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Polar localization of the MinD protein of *Bacillus subtilis* and its role in selection of the mid-cell division site

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Cell division in rod-shaped bacteria is initiated by formation of a ring of the tubulin-like protein FtsZ at mid-cell. Division site selection is controlled by a conserved division inhibitor MinCD, which prevents aberrant division at the cell poles. The *Bacillus subtilis* DivIVA protein controls the topological specificity of MinCD action. Here we show that DivIVA is targeted to division sites late in their assembly, after some MinCD-sensitive step requiring FtsZ and other division proteins has been passed. DivIVA then recruits MinD to the division sites preventing another division from taking place near the newly formed cell poles. Sequestration of MinD to the poles also releases the next mid-cell sites for division. Remarkably, this mechanism of DivIVA action is completely different from that of the equivalent protein MinE of *Escherichia coli*, even though both systems operate via the same division inhibitor MinCD.

**Key Words:** *Bacillus subtilis*; DivIVA; cell division; MinD; cytokinesis

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A central component of division apparatus of bacteria is a highly conserved tubulin-like protein called FtsZ [Lutkenhaus and Addinall 1997]. FtsZ can polymerize in vitro [Bramhill and Thompson 1994; Mukherjee and Lutkenhaus 1994; Erickson et al. 1996] and forms a ring-like structure at the division site in vivo [Bi and Lutkenhaus 1991; Wang and Lutkenhaus 1993; Levin and Losick 1996]. Nucleation of this ‘Z ring’ is thought to be a primary point of control over the timing and positioning of the cell division septum. In most bacteria, several other proteins required for constriction and septal peptidoglycan synthesis associate with the Z ring, including *divIB* [Harry and Wake 1997], *divIC* [Katis et al. 1997], *ftsA* [Addinall and Lutkenhaus 1996; Ma et al. 1997], *pbpB* [Weiss et al. 1997], and *zipA* [Hale and De Boer 1997]. In almost all cases targeting of these proteins to the division site requires *ftsZ*.

The Z ring is normally positioned precisely at the mid point of the cell, so that division gives rise to two equal daughters. Important insights into the mechanism responsible for identifying the mid-cell position have been obtained from studies of minicell producing (*min*) mutants. These mutants divide at approximately the normal frequency but many of the divisions are improperly positioned, occurring close to the cell pole to give spherical, usually anucleate minicells [Adler et al. 1967; Reeve et al. 1973]. Thus, the *min* system seems to be required to inactivate used division sites [Teather et al. 1974]. In *Escherichia coli*, the *min* locus contains three genes, *minC*, *minD*, and *minE*. Mutations of *minC* or *minD* give a minicell phenotype, whereas *minE* null mutations prevent division, giving rise to long aseptate filaments [De Boer et al. 1989]. It is well established that MinC is an inhibitor of cell division, which in conjunction with MinD, prevents division at the cell poles [De Boer et al. 1990, 1992; Mulder et al. 1992]. MinE controls the topological specificity of MinCD, allowing it or forcing it to inhibit division at the cell poles but not at the required mid-cell position [De Boer et al. 1989; Pichoff et al. 1995; Zhao et al. 1995].

The *minCD* division-inhibition system appears to be conserved across a broad range of bacteria. For example, homologs of *minC* and *minD* have been characterized in the Gram-positive bacterium *Bacillus subtilis* [Levin et al. 1992; Varley and Stewart 1992; Lee and Price 1993]. Mutations in these genes give a typical minicell phenotype, consistent with their division inhibition function being conserved. However, the *B. subtilis min* locus lacks a *minE* homolog. Genetic evidence revealed that an unlinked gene, *divIVA*, fulfils the role of MinE in this organism [Cha and Stewart 1997; Edwards and Errington 1997]. Thus, mutations in *divIVA*, or depletion of its protein product in a conditional mutant, result in the inhibition of division leading to formation of long aseptate cell filaments. This Sep<sup>−</sup> phenotype is, like that of

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minE, suppressed by mutations in minD, giving a mini-cell [Min−] phenotype indistinguishable from that of minD single mutants (Cha and Stewart 1997; Edwards and Errington 1997). The sequence of the predicted product of the divIVA gene shows no significant similarity to that of minE, raising the possibility that the two proteins have different functions or that they have arrived at the same function via convergent evolution.

The function of Escherichia coli MinE has been elucidated recently by the demonstration that this protein can localize in the form of a ring at mid-cell and that this localization is independent of FtsZ [Raskin and De Boer 1997]. Thus, MinE must recognize a spatial cue independently at this site. In principle, this 'topological target' might be the same as the one that FtsZ putatively recognizes, or it could be some independent marker. The nature of the target is not yet clear, but interestingly, correct localization of MinE requires minD (Raskin and De Boer 1997).

Previous work with a DivIVA–GFP fusion protein revealed that this protein is also targeted to mid-cell division sites [Edwards and Errington 1997]. Unlike MinE, however, DivIVA–GFP remains detectable at the cell poles well after division is completed. On the basis of these findings, and informed by previous proposals for the E. coli min system [De Boer et al. 1989; Pichoff et al. 1995; Zhao et al. 1995; Rothfield and Zhao 1996], we suggested two alternative classes of model to explain the action of DivIVA [Fig. 1; Edwards and Errington 1997]. In the polar piloting model [Fig. 1A], DivIVA is recruited to the division site as division is in progress, or at least after the division apparatus has achieved some committing step that is sensitive to inhibition by MinCD. DivIVA then attracts the MinCD inhibitor to this mid-cell site. Sequestration of MinCD at the poles of the newborn cells prevents division from occurring again near these sites and also depletes the division inhibitor from mid-cell, allowing the next central division to occur. In the mid-cell inhibition model [Fig. 1B], DivIVA arrives at the mid-cell site early and sets up a zone of inhibition of MinCD (or otherwise prevents MinCD from acting here) so that the septum can form. Incorporation of DivIVA into the septum inactivates it or sequesters it away from MinCD, allowing the division inhibitor to prevent further divisions close to the poles. The latter model is probably most compatible with the recent localization results described for MinE [Raskin and De Boer 1997].

