Establishing a Direct Role for the *Bartonella bacilliformis* Invasion-Associated Locus B (IalB) Protein in Human Erythrocyte Parasitism

SHERRY A. COLEMAN AND MICHAEL F. MINNICK*

Division of Biological Sciences, The University of Montana, Missoula, Montana 59812

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The invasion-associated locus A and B genes (*ialAB*) of *Bartonella bacilliformis* were previously shown to confer an erythrocyte-invasive phenotype upon *Escherichia coli*, indirectly implicating their role in virulence. We report the first direct demonstration of a role for *ialB* as a virulence factor in *B. bacilliformis*. The presence of a secretory signal sequence and amino acid sequence similarity to two known outer membrane proteins involved in virulence suggested that IalB was an outer membrane protein. To develop an antiserum for protein localization, the *ialB* gene was cloned in frame into an expression vector with a six-histidine tag and under control of the *lacZ* promoter. The IalB fusion protein was purified by nickel affinity chromatography and used to raise polyclonal antibodies. IalB was initially localized to the bacterial membrane fraction. To further localize IalB, *B. bacilliformis* inner and outer membranes were fractionated by sucrose density gradient centrifugation and identified by appearance, buoyant density (ρ), and cytochrome *b* content. Inner and outer membrane proteins were analyzed by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE), and IalB was positively identified by Western blot. Contrary to expectations, IalB was localized to the inner membrane of the pathogen. To directly demonstrate a role for IalB in erythrocyte parasitism, the *B. bacilliformis* *ialB* gene was disrupted by insertional mutagenesis. The resulting *ialB* mutant strain was complemented in *trans* with a replicative plasmid encoding the full-length *ialB* gene. PCR and high-stringency DNA hybridization confirmed mutagenesis and transcomplementation events. Abrogation and restoration of *ialB* expression was verified by SDS-PAGE and immunoblotting. In vitro virulence assays showed that mutagenesis of *ialB* decreased bacterial association and invasion of human erythrocytes by 47 to 53% relative to controls. Transcomplementation of *ialB* restored erythrocyte association and invasion rates to levels observed in the parental strain. These data provide direct evidence for IalB’s role in erythrocyte parasitism and represent the first demonstration of molecular Koch’s postulates for a *Bartonella* species.

*Bartonella bacilliformis* is the only bacterium known to invade human erythrocytes. The pathogen is the causative agent of the human disease, Oroya fever, a biphasic illness whose primary-phase symptoms include a severe hemolytic anemia, where up to 100% of the circulating erythrocytes can be parasitized and 80% lysed (1, 15, 31). If untreated, this phase of the disease has a 40% fatality rate (44). Treatment with penicillin, tetracycline, or aminoglycosides is effective (43), but the disease has a 40% fatality rate (44). Treatment with penicillin, tetracycline, or aminoglycosides is effective (43), but
invasion by conferring an erythrocyte-invasive phenotype upon minimally invasive *Escherichia coli* strains (27). IalA has since been characterized as a (di)nucleoside polyphosphate hydrolase thought to be involved in reducing levels of stress-induced dinucleotides during invasion, thus aiding bacterial survival (9, 11). IalB was shown to contain a putative 22-amino-acid secretory signal sequence and to have approximately 60% amino acid similarity to the virulence determinants All of *Yersinia enterocolitica* and Rck of *Salmonella enterica* serovar Typhimurium. The presence of a potential secretory sequence and similarity of IalB to two outer membrane virulence determinants led to our hypothesis that IalB is exported to the bacterial surface, where it functions as an invasion factor. This study was undertaken to localize the IalB protein and directly determine its role in human erythrocyte association by *B. bacilliformis*.

