The C-Terminal Domain of the Bacterial SSB Protein Acts as a DNA Maintenance Hub at Active Chromosome Replication Forks

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Abstract

We have investigated in vivo the role of the carboxy-terminal domain of the Bacillus subtilis Single-Stranded DNA Binding protein (SSBCter) as a recruitment platform at active chromosomal forks for many proteins of the genome maintenance machineries. We probed this SSBCter interactome using GFP fusions and by Tap-tag and biochemical analysis. It includes at least 12 proteins. The interactome was previously shown to include PriA, RecG, and RecQ and extended in this study by addition of DnaE, SbcC, RarA, RecJ, RecO, XseA, Ung, YpbB, and YrrC. Targeting of YpbB to active forks appears to depend on RecS, a RecQ parologue, with which it forms a stable complex. Most of these SSB partners are conserved in bacteria, while others, such as the essential DNA polymerase DnaE, YrrC, and the YpbB/RecS complex, appear to be specific to B. subtilis. SSBCter deletion has a moderate impact on B. subtilis cell growth. However, it markedly affects the efficiency of repair of damaged genomic DNA and arrested replication forks. sSBjCter mutant cells appear deficient in RecA loading on ssDNA, explaining their inefficiency in triggering the SOS response upon exposure to genotoxic agents. Together, our findings show that the bacterial SSBCter acts as a DNA maintenance hub at active chromosomal forks that secures their propagation along the genome.

Introduction

Maintaining genome integrity is a permanent challenge for all organisms, particularly during genome duplication, when accidental replication fork arrests expose the genome to damage. Numerous mechanisms have evolved to counteract the deleterious consequences of fork arrest (reviewed in [1,2]). The multiplicity of these fork repair mechanisms reflects the need to respond appropriately to a variety of damaged fork structures. A key question is therefore how these multiple rescue pathways are coordinated in the cell.

Bacteria can manage chromosomal replication fork arrest without necessarily interrupting other key cell cycle events. Their genome is generally composed of one circular DNA molecule (of several Mbp) replicated by a single pair of divergent forks fired at a fixed origin, oriC. Thus, effective repair of accidentally arrested replication forks is vital to bacteria. In addition to a requirement for removal and repair of the damage originally responsible for a particular replication fork arrest, the cell possesses the machinery necessary for re-assembling the replication machinery (the replisome) at these rescued forks [3]. An emerging model is that components of the replisome determine the recruitment of accessory proteins at the forks to assist their progression. One of these is DnaN, a dimeric protein that forms a ring around double-stranded DNA (dsDNA) and clamps the replicative DNA polymerase [4], and also interacts with several proteins involved in DNA replication and repair (reviewed in [5]). Another protein of the replisome, the Single-Stranded DNA Binding protein (SSB), is also known to interact with accessory proteins at the fork. The primary role of SSB at the fork is to facilitate the activities of replisomal enzymes by preventing the formation of ssDNA secondary structures (for a review, see [6]). SSB is composed of two domains: an N-terminal ssDNA binding domain and a C-terminal domain, SSBCter, enriched in glycine and acidic amino-acids. A short hexapeptide motif with a consensus signature D-D-D-I/L-P-F emerges from the end of the protein [7]. The SSBCter is dispensable for SSB tetramerisation and interaction with ssDNA [8,9] but permits interaction with many proteins of the DNA recombination, repair and replication machineries. The E. coli SSB (jSSB) interactome is currently estimated to include 14 proteins (reviewed in [6]).

Many of the SSB partners are involved in distinct replication fork repair pathways. Thus, SSB might be responsible for coordinating recruitment of these repair proteins at active replication forks. As judged by the analysis of SSB localization in B. subtilis and E. coli [10–12], active forks are the subcellular sites where SSB accumulates in replicating cells grown without genotoxic stress. We previously provided strong support for the idea...
that SSB acts as a protein recruitment platform at active replication forks by localizing in living B. subtilis cells three conserved DNA helicases as GFP fusions. These were PriA, the primary restart protein, which directs replisome re-assembly on branched DNA originating from arrested forks [13–15], and RecG and RecQ, two recombination proteins involved in the maintenance of the genome and of chromosome forks [16,17]. These three proteins accumulate at chromosomal forks in an SSBCter-dependent manner, a discrete localization that does not depend on accidental fork arrest [8]. In addition, we have characterized a B. subtilis PriA mutant unable to interact with SSB, which was no longer targeted to active chromosomal forks and did not support replication restart unless overproduced. This underlines the direct benefit of pre-recruitment and targeting of PriA by SSB on active chromosomal forks: in anticipation of a requirement of PriA repair action, which can occur at any stage of genome replication [8]. Thus, an hypothesis raised by such a preparatory mode of PriA action at replication forks would also apply to the other SSB protein partners.

In this study, we have further defined the B. subtilis SSBCter interactome at active chromosomal forks. First, using cytological and biochemical approaches we have extended the number of B. subtilis SSB partner proteins targeted at forks to twelve, including RarA, SbcC and XseA, which are also present in E. coli but not previously known to interact with ε2-SSB. Among the other proteins identified were key effectors of the RecFOR loading machinery for RecA. In addition, 3 others, including the DNA polymerase DnaE, appear to be specific to the B. subtilis SSB interactome. Paradoxically, although DnaE is one of the two essential B. subtilis DNA polymerases, this interaction is not essential since we have been able to delete SSBCter while retaining cell viability [8]. In parallel to this screening, we have undertaken detailed analysis of the multiple defects caused by the deletion of the SSBCter in vivo. Based on these results we propose an integrated model for replication fork rescue in which SSB coordinates the multiple processes potentially involved in a cascade-like manner. In an initial response to replication fork blockage, the system would first attempt to repair the damage and restart the stalled fork by the coordinated action of proteins present at the fork prior to its blockage. Failure to circumvent the blockage in this way would lead to a second set of responses, in particular the de novo loading of RecA on ssDNA at arrested forks by specific SSB-associated proteins. This would facilitate fork remodeling by homologous recombination (reviewed in [2]). Failure at this step would then lead to a more robust response by induction of the SOS system to provide increased levels of repair proteins to repair damaged forks.

**Results**

**Defining the B. subtilis SSBCter interactome at chromosome replication forks**

A remarkable feature of the B. subtilis SSB protein is that deletion of its C-terminal end is not lethal to the cell, in sharp contrast to that of E. coli [9]. This enabled the demonstration that PriA, RecG and RecQ proteins are targeted to active chromosome replication forks in B. subtilis in a manner which depends on the C-terminal region of SSB [8]. To identify additional proteins targeted to active chromosomal forks in the same way, we have extended these studies by using two B. subtilis ssb alleles truncated for the last 35 (ssbA35) or 6 (ssbA6) codons.

Candidate proteins were chosen according different criteria. Some were E. coli homologues already shown or proposed to interact physically with the ε2-SSB [reviewed in [6]]. Others were selected because of their sequence or functional homology with known partners of B. subtilis SSB. A third group included those already known to be present at active chromosomal forks. The final group comprised proteins selectively purified with B. subtilis SSB using the Tap-tag procedure [18] and identified by mass spectrometry.

All candidates were screened for localization at active replication forks as GFP fusions, expressed ectopically from the amyE locus, in SSBCter deletion strains and in the isogenic wild type strain (ssb3). Most candidates were also screened for physical interaction with SSB as purified proteins in vitro or by Tap-tag analysis with the use of the SPA motif fused to their C-terminal end at their original genetic locus. The combination of these three approaches identified 9 additional proteins which together represent an extended view of the SSBCter interactome targeted to active B. subtilis chromosomal forks.

