Investigation of EscA as a chaperone for the *Edwardsiella tarda* type III secretion system putative translocon component EseC

Bo Wang,1,2 Zhao Lan Mo,1 Yun Xiang Mao,3 Yu Xia Zou,1 Peng Xiao,1,2 Jie Li,3 Jia Yin Yang,1,2 Xu Hong Ye,3 Ka Yin Leung4 and Pei Jun Zhang1

1Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, PR China
2Graduate University of Chinese Academy of Sciences, Beijing 100049, PR China
3Ocean University of China, Qingdao 266003, PR China
4Department of Biological Sciences, Faculty of Science, National University of Singapore, 117543 Singapore

*Edwardsiella tarda* is an important Gram-negative enteric pathogen affecting both animals and humans. It possesses a type III secretion system (T3SS) essential for pathogenesis. EseB, EseC and EseD have been shown to form a translocon complex after secretion, while EscC functions as a T3SS chaperone for EseB and EseD. In this paper we identify EscA, a protein required for accumulation and proper secretion of another translocon component, EseC. The escA gene is located upstream of eseC and the EscA protein has the characteristics of T3SS chaperones. Cell fractionation experiments indicated that EscA is located in the cytoplasm and on the cytoplasmic membrane. Mutation with in-frame deletion of escA greatly decreased the secretion of EseC, while complementation of escA restored the wild-type secretion phenotype. The stabilization and accumulation of EseC in the cytoplasm were also affected in the absence of EscA. Mutation of escA did not affect the transcription of eseC but reduced the accumulation level of EseC as measured by using an EseC-LacZ fusion protein in *Ed. tarda*. Co-purification and co-immunoprecipitation studies demonstrated a specific interaction between EscA and EseC. Further analysis showed that residues 31–137 of EseC are required for EseC-EscA interaction. Mutation of EseC residues 31–137 reduced the secretion and accumulation of EseC in *Ed. tarda*. Finally, infection experiments showed that mutations of EscA and residues 31–137 of EseC increased the LD50 by approximately 10-fold in blue gourami fish. These results indicated that EscA functions as a specific chaperone for EseC and contributes to the virulence of *Ed. tarda*.

**INTRODUCTION**

*Edwardsiella tarda* is a facultative aerobic Gram-negative pathogen with a wide host range, infecting animals including fish (Sae-Oui *et al.*, 1984), amphibians (Kourany *et al.*, 1977), reptiles (Goldstein *et al.*, 1981), birds (Cook & Tappe, 1985) and mammals (including humans) (Janda & Abbott, 1993). Edwardsielliosis, caused by *Ed. tarda*, has been found in many commercially important cultured fish, and leads to extensive losses in both freshwater and marine aquaculture (Thune *et al.*, 1993). In humans, *Ed. tarda* can cause gastrointestinal (Janda & Abbott, 1993) and extra-intestinal infections (Yang & Wang, 1999). The pathogenesis of *Ed. tarda* is multifactorial, including factors that enable the bacteria to invade non-phagocytic cells (Kourany *et al.*, 1977; Ling *et al.*, 2000), survive in phagocytes (Srinivasa Rao *et al.*, 2001, 2003), and produce virulence factors such as haemolysins (Janda & Abbott, 1993; Chen *et al.*, 1996) and catalases (Srinivasa Rao *et al.*, 2003). Recently, two important protein secretion systems, a type III secretion system (T3SS) (Tan *et al.*, 2005; Zheng *et al.*, 2007) and a type VI secretion system (T6SS) (Zheng & Leung, 2007), have been demonstrated to be virulence-associated.

Flagellar and non-flagellar systems (Saier, 2004; Pallen *et al.*, 2005) constitute two broad classes of T3SSs. Flagellar type III secretion systems (F-T3SSs) are responsible for the export of flagellum components (Macnab, 2003), while non-flagellar type III secretion systems (NF-T3SSs) translocate proteins across both the bacterial envelope and the eukaryotic plasma membrane in an ATPase-dependent fashion (Pallen *et al.*, 2005). Two kinds of proteins secreted...
include the anti-host effectors, which are translocated into the cytosol of the target cells, where they subvert a variety of cellular processes (Waterman & Holden, 2003; Ghosh, 2004), and the translocon proteins, which form pores in a host cell’s plasma membrane through which the effectors can enter the infected cell (Büttner & Bonas, 2002).

Efficient secretion of proteins through any T3SS usually depends upon the presence of chaperones that bind to the T3SS-secreted proteins (Parsot et al., 2003). Chaperones stabilize newly synthesized proteins, protecting them from aggregation and proteolysis in the cytoplasm, and then deliver proteins to the secretion apparatus (Parsot et al., 2003; Ghosh, 2004). In addition, some T3SS chaperones also function as regulators for T3SS gene expression and/or protein secretion (Darwin & Miller, 2001; Francis et al., 2002). Two distinct functional classes of chaperones exist for NF-T3SSs: class I chaperones, which bind to effectors, and class II chaperones, which bind to translocons (Page & Parsot, 2002; Parsot et al., 2003). Class I chaperones share a moderate degree of sequence homology, with a common mixed αβ-helical fold (Parsot et al., 2003; Pallen et al., 2005), while some class II chaperones have been recently reported to share TPR-like motifs (Bröms et al., 2006; Edqvist et al., 2006; Büttner et al., 2008). Interactions of class II chaperones and their substrates are necessary for functions involving regulatory, structural and effector mechanisms (Delahay & Frankel, 2002; Olsson et al., 2004), while some class II chaperones are reported to have defined regions that interact with their cognate substrates (Daniell et al., 2003; Edqvist et al., 2006).

In pathogenic Ed. tarda, an identified T3SS contains 35 open reading frames. EseB, EseC and EseD have been shown to be major components of the extracellular proteins secreted by the T3SS (Tan et al., 2005), and these three proteins form a protein complex after secretion (Zheng et al., 2007). EseB, EseC and EseD are respectively homologous to translocon components EspA, EspD and EspB of enteropathogenic Escherichia coli (EPEC) (Ide et al., 2001), and to the translocon components SseB, SseC and SseD of Salmonella spp. (Nikolaus et al., 2001). These findings suggest that EseB, EseC and EseD may function as translocon components, facilitating the translocation of effectors. These three Ese proteins contribute to Ed. tarda pathogenesis, as mutation of eseB, eseC or eseD led to a 10-fold decrease in virulence compared to the wild-type (Tan et al., 2005).

