for example, YopE, implying that YopM might have an extracellular function *in vivo* (Benner *et al.*, 1999). It is, therefore, quite possible that YopM has intracellular and extracellular functions during an infection, and that the extracellular function is related to YopM’s interaction with AAT. While we favour a model where YopM interacts with AAT extracellularly, YopM might also interact with intracellular AAT to prevent or at least reduce its secretion. In response to inflammatory mediators like interleukin 6 or endotoxin, the amount of secreted AAT is increased (Kalsheker *et al.*, 2002), and YopM might interfere with this process. However, although YopM interacts with AAT from cellular lysates, we were not able to detect intracellular interaction by co-immunofluorescence analysis, but this might also be due to the relatively low amounts of both
proteins in the cell after infection, and to the relatively low specificity of the antiserum used in the experiment. The interaction of YopM with PRK2 and RSK1 was, for example, identified after transfecting YopM expression constructs into eukaryotic cells, thereby experimentally increasing the amount of intracellular YopM (McDonald et al., 2003).

With the data currently at hand, whether the AAT–YopM interaction is beneficial for the host or for the pathogen cannot be determined. In one scenario, the interaction might provide an advantage for the pathogen. This is not linked to AAT’s anti-protease activity, as elastase was still efficiently inhibited by AAT in the presence of YopM. Furthermore, binding to AAT did not protect YopM against proteolytic degradation. This could imply that YopM might target a different function of AAT, as it is becoming evident that AAT has a much broader activity than previously anticipated that is not related to its antiprotease activity. This includes a role of AAT as a signalling molecule for the expression of pro-inflammatory cytokines (Aldonyte et al., 2004; Brantly, 2002; Hiemstra, 2002). Furthermore, various studies indicate that YopM targets the innate immune response of the host (Kerschen et al., 2004; Marketon et al., 2005). As AAT is an acute-phase protein, interaction of YopM with AAT is well in agreement with the idea that this interaction might interfere with the host’s unspecific immune response. The best-characterized effect of YopM is the depletion of NK cells after systemic infection with Y. pestis, which is not detectable after infection with a yopM mutant strain (Kerschen et al., 2004). How YopM acts at the molecular level in this process remains elusive. Interestingly, AAT is able to inhibit NK cell activity (Laine et al., 1990; Okumura et al., 1985), implying a putative link between YopM–AAT interaction and NK cell depletion.

In an alternative scenario, the AAT–YopM interaction is beneficial for the host, comparable to the effect of AAT on EPEC virulence (Knappstein et al., 2004). However, as it is currently not known how YopM contributes to virulence at the molecular level, it cannot be assessed how AAT could interfere with YopM’s function in virulence. Although our data provide new insights into AAT’s and YopM’s function, the role of YopM during infection remains enigmatic, and future experiments have to be aimed at determining the biological role of the molecular interaction between AAT and YopM during an infection.

ACKNOWLEDGEMENTS

We thank Erwin Bohn for the gift of YopM antiserum and Silke Michgeh for help with experiments. This work was supported by Innovative Medical Research grant (IMF: HE110401) of the Medical School of the University of Münster and in part by grants of the Deutsche Forschungsgemeinschaft (DFG SFB293/B5, SCHM770/10).

REFERENCES