The results of this screening are compiled in Table 1 and described in the following sections.

**RecS, a parologue of RecQ in B. subtilis, interacts with SSB in association with YpbB**

B. subtilis and closely related bacteria encode two RecQ homologues [19]. The first, initially annotated as YocI, was renamed RecQ since it is highly homologous to the single RecQ protein generally encoded in bacterial genomes (including E. coli). B. subtilis RecQ co-localizes with active replication forks in an SSBCter-dependent manner and Tap-tag analysis of RecQ provided further evidence for its ability to interact unaided with SSB [8]. The second RecQ homologue, RecS (also annotated as YpbC), is smaller. The RecQ family is typified by 8 helicase motifs. In both RecQ and RecS, they are located towards the N-terminal (Nter) region and are followed by a more divergent C-terminal (Cter) region. In ε2-RecQ, the latter region carries the site of interaction with SSB [20,21].

As shown in Figure 1A, Tap-tag analysis of RecS revealed a prominent interaction with SSB and a protein of unknown function, YpbB, encoded immediately upstream of recS. The stop codon of ypbB overlaps the start codon of recS, suggesting translational coupling of the two proteins (Figure 1B). In the few bacterial species encoding a ypbB homologue, this invariably appears upstream of a recS homologue in a common operon (see Figure S1). In the Tap-tag experiments, RecS and YpbB appear in almost equimolar amounts after purification, as does the co-captured SSB (Figure 1A). In addition, the cellular concentrations
of RecS and RecQ appear similar (between 150 and 300 copies per cell) as judged by western-blotting of total protein extracts of cells expressing the RecS-SPA or RecQ-SPA fusions and probed with anti-Flag antibodies against the SPA motif (not shown). To test whether RecS and/or YpbB are targeted to chromosomal replication forks, we first constructed N-ter GFP fusions of each protein individually at replication forks, we first constructed N-ter GFP fusions of each protein individually at active chromosome replication forks. Biochemical evidence for active chromosome replication forks. Biochemical evidence for a physical interaction between YpbB and RecS comes from our attempts to purify them from E. coli (described in Text S1); YpbB could not be prepared as a soluble protein alone but only as a stable complex with RecS. Furthermore, the YpbB/RecS complex, but not RecS alone, interacts physically with SSB (Figure S2). Finally, no localization of GFP-YpbB was observed in ssbΔ35 and ssbΔ6 cells (Figure 1D and Table S1).

Altogether, these results show that YpbB is targeted to active chromosomal forks in an SSB_{Cter}-dependent manner. They also indicate that the GFP-YpbB foci depend on RecS, with which YpbB forms a stable complex. Reciprocally, RecS could also be present at forks via its association with YpbB. The detection of RecS in the Tap-tag of SSB argues for this is the case (see below).

### PcrA and DinG DNA helicases do not belong to the interactome of SSB

To test whether localization at active forks is a property shared by other DNA helicases known to act in repair of arrested replication forks, we analyzed PcrA [22]. A functional GFP-PcrA fusion did not form foci in growing cells but appeared to localize non-specifically to the nucleoid (Figure S3A). In addition, SSB was not detected among the proteins that co-purified with PcrA in Tap-tag experiments (Figure S3B). The Tap-tag is nevertheless validated by the recovery of 2 known partners of PcrA with the functional PcrA-SPA fusion: RNA polymerase [23], and RecA [24,25]. Furthermore, we did not detect an interaction between purified SSB and PcrA (active as a DNA helicase) in a specific SSB pull-down assay (Figure S4C) detailed below. A lack of discrete targeting in the cell was also observed for the widespread DinG DNA helicase (Figure S3A), recently demonstrated in E. coli to function in concert with Rep or UvrD (the functional equivalents of PcrA; [26,27]) in resolving accidents caused by collision between the replication and transcription machineries. In addition, SSB was not detected in the Tap tag of DinG (Figure S3B). Most of the proteins co-purified with DinG were ribosomal proteins, indicative for a putative role of DinG in translation and/or ribosome biogenesis in B. subtilis.

Thus, anchorage to active chromosomal forks visualizable by focus formation would not be a hallmark of all effectors of DNA replication rescue. We could not exclude, however, that specific interactions of PcrA and DinG with one component of the fork might occur without being strong or cumulative enough to generate a detectable focus.

### The essential DNA polymerase DnaE accumulates at active chromosomal DNA replication forks in an SSB_{Cter}-dependent manner

We previously showed that DnaX, a homologue of the E. coli Holopolymerase III (εPolIII) subunit, still formed foci in ssbΔ35 dividing cells [8]. This is also true for other components of εPolIII conserved in B. subtilis, i.e. HolA, HolB and DnaN, as well as for the replicative DNA helicase, DnaC (Table S1). We could not test the primase, DnaG, since neither N- nor C-terminal GFP fusions gave rise to discrete foci in wild-type B. subtilis cells [10]. B. subtilis encodes two DNA polymerases essential for genome duplication, PolC and DnaE [28]. Both are homologous to the single essential E. coli DNA polymerase, εDnaE. GFP fusions to PolC and DnaE were both shown to localize at active chromosomal forks [28,29]. Remarkably, and in sharp contrast with PolC-GFP, we found that DnaE-GFP did not form foci in ssbΔ35 cells (Figure 2A and Table S1) nor in ssbΔ6 cells (Table S1). This suggests that DnaE accumulates at active chromosomal forks via a physical interaction with SSB whereas PolC does not. Tap-tag analysis of DnaE was not informative, since only the DnaE-SPA prey was recovered (not shown). We therefore explored the potential interaction between DnaE and SSB in vitro with purified recombinant proteins. We used a pull-down assay based on magnetic beads coated with ssDNA fully bound by

### Table 1. The B. subtilis SSB interactome targeted to active chromosomal replication forks.

| Protein partners of B. subtilis SSB | GFP foci formations | in vitro interaction with SSB | Tap-tag experiments |
|----------------------------------|---------------------|-----------------------------|---------------------|
|                                   |                     |                             | protein candidates  | SSB^d               |
| Prk^a                            | +                   | -                           | -                   |                     |
| RecQ^a                           | +                   | +                           | +                   |                     |
| RecS^a                           | +                   | -                           | +                   |                     |
| YpbB^b RecS^c                     | +                   | ND/+                        | ND/+               | -/-                 |
| DnaE                             | +                   | +                           | +                   |                     |
| SbcC^s                           | +                   | ND                           | ND                  |                     |
| RarA^d                           | +                   | ND                           | ND                  |                     |
| RecS^a                           | +                   | ND                           | +                   |                     |
| RecQ^a                           | +                   | +                           | -                   |                     |
| YrrC^e                           | +                   | ND                           | ND                  | +                   |
| XseA^c                           | +                   | ND                           | ND                  | +                   |
| Ung^d                            | ND                  | ND                           | ND                  | +                   |

In the first column are listed all B. subtilis candidate proteins found to belong to the SSB interactome targeted to active forks. The *denotes proteins that were previously known to interact with SSB in B. subtilis or in other bacteria [6,8].