We have now tested these models by examining the effects on DivIVA localization of mutations in various division genes. In striking contrast to the results of similar experiments with MinE [Raskin and De Boer 1997], we show that targeting of DivIVA requires most, if not all, of the components of the division apparatus, but not MinD. We have also examined the localization of B. subtilis MinD by use of a GFP fusion and by immunofluorescence. We show for the first time that MinD forms ring-like accumulations at mid-cell, and that the protein is retained at the newly formed poles after division. Also, this DivIVA-like localization requires divIVA. The results provide important insights into the mechanism of division site selection in B. subtilis and show that even though both E. coli and B. subtilis use a common molecule [MinCD] to inhibit division at the cell poles, the mechanisms used to control the topological specificity of this inhibitor are fundamentally different.

Results

DivIVA localization is a late step in the hierarchy of assembly of division proteins

Conditional mutants were used to test whether DivIVA bands can form in the absence of various division proteins. Because some of these experiments required the mutants to be incubated at high [nonpermissive] temperatures at which GFP fluorescence is reduced, we raised an antiserum against DivIVA so that localization could be determined by immunofluorescence microscopy (IFM). Figure 2A shows that the antiserum used in these experiments was highly specific for DivIVA. At a high dilution (1/5000) with extracts of the wild-type strain (168CA), it reacted with only a single protein of ~19 kD, corresponding to the predicted mass for DivIVA [lane 1]. In extracts of a strain with divIVA under the control of an IPTG-dependent promoter, the 19-kD band was detected after growth in the presence of

Figure 1. Models for functioning of the Min system of B. subtilis. Possible models for functioning of the B. subtilis Min system [adapted from Edwards and Errington 1997]. The solid triangles represent DivIVA molecules, and shaded circles the MinCD division inhibitor [we assume that MinC and MinD associate, but it is possible that they act separately]. The symbols are solid if the proteins are active, and open if they are inactive. The shaded triangle represents a hypothetical early step in septation that is sensitive to MinCD inhibition. A] The polar piloting model, in which DivIVA delivers active MinCD to the poles. B] The mid-cell inhibition model, in which DivIVA blocks MinCD action at mid-cell.

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but not the absence (lane 3) of inducer. The staining pattern obtained by IFM (Fig. 2B) was similar to that of DivIVA–GFP in unfixed cells (Edwards and Errington 1997). Thus, in these wild-type cells the fluorescence was localized to discrete bands near the mid points of cells and at spots or bands near the cell poles. Interestingly, some central bands had a doublet appearance. We assume that the lysozyme treatment used to permeabilize the cells enhances the separation of newly divided cells. These observations are consistent with DivIVA being targeted to nascent division sites and remaining there until well after the completion of division.

Localization of DivIVA in the absence of FtsZ was tested with a strain carrying an IPTG-inducible allele of ftsZ and a divIVA–gfp fusion. Figure 2D shows the regular banding pattern for DivIVA–GFP in the presence of inducer. In the absence of inducer, repression of FtsZ synthesis leads to inhibition of division and hence formation of long aseptate filaments. In these cells, DivIVA–GFP showed a much more diffuse signal, with occasional spots scattered along the filament and major concentrations of fluorescence only apparent at the ends of the filaments, representing the sites at which the last cell divisions had occurred (Fig. 2C). Similar results were obtained by IFM using a strain with wild-type DivIVA (not shown). The dependence of DivIVA localization on divIB and divIC was tested using thermosensitive mutants. Control experiments showed that DivIVA localization was not affected at the high nonpermissive temperature needed for the divIC mutant (not shown). Figure 2, E and F, shows that localization of DivIVA was lost in both of these mutants, apart from at pre-existing poles and at the rare division sites in the divIB mutant. Thus, DivIVA requires at least three components of the division machinery for targeting to the division site.

In contrast to these results, DivIVA readily formed bands at intermediate positions in cells of a minD mutant, whether examined by IFM (Fig. 2G) or with a DivIVA–GFP fusion (Fig. 2H,I). The pattern of bands in these cells was not normal but rather their placement appeared to follow the irregularly positioned division septa produced by the minI mutant. Indeed, the DivIVA protein appeared to follow faithfully the division apparatus to either mid-cell sites or to aberrant polar sites, as indicated by the presence of double or triple rings at the poles of some cells in which minicells had been formed (stars in Fig. 2, G and H). Moreover, the formation of extra polar rings was accompanied by a tendency for

Figure 2. Localization of DivIVA in division mutants. (A) Western blot demonstrating the specificity of the crude anti-DivIVA antiserum. Extracts of wild-type B. subtilis (168CA; lane 1), and a divIVA repressible strain (1756) grown in the presence (lane 2) or absence (lane 3) of inducer. Lane M indicates the positions of prestained molecular mass markers (kD). (B–H) Fluorescence micrographs showing the localization of DivIVA by immunofluorescence (B, E–G) or a DivIVA–GFP fusion (C, D, H). (B) Wild-type cells (168CA); (C) FtsZ-repressed (strain 1759); (D) FtsZ-induced (strain 1759); (E) divIB mutant (1802); (F) divIC mutant (SU347); (G, H) minD mutant (strains 1901 and 1922, respectively). (I) Phase-contrast image of the cells in H. Arrows in G and H point to relatively long cells with no central band of DivIVA. Asterisks in G and H show examples of doublet or triplet bands of DivIVA.
rings to be missing in the body of longer cells (arrows in Fig. 2, G and H), just as for division septa in min mutants. We conclude that recruitment of DivIVA to sites of cell division requires at least partial assembly of the division apparatus but that it does not require minD.

