Polar Positioning of a Conjugation Protein from the Integrative and Conjugative Element ICEBs1 of Bacillus subtilis

Melanie B. Berkmen,1,2 Catherine A. Lee,1 Emma-Kate Loveday,2† and Alan D. Grossman1*

Department of Biology; Massachusetts Institute of Technology; Cambridge, Massachusetts 02139,1 and Department of Chemistry and Biochemistry; Suffolk University; Boston, Massachusetts 021142

Received 30 June 2009/Accepted 28 August 2009

ICEBs1 is an integrative and conjugative element found in the chromosome of Bacillus subtilis. ICEBs1 encodes functions needed for its excision and transfer to recipient cells. We found that the ICEBs1 gene conE (formerly yddE) is required for conjugation and that conjugative transfer of ICEBs1 requires a conserved ATPase motif of ConE. ConE belongs to the HerA/FtsK superfamily of ATPases, which includes the well-characterized proteins FtsK, SpoIIIE, VirB4, and VirD4. We found that a ConE-GFP (green fluorescent protein) fusion associated with the membrane predominantly at the cell poles in ICEBs1 donor cells. At least one ICEBs1 product likely interacts with ConE to target it to the membrane and cell poles, as ConE-GFP was dispersed throughout the cytoplasm in a strain lacking ICEBs1. We also visualized the subcellular location of ICEBs1. When integrated in the chromosome, ICEBs1 was located near midcell along the length of the cell, in a position characteristic of that chromosomal region. Following excision, ICEBs1 was more frequently found near a cell pole. Excision of ICEBs1 also caused altered positioning of at least one component of the replisome. Taken together, our findings indicate that ConE is a critical component of the ICEBs1 conjugation machinery, that conjugative transfer of ICEBs1 from B. subtilis likely initiates at a donor cell pole, and that ICEBs1 affects the subcellular position of the replisome.

Integrative and conjugative elements (also known as conjugative transposons) and conjugative plasmids are key elements in horizontal gene transfer and are capable of mediating their own transfer from donor to recipient cells. ICEBs1 is an integrative and conjugative element found in some Bacillus subtilis strains. Where found, ICEBs1 is integrated into the leucine tRNA gene trnS-leu2 (Fig. 1) (7, 14, 21).

ICEBs1 gene expression, excision, and potential mating are induced by activation of RecA during the SOS response following DNA damage (7). In addition, ICEBs1 is induced by increased production or activation of the ICEBs1-encoded regulatory protein RapI. Production and activity of RapI are indicative of the presence of potential mating partners that do not contain a copy of ICEBs1 (7). Under inducing conditions, the ICEBs1 integrator ImmR (6) is inactivated by proteolytic cleavage mediated by the antirepressor and protease ImmA (12). Most ICEBs1 genes then become highly expressed (7). One of these genes (xis) encodes an excisionase, which in combination with the element’s integrase causes efficient excision and formation of a double-stranded circle (7, 38). The circular form is nicked at the origin of transfer, oriT, by a DNA relaxase, the product of nickK (39). Under appropriate conditions, ICEBs1 can then be transferred by mating into B. subtilis and other species, including the pathogens Listeria monocytogenes and Bacillus anthracis (7). Once transferred to a recipient, ICEBs1 can be stably integrated into the genome at its attachment site in trnS-leu2 by the ICEBs1-encoded integrase (38).

In contrast to what is known about ICEBs1 genes and proteins involved in excision, integration, and gene regulation, less is known about the components that make up gram-positive organisms’ mating machinery, defined as the conjugation proteins involved in DNA transfer (18, 24). The well-characterized mating machinery of gram-negative organisms can serve as a preliminary model (15, 16, 37, 48). Gram-negative organisms’ mating machinery is a type IV secretion system composed of at least eight conserved proteins that span the cell envelope. For example, the conjugation apparatus of the Agrobacterium tumefaciens Ti plasmid (pTi) is composed of 11 proteins (VirB1 through VirB11), including the ATPase VirB4 (16). VirB4 family members interact with several components of their cognate secretion systems and may energize machine assembly and/or substrate transfer (16, 48). The secretion substrate is targeted to the conjugation machinery by a coupling protein. Coupling proteins, such as VirD4 of pTi, interact with a protein attached to the end of the DNA substrate and couple the substrate to other components of the conjugation machinery. Coupling proteins might also energize the translocation of DNA through the machinery. Both VirB4 and VirD4 belong to the large HerA/FtsK superfamily of ATPases (29). Two other characterized members of this superfamily are the chromosome-partitioning proteins FtsK and SpoIIIE (29), which are ATP-dependent DNA pumps (reviewed in reference 2).