^a: + signifies that discrete GFP foci for each fusion protein observed in ssbΔ34 cells were no longer detected in ssbΔ35 cells. +: + signifies that in pull-down and/or in gel-filtration assays most of the retention of candidate proteins by SSB is no longer seen with SSBΔ36.

^c: + and - signify ability/inability of candidate proteins to capture SSB in Tap-tag experiments.

^d: + and - signify detection/non detection of the protein candidate in the SSB-SPA purification experiment presented in Figure 3. -/+ indicates that RecB but not YpbB was detected: ND: not determined.

The # denotes GFP fusions that have not been tested functionally.

The * denotes proteins naturally expressed at very low levels in the cell; this provides a simple explanation for inactivity to detect them in the Tap-tag experiment of SSB, and reciprocally, the non detection of SSB in the Tap-tag experiments performed with these proteins.

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purified SSB or SSB\(\Delta 6\) (or SSB\(\Delta 35\), which behaved as SSB\(\Delta 6\); Figure S5) to test specific interaction between a protein and the SSB\(\text{Cter}\). These contaminants have been indicated in italic, as a matter of distinction with the others considered as specific partners of RecQ or RecS proteins. All bands that have given a positive spectrum in the predicted \textit{B. subtilis} protein database (excepted for the TEV protease added during the purification) have been accordingly annotated on the picture of the gel.

**Figure 1.** RecS assembles with YpbB into a complex targeted to active chromosomal replication forks via the SSB\(\text{Cter}\). (A) Tap-tag purification of RecS-SPA and RecQ-SPA fusions. Purified proteins have been separated on a 12.5% SDS-PAGE, revealed by Coomassie staining and identified by MALDI-TOF analysis following in-gel trypsinolysis. The ribosomal RpsE and RplQ proteins are prominent contaminants systematically recovered by this purification method with \textit{B. subtilis}. These contaminants have been indicated in italic, as a matter of distinction with the others considered as specific partners of RecQ or RecS proteins. All bands that have given a positive spectrum in the predicted \textit{B. subtilis} protein database (excepted for the TEV protease added during the purification) have been accordingly annotated on the picture of the gel. (B) Genetic organization of the ypbB-recS region. The Comprehensive Microbial Resource [54] was used to identify coordinates of the genes contained in the Genbank \textit{B. subtilis} genome sequence version AL009126. (C) and (D) GFP (green), and DAPI (blue) fluorescent signals from cells expressing the GFP protein fusions indicated above each panel. In (D), white arrowheads point to GFP foci on the DAPI-stained nucleoid of 2 representative ssb\(3^+\) cells (see Table S1 for statistical analysis of this foci distribution). doi:10.1371/journal.pgen.1001238.g001

**Extending the \textit{B. subtilis} SSB interactome at active forks**

We next examined the localization of other proteins known or expected to co-localize with \textit{B. subtilis} chromosomal forks but not essential for their propagation. These included SbcC, a subunit of the heterodimeric SbcCD nuclease that acts specifically on ssDNA palindromic structures [30]; YabA, a negative regulator of initiation of DNA replication at \textit{oriC} in \textit{B. subtilis} [31]; RarA, which, in \textit{E. coli}, is required for RecA loading on arrested chromosomal forks [32]; and RecO and RecJ, which are also involved with RecA loading at arrested forks in concert with RecF, RecR and RecQ.

Among these, only YabA was found to localize in \textit{ssb}\(\Delta 35\) cells (Figure 2C, Table S1). Since YabA localizes at forks in a DnaA- and DnaN-dependent manner [33], this result implies that DnaN and DnaA act in \textit{ssb}\(\Delta 35\) cells as in wild-type cells.

GFP-SbcC was previously shown to co-localize with \textit{B. subtilis} replication forks [10]. Here we find that this localization is dependent on the C-terminal domain of SSB (Figure 2C and Table S1).

The three others candidate proteins, i.e. RarA, RecO, and RecJ, which did not localize in \textit{ssb}\(\Delta 35\) cells in contrast to wild type \textit{ssb}\(3^+\) cells (Figure 2C and Table S1), were found to interact...
physically with SSB. This was demonstrated, by Tap-tag analysis in the case of RecJ (Figure 2D), by pull-down and gel filtration assays for RarA (Figure 2E and Figure S6) and by pull-down assays for RecO (Figure 2F). The precise targeting of the functional GFP-RecO fusion to active forks (and not to ssDNA gaps that could be formed elsewhere on the genome) was confirmed by its co-localization with the replisome protein DnaX (Figure S7).

These results imply that although RecA is not normally present at active forks [34], these are equipped with key components of the RecFOR machinery (i.e. RecO, RecJ, RecQ and RarA) permitting recruitment of RecA at replication forks upon accidental arrest [34].

**Tap-tag analysis of B. subtilis SSB**

To identify a more complete repertoire of SSB partners, we used SSB as a prey in Tap-tag analysis. However, in contrast to EcSSB [35], we were unable to construct an SSB-SPA fusion at the ssb locus suggesting that capping SSBCter with the SPA motif inactivates SSB and leads to cell lethality. We therefore inserted the ssb-SPA construct under the P$_{xyl}$ promoter at amyE to generate mixed SSB complexes composed of both SSB-SPA and wild-type SSB subunits. Their selective capture, via the SSB-SPA component should permit the co-capture of protein partners interacting with the uncapped wild-type SSB subunits. Ectopic expression of SSB-SPA had no observable negative effect on cell growth (not

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**Figure 2. Extending the composition of the SSB$_{C_{ter}}$-dependent interactome.** (A), (C) GFP (green), and DAPI (blue) fluorescent signals from cells expressing GFP fusions (listed on the left of each set of panels) in sssb$^+$ or sssb$^{35}$ cells. White arrowheads point to GFP foci visible on the DAPI-stained nucleoid of two representative cells (see Table S1 for statistical analysis of this foci distribution). (B), (E), (F) In vitro binding assay between purified DnaE, RarA or RecO respectively (at the amounts indicated on the top of the gels) and 80 pmol of tetramer of SSB or SSB$_{Δ6}$ molecules (see Materials and Methods for details). Proteins are indicated on the left of the 14% SDS-PAGE gel stained by Coomassie-blue. Strep stands for streptavidin. The ‘load’ on the right side of each gel corresponds to the range of each protein tested for interaction on the SSB (SSB$_{Δ6}$)-coated beads.

(D) Tap-tag of a RecJ-SPA fusion protein (the experiment was done and presented as in Figure 1). RecJ$^*$ indicates degradation product of RecJ-SPA. doi:10.1371/journal.pgen.1001238.g002
shown). As shown in Figure 3, wild type SSB and SSB-SPA subunits were recovered in equal amounts from cells grown with (lane 3) or without (lane 1) D-xylose induction of SSB-SPA expression. As expected, the total yield of the hetero-tetrameric SSB/SSB-SPA complexes was higher with than without D-xylose.