**MATERIALS AND METHODS**

**Bacterial strains and culture conditions.** *B. bacilliformis* strains (Table 1) were cultured on heart infusion agar blood (HIAB) plates (heart infusion agar supplemented with 4% sheep erythrocytes and 2% sheep serum) in a water-saturated incubator at 30°C. When required, strains were cultured in the presence of 5% CO₂. *B. bacilliformis* strains (Table 1) were cultured on heart infusion agar blood (HIAB) plates (heart infusion agar supplemented with 4% sheep erythrocytes and 2% sheep serum) in a water-saturated incubator at 30°C. When required, strains were cultured in the presence of 5% CO₂. *E. coli* strains (27) were cultured in Luria-Bertani (LB) broth at 37°C in the presence of antibiotics (9, 15). Cultures were induced for 3 h, and the bacterial pellet was harvested by centrifugation at 4,000 × g for 20 min at 4°C. Bacterial pellets were solubilized in Laemmli sample buffer and proteins separated by SDS-PAGE. The IalB protein was excised from unfixed Coomassie blue-stained gels, minced, suspended in 1 ml of phosphate-buffered saline (PBS; pH 7.4), and used to generate antibody in a female New Zealand White rabbit as previously described (34). For immunoblots, 20 to 80 μg of protein was separated by SDS-PAGE (12.5 or 15% [wt/vol] acrylamide), electropherotically transferred to a supported nitrocellulose membrane (pore size, 0.45 μm; Schleicher & Schuell, Keene, N.H.) by the method of Southern (37) and then baked for 1 h at 80°C. DNA probes were made by random primer extension (2) with [α-32P]dCTP (New England Nuclear, Boston, Mass.). High-stringency hybridization, washes, and visualization were done as previously described (6).

**SDS-PAGE.** Protein concentrations were determined using a bichinonic acid protein kit per the manufacturer’s instructions (Sigma Chemical Co., St. Louis, Mo.). Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) was done following the general procedures of Laemmli (20) with either 12.5, 15, or 10 to 20% gradient polyacrylamide (wt/vol) gels. Either 20 or 100 μg of protein was loaded per lane for gels that were silver stained (45).

**Preparation of polyclonal antibodies and immunoblotting.** To prepare antibodies against IalB, *E. coli* M15 (pQIALB, pREP4) was grown overnight with vigorous shaking in LB broth containing ampicillin and kanamycin. The overnight culture was used to inoculate LB broth plus antibiotics and grown to an optical density at 600 nm (OD600) of 0.7 to 0.9, and IalB expression was induced by the addition of isopropyl-β-D-thiogalactopyranoside (IPTG; 2 mM final concentration). Cultures were induced for 3 h, and the bacterial pellet was harvested by centrifugation at 4,000 × g for 20 min at 4°C. Bacterial pellets were solubilized in Laemmli sample buffer and proteins separated by SDS-PAGE. The IalB protein was excised from unfixed Coomassie blue-stained gels, minced, suspended in 1 ml of phosphate-buffered saline (PBS; pH 7.4), and used to generate antibody in a female New Zealand White rabbit as previously described (34). For immunoblots, 20 to 80 μg of protein was separated by SDS-PAGE (12.5 or 15% [wt/vol] acrylamide), electropherotically transferred to a supported nitrocellulose membrane (pore size, 0.45 μm; Schleicher & Schuell), and reacted with anti-IalB antisera (diluted 1:1,000) as previously described (34).

**PCR and oligonucleotide primers.** PCR amplification was done in a GeneAmp 2400 thermocycler (Perkin-Elmer, Norwalk, Conn.) as previously described (5).