Localization of MinD to division sites

To further distinguish between the two models shown in Figure 1, we examined the subcellular localization of MinD. B. subtilis MinD was purified and used to raise a polyclonal antiserum. The specificity of this antiserum was again examined by Western blotting (Fig. 3A). Two bands were detected in vegetative cells of B. subtilis (lane 1). The faster migrating band was of mobility expected for MinD and was absent from a minD null mutant (lane 2). Affinity purification resulted in a highly specific antibody preparation, which no longer detected the slower migrating band (lane 3).

The purified antibody was used to examine the localization of MinD by IFM (Fig. 3B–D). The protein showed a relatively uneven distribution in the cell, with scattered spots and patches of fluorescence. However, the strongest signals were almost always associated with the cell poles or at mid-cell regions between separated sister nucleoids. Because the fixation and permeabilization procedures required for IFM are damaging and do not completely preserve the structure of the cell, we also wished to examine MinD localization by use of GFP fusions. Attempts to fuse GFP to the carboxyl terminus of MinD were unsuccessful: The gene fusion proved to be nonfunctional as judged by its inability to complement a minD mutation (results not shown). However, fusion of gfp to the amino-terminal coding part of minD did give a functional fusion protein. B. subtilis strain 1981 was constructed to carry a null mutation in minD and, elsewhere in the chromosome, a gfp–minD fusion driven by a xylose-inducible promoter (Pxyo). Therefore, gfp–minD expression can be controlled by growing the cells in the presence or absence of xylose. In the absence of xylose the strain had a typical Min phenotype, with elongated cells and minicells (Fig. 3E). However, in the presence of 0.5% xylose the cells appeared normal (Fig. 3F), demonstrating that the gfp–minD fusion can complement the minD null mutation and thus that the GFP–MinD fusion protein retains MinD function.

Microscopic examination of the distribution of GFP–MinD in induced living cells revealed a similar overall distribution of MinD to that of IFM but a considerably improved image quality (Fig. 3G). The protein was indeed concentrated at the cell poles and at some mid-cell sites. At the cell poles, the prominent fluorescence was
minD

sion that occurs in the absence of DivIVA is

We reported previously that the inhibition of cell divi-

tion of FtsZ in the absence of FtsZ [again by use of a

background signal diffusing away from the cell

seemed less precisely targeted than DivIVA, with a

pending and old cell division sites. However, MinD

similar to that of DivIVA, in being mainly found at im-

the pole towards mid-cell (data not shown).

In summary, the pattern of localization of MinD was

similar to that of DivIVA, in being mainly found at im-

pend and old cell division sites. However, MinD

seemed less precisely targeted than DivIVA, with a

greater background signal diffusing away from the cell

poles.

MinD requires divIVA for targeting to the cell poles

We reported previously that the inhibition of cell divi-

tion that occurs in the absence of DivIVA is minD de-

pendent [Edwards and Errington 1997]. It was therefore

interesting to test whether a divIVA mutation affects the

targeting of MinD to division sites. To avoid the problem

of the near-lateral filamentous phenotype of a null

divIVA mutant (Cha and Stewart 1997; Edwards and Err-

ington 1997) we again made use of the inducible gfp–

minD construct, so that in the absence of xylose [effect-

ively giving a minD divIVA double mutant], the mutant

strain [1984] had a Min− phenotype [not shown]. As ex-

pected, these uninduced cells did not fluoresce detect-

ably [not shown], confirming that gfp–minD was re-

pressed. Upon addition of xylose, synthesis of the func-

tional GFP–MinD fusion protein resulted in cell fil-

amentation, consistent with the idea that in the abso-

ence of DivIVA, the uncontrolled action of MinCD in-

hibits division at polar and mid-cell sites. Figure 3H

shows that in these aseptate filaments the normal polar

localization of GFP–MinD was abolished. Instead, the

fluorescence was mainly diffusely distributed along the

length of the filament. Interestingly, there were some

bands of MinD–GFP at intermediate positions possibly

corresponding to potential division sites [arrowed]. How-

ever, these concentrations of MinD–GFP were much

weaker than in the wild type and the lack of MinD–GFP

concentrations at the completed cell poles was strikingly

different from the wild type. Similar results were ob-

tained in an experiment in which DivIVA protein was

depleted by repression (using a P_gsp–divIVA construct;

strain 1756) and wild-type MinD protein was visualized

by IFM [data not shown]. It thus appears that targeting of

MinD to the cell poles is dependent on DivIVA.