Many proteins were observed to co-purify with SSB/SSB-SPA complexes (Figure 3). These included those reproducibly recovered in other Tap-tag experiments performed with other B. subtilis proteins (e.g. GyrA and many ribosomal proteins) and were not considered further. The others appeared to be specific partners of SSB. They were not observed in control experiments where the ectopic ssb-SPA was replaced with a wild type ssb allele (lane 2). In addition, their levels were increased when SSB-SPA expression was induced (compare lanes 1 and 3). Many of these proteins (e.g. RecJ, RecQ, RecG, and RarA) were identified in the experiments described above as direct partners of B. subtilis SSB. Very few peptides of RecS were unambiguously detected by mass spectrometry. As reported above, RecS alone could not stably interact with SSB in vitro but could do so in a complex with YpbB (Figure S2). YpbB was not detected in the Tap tag of SSB, possibly because the number of YpbB molecules recovered was below the level of detection by mass spectrometry, RecS being very close to this limit. The Ung protein was identified in the Tap tag of SSB. Ung was identified previously as a partner of EcSSB [36]. However, some known SSB partners, such as RecO, PriA, DnaE, SbcC and YpbB, were absent. This is probably due to differences in affinity between SSB and each of its partners and to variation in their natural cellular levels since some are known to be present in very low amounts (for instance, ~50 copies of PriA per cell; [15]).

The same dual explanation may also account for the differential yield of some SSB partners recovered in the experiment e.g. RecJ which is by far the most abundant protein co-purified with the SSB/SSB-SPA complex (Figure 3).

We also identified several new candidate partners. These included XseA, the large subunit of ExoVII, and YrrC, a protein of unknown function conserved in gram positive bacteria and

![Figure 3. Tap-tag of B. subtilis SSB.](image-url)

Figure 3. Tap-tag of B. subtilis SSB. Cells harbouring the P_{xyl} ssb-SPA construct at amyE were grown to mid-log phase in LB medium without (−) or with (+) 0.2% D-xylose (lanes 1 and 3). The SSB-SPA fusion was purified and analyzed as described in Figure 1. The isogenic strain containing the wild type ssb instead of the ssb-SPA construct at amyE was treated in the same way (lane 2). All proteins identified by MALDI-TOF analysis of Coomassie-stained bands have been reported on the gel picture. RecJ* indicates RecJ degradation products. SSBt stands for the SSB-SPA purified after cleavage by the TEV protease. SSB* indicates degradation products of SSBt or of wild-type SSB. doi:10.1371/journal.pgen.1001238.g003
predicted to be a helicase/nuclease by sequence analysis. GFP fusions to XseA and YvrC were also both found to form foci on the nucleoid of ssb-3 cells but not in ssb-35 cells (Table S1).

This screening identified a repertoire of 12 proteins belonging to the B. subtilis SSB interactome escorting active chromosomal forks. Together, these proteins fulfill a large variety of functions concerned with DNA processing. As a result, the SSB>Cter emerges as a central hub of DNA processing functions at chromosomal replication forks, where SSB naturally concentrates in the cell.

**Growth and cellular defects of B. subtilis ssb-135 mutant cells**

While deletion of the SSB>Cter is not lethal, ssb-35 cells show viability defects. They exhibit a ~5-10 fold lower plating efficiency during growth in rich medium, i.e. under fast growing conditions (Figure 4A), as well as in minimal medium (not shown), and smaller colonies on solid medium (Figure 5A). The reduced viability was also directly inferred by observation of exponentially growing cells (in rich medium) under the microscope where up to 15% of ssb-35 cells show various kinds of cellular and/or nucleoid morphological defects (i.e. distribution, shape, length, segregation; see Figure S8). Similar observations were made with the ssb-6 strain (Figure S9A and S9B and not shown).

**The SSB>Cter is crucial for rescuing the damaged genome**

The SSB>Cter interactome includes many proteins involved in maintaining genome integrity. The importance of the SSB>Cter might therefore be expected to be more pronounced under growth conditions that are stressful for the genome. Indeed, ssb-35 and ssb-6 cells are nearly as sensitive to UV irradiation as recA cells (Figure 4B and Figure S9C). Similarly, both mutants are also more sensitive to Mitomycin C (MMC) than the ssb-3 strain (Figure S9D).

To investigate further the intracellular role of the SSB>Cter, we examined the effect of complementation of the defects of ssb-35 and ssb-6 cells by ectopic expression of wild-type SSB at the P_xyl promoter. Upon induction with D-xylose fusions to XseA and YvrC were also both found to form foci on the nucleoid of ssb-35 cells but not in ssb-35 cells (Table S1). This screening identified a repertoire of 12 proteins belonging to the B. subtilis SSB interactome escorting active chromosomal forks. Together, these proteins fulfill a large variety of functions concerned with DNA processing. As a result, the SSB>Cter emerges as a central hub of DNA processing functions at chromosomal replication forks, where SSB naturally concentrates in the cell.

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**The SSB>Cter is crucial for rescuing the damaged genome**

The SSB>Cter interactome includes many proteins involved in maintaining genome integrity. The importance of the SSB>Cter might therefore be expected to be more pronounced under growth conditions that are stressful for the genome. Indeed, ssb-35 and ssb-6 cells are nearly as sensitive to UV irradiation as recA cells (Figure 4B and Figure S9C). Similarly, both mutants are also more sensitive to Mitomycin C (MMC) than the ssb-3 strain (Figure S9D).

To investigate further the intracellular role of the SSB>Cter, we examined the effect of complementation of the defects of ssb-35 and ssb-6 cells by ectopic expression of wild-type SSB at the P_xyl promoter. Upon induction with D-xylose production of SSB from the P_xyl promoter was ~10% that of the natural SSB level (Figure 4C; compare lane 2 with lane 6). This low concentration was, however, sufficient to fully suppress the plating defect of the ssb-35 strain (not shown). It also fully restored UV resistance at doses up to 10 J/m² (Figure 4D). Above this dose, the cells exhibited sensitivity intermediate between that of ssb-3 and ssb-35 cells indicating that the intracellular concentration of SSB>Cter is determinant for an optimal response to DNA damage.

We next investigated whether SOS, a well known cellular response to DNA damaging agents, could be triggered in ssb-35 cells. In B. subtilis, the SOS system is regulated by RecA-induced auto-cleavage of the LexA repressor. We used a P_lexA-lexA reCter construct as a reporter of SOS activity and another DNA damaging agent, MMC, as an inducer [37]. The MMC-induced SOS response was dramatically reduced in ssb-35 cells compared to ssb-3 cells (Figure 4E). These results therefore underline a pivotal role for the SSB>Cter in triggering the SOS response.

**SSB>Cter deletion mutants are temperature-sensitive**

Another notable defect of ssb-35 cells is their temperature-sensitive growth, as measured by plating assay (Figure 5A). This lethality is fairly low compared to SSB expression induced from the ectopic P_xyl:sub (not shown). Since some SSB partners are independently important for cell viability, we tested whether the temperature sensitivity of ssb-35 cells could be corrected by increasing individual expression of these partners placed under the P_xyl promoter from the amyE locus. Overexpression of DnaE or PriA, the two most important components of the SSB interactome for cell viability, did not alleviate the temperature sensitivity of ssb-35 cells (not shown). Unexpectedly, however, induced expression of RecO (as a functional RecO-SPA fusion) did so (Figure 5B). In contrast, the plating defect characteristic of the ssb-35 strain observed at permissive temperature is not corrected by RecO overexpression (Figure 5B).

RecO is a recombination mediator protein that, with RecR and RecF, directs loading of RecA onto ssDNA coated by SSB [38]. We therefore tested whether suppression of ssb-35 temperature sensitivity by overexpression of RecO was dependent on RecA. We introduced the recA::tet allele into the ssb-35 and ssb-3 strains carrying the P_0_qrecO-SP24 cassette. Inactivation of recA in the ssb-3 strain provoked weak temperature sensitivity (Figure 5C). Disruption of recA prevented RecO suppression of ssb-35 temperature sensitivity (Figure 5C). This implies that RecA loading on ssDNA is needed for this suppression. The formation of a RecA-ssDNA nucleofilament is the pre-synaptic intermediate of homologous DNA recombination and the inducing signal of SOS, which we have shown above to be defective in MMC-treated ssb-35 cells (Figure 4E). However, individual overexpression of RecO neither restored SOS induction by MMC in this mutant, nor suppressed its sensitivity to MMC (not shown).