**TABLE 1. Bacteria and plasmids used in this study**

<table>
<thead>
<tr>
<th>Strain or plasmid</th>
<th>Relevant characteristics</th>
<th>Source or reference</th>
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<tbody>
<tr>
<td><strong>Strains</strong></td>
<td></td>
<td></td>
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<tr>
<td><em>B. bacilliformis</em></td>
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<tr>
<td>JB84</td>
<td>Transformation-competent strain of <em>B. bacilliformis</em></td>
<td>5</td>
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<tr>
<td>SC1</td>
<td>JB84 with IalB interrupted by pSAC100 (Km’), <em>ialB</em> mutant</td>
<td>This study</td>
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<tr>
<td>SC2</td>
<td>SC1 complemented in <em>trans</em> with pSAC200 (Km’, Cm’, <em>ialB</em>’</td>
<td>This study</td>
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<td><strong>E. coli</strong></td>
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<tr>
<td>DH5α</td>
<td>Host strain for cloning and plasmid propagation</td>
<td>Gibco-BRL</td>
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<tr>
<td>M15</td>
<td>Host strain for fusion protein expression</td>
<td>41</td>
</tr>
<tr>
<td><strong>Plasmids</strong></td>
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<tr>
<td>pIAL1</td>
<td>pUC19 containing <em>ialA</em> and <em>ialB</em> of <em>B. bacilliformis</em></td>
<td>27</td>
</tr>
<tr>
<td>pIALB</td>
<td>pUC19 containing <em>ialB</em> of <em>B. bacilliformis</em></td>
<td>27</td>
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<td>Expression vector</td>
<td>Qiagen Inc.</td>
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<tr>
<td>pREP4</td>
<td>Plasmid encoding lacT</td>
<td>Qiagen Inc.</td>
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<td>pQIALB</td>
<td>pQE-31 with 574-bp <em>PvuII</em>-PstI fragment encoding <em>ialB</em> minus its secretory signal sequence plus 15 nucleotides</td>
<td>This study</td>
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<td><em>B. bacilliformis</em> suicide plasmid; Km’</td>
<td>5</td>
</tr>
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<td>pSAC100</td>
<td>pUB1 with an internal 430-bp <em>PvuII</em>-MfeI fragment of <em>ialB</em>; Km’</td>
<td>This study</td>
</tr>
<tr>
<td>pBBRM1CS</td>
<td><em>B. bacilliformis</em> shuttle vector; Cm’</td>
<td>18</td>
</tr>
<tr>
<td>pSAC200</td>
<td>Complementation plasmid; pBBR1MCS with 756-bp SwaI-BamHI fragment containing intact <em>ialB</em>; Cm’</td>
<td>This study</td>
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DNA was denatured at 94°C for 5 min, amplified for 30 cycles (1 min at each of the following temperatures: 94, 59 or 65, and 72°C), and extended for 10 min at 72°C. Single-strand oligonucleotide primers for the *ialB* gene, IALBF (5’-GTA TTAGAATTACTACGAGATAA-3’) and IALBR (5’-ATCCGACCTAA TACTTACTTCT-3’), and for the neomycin phosphotransferase I gene (opd), NPTI5’ (5’-AGCCACGTGTTGTGTCATAATCTC-3’) and NPTI3’ (5’-CGTCCGTCAGTGTACCTGATGC-3’), were used. A “junction” primer set consisting of IALBR and NPTI5’ was designed to amplify the site of homologous recombination between the chromosomal *ialB* gene and the suicide plasmid, pSAC100. Annealing sites for all primers are depicted in Fig. 2.

**DNA hybridization analysis.** Genomic DNA from *B. bacilliformis* and plasmid DNA were digested to completion with *ClaI* and separated on a 1.2% (wt/vol) agarose gel stained with ethidium bromide. DNA was transferred to a supported nitrocellulose membrane (pore size, 0.45 μm; Schleicher & Schuell, Keene, N.H.) by the method of Southern (37) and then baked for 1 h at 80°C. DNA probes were made by random primer extension (2) with [α-32P]PdCTP (New England Nuclear, Boston, Mass.). High-stringency hybridization, washes, and visualization were done as previously described (6).
Localizaton of IalB. Accessible outer membrane proteins of intact B. bacilliformis were extrinsically radiiodinated as previously described (24) and then analyzed by SDS-PAGE. Whole bacteria were treated with various proteases (proteinase K, trypsin, subtilisin, papain, and thermolysin) to cleave any accessible, sensitive surface proteins as previously described (24), and protein profiles were analyzed by gradient SDS-PAGE. Immunofluorescent labeling of intact B. bacilliformis strains using anti-IalB polyclonal antibodies was done according to standard protocols (2). Twenty plates of 3-day-old B. bacilliformis were harvested into 1 ml of ice-cold Dulbecco's PBS, and membranes were isolated and fractionated as previously described for B. quintana (8). Cytochrome assays were performed using inner and outer membrane fractions (final protein concentration, 1 µg/µl) by the methods of Osborn et al. (30).