Given that targeting of DivIVA to the division site is

in turn dependent on several components of the division

machinery, MinD targeting should show a similar de-

pendence. To test this, we examined localization of

gfp–MinD in the absence of FtsZ [again by use of a

repressible ftsZ allele]. Figure 3I shows that the MinD

protein in long ftsZ filaments was, as in the wild type,

concentrated at the cell poles. However, in the absence

of new divisions, there were no strong bands within the

filaments, only a weak diffuse signal. This distribution

was quite different from that of the DivIVA− filaments

(Fig. 3H) and much more reminiscent of the localization

of DivIVA itself in FtsZ-depleted cells [Fig. 2C]. It thus

appears that MinD localization at the cell poles requires

DivIVA, though it may have a weak affinity for potential

division sites in the absence of DivIVA.

DivIVA and MinD assemble approximately

simultaneously at mid-cell before septal constriction

The above results suggested that MinD should assemble

at mid-cell at about the same time or slightly later in the

cell cycle than DivIVA. We therefore examined the for-
mation of DivIVA and MinD bands as a function of cell

length. Cells of strains 1918 (divIVA−gfp) and 1981 (gfp–

minD), were grown to mid-exponential phase and

samples from the cultures were fixed and examined mi-

croscopically. About 200 cells from each sample were

scored for length and the presence or absence of a medial

band of GFP [Fig. 4]. Clearly, bands at mid-cell were only

found in the longer cells. Not only were the propor-

tions of cells with medial bands of DivIVA [Fig. 4A] and MinD

[Fig. 4B] very similar, the average length at which bands

appeared at mid-cell were also similar [calculated as 2.5

µm for both cultures, based on the methods of Sharpe et

al. 1998].

Interestingly, these average cell lengths correspond to

about the time of completion of DNA replication, ~25

min before septal constriction begins [see Sharpe et al.

1998]. Thus, the division inhibitor, or at least the MinD

component of the inhibitor, assembles at mid-cell well

before septation begins. In work to be described else-

where, we have found that assembly of DivIVA, at least,

seems to occur at about the time of termination of DNA

replication under a range of other growth conditions

(M.E. Sharpe, unpubl.).

Min–DivIVA control of division site selection acts

at the level of FtsZ ring assembly

To test whether the B. subtilis division inhibition sys-
tem acts on FtsZ ring formation, we examined the local-
ization of FtsZ protein in cells depleted for DivIVA. As

discussed above, the cell filamentation that occurs in

divIVA mutants seems to be caused by uncontrolled ac-

tion of the MinCD inhibitor of cell division. As shown in

Figure 5A, all but the shortest cells of strain 1756 grown

in the presence of inducer [IPTG] had regularly posi-

tioned bands of FtsZ protein at mid-cell, corresponding

to nascent and future division sites [see Levin and Losick

1996; Addinall et al. 1997]. Although there was a diffuse

signal throughout most of the cells, the finished cell
poles generally did not show significant enrichment of FtsZ, indicating that, unlike DivIVA and MinD, the protein is not retained at the poles after division (Levin and Losick 1996). After growth in the absence of inducer, however, the pattern of FtsZ staining in the elongated cells was much more uniform with few prominent accumulations of protein (Fig. 5C). The occasional bright bands of FtsZ detected (e.g., arrowed in Fig. 5C) probably represent precursors to the rare divisions that occur in divIVA mutants, sometimes producing small oblique minicells (Reeve et al. 1973; Edwards and Errington 1997). In support of this interpretation, the bright bands usually coincided with larger spaces between the nucleoids (Fig. 5D). The fainter bands, again generally located between nucleoids, could correspond to the weak bands of MinD–GFP seen in similar cells (Fig. 3H). The near absence of FtsZ bands in these filaments shows that the MinCD inhibitor of \textit{B. subtilis} acts, like that of \textit{E. coli} (Bi and Lutkenhaus 1993), at the level of FtsZ ring formation.

Discussion

Targeting of DivIVA requires a late step in assembly of the division apparatus

Previous results showed that DivIVA–GFP is targeted to regularly spaced sites corresponding to mid-cell and polar positions. We have now characterized this targeting in more detail. Immunofluorescence microscopy showed a similar pattern of targeting to that of the GFP fusion, confirming that the GFP fusion provides a reliable indication of DivIVA localization. Characterization of DivIVA–GFP localization relative to cell length, showed that new DivIVA bands appear at mid-cell in a cell-cycle-dependent manner. After division, the protein remains present at the poles. The polar localizations must remain for a protracted period (or more DivIVA protein must continue to be recruited to the poles), because the poles of most cells had readily discernible accumulations of DivIVA (though always less than in the mid-cell bands). DivIVA bands appeared at a cell length corresponding approximately to the time of termination of DNA replication (Fig. 4, M.E. Sharpe, unpubl.). Interestingly, this is well before septation, confirming the notion that formation of an FtsZ ring and recruitment of late-division proteins to the ring occur well before the ring begins to contract (Addinall et al. 1996).

Although it now appears that DivIVA assembly occurs well before septation, its recruitment to the division site was dependent on FtsZ and on later assembling components of the division apparatus, DivIC and DivIB. So the topological target for DivIVA would appear to be a component of the division apparatus itself, possibly a relatively late-assembling component (or an early component that is modified or undergoes a change in conformation). In accordance with this idea, when the division-site specificity was relaxed, in a minD mutant, DivIVA continued to localize at the sites of division, whether they occurred at mid-cell or at the poles. Furthermore, this experiment showed that targeting of DivIVA to division sites is independent of MinD. The precise target for DivIVA in the division machinery is not yet clear, but it should be possible to resolve this by examining its
requirements for other division proteins, such as *ftsL* and *pbpB*. Whatever the nature of the primary target directing the assembly of DivIVA at the division site, it is interesting to note that the protein remains at the pole after the septum has been completed and the primary target has presumably been removed. In this respect DivIVA differs from most other division proteins that have been studied. The results suggest that DivIVA may have at least two distinct targeting mechanisms.