Some of the proteins encoded by the conjugative elements of gram-positive organisms are homologous to components of the conjugation machinery from gram-negative organisms (1, 9, 14, 29), indicating that some aspects of conjugative DNA transfer may be similar in gram-positive and gram-negative organisms. For example, ConE (formerly YddE) of ICEBs1 has sequence

* Corresponding author. Mailing address: Department of Biology, Building 68-530, MIT, Cambridge, MA 02139. Phone: (617) 253-1515. Fax: (617) 253-2643. E-mail: adg@mit.edu.
† Present address: Department of Microbiology and Immunology, 2350 Health Sciences Mall, University of British Columbia, Vancouver, BC, Canada V6T 1Z4.
‡ Published ahead of print on 4 September 2009.
The results indicate that ConE is likely a crucial ATPase component of the ICE Brow conjugation machinery. We found that ConE and excised ICE Brow DNA were located at or near the cell poles. We propose that the conjugation machinery is likely located at the cell poles and that mating might occur from a donor cell pole.

Our analysis of the functional and subcellular location of ConE of ICE Brow indicated below each gene. Other topology programs yield similar but not identical predictions.

Table 1. B. subtilis strains used

<table>
<thead>
<tr>
<th>Strain</th>
<th>Relevant genotype or characteristics (reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAL85</td>
<td>ICEB1&lt;sup&gt;+&lt;/sup&gt; str (39)</td>
</tr>
<tr>
<td>CAL419</td>
<td>ICEB1&lt;sup&gt;+&lt;/sup&gt; str comK:cat (39)</td>
</tr>
<tr>
<td>CAL65</td>
<td>yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>CAL66</td>
<td>yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>CAL68</td>
<td>Δxis190 (unmarked) yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB982</td>
<td>dnaX-yfpmut2 (tet) yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;)</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan lacA::[(Pen-yddD conE-mgfpmut2) tet amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB999</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB999</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
<tr>
<td>MMB998</td>
<td>ICEB1::kan ydeDE::yddM(47&lt;sup&gt;-&lt;/sup&gt;):lacO cat thr::(Pen-lac:&lt;i&gt;ΔL11-cfp&lt;/i&gt;) amylE::[(Pen-rapI) spc]</td>
</tr>
</tbody>
</table>

<sup>a</sup> All strains are derived from JH642 (45) and contain pheA1 and pheC2.
converting the aspartate and glutamate codons at 703 and 704 in conE to alanine codons. DNA fragments (3 kb) containing the conE alleles were generated by PCR and cloned into pGK1 (7). The resulting plasmids, pMMB1083 and pMMB1231, were used to introduce conE(K476E) and conE(D703A/E704A), respectively, into the chromosome.

(ii) Constructs for complementation of conE alleles. The thrC::[::(panyE-(conE-lacZ)) mls] allele was constructed to express conE from its presumed native promoter (P808) of ICEB1. conE was cloned into pKG1, downstream of P808 and upstream of lacZ, creating plasmid pMMB943. pMMB943 was transformed into HJo42 to create the thrC::[::(panyE-(conE-lacZ)) mls] allele. A similar strategy was used to produce thrC::[::(plys-dld-conE-lacZ)] mls from plasmid pMMB942, thrC::[::(polyamE-dld-conE-lacZ)] mls from plasmid pMMB1004, and thrC::[::(plys-dld conE(K476E)-lacZ)] mls from pMMB1083. The thrC::[::ICEB1-311 (D(mR::tet) mls) allele (strain MMB1218) contains ICEB1 inserted at thrC. It is incapable of excision due to deletion of the right-side attachment site attR as described previously (39).

(iii) Overexpression of RapI. rapI was overexpressed from Pspakyn(hy) in a single copy in the chromosome by amyE::[::(Pspakyn(hy)-rapI)] spc as described previously (7), or from Ppyl, also at amyE. To construct amyE::[::(Ppyl- rapI)] spc, rapI was cloned downstream of Ppyl in vector pDR160 (from D. Rudner, Harvard Medical School, Boston, MA). The resulting plasmid, pMMB856, was integrated at amyE in B. subtilis by homologous recombination.

(iv) Construction of a vector for double integration at lacA. We constructed the vector pMMB752 for introducing DNA via double crossover at lacA. First, an 891-bp PCR fragment of the 5’ end of lacA was cloned into the tetrasaccharide vector pDG1513 to generate pMMB759. Second, a 1,042-bp PCR fragment of the 3’ end of lacA was cloned into pMMB759 to generate pMMB752.