Human erythrocyte association assay. Blood was drawn from human volunteers into an acid citrate-dextrose Vacutainer tube and stored overnight at 4°C to separate plasma from the erythrocytes. After removal of the plasma, erythrocytes were washed with 10 ml of sterile saline (0.9%, wt/vol) and centrifuged at 700 g for 5 min. Erythrocytes were washed a second time, counted, and resuspended in recovery broth for 10 min to create a continuous gradient. Then, 0.1 ml of each association reaction was carefully layered onto the preformed Percoll gradient and centrifuged at 1,500 g for 10 min. The pellet was resuspended in 0.5 ml of recovery broth (5) to a final concentration of 10^9 erythrocytes per ml.

Three- to four-day-old B. bacilliformis cultures were harvested into recovery broth and diluted to an OD_L of 1.0 (~1.6 x 10^9 CFU/ml). Approximately 5 x 10^9 bacteria were gently mixed with 10^9 erythrocytes (multiplicity of infection 5:1) in a total volume of 0.5 ml of recovery broth. Association reactions were incubated for 8 h at 30°C in a water-saturated environment. Erythrocytes and parasitized erythrocytes were separated from free bacteria by Percoll gradient centrifugation. Briefly, 1 ml of 70% Percoll (Sigma) containing 154 mM NaCl was centrifuged at 16,000 x g for 10 min to create a continuous gradient. Then, 0.1 ml of each association reaction was carefully layered onto the preformed Percoll gradient and centrifuged at 1,500 x g for 5 min. The erythrocyte-bacterium band was collected, washed twice with sterile saline, and pelleted by centrifugation at 1,000 x g for 15 s. The pellet was resuspended in 0.5 ml of heart infusion broth, serially diluted, and then plated onto HIAB plates. Plates were incubated at 30°C in a water-saturated incubator for 10 days and then counted for CFU.

Statistical analysis. Numerical data reported for human erythrocyte association assays are the means of three independent samples ± the standard errors of the mean (SEM). The statistical significance of the data was determined by use of the Student's t test. A P value of <0.05 was considered significant.

RESULTS

Expression and purification of IalB fusion protein. To obtain sufficient amounts of IalB protein to generate antibodies, the ialB gene (excluding the portion encoding its secretory signal sequence plus five N-terminal amino acids) was cloned in frame into the expression vector pQE-31. This vector contains a six-histidine tag and a polylinker under the control of the lacZ promoter. The resulting construct, pQIALB, was transformed into E. coli M15, and IalB expression was induced with IPTG. The IalB fusion protein was synthesized at high levels and localized to the insoluble fraction of E. coli. The insoluble fraction was treated with a strong denaturant (6 M guanidine hydrochloride), and the recombinant IalB was purified using nickel affinity chromatography. IalB was purified to apparent homogeneity when analyzed by using Coomassie blue-stained SDS-PAGE gels (data not shown). Polyclonal anti-IalB antibodies were generated and found to recognize both the IalB fusion protein synthesized in E. coli and wild-type IalB synthesized by B. bacilliformis in Western blots (Fig. 1B). On Western blots, the IalB fusion protein and IalB from B. bacilliformis have estimated masses of 18.6 and 17.1 kDa, respectively. From its DNA sequence, the mature IalB protein was predicted to be 17.5 kDa (27), in close agreement with our finding. Presumably, the larger estimated mass of the IalB fusion protein is due to the presence of the charged, six-histidine tag.

Generating an ialB mutant and a transcomplemented strain of B. bacilliformis. A 426-bp, PvuII-MfeI internal fragment of the ialB gene was cloned into pU1 to create the suicide vector, pSAC100. The pMB1 origin of pSAC100 is not func-

FIG. 1. Recognition of B. bacilliformis IalB and the IalB fusion protein by polyclonal anti-IalB antibodies. Cell lysates of IPTG-induced E. coli M15(pQIALB) (lane 1) and B. bacilliformis (lane 2) analyzed by an SDS-PAGE gel stained with Coomassie blue (A) or immunoblot reacted with polyclonal anti-IalB antibodies (B). Both B. bacilliformis IalB and the IalB fusion protein are specifically detected with the antiserum. Molecular mass standards in kilodaltons are indicated on the left.
tional in *B. bacilliformis* (5); therefore, expression of the \( nptI \) gene, conferring kanamycin resistance, would only occur following recombination of the suicide plasmid into the chromosome. Cloning an internal fragment of the \( ialB \) gene ensured that homologous recombination between pSAC100 and the chromosome would not result in reconstitution of a full-length gene.