As chaperones are key mediators of the T3SS virulence strategy, previous research was designed to identify the chaperones of Ed. tarda T3SS. One chaperone, EscC, was shown to function as a T3SS chaperone for the putative translocon components EseB and EseD (Zheng et al., 2007). However, no chaperone has hitherto been identified for another putative translocon component, EseC. EseC is homologous to proteins belonging to the EspD family (YopB from Yersinia and IpaB from Shigella), which require chaperones in order to properly perform their functions (Cornelis & Van Gijsenem, 2000; Büttner & Bonas, 2002). Analysis of the secondary structure indicated that the EseC protein contains two predicted hydrophobic transmembrane domains and two coiled-coil domains (Fig. 1B), similar to its homologues, such as EspD and YopB. These observations suggested that EseC may have functions similar to those of homologues involved in the pathogenesis process of cell attachment, pore formation and translation of effectors (Cornelis & Van Gijsenem, 2000; Büttner & Bonas, 2002). The eseC gene is located upstream of eseC (Fig. 1A) and the EseC protein is homologous to the class II chaperones in other bacterial species such as CesD (38 % identity and 57 % similarity) in EPEC (Wainwright & Kaper, 1998), LcrH/SycD (24 % identity and 48 % similarity) in Yersinia spp. (Neyt & Cornelis, 1999), PcrH (23 % identity and 42 % similarity) in Pseudomonas spp. (Bröms et al., 2003) and IpGC (23 % identity and 42 % similarity) in Shigella spp. (Ménard et al., 1994). Interestingly, CesD was shown to interact with EspD but not EspB; this interaction is required in order to ensure proper secretion of EspD and EspB. However, IpGC was shown to bind directly to two translocon proteins (IpaB and IpaC) in the cytoplasm (Ménard et al., 1994). Given the similarity of EseC and EspD, EscA could play a role similar to that of CesD and may be required for proper secretion of EseC. Here we present evidence that EscA functions as a specific chaperone responsible for the stabilization and efficient secretion of EseC in Ed. tarda. In addition, a defined domain in EseC is demonstrated to be required for the interaction between EseC and EscA to occur. This domain also plays a role in the pathogenesis of Ed. tarda.

METHODS

Bacteria strains, plasmids, culture media and growth conditions. The bacterial strains and plasmids used in this study are listed in Table 1. E. coli strains were routinely grown at 37 °C on LB-agar plates or with shaking in LB-broth (Difco). Ed. tarda strains were grown at 25 °C on tryptic soy agar (TSA) plates or with shaking in tryptic soy broth (TSB, Difco). For the induction of T3SS expression, Ed. tarda strains were grown without shaking in a 5 % (v/v) CO2 incubator at 25 °C in Dubbecco’s modified Eagle medium (DMEM, Invitrogen). When required, culture media were supplemented with appropriate antibiotics: ampicillin (Amp, 50 μg ml⁻¹), colistin (Col, 12.5 μg ml⁻¹), kanamycin (Km, 50 μg ml⁻¹), chloramphenicol (Cm, 34 μg ml⁻¹) and tetracycline (Tet, 50 μg ml⁻¹).

Construction of in-frame deletion mutants of Ed. tarda PPD130/91. Overlap PCR was used to generate in-frame deletion fragments. The unmarked in-frame deletion mutants in Ed. tarda PPD130/91 were constructed according to a previously described method (Mo et al., 2007). The ΔeseC mutation removed codons 2–130 of EseC, whereas the ΔeseCmutant removed an internal fragment of codons 31–137 of EseC.

To create a complementing plasmid for the ΔeseC mutant, the escA gene was amplified and introduced into plasmid pACYC184. The resulting plasmid, pACYC184-escA, was transformed into the ΔeseC mutant to produce ΔescA + escA.

Construction of the recombinant EscA protein and generation of polyclonal antibody. The polyclonal anti-EscA antibody was
Fig. 1. Effect of EscA on the secretion and accumulation of EseC. (A) Schematic representation of the escA–eseC region of Ed. tarda. (B) Schematic representation of the secondary structure of the EseC protein, indicating the predicted transmembrane (T) and coiled-coil (C) regions. (C) 2D PAGE analysis of the supernatant proteins of the Ed. tarda wild-type strain and ΔescA mutant cultured in DMEM at 25 °C with 5% (v/v) CO₂ for 24 h. Supernatant proteins of each strain were separated on Immobiline DryStrips (pH 3–10) and adjusted according to the relative amount of proteins secreted by each strain: wild-type (10 μg) and ΔescA (5 μg). Gels (12.5% polyacrylamide) were silver-stained. Translocon proteins EseB, EseC and EseD are indicated. (D) Western blotting analysis of the extracellular proteins (ECPs) and intracellular proteins (ICPs) of Ed. tarda wild-type, ΔescA and ΔescA+escA strains. Bacteria were adjusted to an equivalent amount of cells (OD₅₄₀ 0.5). The ECPs and ICPs of each strain were extracted from equal amounts of cells and analysed by Western blotting using anti-EscA, -EseB, -EseC and -EseD polyclonal antibodies. Relative units of the EseC proteins in (D), as measured with the Fluor-S Multi-imager (Bio-Rad), were as follows: wild-type ECP (lane 1), 100.0; ΔescA mutant ECP (lane 2), 1.5 ± 0.5; ΔescA + escA ECP (lane 3), 95.2 ± 3.0; wild-type ICP (lane 4), 36.6 ± 3.4; ΔescA mutant ICP (lane 5), 9.7 ± 1.2; and ΔescA + escA ICP (lane 6), 35.4 ± 4.2.
**Table 1.** Strains and plasmids used in this study