(v) GFP fusions to ConE, ConE∆(88–808), and ConE(K476E). The vector pMMB759 was derived from pMMB752. It allows fusion of the C terminus of a protein to a 23-amino-acid linker followed by monomeric GFPmut2 (mGFPmut2). A fragment (encoding the 23-amino-acid linker and mGFPmut2) was digested from pLS31 (49) with XhoI and SpII and ligated into pMMB752 to generate pMMB759.

The lacA::[::plys-dld conE-mgff2mut2] ter allele was transferred ICEB1 conE-lacZ) mls strains express ydlD and conE-mgff2mut2 from the presumed native promoter (P808) of ICEB1. We inserted a 363-bp PCR fragment containing the P808 promoter into pMMB759, upstream of mgff2mut2, generating pMMB756. A 2.9-kb PCR fragment of ydlD and conE missing its stop codon was cloned into the KpnI and XhoI sites of pMMB762, downstream of P808 and upstream of mgff2mut2, creating plasmid pMMB786, pMMB786 was transformed into HJo42 to create the lacA::[::plys-dld conE-mgff2mut2] ter allele. lacA::[::plys-dld conE(K476E)-mgff2mut2] ter and lacA::[::plys-dld conE(K476E)-mgff2mut2] ter were generated using a similar strategy, but using PCR fragments synthesized from templates pMMB1082 for conE(K476E) and pMMB1083 for conE(K476E).

ConE-GFP was partially functional in mating. Expression of ydlD and conE-gfp from their presumed native promoter (P808) at the heterologous site (lacA) in conE∆(88–808) mutant donor strains increased the frequency of mating at least 250-fold (0.001% mating efficiency for strain MMB1134 compared to <0.000006% for MMB1118). In addition, expression of conE-gfp at lacA in conE+ donor strains had no effect on mating frequency (8% mating efficiency for strain MMB1068 compared to 7% for JMA168).

(vi) Visualization of chromosomal regions using the lac operator/lac repressor system. The lac operator/lac repressor system has been used previously to visualize chromosomal regions in B. subtilis (e.g., see references 42, 50, and 56). To mark the 47° (in ICEB1) and 48° (outside of ICEB1) regions, we inserted a plasmid containing a tandem array of lac operators near ydlD (pMMB779) and ydlE (pMMB854), respectively, by single crossover. ydlD (47°) and ydlE (48°) are not disrupted in these constructs. We inserted a 466-bp PCR fragment of the 5’ end of ydlD into the NheI and EcoRI sites of pPSL44a to generate pMMB779, pPSL44a is pGEMcat containing an XhoI fragment from pLAU43 that includes a 4.5-kb array of lac operators (11). Ten base pairs of random sequence is interspersed between the lacO sites of pLAU43, leading to greater genetic stability by reducing the frequency of recombination (35). We inserted a 728-bp PCR fragment including the 3’ ends and intergenic region between ydlD and ydlE into the NheI and EcoRI sites of pPSL44a to generate pMMB845. The lac operator arrays were amplified in vivo by selecting for resistance to chloramphenicol (25 μg/ml) as described previously.

We performed assays. We assayed ICEB1 DNA transfer as described previously (7). We used donor B. subtilis cells in which ICEB1 contained a kanamycin resistance gene. Recipient cells lacked ICEB1 (ICEB1*) and were distinguishable from donors, as they were streptomycin resistant. Donor and recipient cells were grown separately in minimal glucose medium for at least four generations.

ICBE1 was induced in the donors in mid-exponential phase (optical density at 600 nm to ~0.4) by addition of IPTG (isopropyl-β-D-thiogalactopyranoside; 1 mM) for 1 h to induce expression of rapI (from Pspakyn(hy)-rapI). Donors and ICEB1+ recipient cells (CAL419) were mixed and filtered on sterile cellulose nitrate membrane filters (0.2-μm pore size). Filters were placed in petri dishes containing Spizizen’s minimal salts (27) and 1.5% agar and incubated at 37°C for 3 h. Cells were washed off the filter, and the number of transconjugants (recipients that received ICEB1+) per ml was measured by determining the number of Kan’ Strep’ CFU after the mating. Percent mating is calculated as (number of transconjugant CFU per donor CFU) × 100%.