**MinD is targeted to the cell poles in a DivIVA-dependent manner**

IFM and a GFP fusion were also used to determine the localization of MinD (Fig. 3). The images obtained with the GFP fusion gave a much clearer indication of the distribution of MinD in the cell. The less homogeneous signal detected by IFM probably reflects the poorer preservation of the samples after fixation and permeabilization. The pattern of localization observed was similar to that of DivIVA in some respects, most notably in the appearance of discrete bands at mid-cell (which formed at about the same point in the cell cycle as for DivIVA), and in the retention of the signal at the completed poles. MinD differed in exhibiting a greater signal at the cell poles and a much greater background signal, apparently in the form of a gradient of protein diminishing away from the main targeting sites at the poles.

A polar piloting mechanism for division-site-selection in *B. subtilis*

Figure 6 outlines in schematic form a possible mechanism for Min–DivIVA control of division site selection in *B. subtilis*. In Figure 6 we assume that the location of MinD coincides with the site of action of the MinC inhibitor. Yeast two-hybrid experiments with the *E. coli* genes suggest that MinC and MinD interact strongly (Huang et al. 1996), and we have obtained similar results with the *B. subtilis* genes [A. L. Marston and J. Errington, unpubl.]. We also assume that nucleation of FtsZ rings is favored at the poles and mid-cell, perhaps by FtsZ or a factor needed for polymerization being excluded from the vicinity of the nucleoid. Wake and colleagues have
shown that a minimum amount of DNA replication (~70% of the chromosome) is needed before septation can occur at mid-cell in *B. subtilis* [McGinness and Wake 1979; Wu et al. 1995]. After this amount of replication, the nucleoid undergoes a conformational change, becoming bilobed [Sharpe et al. 1998]. This bilobation could produce a region deficient in DNA thereby facilitating the accumulation of sufficient FtsZ at mid-cell to allow polymerization to begin.

The model begins with a newborn cell [Fig. 6A] that contains DivIVA and MinD at both poles. Although these polar DNA-free zones would be favorable locations for nucleation of Z rings, they do not form there because of the presence of the MinD inhibitor. At about the time of completion of DNA replication, a new potential site for Z ring assembly is revealed at mid-cell [Fig. 6B]. The depletion of MinD from this site, probably caused by its sequestration to the poles, allows assembly of the Z ring [Fig. 6C] and recruitment of other division proteins. The division machinery can thus mature beyond some point, as yet undefined, at which it becomes resistant to MinCD inhibition [Fig. 6D]. DivIVA then assembles at the site of impending division [Fig. 6E], allowing MinD, in turn, to assemble there [Fig. 6F]. All of this happens before contraction of the ring begins. After division, most of the division proteins leave the newly formed poles but DivIVA and MinD remain. The presence of MinD at the new poles prevents further (minicell) divisions from occurring there [Fig. 6G], thus explaining the inactivation of used division sites [Teather et al. 1974]. It may be especially important to have MinCD at the newly formed cell poles because immediately after division there could be a high concentration of division proteins close to the poles, following their release from the constricting septum. The failure to retain MinD at the poles in *divIVA* mutant filaments could explain why these mutants make some minicells.

According to this model, based on the polar piloting model of Figure 1, DivIVA operates by assembling at the committed division site, acting to mark this as a used division site. By attracting MinD to this location [directly or indirectly], it both prevents these potential division sites from being used again and facilitates release of new mid-cell division sites.

*B. subtilis* and *E. coli* use different mechanisms to control the topological specificity of a common division inhibitor MinCD

Comparison of the *B. subtilis* and *E. coli* division site-selection system reveals some remarkable similarities and differences. The MinD protein is highly conserved between the two organisms, exhibiting 42% identical amino acids across the whole protein. In *E. coli* this protein has at least two functions [De Boer et al. 1992]. It is required first as a coinhibitor for functioning of the MinC division inhibitor. Second, it is needed to make the division inhibitor sensitive to the topological specificity factor [MinE or DivIVA]. The classical minicell phenotype produced by mutations in the *B. subtilis* minD gene [Levin et al. 1992; Varley and Stewart 1992; Lee and Price 1993] suggests that these functions are conserved. The MinC proteins of *B. subtilis* and *E. coli* are recognizable as likely homologs through the conserved position of their coding regions, immediately upstream of minD. The sequence conservation is much less, comprising only ~29% of identical residues, restricted to the carboxy-terminal part of the protein. In *E. coli*, this domain of the protein is probably involved in interacting with MinD. Unfortunately, although a minC insertion produced a Min phenotype [Varley and Stewart 1992], the possibility that this phenotype is caused by a polar effect on the downstream minD gene cannot be excluded. Nevertheless, it seems likely that MinC is also the division inhibitor in the *B. subtilis* system and we have shown above that the inhibition of division mediated by the *B. subtilis* Min system operates, as in *E. coli* [Bi and Lutkenhaus 1993], at the level of FtsZ ring formation [Fig. 5].