<table>
<thead>
<tr>
<th>Strain or plasmid</th>
<th>Description or genotype</th>
<th>Reference or source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E. coli</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DH5x</td>
<td>supE44 ΔlacU169 (ϕ80 lacZΔM15) hisdRI7 recA1 gyrA96 thi-1 relA1</td>
<td>Hanahan (1983)</td>
</tr>
<tr>
<td>MCI061 (pir)</td>
<td>thi-1 thr-1 leu6 proA2 his-4 argE2 lacY1 galK2 ara14 xyl5 supE44 pir</td>
<td>Rubíres et al. (1997)</td>
</tr>
<tr>
<td>SM10 (pir)</td>
<td>thi thr leu tonA lacY supE recA RP4-2-Tc-Mu Km' pir</td>
<td>Miller &amp; Mekalanos (1988)</td>
</tr>
<tr>
<td>BL21(DE3)/pLysS</td>
<td>F' ompT hsdS (rM mg') gal dcm (DE3) tonA pLysS (Cm')</td>
<td>Tan et al. (2005)</td>
</tr>
<tr>
<td>SY327 (pir)</td>
<td>Δ(lac, pro) argE(Am) rif malA recA565 pir</td>
<td>Miller &amp; Mekalanos (1988)</td>
</tr>
<tr>
<td>S17-1 (pir)</td>
<td>Tp' Sm' recA thi pro hsdR'M + RP4 : 2-Tc: Mu: Km: Tn7 pir</td>
<td>Simon et al. (1983)</td>
</tr>
<tr>
<td><strong>Ed. tarda</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPD130/91</td>
<td>Wild-type, Col' Km' Amp'</td>
<td>Ling et al. (2000)</td>
</tr>
<tr>
<td>ΔescA</td>
<td>PPD130/91, escA in-frame deletion of codons 2–130</td>
<td>This study</td>
</tr>
<tr>
<td>ΔescC31–137</td>
<td>PPD130/91, escC in-frame deletion of codons 31–137</td>
<td>This study</td>
</tr>
<tr>
<td>ΔescA + escA</td>
<td>PPD130/91, ΔescA carrying pACYC184-escA</td>
<td>This study</td>
</tr>
<tr>
<td>escC::pVIK111</td>
<td>PPD130/91, in-frame escC-lacZ translational fusion</td>
<td>This study</td>
</tr>
<tr>
<td>escC::pVIK112</td>
<td>PPD130/91, in-frame escC-lacZ translational fusion</td>
<td>This study</td>
</tr>
<tr>
<td>ΔescA escC::pVIK111</td>
<td>ΔescA; in-frame escC-lacZ translational fusion</td>
<td>This study</td>
</tr>
<tr>
<td>ΔescA escC::pVIK112</td>
<td>ΔescA; in-frame escC-lacZ transcriptional fusion</td>
<td>This study</td>
</tr>
<tr>
<td><strong>Plasmids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pGEMT-easy</td>
<td>Cloning vector; Amp'</td>
<td>Promega</td>
</tr>
<tr>
<td>pRE112</td>
<td>pGP704 suicide plasmid, pir dependent, Cm' oriT oriV sacB</td>
<td>Edwards et al. (1998)</td>
</tr>
<tr>
<td>pETDuet-1</td>
<td>Expression vector, Amp'</td>
<td>Novagen</td>
</tr>
<tr>
<td>pACYC184</td>
<td>Cloning vector, Cm' Tc'</td>
<td>Fermentas Life Sciences</td>
</tr>
<tr>
<td>pAC</td>
<td>Cloning vector, Km' Te'</td>
<td></td>
</tr>
<tr>
<td>pA1</td>
<td>pETDuet-1 with escA in MCS1 (encodes His6-EscA)</td>
<td>This study</td>
</tr>
<tr>
<td>pC1</td>
<td>pETDuet-1 with escC in MCS1 (encodes His6-EscC)</td>
<td>This study</td>
</tr>
<tr>
<td>pC2</td>
<td>pETDuet-1 with escC in MCS2 (encodes EscA)</td>
<td>This study</td>
</tr>
<tr>
<td>pAC</td>
<td>pETDuet-1 with escC in MCS1 and escC in MCS2 (encodes His6-EscA + EscC)</td>
<td>This study</td>
</tr>
<tr>
<td>pAC31–30</td>
<td>escA31–30 fragment introduced into MCS2 of pA1</td>
<td>This study</td>
</tr>
<tr>
<td>pAC31–137</td>
<td>escA31–137 fragment introduced into MCS2 of pA1</td>
<td>This study</td>
</tr>
<tr>
<td>pAC318–193</td>
<td>escA318–193 fragment introduced into MCS2 of pA1</td>
<td>This study</td>
</tr>
<tr>
<td>pAC194–243</td>
<td>escA194–243 fragment introduced into MCS2 of pA1</td>
<td>This study</td>
</tr>
<tr>
<td>pAC255–318</td>
<td>escA255–318 fragment introduced into MCS2 of pA1</td>
<td>This study</td>
</tr>
<tr>
<td>pAC319–402</td>
<td>escA319–402 fragment introduced into MCS2 of pA1</td>
<td>This study</td>
</tr>
<tr>
<td>pAC403–429</td>
<td>escA403–429 fragment introduced into MCS2 of pA1</td>
<td>This study</td>
</tr>
<tr>
<td>pAC440–506</td>
<td>escA440–506 fragment introduced into MCS2 of pA1</td>
<td>This study</td>
</tr>
<tr>
<td>pVIK111</td>
<td>lacZ for transcription fusions, Km'</td>
<td>Kalogeraki &amp; Winans (1997)</td>
</tr>
<tr>
<td>pVIK112</td>
<td>lacZ for translation fusions, Km'</td>
<td>Kalogeraki &amp; Winans (1997)</td>
</tr>
</tbody>
</table>

generated according to a previously established method (Zheng et al., 2007). For generation of the EscA recombinant protein, the escA gene was amplified by PCR and cloned into the MCS1 (multiple cloning site 1) of pETDuet-1, yielding plasmid pA1 with an N-terminal His6-tag. The recombinant EscA was expressed in *E. coli* BL21(DE3)/pLysS and purified with Ni<sup>2+</sup>-NTA agarose beads under conditions recommended by the manufacturer (Qiagen). The purified His<sub>6</sub>-EscA protein was used to immunize New Zealand White rabbits.