Live-cell fluorescence microscopy. Microscopy was performed as described previously (10). Cells were grown for at least four generations to mid-exponential phase (optical density at 600 nm to ~0.4) in minimal medium. RapI overexpression was induced with either 1 mM IPTG for 1 h for strains containing amyE::[::(Ppyl- rapI)] spc or with 1% xylose for ~2 h for strains containing amyE::[::(Ppyl- rapI)] spc. Cells were stained with FM4-64 (1 μg/ml; Molecular Probes) to visualize membranes. Live cells were immobilized on pads of 1% agarose containing Spizizen’s minimal salts. All images were captured at room temperature with a Nikon E800 microscope equipped with a 100× differential interference contrast objective and a Hamamatsu digital camera. We used the Chroma filter sets 41020b (TRITC [tetramethyl rhodamine isothiocyanate]) for 44-64, 31044 for CFP (cyan fluorescent protein), 41012 for GFP, and 41028 for YFP. Improvision Openlab 4.0 software was used to process images. Cell length and focus positions were measured and plotted as described previously (10, 46). Each strain was examined in at least two independent experiments with similar results.

RESULTS

conE is required for mating. Conjugative transfer of ICEB1 is a multistep process. Previous work indicated that conE is not required for ICEB1 gene expression, excision, integration, circularization, or nicking (6, 7, 12, 38, 39). Since ConE is a putative ATPase and distantly related to other ATPases known to be required for conjugation, we tested the effects of conE mutations on mating of ICEB1.

We constructed three different conE alleles: (i) an in-frame deletion [conEΔ(88–808)] removing codons 88 through 808 (of 831), (ii) a missense mutation in the Walker A box [conE(K476E)] that is predicted to eliminate nucleotide binding, and (iii) a double missense mutation in the Walker B box [conE(D703A/E704A)] that is predicted to eliminate ATPase activity (reviewed in reference 26). Each conE mutant allele was introduced unmarked into ICEB1, replacing the wild-type allele (see Materials and Methods).

We found that conE is required for ICEB1 conjugative transfer. We compared mating efficiencies of ICEB1 from donor strains containing the various conE alleles into recipient B. subtilis cells lacking ICEB1 (Fig. 2). ICEB1 was induced by overproduction of RapI from a heterologous promoter, and potential donor cells were mixed with potential recipients that lacked ICEB1, essentially as described previously (7). The donor ICEB1 contained an antibiotic resistance marker that had been inserted to allow selection and monitoring of ICEB1 acquisition (7). A donor strain with an intact conE+ (conE+) transferred ICEB1 with an average mating frequency of ~7% (percent transconjugant CFU per donor CFU [Fig. 2, row a]). In contrast, there were no detectable transconjugants from the ICEB1 conE+ mutants (Fig. 2, rows b to d).

Consistent with previous results indicating that conE is not involved in ICEB1 gene expression, excision, or circularization (6, 7, 12, 38, 39), we found that neither conE(K476E) nor conEΔ(88–808) mutant alleles had any detectable effect on these processes (data not shown).
Complementation tests with conE. We used complementation tests to determine if the defect in mating caused by the conE(K476E) mutation was due to loss of ConE function and/or an unintended effect on some other gene. The defect in mating caused by the conE(K476E) mutation was complemented partially when wild-type conE was provided in the donor in trans under the control of the ICEBs1 promoter Pxis (Fig. 2, row e). Measurements of mRNA levels using DNA microarrays indicated that the partial complementation is not due to unexpected defects in expression of other ICEBs1 genes or of Pxis-conE (data not shown).

The partial complementation of the conE(K476E) mutation is probably due, in part, to inefficient translation of wild-type ConE expressed from Pxis-conE, yddD, the gene immediately upstream of conE, is predicted to overlap with the first 37 codons of conE, and thus, the two are likely to be translationally coupled. Complementation of the conE(K476E) mutant was significantly higher when yddD and conE were expressed together (Pxis-yddD conE) than when conE was expressed alone (Pxis-conE) (Fig. 2, rows e and f). Neither expression of yddD alone nor expression of yddD and conE(K476E) together improved the efficiency of transfer of the ICEBs1 conE mutant (Fig. 2, rows g and h). conE(K476E) was complemented fully if an additional copy of ICEBs1 was placed at the ectopic locus thrC (Fig. 2, row i). These results and results from additional mating experiments with conE expressed in recipients indicate that conE function is needed in the donor and not the recipient (data not shown). Based on these findings, we suspect that ConE is not efficiently translated and assembled into an active complex when expressed in trans to YddD and other ICEBs1 proteins.

Taken together, our results indicate that ConE and its ATPase domain are required in the donor for mating of ICEBs1 but are not required for induction of ICEBs1, excision, circularization, nicking, or integration. Based on these results and the homology of ConE to VirB4-like conjugative ATPases, the simplest interpretation is that ConE is a component of the ICEBs1 conjugation machinery and that ATP binding and hydrolysis are required for ConE function in ICEBs1 DNA transfer.