In contrast to MinC and MinD, the topological specificity factors, MinE of *E. coli* and DivIVA of *B. subtilis*, show no significant sequence similarity. Moreover, the minE gene lies immediately downstream of minD in *E. coli*, whereas divIVA lies in a distant locus in the *B. subtilis* chromosome. Raskin and De Boer [1997] recently showed that MinE, like DivIVA [Edwards and Errington 1997; Fig. 2] is targeted to mid-cell. However, the requirements for targeting of MinE to mid-cell are completely different from those of DivIVA. Thus, MinE targeting is independent of FtsZ and presumably all other later-assembling components of the division apparatus, whereas it requires minD. Moreover, MinE arrives at mid-cell relatively early and disappears before constriction is complete, whereas DivIVA arrives late and is retained at the cell pole after division. These observations strongly support the mid-cell inhibition model of Figure 1 for MinE, as described in detail by Raskin and De Boer [1997]. Therefore, even though *B. subtilis* and *E. coli* use a common division inhibitor, MinCD, to control division-site selection, their respective topological-specificity factors operate by completely different molecular mechanisms.

**Materials and methods**

*Bacterial strains and plasmids*

The bacterial strains and plasmids used in this study are described in Table 1.

**Media and general methods**

*B. subtilis* cultures were grown in either hydrolyzed casein (CH) medium [Sterlini and Mandelstam 1969], S medium [as described by Karamata and Gross 1970, but supplemented with 1% CH medium], or PAB (oxoid antibiotic medium no. 3). All media were supplemented with tryptophan (20 µg/ml). *B. subtilis* strains were transformed by the method of Anagnostopoulos and Spizizen [1961], as modified by Jenkinson [1983], or as described by Kunst and Rapoport [1995], except that 20 min
after addition of DNA the transformed cultures were supplemented with 0.66% casamino acid solution. Transformants were selected on oxioid nutrient agar containing, as necessary, erythromycin (either 5 µg/ml or 1 µg/ml together with 25 µg/ml lincomycin), chloramphenicol (5 µg/ml), phleomycin (0.2 µg/ml), spectinomycin (100 µg/ml), or tetracycline (10 µg/ml).

DNA manipulations and *E. coli* transformations were done by standard methods (Sambrook et al. 1989).