**Construction of recombinant plasmids encoding His<sub>6</sub>-EscA and His<sub>6</sub>-EscA + EseC.** For construction of the recombinant plasmid encoding His<sub>6</sub>-EscA and EseC, the escC gene was amplified and introduced into MCS2 (multiple cloning site 2) of pA1, yielding the plasmid pAC. For comparison, the escC gene was then introduced into MCS1 and MCS2 of pETDuet-1 to produce plasmids pC1 and pC2, respectively.

The in-frame deletion fragments of escC were constructed following the overlap extension PCR procedure described above. The resulting fragments were introduced into MCS2 of pA1, giving plasmids pAC31–30, pAC31–137, pAC318–193, pAC194–243, pAC255–318, pAC319–402, and pAC403–429 and pAC440–506 (Table 1). These plasmids encode various His<sub>6</sub>-EscA + EseC proteins. The recombinant plasmids were transformed into *E. coli* BL21(DE3)/pLysS.

**Preparation of proteins of cell fractions.** To prepare each protein fraction, *Ed. tarda* was cultured in DMEM to induce expression of the T3SS, and the equivalent of OD<sub>600</sub>=0.5 bacterial cultures were analysed. The supernatant proteins, cell surface proteins and intracellular proteins were collected according to the method described by Beuzón et al. (1999) with some modification. Briefly, the bacterial cells were separated from 5 ml culture by centrifugation at 5000 g for 5 min at 4 °C; the culture supernatant was filtered through a 0.22 μm Millipore membrane filter and subsequently precipitated with 10% (w/v) trichloroacetic acid (TCA). The cell pellet was resuspended with 0.3 ml PBS (pH 7.4). The suspension was then mixed with 0.2 ml p-xylene for 5 min at room temperature and centrifuged at 2500 g for 10 min at 4 °C. The organic layer was discarded and the aqueous layer for

---

To prepare each protein fraction, *Ed. tarda* was cultured in DMEM to induce expression of the T3SS, and the equivalent of OD<sub>600</sub>=0.5 bacterial cultures were analysed. The supernatant proteins, cell surface proteins and intracellular proteins were collected according to the method described by Beuzón et al. (1999) with some modification. Briefly, the bacterial cells were separated from 5 ml culture by centrifugation at 5000 g for 5 min at 4 °C; the culture supernatant was filtered through a 0.22 μm Millipore membrane filter and subsequently precipitated with 10% (w/v) trichloroacetic acid (TCA). The cell pellet was resuspended with 0.3 ml PBS (pH 7.4). The suspension was then mixed with 0.2 ml p-xylene for 5 min at room temperature and centrifuged at 2500 g for 10 min at 4 °C. The organic layer was discarded and the aqueous layer was mixed with 1.2 ml acetone and maintained at −20 °C to precipitate the secreted surface proteins. The cell pellet was collected and used for preparation of intracellular proteins (ICPs). The extracellular proteins (ECPs) consisted of the fraction of detached surface proteins plus the fraction of supernatant proteins.
For subcellular fractionation, the cytoplasmic membrane and the cytoplasm proteins were prepared using the method described by Neyt & Cornelis (1999). Briefly, Ed. tarda bacteria cultured in DMEM were harvested from the supernatant, and the supernatant proteins were separated by precipitation with 10% TCA as described above. The bacterial cells were resuspended in 10 mM cold Tris/HCl (pH 8.0) and 5 mM MgCl₂, and sonicated. The cellular debris was precipitated by centrifugation at 10000 g for 5 min, and the supernatant was centrifuged for 30 min at 100 000 g to separate the membrane (insoluble) fraction from the cytosolic (soluble) fraction.

Each protein sample was dissolved in 50 μl ReadyPrep reagent 3 (Bio-Rad), and an equal volume (10 μl per lane) of each fraction was loaded on the SDS-PAGE gel for Western blotting.

**2D PAGE and Western blotting.** 2D PAGE was performed as previously described (Srinivasa Rao et al., 2004). For Western blotting, protein fractions were resolved by 12% SDS-PAGE and electrotransferred onto nitrocellulose membranes according to the method described by Towbin et al. (1979). EscA and EseC were detected by incubation overnight at 4°C with a 1:1000 dilution of anti-EscA and anti-EseC rabbit polyclonal antibodies, respectively, followed by a 1:2000 dilution of goat anti-rabbit IgG conjugated to horseradish peroxidase (Sigma). Antibody complexes were detected by development in 3,3-diaminobenzidine tetrahydrochloride (DAB). Anti-DnaK monoclonal antibody (Merck) was used at a dilution of 1:2000 for detection of cell fractions.

**The relative concentration of EseC in cell fractions was estimated by refractive densitometry using a Fluor-S Multi-imager (Bio-Rad) in the reflective mode. Values were calculated from optical density units (ODu) adjusted for band volume (ODu x mm²) using the Quantity One 4.3.0 software package (Bio-Rad). Wild-type EseC protein in the ECP fraction was used as an internal quantity standard. Three individual repetitions were analysed for each experiment.**

**Construction of transcriptional and translational fusions, and β-galactosidase assay.** Plasmids pVIK112 and pVIK111 have been used to study the regulation of genes at the transcriptional and the translational levels (Kalogeraki & Winans, 1997). For the construction of LacZ transcriptional or translational strains, a 486 bp internal fragment (corresponding to positions 902–1387 bp) of eseC was amplified from PPD130/91 genomic DNA and introduced into the XbaI/EcoRI-digested sites of pVIK112 or pVIK111, respectively. The resulting plasmids were transferred from S17-1 λpir into wild-type Ed. tarda or the ΔescA mutant strain via conjugation and integrated into the chromosome by homologous recombination. The resulting strains (eseC::pVIK111, escC::pVIK112, ΔescA escC::pVIK111 and ΔescA escC::pVIK112) were grown in DMEM for 24 h at 25°C with 5% (v/v) CO₂. Bacterial cells were harvested and β-galactosidase activity was measured as described by Zheng et al. (2007). Each measurement was performed with triplicate samples.