ConE-GFP localizes to the cell poles, in close association with the membrane. We found that ConE is located predominantly at the cell poles, in close association with the membrane. We visualized the subcellular location of ConE in live cells by visualizing a fusion of GFP to the C terminus of ConE. conE-gfp was expressed from its presumed native promoter (Pxis), together with yddD, at the heterologous locus (lacA) outside of ICEBs1. This fusion was partially functional and did not interfere with transfer of conE.” ICEBs1 (see Materials and Methods). Most experiments using ConE-GFP were done with strains that also contained a wild-type version of conE in ICEBs1.

We monitored ConE-GFP prior to and after induction of ICEBs1 gene expression. Little or no fluorescence was observed in cells in which ICEBs1 gene expression was not induced (data not shown). This was expected, since the Pxis promoter driving expression of conE-gfp is not active without induction (6, 7, 12). When ICEBs1 gene expression was induced by overproduction of RapI, ConE-GFP was found predominantly at the cell poles in most cells (Fig. 3A). This is most evident with simultaneous visualization of ConE-GFP and the cell membrane stained with the dye FM4-64 (Fig. 3B). ConE-GFP appeared to form a “polar cap” along the entire pole near the membrane. ConE-GFP was most often found at both cell poles but was also commonly observed at only one pole. A lower level of fluorescence was also detected throughout the cell and sometimes along the lateral sides of the cells.

Positioning of ConE-GFP at the cell poles requires at least one other ICEBs1 gene. The polar positioning of ConE-GFP did not depend on the wild-type conE in ICEBs1. We visualized ConE-GFP in cells deleted for conE [conEΔ(88–808)] at its native locus in ICEBs1 and found that its subcellular positioning was indistinguishable from that in cells expressing wild-type conE (Fig. 3C). These results indicate that the positioning of ConE-GFP at the poles does not depend on expression of wild-type conE in ICEBs1. In addition, we fused conEΔ(88–808) to gfp and expressed this from Pxis (along with yddD) as described above. The ConEΔ(88–808)–GFP fusion was found throughout the cytoplasm, in both the presence and absence of functional conE in ICEBs1 (Fig. 3D; also data not shown). These results indicate that ConEΔ(88–808)–GFP is not capable of localizing at the cell poles.

We found that positioning of ConE-GFP to the membrane and cell poles required at least one other ICEBs1 gene. In cells missing ICEBs1 entirely (ICEBs1Δ), ConE-GFP was dispersed throughout the cytoplasm (Fig. 3E). In these experiments, ConE-GFP was produced constitutively from Pxis in combination with YddD (Pxis-yddD conE-gfp). These results indicate that proper positioning of ConE-GFP at the poles and near the membrane requires an ICEBs1 gene product and that YddD is not sufficient to recruit ConE-GFP to the membrane. Alterna-
not yet know which, if any, of these proteins are involved in or more predicted transmembrane segments (Fig. 1). We do, cwlT yddG subtilis other ICE Phobius (31), Polyphobius (32), HHMTOP (52, 53), TopPred and subcellular localization prediction programs, including consistent with a prior report that identified ConE (YddE) as ICE Bs1 respectively, positioning of ConE-GFP could require interaction with other induced ICE hy xyl-rapI (A to F) or IPTG-inducible Pspank(hy)-rapI (G). Cells were grown in minimal succinate, and 1% xylose (A to F) was added for 2 h prior to sampling. Cells were grown in minimal glucose with 1 mM IPTG (G) for 1 h prior to sampling. ConE-GFP localization in other induced ICEBs1+ strain backgrounds (MMB908, control for panel G; MMB974, control for panel D) was similar to that shown in panel A (data not shown). We also observed similar localization patterns for all GFP fusions in either conE(Δ88–808) or conE(K476E) donors (data not shown). (A and B) ConE-GFP in ICEBs1+ donor cells (MMB918); (C) ConE-GFP in conE(Δ88–808) cells (MMB973); (D) ConE(Δ88–808)-GFP in ICEBs1+ donor cells (MMB1135); (E) ConE-GFP in ICEBs1+ cells (MMB948); (F) ConE(K476E)-GFP in ICEBs1+ donor cells (MMB1137); (G) ConE-GFP Δris donor cells (MMB1206).