The JB584 strain of *B. bacilliformis* was electroporated with pSAC100. Kanamycin-resistant colonies were isolated, cultured, and initially characterized by PCR. The \( ialB \) gene, the \( nptI \) gene, or the junction where pSAC100 recombined with the chromosomal \( ialB \) gene were PCR amplified as depicted in Fig. 2. The \( nptI \) gene primer set (NPTI5′ and NPTI3′) amplified a 983-bp segment of the \( nptI \) gene in the kanamycin-resistant strain, SC1, but not the parental strain, JB584 (Fig. 3A, lanes 3 and 2, respectively), showing that kanamycin resistance in SC1 was due to \( nptI \) and not to selection of spontaneous kanamycin-resistant mutants. The \( ialB \) gene primer set (IALBF and IALBR) was expected to produce a 4,097-bp product from the site of homologous recombination or a 688-bp product from an intact \( ialB \) gene. Upon analysis, an amplicon of approximate 4,000-bp was obtained from the kanamycin-resistant strain, SC1, indicating that pSAC100 had recombined with the chromosomal \( ialB \) (Fig. 3A, lane 6). No PCR product would be amplified from unintegrated pSAC100 since the \( ialB \) primers are complementary to chromosomal sequences flanking the \( ialB \) gene and absent in pSAC100. As expected, a 688-bp amplicon was obtained from the intact \( ialB \) gene in JB584 (Fig. 3A, lane 5).

The junction primer set (NPTI5′ and IALBR) produced an amplicon of approximately 1,700-bp from SC1 and no product from the parental strain, JB584 (Fig. 3A, lanes 11 and 8, respectively). As expected, no amplicon was obtained when pSAC100 DNA was added to JB584 genomic DNA and then amplified with the junction primer set (Fig. 3A, lane 10). From these data we concluded that homologous recombination had occurred between pSAC100 and the chromosomal \( ialB \) gene, creating an \( ialB \) mutant strain, SC1.

We then proceeded to create a transcomplemented strain using SC1 as the parental strain. The pIALB plasmid was digested with SwaI and BamHI, the 756-bp fragment containing the intact \( ialB \) gene isolated, and cloned into the broad-host-range plasmid, pBRR1MCS to produce the shuttle plasmid, pSAC200. pSAC200 was subsequently electroporated into SC1, and transformants were selected on HIAB plates supplemented with both kanamycin and chloramphenicol. Potential
transcomplemented strains were isolated, cultured, and characterized by PCR.

The ialB gene primer set (IALBF and IALBR) was used to screen for potential transcomplemented strains. One strain, SC2, produced amplicons of 4,097 and 688 bp representing the intact ialB gene on the bacterial chromosome and the ialB gene on pSAC200, respectively (Fig. 3B, lane 3). PCR amplification of SC2 DNA using the junction primer set (NPTI5 and IALBR) resulted in a product of approximately 1,700 bp (Fig. 3B, lane 4), indicating that the original site of integration was intact.

To determine whether expression of the ialB gene had been disrupted in SC1 and transcomplemented in SC2, cell lysates of the bacteria were analyzed by SDS-PAGE and Western blot (Fig. 4). A 17.1-kDa band was present in both JB584 and SC2 lysates but absent in SC1 lysates. This protein was positively identified as IalB by Western blots (Fig. 4B). We consistently observed more IalB in cell lysates of SC2 relative to JB584, by both SDS-PAGE and Western blots. Presumably, increased synthesis in SC2 is due to the multiple copies of pSAC200 encoding ialB (Fig. 5B).

Genotypes of the mutant and transcomplemented strains were corroborated using DNA hybridization (Fig. 5). Restriction endonuclease digestion of pIALB with KpnI and HinfI yielded a 744-bp fragment containing ialB that was used to probe Southern blots of ClaI-digested genomic DNA from each strain (Fig. 5A). Hybridization of the probe with JB584 DNA showed a single, distinct band of ~23 kb (Fig. 5B, lane 2), while hybridization with the ialB mutant strain, SC1, gave two bands of ~23 and ~3.7 kb (Fig. 5B, lane 3). The two hybridization products in SC1 are due to the presence of a ClaI restriction enzyme site in the integrated suicide plasmid (Fig. 2). Each band contains a portion of the ialB gene. The insertionally mutagenized ialB gene of the transcomplemented strain SC2 gives the expected two-band pattern like SC1, plus an additional hybridization band of ~5.4 kb from ialB on pSAC200 (Fig. 5B, lane 4).