**Analysis of EseC stabilization.** Ed. tarda wild-type and ΔescA strains were grown in DMEM at 25°C with 5% (v/v) CO₂ to an OD₆₀₀ of 0.5. Chloramphenicol was then added to a final concentration of 200 μg ml⁻¹ to inhibit protein synthesis. Bacterial cultures (1.5 ml) were sampled at 15 min intervals from time 0 to 120 min. Ed. tarda cells were collected by centrifugation (12 000 g, 4°C, 2 min), and the bacterial samples were boiled in the SDS-PAGE loading buffer (Fermentas) for 5 min and analysed by Western blotting using anti-EseC sera.

**Co-immunoprecipitation of EscA and EseC.** An experiment for co-immunoprecipitation of EscA and EseC was performed using the Seize primary immunoprecipitation kit (Pierce). A 200 μl volume of the beads was mixed with 100 μg of the purified anti-EscA antibody, and the mixture was incubated with gentle shaking at room temperature for 4 h. After washing, the mixture was incubated with the ECPs or ICPs overnight at 4°C with shaking. After washing the mixture three times with washing buffer, the complexes were recovered from the beads with elution buffer. The purified proteins were then analysed by SDS-PAGE followed by Western blotting with anti-EseC and anti-EscA sera.

**Co-purification assay.** The interactions of EscA-EseC and EscA-ΔescA were determined by co-purification of the His₆-EscA + EseC and His₆-ΔescA + EseC complexes in a Ni²⁺-NTA column. After induction with 1 mM IPTG, bacteria containing the corresponding recombinant plasmids were harvested and resuspended in NTM buffer [300 mM NaCl, 50 mM Tris/HCl (pH 8.0), 10 mM β-mercaptoethanol] supplemented with 20 mM imidazole before being lysed by sonication. The lysates were cleared by centrifugation and incubated at 4°C for 1 h with 50 μl Ni²⁺-NTA agarose beads, with gentle mixing. The suspensions were successively transferred into a column and washed five times with NTM buffer supplemented with 30 mM imidazole. The bound proteins were eluted from the column with 50 μl NTM buffer supplemented with 200 mM imidazole.

**Virulence of mutant Ed. tarda in fish.** Healthy naive blue gourami fish (Trichogaster trichopterus Pallas) were infected with Ed. tarda wild-type and mutant strains as previously described (Ling et al., 2000). The mortality of the fish was recorded over a period of 7 days after intramuscular injection. The LD₉₀ values were calculated according to the method developed by Reed & Muench (1938).

**RESULTS**

**Influence of EscA on the accumulation and secretion of EseC**

Chaperones for the type III secretion translocon components and effectors often affect the secretion and/or stabilization of the target proteins (Page & Parsot, 2002). To ascertain the role of escA, a non-polar in-frame deletion mutant of ΔescA was constructed. The ΔescA mutant and the wild-type strain were grown in DMEM at 25°C in a 5% (v/v) CO₂ incubator to induce the expression of the T3SS proteins. The supernatant of each strain was collected and analysed by 2D PAGE (Fig. 1C). Significant, the ΔescA mutant was determined to have lost the EseC protein in the supernatant, yet still displayed the characteristic EseB and EseD protein spots.

ECPs containing the proteins secreted on the cell surface and into the culture medium were collected from the wild-type, ΔescA and ΔescA + escA strains. Samples representing the equivalent number of bacteria were loaded and analysed by Western blotting. As illustrated in Fig. 1(D), EscA was not detected in ECPs, and the secretion of EseC was greatly decreased (1.5 ± 0.5 relative units) (lane 2) in the ΔescA mutant compared to that in the wild-type strain (100 relative units) (lane 1). The phenotype of decreased secretion of EseC was due to the mutation of escA, as complementing the ΔescA mutant with escA restored the secretion of EseC (95.2 ± 3.0 relative units) (lane 3) to almost the wild-type level. As calculated, the wild-type strain produced about 136.6 relative units of EseC (100.0 in ECP and 36.6 ± 3.4 in ICP), but the ΔescA mutant produced about 11.2 relative units of EseC (1.5 ± 0.5 in...
ECP and 9.7 ± 1.2 in ICP). Thus, only 13.4 % of EseC was secreted in the absence of escA, while 73.2 % of EseC was secreted in the wild-type strain. The accumulation and secretion of EseB and EseD were not obviously affected in the ∆escA mutant and were comparable to those of the wild-type strain and the complemented strain (Fig. 1D and data not shown). This finding suggested that escA affects the accumulation and secretion of EseC in *Ed. tarda*.

### Influence of EscA on the stabilization of EseC in *Ed. tarda*

To determine whether the reduced amount of accumulation or secretion of EseC was due to the reduced stabilization of this protein in the absence of escA, the amount of EseC in the *Ed. tarda* culture was monitored after adding chloramphenicol to inhibit bacterial protein synthesis. As shown in Fig. 2, in the presence of chloramphenicol the amount of EseC in the ∆escA mutant gradually reduced over time, and was practically undetectable after 90 min. However, the amounts of EseC in the wild-type and complemented strains were not affected during the monitoring period. This result demonstrated that EscA may affect the stabilization of EseC.

### Lack of influence of EscA on the transcription of eseC

Some chaperones reportedly affect the transcription and even the translation of their cognate substrates (Tucker & Galán, 2000; Darwin & Miller, 2001). Therefore, the effect of ∆escA on EseC could be partially explained by EscA’s alteration of the transcription and/or translation of the eseC gene. To investigate this possibility, we examined the effect of a deletion mutation in escA on EseC at the transcription and translation levels. Following the method described in Methods, a 486 bp fragment of eseC (positions 902–1387 bp) was transferred into plasmids pVIK112 and pVIK111, creating β-galactosidase transcriptional and translational fusions, respectively. The resultant plasmids were then integrated into the chromosomes of *Ed. tarda* wild-type strain and ∆escA mutant, creating the transcriptional fusion strains eseC::pVIK112 and ∆escA eseC::pVIK112, respectively.