Thus, the suppression is not solely due to RecO action, but also relies on RecA, leading to the proposal that it proceeds through the RecO-dependent loading of RecA on ssDNA.

**The SSB>Cter is needed for supporting genomic DNA replication**

The previous experiments demonstrated that SSB>Cter was required for repair of lesions throughout the genome. They did not address the question of whether the SSB>Cter specifically assists chromosomal fork progression. To specifically stress the replication fork, we used two B. subtilis strains bearing temperature sensitive alleles, dnaN5 and dnaX51, whose products are exclusively associated with the replisome [39] and analyzed how deletion of the SSB>Cter affects their viability. The ssb-35 allele, genetically linked to the erythromycin resistance marker (EryR) 8, was introduced by transformation at low temperature into strains carrying the replication mutations. An isogenic EryR linked ssb-3 allele was also used as a control. Viable EryR clones were obtained upon transformation at 30°C of the dnaN5 and dnaX51 strains with the ssb-35 and ssb-3 alleles. The ssb-35 dnaN5 and ssb-35 dnaX51 recombinants exhibited the characteristic plating and growth defects of the ssb-35 strain (Figure 6). Interestingly, they were both significantly more temperature sensitive for growth than their ssb-3 counterparts (Figure 6A–6C). Thus the SSB>Cter is crucial for growth of ssb-3 dnaN5 and ssb-3 dnaX51 cells at semi-permissive temperatures. In addition, we also found that ssb-35 cells were markedly more sensitive than ssb-3 cells to DNA replication stresses induced either by hydroxyurea, which diminishes the dNTP pools, or by HU, an antibiotic that specifically inactivates the essential DNA polymerase, PolC (not shown).

The exact nature of the defects provoked by a dysfunction of the replisomes made with the mutated DnaN or DnaX proteins is not known. These defects could be either fork arrest or lesions left by continuing forks. These results provide evidence that the SSB>Cter is crucial for ensuring the proper duplication of a genome damaged by stresses that specifically impair the replisome.

**Discussion**

In this study, we have extended the number of known B. subtilis proteins involved in the SSB>Cter interactome and targeted to active...
Figure 4. The SSB<sub>core</sub> is crucial for optimal cell growth and genome maintenance. (A) Growth kinetics of ssb<sup>+</sup> (triangles) and ssb<sup>-</sup> (squares) strains in LB supplemented with erythromycin and IPTG at 37°C. Growth was followed by monitoring A<sub>650nm</sub> (dashed lines) and Colony Forming Unit/ml (CFU, solid lines) as a function of time. (B) UV sensitivity of ssb<sup>+</sup> (squares), ssb<sup>Δ35</sup> (triangles) and recA<sup>+</sup> (circles) cells grown in LB at 37°C with appropriate antibiotics. (C) Western blot analysis of SSB and SSB<sub>Δ35</sub> proteins in ssb<sup>+</sup>, ssb<sup>Δ35</sup> and ssb<sup>Δ35</sup> Pxyl:ssb cells grown in presence (+) or not (−) of D-xylose in the medium. Analyses were done as described in Materials and Methods. Signals corresponding to SSB and/or SSB<sub>Δ35</sub> are indicated on the left of the membrane. (D) UV sensitivity of ssb<sup>+</sup> (squares), ssb<sup>Δ35</sup> (triangles) and ssb<sup>Δ35</sup> Pxyl:ssb (diamonds) cells grown in LB supplemented with erythromycin, IPTG and 0.2% D-Xylose. For A, B and D, one typical experiment is reported (they have been reproduced at least 3 times with independent clones and led to similar results). (E) Measurement of the MMC-induced SOS response in ssb<sup>+</sup>/P<sub>lexA- lacZ</sub> (squares) or ssb<sup>Δ35</sup>/P<sub>lexA- lacZ</sub> (triangles) strains. Absorbance at 650 nm of treated (gray dashed lines) and untreated (gray continuous lines) cultures was monitored after MMC treatment (40 ng/ml added to the cultures at time 0 min). β-galactosidase specific activities were measured using extracts prepared from treated and untreated cells at different times after addition of MMC (see Materials and Methods). Ratios of β-galactosidase activities of treated to untreated cells for each time point are plotted (black lines). Error bars indicate the standard deviation from the mean calculated from two independent experiments.

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chromosomal DNA replication forks. It includes at least 9 additional members (Table 1), in addition to the PriA, RecG and RecQ DNA helicases [8]. Collectively these constitute a multipurpose DNA processing toolbox able to unwind, replicate or cleave DNA and to promote homologous DNA recombination. Replication forks can consequently marshal a large repertoire of enzymes for their rescue or for preventing their accidental arrest. This is revealed by an increased sensitivity to a variety of replication stresses of B. subtilis cells carrying an ssb allele truncated for its C-terminal domain, SSBCter (Figure 6). Thus, in addition to assisting the activities of the enzymes of the replisome by polymerizing along ssDNA via its Nter domain, SSB provides constant support for fork progression via its Cter domain by mediating multiple DNA transactions. It does so by concentrating a specific subset of proteins of the DNA recombination, repair and replication machineries at active forks.

The SSBCter acts as a general hub of DNA maintenance proteins

SSB is not the only source of accessory proteins at the replication fork. DnaN and the replicative helicase also act as anchors for distinct replication accessory proteins (for reviews, see [5,40]). While DnaN and the replicative helicase are expected to be confined to replication forks, the spectrum of SSB activity on the genome could be larger since its localisation is primarily determined by availability of ssDNA. Assembly of the SSB interactome at a precise site on the genome is nevertheless expected to be qualitatively and quantitatively modulated by the length of the ssDNA available for SSB polymerisation. Indeed, the local concentration of SSBCter will increase with the length of the SSB-ssDNA nucleofilament. With an average length of 1 kb for single strand DNA on the lagging strand template at an active bacterial DNA replication fork and a binding mode of SSB of ~65 nts per tetramer, a minimum of ~60 copies of SSBCter may be present at each fork. This would generate a filament capable of attracting many molecules of the different SSB interactome members. Consequently, chromosomal DNA replication forks constitute permanent subcellular sites for assembling the SSB interactome anywhere on the genome (as in the case of the repair of DNA double-strand breaks). Thus, the DNA toolbox associated with the

Figure 5. RecO overexpression suppresses temperature-sensitive growth of ssbΔ35 cells. (A) ssb3+ and ssbΔ35 cells (as indicated on the left of the pictures) were grown to mid-log phase at 37°C in LB with (+ xyl) or without (− xyl) 0.2% D-xylose, serially 10 fold diluted, spotted on agar plates containing the same medium and incubated at 37°C or 52°C. (B) Identical spot assay as in (A), with the Pxy:recO-SPA construct inserted at amyE. (C) Identical spot assay as in (B) in a recA background.

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SSB<sub>Cter</sub> should not be considered as exclusively devoted to the progression of replication forks. In contrast to DnaN and the replicative helicase, the SSB<sub>Cter</sub> may therefore be a general determinant for the maintenance of genome integrity.