No overt phenotypic differences between the parental, ialB mutant, and transcomplemented strains were apparent.

Localization of IalB in the bacterium. As expected, SDS-PAGE analysis of total membranes showed that IalB was present in the membrane fraction of JB584 and SC2 but not the mutant strain, SC1, and its identity as IalB was verified by Western blot (data not shown). Extrinsic radioiodination of intact JB584 and SC1 showed no difference in protein profiles.
The buoyant densities of the inner and outer membrane fractions were determined for B. bacilliformis strains using DNA hybridization. (A) Ethidium bromide-stained agarose gel (1.2%, wt/vol) of CiaI-digested genomic DNA from the parental B. bacilliformis strain, JB584 (lane 2), the ialB mutant strain, SC1 (lane 3), and the transcomplemented strain, SC2 (lane 4). The shuttle plasmid used in transcomplementation, pSAC200, digested with CiaI is shown in lane 5, and DNA size standards (Lambda DNA/HindIII markers) are provided in lane 1. (B) Corresponding Southern blot hybridized with the ialB probe. Lane 1, DNA size standards; lane 2, single hybridization band of ~23 kbp from the parental B. bacilliformis strain, JB584; lane 3, two-band hybridization pattern from the disrupted ialB gene in the ialB mutant strain, SC1; lane 4, two-band hybridization pattern from the disrupted ialB gene, as well as the ~5.4-kbp hybridization band from pSAC200 in the transcomplemented strain, SC2; lane 5, single hybridization band from pSAC200. Size standards in kilobase pairs are indicated on the left.

When analyzed by SDS-PAGE (data not shown). Whole JB584 bacteria extrinsically treated with several proteases showed no alteration in the migration of IalB on gradient SDS-PAGE gels (data not shown). No difference in immunofluorescence was seen when whole JB584 and SC1 bacteria were surface labeled using anti-IalB polyclonal antibodies (data not shown). Radiiodination, proteolysis, and immunofluorescence data suggested that IalB is an inner membrane protein.

To conclusively localize IalB to the inner membrane, crude lysates were subjected to sucrose density gradient centrifugation as we previously described for B. quintana (8). Inner and outer membrane bands were collected from gradients and identified on the basis of their appearance. Outer membrane fractions typically showed a white flocculent appearance, while inner membrane fractions were typically tea colored (28). The average buoyant densities (ρ) were determined from three membrane preparations and calculated to be 1.08 g/cm³ for the inner membrane and 1.22 g/cm³ for the outer membrane. These values are very similar to the buoyant densities for the outer and inner membranes of E. coli (28) and Salmonella spp. (30) and are nearly identical to those we obtained from B. quintana membrane fractions (8). Outer membrane fractions analyzed by SDS-PAGE on a 15 to 20% gradient gel and stained with silver gave a protein profile similar to that previously reported for B. bacilliformis (24). In addition, the outer, but not the inner, membrane fractions contained the 42-kDa flagellin protein (34) and three bacteriophage proteins with molecular masses of 32, 34, and 36 kDa (4). The identity of the inner membrane fraction was unequivocally established by the presence of cytochrome b. Difference spectra for the inner and outer membrane fractions were obtained between 499 and 600 nm. The inner, but not the outer, membrane fraction had an absorbance peak at 558 nm, which is characteristic of cytochrome b. Once the identity of the inner and outer membrane fractions was established, their respective protein profiles were analyzed using SDS-PAGE. Contrary to our hypothesis that IalB was an outer membrane protein, the protein was found in the inner membrane fractions of both JB584 and SC2 (Fig. 6, lanes 3 and 7). The identity of IalB was confirmed by Western blot (Fig. 6B).