The resultant strains, containing the intact N-terminus of EseC (462 residues), were selected by PCR. Cells of the fused strains were collected and used for measuring β-galactosidase activities. No significant difference in β-galactosidase activity was observed between eseC::pVIK112 (55 ± 12 Miller units) and ∆escA eseC::pVIK112 (58 ± 5 Miller units) (*P* > 0.05), suggesting that the deletion of escA did not affect the transcription of EseC-LacZ in the bacteria. In contrast, the β-galactosidase activity in ∆escA eseC::pVIK111 (6 ± 4 Miller units) was reduced approximately 5–10-fold compared to that in eseC::pVIK111 (48 ± 10 Miller units), demonstrating that escA affected the EseC-LacZ level in the bacteria (*P* < 0.05). Because the ∆escA eseC::pVIK111 strain detected contained the intact N-terminus of EseC, it is impossible that the decrease in β-galactosidase activity was due to the absence of the interaction region of EseC-EscA, which was located at residues 31–137 of EseC (see below). Furthermore, the results supported the conclusion that deletion of escA might affect the stabilization of EseC in the cytoplasm due to the fact that ∆escA did not affect the transcription of eseC. However, the possibility cannot be excluded that EscA could play a role in the translation of EseC.

### Localization of EscA to the membrane and the cytoplasm

Based on the lack of any recognizable signal peptide sequence in EscA, it was hypothesized that EscA would be localized in the bacterial cytosol, like its homologues (Neyt & Cornelis, 1999). To examine the cellular location of EscA, protein fractions of supernatant, membrane (insoluble) and cytoplasm (soluble) from wild-type, ∆escA and complemented strains were analysed by Western blotting. As illustrated in Fig. 3, EscA was detected in both the soluble and insoluble fractions in the wild-type and complemented strains. However, it was not detected in the supernatant fractions or in the ∆escA background. DnaK, a cytosolic protein, was found only in the soluble fractions and was absent in the ECPs and insoluble fractions, indicating that the membrane fractions were not contaminated by the bacterial cytoplasm. These results suggested that EscA is not a secreted protein but a protein located in the cytoplasm and on the bacterial membrane.

![Fig. 2. Effect of EscA on the stabilization of EseC. *Ed. tarda* wild-type and ∆escA strains were grown in DMEM at 25 °C with 5% (v/v) CO2 to an OD540 of 0.5. Chloramphenicol (200 µg ml⁻¹) was then added to the medium. Bacterial cultures were sampled at 15 min intervals and equal amounts of cells (OD540 0.5) were analysed by Western blotting using anti-EseC polyclonal antibody.](image-url)
However, it is possible that EscA formed small insoluble aggregates and was fractionated with the insoluble fractions, and was therefore detected in these fractions.

**Association of EscA and EseC in *E. coli* and *Ed. tarda***

Chaperones often perform their function by associating specifically with their cognate substrates (Daniell *et al.*, 2001; Zheng *et al.*, 2007). We hypothesized that the influence of EscA on EseC is mediated via protein–protein interaction. To investigate the potential interaction between EscA and EseC, the pETDuet-1 co-expression system and the His$_6$-tag purification system were exploited in the sense that only proteins linked with His$_6$ were eluted from Ni$^{2+}$-NTA agarose beads. A plasmid (pAC) that encodes both His$_6$-EscA and EseC was generated, and the proteins were produced simultaneously in *E. coli* BL21(DE3)/pLysS. To serve as controls, plasmids encoding His$_6$-EscA (pA1), His$_6$-EseC (pC1, with escA in MCS1), and EseC (pC2, with escC in MCS2) were constructed. After overproduction of these proteins in *E. coli*, clear extracts were mixed with Ni$^{2+}$-NTA agarose beads and proteins adsorbed on the beads were analysed by Western blotting. The result (Fig. 4A) clearly indicated that EseC was co-purified with His$_6$-EscA (pAC). As negative controls, only EseC or EscA alone was detected on the Ni$^{2+}$-NTA beads incubated with extracts from bacteria expressing His$_6$-EseC (pC1) or His$_6$-EscA (pA1), respectively. These results demonstrated that EseC and EscA specifically interact with each other *in vitro*.

Overproduction of EseC (which reacts with anti-EseC antibody) in *E. coli* produced multiple lower bands, while His$_6$-EseC (pC1) produced more bands than His$_6$-EseC-EseC (pAC), suggesting that the interaction between EscA and EseC may also be important for the stabilization of EseC *in vitro*. To investigate this effect in detail, the EseC patterns expressed in *E. coli* were analysed without co-purification in the absence and in the presence of EscA. As shown in Fig. 4(B), the reaction between His$_6$-EseC (pC1) and anti-EseC resulted in a greater number of low bands than His$_6$-EseC-EseC (pAC), regardless of the IPTG induction time (1, 2, 3 or 4 h). Thus the data showed that the presence of EscA causes the EseC protein to be more stable in *E. coli*, supporting the finding that EscA is required for the stabilization of EseC.

The fractionation experiments which showed that EscA and EseC were both found in the cytoplasm of *Ed. tarda* suggested that the two proteins may interact with each other *in vivo*. To demonstrate such an interaction, experiments were conducted to co-immunoprecipitate this putative complex. Synthesis of T3SS proteins was induced in the wild-type, ΔescA and complemented strains. The cell pellets were collected and washed with p-xylene to eliminate secreted T3SS proteins that could be absorbed to the outer membrane. After sonication, the clear extracts were incubated with anti-EseC polyclonal antibody and the complex was recovered on Protein A-Sepharose beads. The purified proteins were analysed by Western blotting after washing and eluting. As shown in Fig. 4(C), EscA and EseC were recovered from the extracts of the wild-type and complemented strains, but not from the ΔescA mutant, indicating that cytoplasmic EseC is physically associated with EscA in bacterial cells. These results provided strong evidence that EscA and EseC are associated in *Ed. tarda*.