**The SSB<sub>Cter</sub> interactome is specific**

Comparison of the SSB<sub>Cter</sub> interactome of *E. coli* (compiled in [6]) and that determined here for *B. subtilis* provides several important general conclusions concerning SSB<sub>Cter</sub> function.

Homologues of prominent <i>Ec</i>SSB partners such as PriA, RecQ, RecG, RecJ, RecO and Ung which are conserved in *B. subtilis* (and generally widespread in bacteria) have also been demonstrated to interact with *B. subtilis* SSB. This points to a strong selective pressure in maintaining such a conserved and abundant SSB<sub>Cter</sub> interactome. In this study, we have identified additional *B. subtilis* SSB partners (i.e. RarA, SbcC and XseA) also widely conserved in bacteria (including *E. coli*) but not yet identified as part of the <i>Ec</i>SSB interactome. Conversely, we have not yet identified other known conserved <i>Ec</i>SSB partners, such as DnaG primase and Topoisomerase III [41,42], in the SSB interactome of *B. subtilis*. Further experiments will be required to determine whether these proteins are indeed members of the SSB interactome.

*B. subtilis* SSB partners that are not widely conserved in bacteria have also been identified, e.g. YrrC (a putative helicase/nuclease encoded in the genomes of gram positive bacteria also annotated as RecD) and the YpbB/RecS complex (see Figure S1). Conversely, <i>Ec</i>SSB partners, such as the <i>χ</i> subunit of the <i>Ec</i>Holopolymerase III [43,44], have no equivalent in *B. subtilis*. Thus, the interactome of SSB also includes some specific proteins representative of subgroups of bacteria. This reveals particular needs in genome metabolism, suggesting that not all bacteria require these functions and/or have evolved distinct alternative strategies to execute identical functions.

Another specific part of the *B. subtilis* SSB<sub>Cter</sub> interactome is the replisomal DNA polymerase DnaE [28]. Neither its homologue PolC, nor any other known proteins of the *B. subtilis* replisome, depend on the SSB<sub>Cter</sub> for their targeting to active chromosomal forks (Table S1). DnaE remains essential for viability of <i>ssbΔ35</i> cells (not shown). Interestingly, it has recently been shown that the essential role of DnaE in the replisome is to elongate a short DNA stretch on the RNA primers synthesized by the DnaG primase before a hand-off to the bona fide replicative polymerase, PolC [45]. Thus, DnaE has presumably evolved distinct interactions with the replisome to functionally link the activities of DnaG and PolC. However, these interactions are not strong enough to produce detectable fluorescent foci with the DnaE-GFP fusion at active forks in <i>ssbΔ35</i> cells. In line with this reasoning, the DnaE interaction with the SSB<sub>Cter</sub> might serve an additional role. *E. coli* encodes a single DNA polymerase of the DnaE family, which is not part of the <i>Ec</i>SSB interactome [6]. In contrast, the <i>Ec</i>DNA polymerase II (<i>Ec</i>PolII) has been found to interact with the <i>Ec</i>SSB [46]. <i>Ec</i>PolII is not essential for the cell, is involved in distinct pathways of replication re-activation and belongs to the *E. coli* SOS system [47]. Remarkably, *B. subtilis* <i>dnaA</i> also belongs to the SOS regulon [48]. This raises the possibility that *B. subtilis* DnaE might also be involved in certain fork maintenance pathways, as demonstrated for many members of the SSB interactome.

**The SSB<sub>Cter</sub> is needed for RecA loading**

A central piece of the SSB interactome is RecO, which acts with RecR and RecF to direct the loading of RecA on SSB-coated ssDNA [49]. Temperature sensitivity of <i>ssbΔ35</i> cells can be suppressed by RecO overexpression, and in a RecA-dependent manner. This shows that ssDNA accessible to RecA is generated in...
SSB and Replication Fork Maintenance

Defining the role of the SSBCore in the rescue of arrested forks

Together, these results support a model in which the SSBCore interactome associated with active forks provides a series of solutions for promoting their restart upon accidental blockage (Figure 7), as well as for dealing with errors left behind the passage of the fork. A key step is replisome assembly on the branched DNA backbone of the fork. The PriA protein and its interaction with the SSBCore are central to this event [8]. This could be the only response necessary if arrest is due to replisome dismantling. In more complex situations, other actions aim at protecting and/or clearing the fork, via individual or concerted actions of the many members of SSBCore interactome. DNA repair is obviously crucial. This could be handled either immediately by the proteins already present, or delayed via RecA loading that could then act in two ways. RecA may reconstruct the fork by homologous recombination, and may induce the SOS response to provide more effectors for DNA repair. Amongst the new effectors coming into play are the error-prone DNA polymerases. Interestingly, it has been shown that the recruitment of E. coli PolIV at the 3' end of a DNA gap flanked by RecA filaments is increased by an interaction with the priA SSBCore [51]. A distinct class of repair pathways not drawn in the model of Figure 7, are those acting on lesions caused by the repressor but not accompanied by fork arrest. ssDNA gaps are prominent examples of such lesions. In such cases, ssDNA gaps are expected to remain coated by several copies of SSB still interacting with or attracting the proteins that will promote repair.

In conclusion, the SSBCore emerges as a general maintenance pivot of bacterial genome integrity. Long stretches of ssDNA are intimately associated with the functioning of active bacterial forks. These form primary targets of SSB in living cells and, consequently, of its interactome. One consequence is that replisomes of chromosomal forks are escorted throughout their progression along the bacterial genome (generally for more than 2 Mbp per fork, as in the case of E. coli and B. subtilis model bacteria). In addition and in a reciprocal way, the forks behave as vehicles for many DNA repair proteins, providing also a convenient way to scan DNA integrity during genome duplication.

Materials and Methods

Bacterial strains and plasmids

B. subtilis strains used in this study, all based on the 168 or L1430 derivatives, are listed in Table S2 along with the strategies used for their construction. They were propagated in LB medium supplemented, unless otherwise indicated, with appropriate antibiotics (erythromycin, 0.6 μg/ml; spectinomycin, 60 μg/ml; chloramphenicol, 5 μg/ml; tetracycline, 15 μg/ml; phleomycin, 2 μg/ml). ssk3, sshD, sshD6 and all strains carrying a gene tagged with the SPA motif at its locus were maintained with IPTG (1 mM). Expression of a gene under the PcrA promoter was achieved by adding 0.2% of D-xylose to the medium. All new chromosomal structures were verified by PCR using appropriate pairs of primers. In case of insertions at the amyE locus, these were also verified by the loss of amylose activity on starch containing media plates.

E. coli strains used were MIT898 [15] for plasmid constructions and ER2566 from NEB, Rosetta (DE3 pLys) or BL21-Gold (DE3) from Novagen for protein expression and purification.

All plasmids used in this study are listed in Table S3. Details of their construction are presented in Text S1.

Microscopy and analysis of the localization patterns

Microscopy analyses were done as described previously [8]. Cells, grown at 30°C until mid-exponential growth phase in LB medium supplemented with appropriate antibiotics and 0.2% D-xylose, were examined with a Leica DMRA2 microscope equipped with a ×100 magnification oil-immersion objective and a COOLSNAP HQ camera (Roper Scientific, USA). Images were captured and processed with METAMORPH V7.5r5.