Role of IalB in erythrocyte adhesion and invasion. Following the 8-h association assays, Percoll gradient centrifugation was used to separate erythrocytes from free bacteria. Since both adherent and invaded bacteria were complexed with erythrocytes, CFU counts from these assays include bacteria that are adhering to, or have invaded, erythrocytes.

Association assays were carried out at least four times, with each experiment containing two to five independent samples. While the number of CFU varied between experiments, the data trends remained consistent. For the association assays conducted with the ialB mutant strain, SC1, and the parental strain, JB584, SC1 adherence and invasion decreased 47 to 53% compared to JB584. In a representative experiment, SC1 showed a significant decrease (P < 0.05) of 53% in adherence and invasion compared to JB584 (mean CFU of 91,750 ± 14,655 versus 196,300 ± 12,537, respectively) (Fig. 7A). Association assays conducted with JB584 and the complemented strain, SC2, showed statistically insignificant differences in adherence and invasion, although the range of values varied more than that observed in assays with JB584 and SC1. This increased scatter in SC2 values may be due to multiple plasmid copies of the ialB gene in SC2. In a representative experiment, the trans-complemented strain, SC2, showed no significant change (P = 0.7825) in association assays when compared to JB584 (mean CFU of 10,833 ± 1,906 versus 11,775 ± 2,575, respectively) (Fig. 7B).

**DISCUSSION**

This study is the first demonstration of molecular Koch’s postulates (12) for a Bartonella species. Insertional mutagenesis of ialB, creating the B. bartonella mutant strain, SC1, resulted in a 47 to 53% decrease in human erythrocyte adherence and invasion compared to the parental strain, JB584. Transcomplementation of ialB, creating the SC2 strain, restored erythrocyte adherence and invasion to parental levels. These data clearly establish IalB as a virulence determinant for B. bacilliformis erythrocyte parasitism.

Mitchell and Minnick originally isolated and characterized the two-gene locus, ialAB, reporting that both ialA and ialB were necessary to confer an invasive phenotype upon E. coli (27). However, the results of the present study demonstrate that ialB has a significant effect on B. bacilliformis erythrocyte parasitism. In vivo experiments with the rat pathogen, B. tribico rum, support our findings that ialB is a virulence factor. Specifically, an ialB mutant strain of B. tribico rum failed to...
A.

E. coli
(pQIALB)  

E. coli
(pQIALB)  

OM  IM  OM  IM  OM  IM  OM  IM

IalB Fusion  

IalB  

B.

E. coli
(pQIALB)  

E. coli
(pQIALB)  

OM  IM  OM  IM  OM  IM  OM  IM

IalB Fusion  

IalB  

FIG. 6. Localization of IalB to the B. bacilliformis inner membrane. (A) Proteins (2.5 μg/lane) were separated by SDS-PAGE (15 to 20% [wt/vol] gradient), and the gel was silver stained. IalB was found in the inner membrane fractions of JB584 (lane 3) and SC2 (lane 7), the parental and transcomplemented B. bacilliformis strains, respectively. IalB was absent from all outer membrane fractions and the inner membrane fraction of SC1, the ialB mutant strain. (B) Corresponding immunoblot reacted with polyclonal anti-IalB antibodies. IalB localized to the inner membrane fractions of JB584 and SC1 (lanes 3 and 7, respectively). IPTG-induced E. coli M15(pQIALB) cell lysate is provided as a control in lane 1.

ialA and ialB homologues are present in the three most prevalent, human pathogenic species of Bartonella: B. henselae, B. quintana, and B. bacilliformis (26). B. henselae and B. quintana cause cat-scratch disease and trench fever, respectively. All three species share phenotypic similarities: they are transmitted by arthropod vector, are intracellular parasites, and have an absolute growth requirement for hemin. All three species invade or attach to erythrocytes during the course of infection (17, 22, 23) and can cause neovascularization of infected tissue (25). Erythrocyte parasitism and neovascularization may provide the blood and heme required for these pathogenic bacteria. Given the phenotypic similarities of B. bacilliformis, B. quintana, and B. henselae, IalA and IalB may share similar functions contributing to the virulence of all three species.