**Construction of a null allele of minD**
The *ermC* cassette from pSG250 was released by SstI digestion,

## Table 1. Bacterial strains and plasmids

<table>
<thead>
<tr>
<th>Strain/plasmid</th>
<th>Relevant characteristics</th>
<th>Source/construction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B. subtilis</strong></td>
<td></td>
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</tr>
<tr>
<td>BB11</td>
<td>chr::pSIZΔpble (P&lt;sub&gt;spac&lt;/sub&gt;−ftsZ ble)</td>
<td>Beall and Lutkenhaus [1991]</td>
</tr>
<tr>
<td>SG38</td>
<td>trpC2 amyE</td>
<td>Errington and Mandelstam [1986]</td>
</tr>
<tr>
<td>SU1847</td>
<td>trpC2 divIC35</td>
<td>Katis et al. [1997]</td>
</tr>
<tr>
<td>168CA</td>
<td>trpC2</td>
<td>Kunst and et al. [1997]</td>
</tr>
<tr>
<td>1306</td>
<td>trpC2 (amyE[:gpr−]&lt;lacZ cat) Ω(divIB::spe)</td>
<td>A. Feucht [unpubl.]</td>
</tr>
<tr>
<td>1756</td>
<td>trpC2 chr::pSG1043(P&lt;sub&gt;spac&lt;/sub&gt;−divIVA P&lt;sub&gt;divIVA&lt;/sub&gt;−lacZ ermC)</td>
<td>Edwards and Errington [1997]</td>
</tr>
<tr>
<td>1757</td>
<td>trpC2 chr::pSG1044 (divIVA−gfp&lt;sup&gt;+&lt;/sup&gt; divIVA− cat)</td>
<td>Edwards and Errington [1997]</td>
</tr>
<tr>
<td>1759</td>
<td>trpC2 chr::pSIZΔpble (P&lt;sub&gt;spac&lt;/sub&gt;−ftsZ ble) divIVA::pSG1044 (divIVA−gfp&lt;sup&gt;+&lt;/sup&gt; divIVA− cat)</td>
<td>1757 transformed to phleomycin resistance with BB11 DNA</td>
</tr>
<tr>
<td>1801</td>
<td>trpC2 chr::pSIZΔpble (P&lt;sub&gt;spac&lt;/sub&gt;−ftsZ ble)</td>
<td>168CA transformed to spectinomycin resistance with BB11 DNA</td>
</tr>
<tr>
<td>1802</td>
<td>trpC2 (divIB::spe)</td>
<td>168CA transformed to spectinomycin resistance with 1306 DNA</td>
</tr>
<tr>
<td>1901</td>
<td>trpC2 amyE Ω[minD::ermC]</td>
<td>SG38 transformed to erythromycin resistance with pSG1704 DNA</td>
</tr>
<tr>
<td>1918</td>
<td>trpC2 chr::pSG1044 (divIVA−gfp&lt;sup&gt;+&lt;/sup&gt; divIVA+ cat)</td>
<td>SG38 transformed to chloramphenicol resistance with 1757 DNA</td>
</tr>
<tr>
<td>1920</td>
<td>trpC2 amyE Ω[minD::ermC]</td>
<td>1901 transformed to tetracycline resistance with pSG1042 DNA</td>
</tr>
<tr>
<td>1922</td>
<td>trpC2 Ω[minD::ermC]</td>
<td>1901 transformed to chloramphenicol resistance with pSG1044 DNA</td>
</tr>
<tr>
<td>1979</td>
<td>trpC2 (minD::ermC) amyE:::spe P&lt;sub&gt;xyr&lt;/sub&gt;−gfp&lt;sup&gt;+&lt;/sup&gt;−minD</td>
<td>1981 transformed to phleomycin resistance with BB11 DNA</td>
</tr>
<tr>
<td>1981</td>
<td>trpC2 Ω[minD::ermC] amyE:::spe P&lt;sub&gt;xyr&lt;/sub&gt;−gfp&lt;sup&gt;+&lt;/sup&gt;−minD</td>
<td>1901 transformed to spectinomycin resistance with pSG1730 DNA</td>
</tr>
<tr>
<td>1984</td>
<td>trpC2 Ω[minD::ermC] 1901 Ω(divIVA::tet</td>
<td>1042 amyE:::spe P&lt;sub&gt;xyr&lt;/sub&gt;−gfp&lt;sup&gt;+&lt;/sup&gt;−minD)</td>
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<tr>
<th><strong>E. coli</strong></th>
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<tr>
<td>DH5α</td>
<td>F&lt;sup&gt;−&lt;/sup&gt; endA1 hisD17 supE44 thi-a1 λ&lt;sup&gt;−&lt;/sup&gt; recA1 gyrA96 relA1 Δ[lacZYA-argF]U169 800 K80 lacZΔM15</td>
<td>GIBCO BRL</td>
</tr>
<tr>
<td>NM554 (pREP4)</td>
<td>F&lt;sup&gt;−&lt;/sup&gt; araD139 Δ[ara-leu]7696 galE15 galK16 Δ(lac)X74 rpsL (Str&lt;sup&gt;−&lt;/sup&gt;) hisD2 (r&lt;sub&gt;G&lt;/sub&gt; m&lt;sub&gt;K&lt;/sub&gt;) mcra mcrB1 recA13 (pREP4)</td>
<td>Raleigh et al. [1988]</td>
</tr>
<tr>
<td>BL21(DE3)</td>
<td>F&lt;sup&gt;−&lt;/sup&gt; ompT [lon] hisD&lt;sub&gt;B&lt;/sub&gt; [r&lt;sub&gt;G&lt;/sub&gt; m&lt;sub&gt;K&lt;/sub&gt;]&lt;sup&gt;−&lt;/sup&gt; λ&lt;sup&gt;</td>
<td>DE3</td>
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<th><strong>Plasmids</strong></th>
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<tr>
<td>pET-3a</td>
<td>T7 expression vector</td>
<td>Studier et al. [1990]</td>
</tr>
<tr>
<td>pSG250</td>
<td>bla ermC</td>
<td>Errington et al. [1992]</td>
</tr>
<tr>
<td>pSG1022</td>
<td>pET3a containing minD&lt;sup&gt;−&lt;/sup&gt;</td>
<td>this work</td>
</tr>
<tr>
<td>pSG1042</td>
<td>bla cat Ω(divIVA::tet</td>
<td>1042</td>
</tr>
<tr>
<td>pSG1044</td>
<td>bla cat divIVA− gfp&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Edwards and Errington [1997]</td>
</tr>
<tr>
<td>pSG1151</td>
<td>bla cat gfp&lt;sup&gt;+&lt;/sup&gt;</td>
<td>P.J. Lewis [unpubl.]</td>
</tr>
<tr>
<td>pSG1613</td>
<td>bla H&lt;sub&gt;N&lt;/sub&gt;−divIVA</td>
<td>this work</td>
</tr>
<tr>
<td>pSG1704</td>
<td>bla [minD::erm]</td>
<td>this work</td>
</tr>
<tr>
<td>pSG1717</td>
<td>bla H&lt;sub&gt;N&lt;/sub&gt;−minD</td>
<td>this work</td>
</tr>
<tr>
<td>pSG1729</td>
<td>bla amyE&lt;sup&gt;3&lt;/sup&gt; spe P&lt;sub&gt;xyr&lt;/sub&gt;−gfp&lt;sup&gt;+&lt;/sup&gt; amyE&lt;sup&gt;5&lt;/sup&gt;</td>
<td>P.J. Lewis and A.L. Marston [unpubl.]</td>
</tr>
<tr>
<td>pSG1730</td>
<td>bla amyE&lt;sup&gt;3&lt;/sup&gt; spe P&lt;sub&gt;xyr&lt;/sub&gt;−gfp&lt;sup&gt;+&lt;/sup&gt;−minD amyE&lt;sup&gt;5&lt;/sup&gt;</td>
<td>this work</td>
</tr>
<tr>
<td>pQE-30</td>
<td>vector for H&lt;sub&gt;K&lt;/sub&gt;-tagged protein overproduction</td>
<td>Qiagen</td>
</tr>
</tbody>
</table>

<sup>a</sup>S65T variant of GFP [Heim et al. 1995].

<sup>b</sup>F64L, S65T variant of GFP [Cormack et al. 1996].
gel purified, and inserted into the unique Sst site of pSG1022 to produce pSG1704. *B. subtilis* SG38 was transformed with pSG1704 with selection for erythromycin resistance. Disruption of minD was confirmed in the resulting strain [J901] by PCR analysis using primers 6780 and 6781 (see below).

**Construction of a gfp–minD fusion**

The *B. subtilis* minD coding sequence was amplified by PCR from the chromosome of strain SG38 using primers AM1 [5’-GGGAGGAACTCAGTTGGTGAGGC-3’] and AM2 [5’-GATTCTTCCTTGAATCTATACATTAAG-3’], introducing Xhol and EcoRI sites, respectively. The Xhol–EcoRI minD fragment was inserted between these sites in pSG1729 to generate pSG1730, which places gfp–minD under the control of *P*_{soy}.