Tap-tag of SPA fusions in B. subtilis

Except for SSB, the SPA purification tag [32] was joined to the 3’ end of each gene candidate at its original locus. Tandem affinity purifications were performed as previously described [9] with slight modifications, which are detailed in Text S1.

Purification of the proteins produced in E. coli

Purification procedures of all the proteins produced in E. coli used in this study are described in Text S1.
Pull-down assays on magnetic ssDNA beads coated by SSB proteins

25 μl of Dynabeads M-280 streptavidin per assay (Invitrogen) were incubated 15 min at 4°C in 20 mM Tris-Cl pH 7.5, 2 M NaCl with 50 pmol of a 65-mer oligonucleotide 5'-CGTCGT-TTACAAACGTCTCCTGGAGAACCCTTGCGTTACC-CAAGTTAATCGCGTTGAGCA-3' biotinilated (with biotin TEG; GeneCust). Beads were washed with 200 μl of the same buffer, resuspended in 200 μl of buffer B (20 mM Tris-Cl pH 7.5; 200 mM NaCl) supplemented with 80 pmol of purified SSB or SSBΔ6 and incubated at 20°C under agitation (300 rpm) in a 96 wells plate in a Thermomixer (Eppendorf). Beads were washed in 200 μl of buffer B and resuspended in 200 μl of the same buffer supplemented with various quantities of purified DnaE, PcrA, RecO, RecG, RecQ, or RarA proteins as indicated in the figures. After 30 min of incubation at 800 rpm and 20°C, beads were washed in 200 μl of buffer B, drained and resuspended in 10 μl of SDS-PAGE loading buffer. The proteins were separated on 14% SDS-PAGE and revealed by Coomassie blue staining.

Cell survival assays

Spot assays were used to measure the viability of *B. subtilis* strains used in this study. O/N cultures, incubated at 30°C or 37°C, as indicated in the figure legend, were diluted in fresh LB medium at the same temperature supplemented as indicated in the figure legend with erythromycin, IPTG and with or without D-xylose. At mid-log phase (A650nm<0.3), 10 μl of 10-fold dilutions (10^1 to 10^-2) in Figure 5 and 10^-1 to 10^-5 in Figure 6) were spotted on LB agar plates containing the same antibiotics and inducers as those used in the liquid culture. Plates were then incubated O/N at different temperatures (as indicated in the figure legends). In UV resistance assays, plates were exposed to UV irradiation at the indicated doses prior to O/N incubation at 37°C. Colonies were counted after 24 or 48 hours of growth (depending on their growth rate and/or the incubation temperature). Cell survival was expressed as the ratios of the CFU (Colony Forming Units) of UV-treated to untreated cells or of CFU obtained at the tested temperature to CFU obtained at 37°C (Figure 5) or 30°C (Figure 6) for each strain.

SOS response assays

O/N cultures of strains containing the *PlexA: LacZ* cassette at *amyE* were propagated at 37°C in LB medium supplemented with erythromycin, spectinomycin and IPTG. Cells in exponential phase (A650nm<0.03), obtained by inoculating O/N cultures in fresh LB medium supplemented with erythromycin and IPTG, were treated or not with 40 ng/ml MMC to induce or not the SOS response respectively. Sample of ~0.5 ml pe unit of A650nm were taken from cultures every 30 min and treated as described previously [53] for the determination of β-galactosidase activity, expressed in nmol of ONP produced per minute and per mg of protein.

Western blot analysis

Whole protein extracts and western blot analysis were done as previously described [8] with slight modifications as reported in Text S1.

Supporting Information

Figure S1 (A, B) The *ypbB-recS* locus organization is conserved in the *Bacillales* and *Lactobacillales* Orders. A search for *B. subtilis* *ypbB-recS* locus type organisation was done on all sequenced bacterial genomes using the Region Genome Comparison tool.
from JVCI ([59]; a minimum of 40% similarity was used). 53 ypbB/recS locus type organisations were identified ([panel A, a total of 526 sequenced genomes was used]. The number of sequenced genomes containing a ypbB-recS locus type is given and compared to the total number of sequenced genomes in different groups of bacteria. Examples of four ypbB/recS loci are given in panel B in three Bacillales (B. subtilis 168, Staphylococcus aureus subsp. aureus MRSA252 and Listeria monocytogenes EGD), and one Lactobacillales (Lactobacillus plantarum WCFS1). Coordinates of these genes on the chromosome are indicated. (C) YpbB displays significant sequence similarities with the C-terminal part of some extended RecQ proteins. A search for proteins with homology to YpbB in bacteria using the sequence of B. subtilis YpbB and the NCBI Blast tool [59] has led to the identification of YpbB proteins in Firmicutes (all associated with a RecS homologous protein). Surprisingly, sequence similarity was found between YpbB and the C-terminal part (approximately the 300 last amino-acids) of proteins annotated as RecQ in different bacteria. All the sequences of these proteins are longer (more than 700 residues) than canonical RecQ from B. subtilis (590 residues) or E. coli (610 residues). An example of this similarity is shown in the panel C by the alignment of YpbB with the C-terminal domain of RecQ2 of Bacillus cereus ATCC10987 (Rec 2B42). Found at: doi:10.1371/journal.pgen.1001238.s001 (0.49 MB TIF)

**Figure S2** RecS and YpbB form a complex able to interact with SSB in vitro. Purified RecS (4 μM) or YpbB/RecS (4 μM) were mixed on ice with SSB (16 μM in panel C, or 40 μM in panel E) and loaded onto a gel-filtration column. Final concentrations for proteins correspond to their monomeric forms. Fractions (0.5 ml, numbered on the top of the gels) were analyzed by 12.5% SDS-PAGE and Coomassie blue staining. Molecular masses in kDa of standard proteins used to calibrate the sizing column are indicated below the last gel. RecS does not stably interact with SSB, as judged by its identical elution from the column when loaded alone or mixed with SSB. (compare panels A and C). By contrast, RecS associates into a complex with YpbB, as judged by a shift in its elution from the column (compare panel A and D). Equivalent amounts of YpbB and RecS appear to be present in the complex. Notably, the apparent molecular mass of RecS is lower than its theoretical mass (43 kDa versus 57 kDa). The same is true for the YpbB/RecS complex, the apparent mass of which is 65 kDa compare with the theoretical mass of 98 kDa if made of one monomer of RecS and of YpbB. These differences argue for a non globular shape of RecS. Finally, the elution of YpbB/RecS complex from the sizing column is further upon mixing with SSB, indicating that the YpbB/RecS complex interacts physically with SSB (compare panels D and E). Found at: doi:10.1371/journal.pgen.1001238.s002 (0.95 MB TIF)

**Figure S3** The PcrA and DinG DNA helicases fused to the GFP do not form foci on the nucleoid of B. subtilis and do not interact directly or indirectly with SSB. (A) GFP and DAPI fluorescent signals in exponentially growing cultures of B. subtilis cells carrying GFP fused to the N-terminus of PcrA (on the left) or DinG (on the right) produced by induction of the PcrA (on the left) or DinG (on the right) promoter. Cells were grown in LB supplemented with 0.2% D-xylene. (B) Isolation and identification of protein complexes containing the PcrA-SPA (on the left) or the DinG-SPA (on the right) protein. Cell extract was prepared and treated as described in [Material and Methods]. Proteins were analysed by SDS-PAGE and Coomassie blue staining. Visible bands were analysed by MALDI-TOF mass spectrometry. PcrA* or DinG* indicates PcrA or DinG degradation products respectively. Unannotated bands corresponding to proteins that gave neither a spectrum nor a match in the predicted B. subtilis proteins database. Contaminants most often recovered by Tap-tag from B. subtilis have been indicated in italic, as a matter of distinction with the others considered as specific partners. Found at: doi:10.1371/journal.pgen.1001238.s003 (0.63 MB TIF)

**Figure S4** A pull-down assay for testing protein interaction with the B. subtilis SSBrecS domain. Pull down assays of interaction between purified RecQ (panel A), RecG (panel B), and PcrA (panel C) proteins and SSB or SSB6 bound to 5’ biotinylated ssDNA oligonucleotides linked to magnetic streptavidin beads (see details in Figure 2).