FIG. 3. ConE-GFP localizes to the cell pole, in close association with the membrane. Cells were grown in minimal medium, and samples were taken for live-cell fluorescence microscopy. Cell membranes, visualized with the vital dye FM4-64, are shown in red. GFP fluorescence is artificially shown in yellow. Except for panel A, all images are merges of yellow and red. ICEBs1 was induced by using xylose-inducible PsyI-rapI (A to F) or IPTG-inducible Pspank(hy)-rapI (G). Cells were grown in minimal succinate, and 1% xylose (A to F) was added for 2 h prior to sampling. Cells were grown in minimal glucose with 1 mM IPTG (G) for 1 h prior to sampling. ConE-GFP localization in other induced ICEBs1+ strain backgrounds (MMB908, control for panel G; MMB974, control for panel D) was similar to that shown in panel A (data not shown). We also observed similar localization patterns for all GFP fusions in either conE(Δ88–808) or conE(K476E) donors (data not shown). (A and B) ConE-GFP in ICEBs1+ donor cells (MMB918); (C) ConE-GFP in conE(Δ88–808) cells (MMB973); (D) ConE(Δ88–808)-GFP in ICEBs1+ donor cells (MMB1135); (E) ConE-GFP in ICEBs1+ cells (MMB948); (F) ConE(K476E)-GFP in ICEBs1+ donor cells (MMB1137); (G) ConE-GFP Δris donor cells (MMB1206).

Positioning of ConE-GFP at the cell poles does not require a functional conE. We found that positioning of ConE at the poles did not require that ConE be functional for mating. We fused the mating-deficient allele conE(K476E) to gfp and expressed this fusion from Pris (along with yddD) as described above. Following induction of ICEBs1, ConE(K476E)-GFP was found at the cell poles near the membrane (Fig. 3F) similar to the location of wild-type ConE-GFP (Fig. 3A and B). This polar localization of ConE(K476E)-GFP did not depend on a functional copy of conE in ICEBs1 (data not shown). Since ConE(K476E) localized properly but did not support mating, these results indicate that positioning of ConE at the cell poles is not sufficient for its function in mating. Furthermore, assuming that the ConE(K476E) mutant protein is defective in nucleotide binding, as predicted, these results indicate that neither binding nor hydrolysis of ATP by ConE is required for its proper subcellular positioning.

Following induction, ICEBs1 DNA is found more frequently at the cell poles. We determined the subcellular location of ICEBs1 DNA in live cells and compared this with the location of nearby chromosomal DNA (Fig. 4). These comparisons were done in cells with ICEBs1 integrated into the genome at its normal attachment site at 47° and in cells in which ICEBs1 was induced to excise (through overproduction of RapI). We inserted an array of lac operators (lacO) in the right end of ICEBs1, adjacent to yddM (47°), or outside of ICEBs1, adjacent to ydeD, at 48° in the chromosome (Materials and Methods). We visualized the location of the lacO array using a fusion of Lac repressor to the cyan fluorescent protein (LacI-CFP). The position of LacI-CFP is indicative of the subcellular position of either double stranded ICEBs1 DNA or chromosomal DNA, depending on the location of the lacO array.

We examined cells growing slowly, when most cells were generally engaged in no more than one round of replication. Under these conditions, most cells contain one incompletely replicated chromosome and therefore contain one or two copies of each chromosomal region. Without induction, ICEBs1 DNA is integrated into the chromosome near 47° (7, 38). As expected, we found that most uninduced cells (88% of 1,535 cells) contained one or two foci of double-stranded ICEBs1 DNA (Fig. 4A). In cells with a single focus, the ICEBs1 DNA was generally located near midcell (Fig. 4A). Approximately 94% of these cells (of 246 cells with a single focus) had the focus in the middle 50% of cell length. Only 6% of cells (of 246) had the focus of ICEBs1 DNA in a polar quarter of the cell. These findings are consistent with expectations for this region of the chromosome based on previously published findings (11, 40, 50, 56).

In contrast to the position of ICEBs1 when integrated in the chromosome, significantly more cells had a focus of ICEBs1 DNA in a polar quarter after induction and excision. Overproduction of RapI causes efficient induction of ICEBs1 gene expression, excision from the chromosome, and formation of a double-stranded circle (7, 38, 39). Under these conditions, most cells (87% of 1,804 cells) contained one or two foci of double-stranded ICEBs1 DNA (Fig. 4B), similar to that in uninduced cells (Fig. 4A). However, following induction, 41%
FIG. 4. ICEBs1 double-stranded DNA and the replisome component Tau are more frequently near the poles following induction of ICEBs1. Cells were grown in minimal succinate medium, and samples were taken for live-cell fluorescence microscopy. FM4-64 fluorescence (membrane stain) is artificially shown in gray scale. The location of lacO arrays was visualized using LacI-CFP (cyan). The replisome subunit Tau was visualized with a DnaX-YFP (yellow) fusion. White arrowheads indicate polar foci. Cells were grown with 1% xylose for 2 h prior to sampling. Strains contained the xylose-inducible Psyl-rapI (B, C, D, and F), (A) ICEBs1 (yddM::lacO lacI-cfp) in uninduced donor cells (CAL686); (B) ICEBs1 (yddM::lacO lacI-cfp) in induced donor cells (CAL688); (C) 48° (yedDE::lacO lacI-cfp) in induced donor cells (MMB938); (D) ICEBs1 (yddM::lacO lacI-cfp) in induced Δxis donor cells (CAL688); (E) replication protein Tau (dnaX-yfp) in uninduced donor cells (MMB929); (F) replication protein Tau (dnaX-yfp) in induced donor cells (MMB920).