**gfp–minD induction experiments**

To study the localization of GFP–MinD in a *divIVA* null mutant, strains 1979 and 1984 were grown to exponential phase (OD 600 = 0.3) in the modified S medium at 30°C. To study the localization of GFP–MinD in a *divIVA* null mutant, strains 1979 and 1984 were grown to exponential phase (OD 600 = 0.3) in the modified S medium at 30°C. To study the localization of GFP–MinD in a *divIVA* null mutant, strains 1979 and 1984 were grown to exponential phase (OD 600 = 0.3) in the modified S medium at 30°C. To study the localization of GFP–MinD in a *divIVA* null mutant, strains 1979 and 1984 were grown to exponential phase (OD 600 = 0.3) in the modified S medium at 30°C.

**DivIVA depletion experiments**

To check the anti-DivIVA antiserum for specificity by Western blotting, strain 1756 was grown at 30°C to late-log phase (OD600 of 1.0) in CH medium. Each culture was then diluted into the same medium to an OD600 of 0.05. Samples for Western blotting were collected when the cultures reached an OD600 of 0.4. The same procedure was followed for IFM with anti-FtsZ antibody except that S medium was used.

**FtsZ depletion experiments**

To examine the effect of FtsZ depletion on DivIVA localization, strain 1759 was grown at 30°C to an OD600 of 1.0 in PAB containing 0.1 mM IPTG. The cells were harvested, washed in PAB, and resuspended to an OD600 of 0.01. The culture was divided into two portions, to one of which was added 0.1 mM IPTG. The cultures were sampled for examination by fluorescence microscopy at an OD600 of 1.4.

To examine the effect of FtsZ depletion on MinD localization, strain 1797 was grown at 30°C in S medium containing 0.5 mM IPTG to an OD600 of 0.4. The cultures were sampled for examination by fluorescence microscopy at an OD600 of 0.4.

**Temperature-shift experiments**

Strains 1802 and SU347 were grown overnight at 30°C to late-log phase (OD600 = 1.0) in CH medium. Each culture was then harvested and washed once in CH before being divided into two and diluted in CH to an OD600 of 0.05. For each strain one culture was left to grow at 30°C, whereas the other was placed at the restrictive temperature (37°C for 1802 and 45°C for SU347). All cultures were grown to a final OD600 of 0.7 before being sampled for IFM.

**Overproduction and purification of His-tagged DivIVA**

Primers 8618 ([5’-GGAGGTGGATCCATGGCCATTAAAGC-3’] and 8619 ([5’-CAGACCAATTTCTTTTCTCAATAATGACCGG-3’]) were used to amplify *divIVA* and replace its stop codon with a *HindIII* restriction site, by PCR. Thus, *divIVA* was cloned into pQE-30 [Qiagen] to give pSG1613. *E. coli* strain NM554 [pREP4] [Qiagen] transformed with pSG1613 was induced to express the fusion protein, H6–DivIVA by addition of 1 mM IPTG. The cells were harvested and lysed by metal affinity chromatography [Qiagen], according to manufacturer’s instructions. Following washes with stringent buffer (8 M urea, 300 mM NaCl, 10 mM Na-phosphate at pH 7.4) and centrifuged (10,000 g), the H6–DivIVA was eluted with 300 mM imidazole. The pure H6–DivIVA was collected by precipitation with 50% acetone, and redisolved in deionized water.

**Antibody production and Western blotting**

Rabbit polyclonal antisera were raised by standard procedures [Harlow and Lane 1988] using H6–DivIVA or gel-purified MinD.
protein. Sheep anti-FtsZ antibodies were a gift of E.J. Harry [University of Sydney, Australia]. The antibodies were affinity-purified as described by Reznegrov et al. [1996]. Anti-FtsZ antibodies were purified against native FtsZ [also from E.J. Harry], and eluted with 0.2 M glycine, 1 mM EDTA at pH 2.2, 50% glycerol. Anti-MinD antibodies were purified against H6–MinD using 4.5 M MgCl₂, 0.1% BSA as eluant. The anti-DivIVA antibodies were used at a dilution of 1:5000 for Western blotting. Unpurified and affinity-purified anti-MinD antiserum were used at dilutions of 1:500 and 1:250, respectively. Western blotting was carried out essentially as described by Wu and Errington (1994) using an enhanced chemiluminescence detection system (Amersham).

Immunofluorescence microscopy

Cells were fixed, permeabilized, and stained for immunofluorescence microscopy as described previously [Pogliano et al. 1995; Lewis et al. 1996; Reznegrov et al. 1996], except that the glutaraldehyde concentration in the 2× fixative was reduced to 0.00005%. Crude anti-DivIVA, affinity-purified anti-MinD and affinity-purified anti-FtsZ antibodies were used at concentrations of 1:1500, 1:500, and 1:20, respectively. Images were grabbed, processed, and assembled as described previously (Lewis and Errington 1997). Exposure times were 1 sec for Cy3; 0.5 sec for DAPI; 3 sec for DivIVA–GFP, and 4 sec for GFP–MinD.

Cell-cycle analysis

The timing of DivIVA and MinD appearance at mid-cell was calculated as described previously [Glaser et al. 1997, Sharpe et al. 1998, Sharpe and Errington 1998].

Acknowledgments

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References