**Figure S5** Pull-down assay of interaction between PriA, RecG, DinE, and SSB or SSB35. Experiments were performed as described in Figure 2 and Figure S4 with purified SSB35 instead of SSB6. In this experiment, 60 pmol of PriA (lanes 1 and 2), RecG (lanes 3 and 4), or DinE (lanes 5 and 6) (indicated by a black triangle on the 14% SDS-PAGE Coomassie-stained) were added to ssDNA magnetic beads coated by 100 pmol (in tetramer) of SSB (lanes 1, 3 and 5) or SSB35 (lanes 2, 4 and 6).

**Figure S6** SSB interacts with RarA. Further validation of SSBrecS-dependent interaction between RarA and SSB by gel filtration. RarA (25 μM) and/or SSB or SSB6 (25 μM) were mixed on ice and loaded onto a gel-filtration column. Final concentrations for proteins correspond to their monomeric forms. Fractions (0.5 ml, numbered on the top of the stained gels) were analyzed by 12.5% SDS-PAGE and Coomassie blue staining. Molecular masses of standard proteins are indicated. Found at: doi:10.1371/journal.pgen.1001238.s004 (0.51 MB TIF)

**Figure S7** Co-localization of YFP-RecO with DnaX-CFP at B. subtilis active chromosomal forks. A. YFP (yellow), CFP (blue) and overlay of both fluorescent images in RecO+ cells carrying the TFP-recO and dnaX-CFP constructs. Experiments were done exactly as for co-localization of PriA and DnaX in [8]. Visible CFP and YFP foci are indicated by white triangles. B. Statistical analysis of the co-localization of DnaX-CFP and YFP-RecO. The percentage of co-localized and individual foci of the two fusions have been calculated from 756 scored foci.

**Figure S8** SSBrecS deletion induces various morphological defects. (A) Growth kinetics in LB medium supplemented with erythromycin and IPTG at 37°C of the ssb35 strain (triangles) and ssb35 control strain (squares). Growth was followed by monitoring Colony Forming Units (CFU)/ml as described in Figure 4A. Error bars indicate the standard deviation from the mean calculated from two independent experiments. (B) The viability defect of the ssb35 strain is accompanied by cell (B) and/or nucleoid (C) morphological defects throughout the growth period. These defects were observed by phase contrast (black), or by FM4-64 (red) and DAPI staining (blue), which allow visualization of the membrane and the nucleoid, respectively. Morphological types (B) observed during growth of ssb35 and/or ssb35 cells are classified into three groups: (i) normal cell morphology (normal); (ii) very long cells with a septation defect generating filaments (filamentous) and (iii) cells lacking nucleoid for which membranes were clearly visible (anucleated, indicated by a white arrow) or almost undetectable (phantom) after FM4-64 staining and observation with an epifluorescence microscope. Nucleoid morphology (C) observed in ssb35 and ssb35 cells are classified (i) normal, (ii) small, (iii) guillotine (when bisected by a septum; white arrow). For each strain, at least 150 cells for each
time point were observed and classified into the previously described groups.

Found at: doi:10.1371/journal.pgen.1001238.s008 (0.64 MB TIF)

**Figure S9** ssbΔ cells suffer the same growth defects and sensitivity to UV and MMC as ssbΔ35 cells. (A, B) Growth kinetics of ssbΔ35 (triangles), ssbΔ6 (circles) and ssbΔ34 (squares) strains in LB supplemented with erythromycin and IPTG at 37°C. Growth was followed by monitoring $\Delta A_{600}$ (A) and Colony Forming Unit/ml (CFU, B) as a function of time. (C) UV sensitivity of ssbΔ6 (squares), ssbΔ35 (triangles) and ssbΔ6 (circles) cells grown in LB at 37°C with erythromycin and IPTG. (D) MMC sensitivity of ssbΔ6 (squares), ssbΔ35 (triangles) and ssbΔ6 (circles) cells grown in LB at 37°C with erythromycin and IPTG. For all panels, an average of at least three independent experiments is reported. Error bars indicate the standard deviation from the mean calculated from all independent experiments.

Found at: doi:10.1371/journal.pgen.1001238.s009 (0.23 MB TIF)

**Table S1** Average number of GFP foci per nucleoid of *B. subtilis* SSB proteins partners fused to GFP in ssbΔ3 or C-terminal mutant of ssb. GFP fusion proteins were visualized by GFP fluorescence and nucleoids by DAPI staining. The average number of foci per nucleoid is presented in the right hand column.

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**Table S2** *B. subtilis* strains used during this work. a. ssbΔ34, ssbΔ35 and ssbΔ6 encode wild-type and C-terminal truncated forms of SSB, respectively. In these three strains, the essential ssbR gene, which is located immediately after ssb, is placed under the control of a P$_{pap}$ promoter. b. These strains were constructed by transformation of competent FLB22 or FLB23 or FLB25 cells with the genomic DNA of the corresponding 168 $\Delta$ssb$_{3}$ $\Delta$ssb$_{5}$-gfp-gene strain. c. These strains were constructed by transformation of competent FLB22 or FLB23 or FLB25 cells with pSG1729 or pSG1154 derivatives. d. SPA tagged genes are under the control of their natural promoter, and the downstream _afs_ are under the control of the IPTG inducible P$_{pap}$ promoter. e. These strains were constructed by transformation of competent 168 cells with JJS100 genomic DNA or pFL43. f. FLB52 cells were transformed with FLB22, FLB23 or MAS617 genomic DNA. g. FLB53, FLB54 and FLB53 cells were transformed with FLB56 genomic DNA. h. These strains were obtained by transformation of the corresponding parental strains with genomic DNA from the HVS567 strain. i. These strains were constructed by transformation of 168 $\Delta$ppf, $\Delta$ink3 cells with genomic DNA of FLB22 or FLB23 cells (i) then by plasmid pFL43 (jj). k. These strains were constructed by transformation of FLB53 or FLB54 cells by JJS100 genomic DNA. l. These strains were constructed by transformation of PPBJ17 competent cells by pSMG205. Θ indicates insertion/duplication of the _recO_ gene at its chromosomal locus, generated by plasmid integration.

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**Table S3** Plasmids used and constructed during this work. a: antibiotic resistance markers Ap: ampicillin; Ery: erythromycin; Spec: spectinomycin; Phleo: pleomycin; Kan: kanamycin.

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**Text S1** Supplementary materials and methods.

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**Author Contributions**

Conceived and designed the experiments: AC FL SQC PP. Performed the experiments: AC FL SM SQC PP. Analyzed the data: AC FL SM SQC PP. Contributed reagents/materials/analysis tools: PP. Wrote the paper: FL PP.

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