of cells (of 489) with a single focus of ICEBs1 DNA had the focus in a polar quarter, an ~7-fold increase compared to the proportion in uninduced cells (6%). These results indicate that ICEBs1 DNA is found more frequently near a cell pole following excision than when integrated into the chromosome.

The subcellular position of the 48° region of the chromosome, near the ICEBs1 attachment site, changed little, if at all, following induction of ICEBs1 gene expression and excision. Following induction of ICEBs1 (by overproduction of RapI), only 10% of cells with a single focus of the 48° region (of 195 cells) had the focus in a polar quarter of the cell (Fig. 4C), compared with 41% of cells with a polar focus of ICEBs1 DNA (Fig. 4B). These results indicate that after excision, ICEBs1 DNA is found more frequently near the cell poles than the previously adjacent chromosomal region. Thus, the change in location of ICEBs1 DNA upon induction is specific to ICEBs1 and not the region of the chromosome where it normally resides. In cells in which ICEBs1 was not induced, the subcellular location of the 48° region of the chromosome was indistinguishable from that of integrated ICEBs1 DNA (at 47°), as expected. Only 6% of cells with a single focus had the focus in a polar quarter of the cell (data not shown).

Polar positioning of ICEBs1 following induction depends on excision. We found that excision of ICEBs1 from the chromosome was required for the increase in ICEBs1 foci that were in the polar quarters of the cell. We induced ICEBs1 gene expression in an xis-null mutant incapable of excision. ICEBs1 gene expression is induced normally in excision-defective mutants (J. Auchtung, C. A. Lee, and A. D. Grossman, unpublished results). After induction of ICEBs1 gene expression in the xis mutant, we found that only 13% of 276 cells with a single focus of ICEBs1 had the focus in a polar quarter (Fig. 4D). This is in contrast to the 41% of xis+ cells with ICEBs1 in a polar quarter (Fig. 4B). Thus, the change in position of ICEBs1 DNA upon induction likely requires its excision from the chromosome. This result is consistent with ICEBs1 DNA appearing at the poles either due to direct association with the conjugation machinery or due to its random positioning in the cell once it is released from the chromosome.

In contrast to the requirement for xis for the high frequency of ICEBs1 DNA found near the cell poles, xis was not required for polar positioning of ConE-GFP. Following induction of ICEBs1 carrying a xis deletion, ConE-GFP localization was indistinguishable from that of xis+ ICEBs1 (Fig. 3G). Together, these results indicate that excisionase is required for the change in position of ICEBs1 DNA upon induction and that polar positioning of ConE-GFP is most likely not due to association with ICEBs1 DNA at the poles.

The position of the replication machinery is altered following induction of ICEBs1. Excision of ICEBs1 generates an extrachromosomal circle, analogous to a circular plasmid. Previous work indicated that the subcellular position of replisome proteins was altered in cells containing a multicopy plasmid (55). We therefore wished to determine if excision of ICEBs1 caused altered subcellular positioning of the replisome. We visualized the location of one component of the replication machinery using a functional fusion of the Tau subunit of DNA polymerase to YFP (42). Components of the replisome (the complex of replication proteins associated with a replication fork) normally form discrete foci at regular positions (41, 43). During slow growth, when most cells are engaged in no more than one round of replication at a time, most cells have one focus or two closely spaced foci of the replisome located near midcell along the length of the rod-shaped cell (10, 41).