**Localization of the binding region in EseC**

Having determined that EscA and EseC interact with each other *in vitro* and *in vivo*, we attempted to identify the interaction site that contributes to the formation of the EscA-EseC complex. A series of eight in-frame deletion mutations spanning the entire escC gene were constructed to determine a discrete binding site in EseC (Table 1). These deletions removed all of the characteristic regions of the protein, including two hypothetical transmembrane helices spanning residues 194–243 and 255–318, and two coiled-coils spanning residues 138–193 and 430–506. All of the truncated proteins were individually co-expressed with EscA in *E. coli* BL21(DE3)/pLysS. The bacterial lysate, not mixed with the Ni$^{2+}$-NTA agarose beads, was used as the input fraction to confirm protein production in the co-expression system by Western blotting. As illustrated in Fig. 5(A), all of the proteins with the expected size were produced in the co-expression system. Subsequently, the clear extracts were mixed with Ni$^{2+}$-NTA agarose beads, and proteins adsorbed on the beads were analysed by Western blotting. As shown in Fig. 5(B), truncated proteins expressed from mutations of escC$_{1–130}$, escC$_{131–137}$, escC$_{155–318}$, escC$_{194–243}$, escC$_{255–318}$, escC$_{319–402}$, escC$_{319–429}$ and escC$_{439–506}$ were co-purified with EscA. However, protein expressed from the mutation of escC$_{31–137}$ failed to be co-purified with EscA, implying that residues 31–137 of EseC (EseC$_{31–137}$) are likely to be involved in the binding site for EscA.
Interaction of EseC<sub>31–137</sub> with EscA in <i>Ed. tarda</i>

Because EseC<sub>31–137</sub> was demonstrated to be the binding region with EscA in vitro, experiments were conducted to determine whether this region interacts with EscA in vivo. <i>Ed. tarda</i> mutant ΔeseC<sub>31–137</sub>, with codons 31–137 of eseC deleted, was constructed. Co-immunoprecipitation and Western blotting were performed with the cell pellets of the wild-type strain and ΔeseC<sub>31–137</sub>. The results showed that the protein complex of EscA and the truncated EseC was not detected in the ICP of ΔeseC<sub>31–137</sub> (Fig. 4C, lane 8), while the protein complex of EscA and EseC was detected in the wild-type and escA complemented strains (Fig. 4C, lanes 5 and 7). As a negative control, this protein complex was not detected in the ECPs of these bacteria. The failure of EseC<sub>31–137</sub> to

---

**Fig. 4.** Interaction between EscA and EseC. (A) Co-purification of EseC with EscA in <i>E. coli</i>. <i>E. coli</i> BL21(DE3)/pLysS bacteria harbouring plasmids encoding His<sub>6</sub>-EscA (pA1), His<sub>6</sub>-EseC (pC1), EseC (pC2) or His<sub>6</sub>-EscA+EseC (pAC) were cultured in LB medium at 37 °C. Cultures induced with 1 mM IPTG were collected at 4 h and adjusted to OD<sub>600</sub> 0.5. The clear extracts of equal amounts of bacterial cells were incubated with Ni<sup>2+</sup>–NTA agarose beads and the proteins binding to the beads were analysed by Western blotting using anti-EscA and anti-EseC polyclonal antibodies. (B) Expression patterns of EseC in the presence and absence of EscA in <i>E. coli</i>. Cultures of <i>E. coli</i> BL21(DE3)/pLysS harbouring plasmids encoding His<sub>6</sub>-EseC (pC1) or His<sub>6</sub>-EscA+EseC (pAC) were collected 1, 2, 3 and 4 h after the addition of 1 mM IPTG. The clear extracts of equal amounts of bacterial cells (OD<sub>600</sub> 0.5) were analysed by Western blotting using anti-EseC polyclonal antibody. The lower bands detected with anti-EseC are degradation products of the hybrid proteins. (C) Co-immunoprecipitation of EseC with anti-EscA antibody. <i>Ed. tarda</i> wild-type, ΔescA, ΔescA+escA and ΔeseC<sub>31–137</sub> strains were cultured in DMEM at 25 °C with 5% (<i>v/v</i>) CO<sub>2</sub> for 24 h. Co-immunoprecipitates were prepared from ECPs (lanes 1–4) and the soluble ICPs (lanes 5–8) of each strain as described in Methods, and analysed by Western blotting using anti-EscA and anti-EseC polyclonal antibodies.
bind to EscA suggested that residues 31–137 in EseC are required for the interaction with EscA in Ed. tarda.

To investigate the effect of EseC<sub>31–137</sub> on the secretion of EseC in Ed. tarda, ECP and ICP from the induced culture of D<sub>eseC</sub><sup>31–137</sup> were collected and analysed by Western blotting. As shown in Fig. 6, accumulation of the smaller EseC<sub>D<sup>31–137</sup></sub> protein was observed in the ICP (12.3 ± 1.2 relative units), but not in the ECP (0.0 relative units) of the D<sub>eseC</sub><sup>31–137</sup> mutant. The amount of EseC<sub>D<sup>31–137</sup></sub> in the ICP was comparable to the amount of EseC (12.1 ± 1.0 relative units) in the ICP of the D<sub>escA</sub> mutant, both of which accounted for about 31% of the EseC (38.7 ± 2.6 relative units) in the ICP of the wild-type strain. This finding indicated that EseC<sub>31–137</sub> is required for the accumulation and secretion of EseC by interacting with EscA in Ed. tarda.

**Contribution of EscA and EseC<sub>A31–137</sub> to the virulence of Ed. tarda**

EseC has been reported to contribute to the pathogenesis of Ed. tarda (Tan et al., 2005). To further investigate if this contribution is related to the normal secretion of EseC, the LD<sub>50</sub> values of the ΔescA and ΔeseC<sub>A31–137</sub> mutants in blue gourami fish were examined. The deletion of escA increased the LD<sub>50</sub> value by about 1 log (10<sup>6.1</sup>) compared to the wild-type strain (10<sup>5.1</sup>), while the complemented strain restored the LD<sub>50</sub> value (10<sup>5.3</sup>) to approximately the same level as that of the wild-type strain. Similarly, ΔeseC<sub>A31–137</sub> also resulted in approximately 1 log increase in the LD<sub>50</sub> value (10<sup>5.9</sup>). These results indicated that EscA and residues 31–137 of EseC contribute to the pathogenesis of Ed. tarda.