Homologues of ialA and ialB have been found in other gram-negative pathogenic bacteria. Brucella melitensis is a facultative intracellular pathogen and the causative agent of ovine brucellosis. The ability of B. melitensis to cause disease is tied to its ability to adapt and survive in a range of environments. B. melitensis’ adaptive responses to heat, oxidative, and acid stress were recently characterized (39). Protein levels, in response to these stresses, were analyzed by two-dimensional PAGE. In response to heat shock (a temperature shift from 37 to 42°C), an appreciable reduction in synthesis was observed for a protein with homology to the IalB protein of B. bacilliformis. No change in synthesis was seen for the IalB homologue in response to either oxidative or acid stress. Brucella and Bartonella are closely related α-proteobacteria, and their phylogenetic relationship is underscored by the ability of both genera to interact with eukaryotic cells in a parasitic or mutualistic association. In light of these similarities, it is interesting that these two species may share a virulence factor associated with eukaryotic cell invasion. We are currently examining the effect of environmental cues on ialB expression, as the transfer of B.
bacilliformis from sandfly to human would be associated with significant changes in temperature, iron availability, pH, and oxidative stress. These environmental cues could serve as signals for expression of virulence factors necessary for human infection.

In another study, differential fluorescence induction was used to identify E. coli K1 genes expressed under environmental conditions favoring bacterial invasion of human brain microvascular endothelial cells (HBMEC) (3). One gene identified in that study was an IaIA homologue (38% homology). Site-directed mutagenesis of this E. coli gene reduced HBMEC invasion twofold, and transcomplementation restored the invasive phenotype to wild-type levels. IaIA and IaIB homologues are being identified in a number of bacterial species, all of which invade eukaryotic cells. Additionally, experimental evidence for the role of these proteins in virulence is accumulating.

We originally hypothesized that IaIB is exported to the bacterial surface, where it functions as an invasion factor. Contrary to our hypothesis, IaIB was localized to the inner membrane in this study. Our original hypothesis was, in part, based on the reported ~60% amino acid sequence similarity of IaIB to Ail and Rck (27). However, although these proteins have significant amino acid similarity, their amino acid identity is actually quite low (~11%). The IaIB protein also lacks a terminal phenylalanine amino acid residue characteristic of most outer membrane proteins (38), including Ail and Rck.

Localization of IaIB to the cytoplasmic membrane necessitated rethinking of its function as a virulence factor. Virulence-related activities for inner membrane proteins include transport of virulence factors, uptake of nutrients, response to environmental stresses, chemotaxis, cell motility, and intracellular survival, to name a few. These various functions fall into one of two general categories: transport or signal transduction. For example, the virB operon of Brucella suis and Brucella abortus was found to be essential for virulence and intracellular survival of these mammalian pathogens. The virB operon encodes homologues to a type IV secretory system including putative inner membrane proteins (29, 36). An intriguing example of a signal-transducing protein is found in Pseudomonas aeruginosa. Normally, the sigma factor responsible for expression of a mucoid phenotype is sequestered at the cytoplasmic membrane by an inner membrane protein. Release of this sigma factor into the cytosol, presumably in response to some signal, results in the expression of mucoidy (32). Phosphorylation is another mechanism by which an inner membrane protein could facilitate signal transduction. The etk gene of E. coli encodes an inner membrane protein capable of autophosphorylation (16). Interestingly, while all E. coli strains possess the etk gene, it is only expressed by a subset of pathogenic strains.

With these examples as precedents for cytoplasmic membrane proteins serving as virulence factors, we are currently investigating whether IaIB functions as a transporter or signal transduction protein. To date, database searches for proteins with homology to IaIB have not suggested any function. This lack of homology to known proteins may reflect IaIB’s unique and unusual role in erythrocyte parasitism by B. bacilliformis.

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FIG. 7. Effect of ialB mutagenesis and transcomplementation on human erythrocyte adherence and invasion on B. bacilliformis strains. (A) The ialB mutant strain, SC1, shows a 53% decrease in erythrocyte adherence and invasion compared to the parental strain, JB584. The n values for JB584 and SC1 are 5 and 4, respectively. (B) Transcomplementation of ialB in SC2 restores erythrocyte adherence and invasion to parental strain levels. The n values for JB584 and SC2 are 3 and 2, respectively. Experimental data presented graphically in panels A and B are the mean ± the SEM from two separate but representative experiments.