Consistent with previous results, we found that during slow growth, only a small fraction of cells with ICEBs1 integrated into the chromosome (uninduced) had a focus of Tau-YFP in a polar quarter. Of 250 cells with a single focus of Tau-YFP, only 4% had the focus in a polar quarter (Fig. 4E). In contrast, following excision of ICEBs1, induced by overproduction of RapI, the replication machinery was much more frequently observed in the polar quarters. Of 212 cells observed with a single focus of Tau-YFP, 32% had the focus in a polar quarter (Fig. 4F). We suspect that the replisome foci were associated with ICEBs1 DNA, although we have not been able to test this directly. Due to photobleaching, we were unable to capture high-quality micrographs of both Tau-YFP and ICEBs1 DNA (LacI-CFP) foci in the same cells to determine if the foci colocalize. Nonetheless, our data indicate that the subcellular position of at least one component of the replication machinery is altered following induction of ICEBs1. These results...
might indicate that ICEBs1 DNA is replicated autonomously after excision. We are currently investigating this possibility.

**DISCUSSION**

We found that ConE (formerly YddE) and its ATPase motifs are required for conjugation of the integrative and conjugative element ICEBs1 of *B. subtilis*. We found that a ConE-GFP fusion was positioned predominantly at the cell poles, apparently associated with the membrane, and that this positioning required at least one other ICEBs1 gene product. In addition, after excision from the chromosome, ICEBs1 DNA was found more frequently near the cell poles. Our results indicate that ConE is most likely part of the ICEBs1 conjugation machinery. If its subcellular location is indicative of where the protein functions, then mating of ICEBs1 from *B. subtilis* likely occurs from a donor cell pole. Attempts to test this by directly visualizing mating pairs have so far been unsuccessful.

**VirB4-like proteins.** ConE belongs to the VirB4 clade of the HerA/FtsK superfamily of ATPases (29). Characterized members of this clade are required for substrate secretion, form membrane-associated oligomers, and interact with several components of their cognate secretion machineries (16, 48). Analysis of virB4 Walker A box mutants indicates that ATP binding and/or hydrolysis is required for DNA transfer through the secretion machinery but not for association of VirB4 with itself or other machinery components (4, 57).

Results with the few VirB4 homologs from gram-positive organisms that have been studied indicate that these proteins likely operate analogously to *A. tumefaciens* VirB4. The VirB4-like TcpF protein of the *Clostridium perfringens* plasmid pCW3 is required for DNA transfer and localizes to the cell poles (9, 51). Another VirB4 homolog, Orf5, found of the broad-host-range plasmid pIP50, interacts with itself and several putative components of its cognate conjugation machinery (1).

**Subcellular location of conjugation proteins.** ConE-GFP appears associated with the cell membrane and predominantly at both cell poles, indicating that mating may occur at either end of a *B. subtilis* donor cell. Mating pairs of live *E. coli* cells have been observed using fluorescence microscopy (8, 36). Transfer of the conjugative plasmid R751 in *E. coli* can occur along any orientation between donors and recipients that are in direct contact, suggesting that the conjugative machinery of R751 may assemble along both the lateral and polar sides of the cell (36). This type of lateral and polar localization of the mating machinery has been directly observed for the R27 conjugative plasmid in *E. coli* (22, 25). R27’s VirB4-like TrhC and coupling protein TraG were distributed at multiple sites along all sides of the cell.

In other systems, the mating machinery is seen at one or both cell poles. For example, the conjugative apparatus of the gram-positive *Clostridium perfringens* plasmid pCW3 likely localizes at both cell poles, as evidenced by immunofluorescence microscopy of the VirB4-like TcpF protein (51). Components of the gram-negative *Agrobacterium* pTi conjugative apparatus are typically located at a single cell pole (3, 5, 30, 33, 34).

For ConE, our results indicate that ATP-binding and hydrolysis are not required for targeting but that at least one other ICEBs1 gene is required. The R27 VirB4-like protein TrhC also does not require a functional ATPase domain for localization but requires 12 of the other 18 R27 transfer proteins (23). VirB4 also does not require a functional ATPase domain for localization but, unlike TrhC or ConE, is able to target itself independently of other conjugation proteins (30).

It is not yet known where other ICEBs1 conjugation proteins are positioned in the cell or how they interact. Recent studies indicate that the gram-positive conjugation apparatus may be as structurally complex as its gram-negative counterpart (1, 9, 51). Since many ICEBs1 genes are conserved between diverse conjugative elements found in a wide range of gram-positive bacteria, we suspect that an understanding of ICEBs1 will likely shed light on other conjugative systems as well.

**ACKNOWLEDGMENTS**

We are grateful to J. M. Auchtung for generous advice, strains, and protocols.

This work was supported primarily by Public Health Service grant GM50895 (A.D.G.) and, in part, by Suffolk University Department of Chemistry and Biochemistry and a Suffolk University Summer Stipend Award (M.B.B.).

**REFERENCES**