**DISCUSSION**

Previous studies have shown that Ed. tarda utilizes a T3SS for its pathogenesis (Tan et al., 2005). EseB, EseC and EseD are T3SS-dependent secreted proteins and form a translocon complex after their secretion (Zheng et al., 2007). EscC is a specific chaperone for EseB and EseD (Zheng et al., 2007), while no chaperone for EseC has hitherto been identified. In this study, escA was demonstrated to function as a specific chaperone for EseC. EscA possesses the
common characteristics of a T3SS chaperone, including a low molecular mass (17.5 kDa), an acidic pI (4.79) and a proximate location of the encoding gene to that of its cognate substrate EseC. The data showed that EscA affects the accumulation and stability of cytoplasmic EseC, as well as its secretion into the culture medium, and the effect of EscA on EseC was demonstrated to be post-transcriptional. As an ICP, EscA interacts with EseC in vitro and in vivo, and a defined region of residues 31–137 in EseC (EseC31–137) is necessary for this interaction. Moreover, EseC31–137 affects the accumulation and secretion of EseC in Ed. tarda. Finally, challenge experiments with blue gourami fish demonstrated that both EscA and EseC31–137 contribute to the virulence of Ed. tarda.

Mutation in EscA reduces the accumulation and secretion of EseC, but has a less severe effect than mutations in some EscA homologues such as SycD/LcrH in Yersinia, CesD and CesD2 in EPEC and SseA in Salmonella, which almost abolish the accumulation and secretion of their cognate substrates (Neyt & Cornelis, 1999; Waterman & Holden, 2003; Zurawski & Stein, 2003; Edqvist et al., 2006). EspD in EPEC requires two chaperones (CesD and CesD2) for complete secretion and accumulation activities (Neves et al., 2003; Waterman & Holden, 2003). The similarity of EseC to EspD leads to the hypothesis that more than one chaperone may exist for EseC. Moreover, even in the presence of EscA, degradation of EseC can be found in the input fractions of His6-EscA+EseC (pAC) (Fig. 4B), implying that EscA does not completely protect EseC from degradation. A putative additional chaperone may exist in native Ed. tarda that is necessary for the stability of EseC. Because EseC is not secreted in the absence of eseE (Zheng et al., 2007), EseE may act as a second chaperone. Further study is needed to clarify this hypothesis.

Unlike most T3SS chaperones localized in the cytoplasm, EscA was found both on the cytoplasmic membrane and in the cytoplasm. A limited number of NF-T3SS chaperones are reported to be membrane-associated, such as CesD and CesT from EPEC (Elliott et al., 1999; Wainwright & Kaper, 1998), YscB from Yersinia (Jackson et al., 1998), SseA from Salmonella (Zurawski & Stein, 2003) and EscC from Ed. tarda (Zheng et al., 2007). This finding is reminiscent of the function of the F-T3SS chaperone. During F-T3SS protein export, the chaperone–substrate complexes dock at the membrane ATPase (Gauthier & Finlay, 2003; Thomas et al., 2004), which facilitates the release of the chaperone from the cognate secreted substrate in an ATP-dependent manner (Akeda & Galán, 2005). After release by an escort mechanism in F-T3SS protein export, free chaperones can be cycled (Evans et al., 2006). Thus, chaperone transition between cytosol and membrane compartments facilitates F-T3SS export of the flagellar component and, by extension, facilitates secretion of NF-T3SS proteins. This view is supported by previous research relating to EPEC T3SS, which indicated that the chaperone CesT and its export substrate Tir can interact independently or collectively with ATPase EcSN (Gauthier & Finlay, 2003); CesT recruits Tir and they co-localize to the EPEC inner membrane (Thomas et al., 2005). Therefore, membrane association may be a necessary step for the interaction of the secreted protein-chaperone complex with T3SS ATPase. These findings may help to explain the dual location of EscA.

The fact that EseC requires residues 31–137 for binding EscA and for its accumulation and secretion is consistent with studies showing that most translocon components associate with their cognate chaperones via the N-terminal regions (Harriott et al., 2003). Transmembrane and coiled-coil domains are found at high frequency among T3SS structural and secreted components and have been shown to play important roles in the function of translocons and effectors (Daniell et al., 2001; Delahay & Frankel, 2002). In this research, however, the two transmembrane helices (EseC194–243 and EseC255–318) and the two coiled-coil regions (EseC138–193 and EseC430–506) in EseC were found not to be involved in the interaction. This finding is not exclusive to EseC. Residues 56–99 of YopB, which contain no typical secondary structure, are responsible for binding the cognate chaperone SycD (Neyt & Cornelis, 1999). The mechanism of this interaction is not clear. However, by using domain linker prediction (Miyaizaki et al., 2002), two domain linkers were predicted in EseC, spanning residues 59–84 and 117–122 (data not shown), implying that regions between these two domain linkers possibly possess a functional secondary structure. Supporting this idea, DNASIS analysis confirmed that many short hydrophobic segments were found dispersely at residues 44–49, 70–76, 80–83, 86–87, 91–92 and 100–101, which may be important with regard to protein–protein interactions (Jones & Thornton, 1995). Whether these
hydrophobic segments located within the N-terminus of EseC have effects on the EseC-EscA interaction is yet to be investigated. We also tried to seek a specific binding region in EscA using the same procedure, but such a linear region responsible for binding to EseC was not detected (data not shown). Further study of the structural mechanism of the EscA-EseC interaction is still needed.

The observation that mutation of escA or eseC increases the LD50 value by approximately 1 log unit provides evidence that an intact translocon is essential for the function of the T3SS in the pathogenesis of Ed. tarda. An understanding of this system will provide greater insight into the virulence mechanism of this pathogen. Our results will also aid in the development of new approaches to combating edwardsiellosis. In a previous study, we reported that an attenuated strain mutated in a T3SS gene elicited good protection against edwardsiellosis in fish (Mo et al., 2007). The findings in this study will be very useful in the future for the development of effective attenuated live vaccines against edwardsiellosis. Furthermore, it is unclear at this point whether there is an additional chaperone for EseC, and EscA's regulatory role in the function of T3SS is likewise not understood. The mutants constructed in this research will also be very helpful in future studies attempting to identify the additional chaperone(s) of EseC and the possible regulatory role of EscA in T3SS function.

ACKNOWLEDGEMENTS

We are grateful to the project of Natural Sciences Foundation of China (30671613), 973 Program (2006CB10803) and 863 Program (2006AA100310) for providing the research grants for this research. We also thank Dr Hai Qi He from Southern Plain Agricultural Research Center, USDA-ARS, USA, for critical reading which helped to improve the manuscript.

REFERENCES


